

Macro Viscous Regime of Natural Dense Granular Mixtures

Anna Maria Pellegrino and Leonardo Schippa

Department of Engineering, University of Ferrara, Italy

ABSTRACT: An experimental study was carried out on several dense-granular mixtures (debris flow mixtures and natural sand mixtures) using several rheometrical tools in order to investigate the rheological behaviour of the “fluid-like” material mixture. The results obtained on debris flow-water mixtures suggest that, in the fluid-like regime, the typical rheological behaviour is that of yield stress fluids and the rheology is strongly dependent on the grain concentration. The velocity profile obtained on natural sand-Newtonian fluid mixtures identify the shearing zone and explain the dependence of the flow characteristics (i.e., transition from quasi-static regime to liquid regime) on viscosity and shear rate. The results suggest that, in that field, the interstitial fluid viscosity influence the shearing material layer and that no flow is possible for solid fraction higher than a maximum value.

Keywords: Dense granular suspensions, Rheology, Solid concentration, Viscosity, Creep test, Velocity profile

1. INTRODUCTION

The study of dense-granular materials became a very important subject in many areas of science and technology [1]. These materials have a lot of physical properties still not well understood and their behaviour can be very complex. The description of geophysical granular flow is not easy because of the uncertainty in the constitutive equations for the flow of granular materials. Most aspects in the physics of granular materials systems remain obscure as the case of shear localization, non Newtonian rheology, intermittent flow regimes, size segregation, etc. [2]. In this field there are also the mixtures composed by fine and coarse natural sediments dispersed in a more or less dense fluid. Typically, this kind of soils is involved in landslides phenomena such as debris flows or mud flows.

In the last 50 years, the risk of landslides has increased enormously. The soil characteristics have already been explored, but there is still a lack of studies focused on the properties of the ‘post-failure’ material. In fact, after starting, these materials are in a viscous-like regime in which the material flows like a fluid. The flow properties of these materials are not so easy to describe and the lack of informations has recently motivated many experimental, numerical and theoretical works but it is still difficult to extract common features and general trend for granular flows. Generally speaking, dense granular flow materials are usually divided into three groups depending on the flow velocity [1]. First, at low velocities, a quasi-static regime in which the grain inertia is negligible and the material is often described using the soil models. Second, at very high velocities, a “gaseous” regime (i.e., the medium is strongly agitated and particles interact through binary collisions) for which a kinetic theory has been developed. The last intermediate regime is the “dense flow regime” in which the grain inertia plays a significant rule but a contact network still exists, i.e. the particles experience multi-contact interactions. This is a viscous like regime in which the material flows more like a fluid. In the field of dense granular fluid mixtures there are also the debris flow material mixtures, on the rheological behaviour of which this paper is focused. The flow behaviour of these mixtures has been considered to be controlled by the rheological

properties of the ‘matrix’, i.e. a mixture of fine (colloidal) sediment and water in which coarse particles are dispersed [10]. Ideas developed on the work of Bagnold [3] are used to describe the flow behaviour of these mixtures: beyond a critical solid concentration (i.e., the ratio of the volume of solids to the total volume) the transition between a colloidal regime and the hydrodynamics regime correspond to a viscoplastic flow behaviour [4]. Most flow models based on the mechanics of granular media have been developed to describe the motion of dry granular flows and particle-fluid suspensions. Unfortunately, for the debris flow material mixtures these mentioned approaches do not provide a unique rheological formula for the solid-fluid composite. Instead, models that employ a fixed rheology of debris flow material mixtures provide an effective alternative. In this frame, the bulk debris flow material mixtures properties can be characterized by relating shear stress to shear rate (i.e., gradient of velocity in a flowing material) and material parameters using viscosity and yield stress (i.e., the stress at which a material begins to flow) as key variables in a rheological approach [5]-[6]-[7]. Within the frame of a fluid mechanics treatment, the rheological characteristics of this flowing material would be useful for a better understanding of the flow characteristics of such events. In this paper, interesting information in that field has been got by studying the rheological characteristics of a debris flow dry soil remixed with different amounts of water and natural monogranular sand remixed with Newtonian fluids having different viscosity. These are materials that may behave like a yield stress fluid and their rheological parameters are strictly related to grain characteristics (i.e., size, shape, etc) and to interstitial fluid viscosity [3]-[5]-[6]-[7]. The material mixtures have been investigated with a conventional rotational rheometer and with a large scale rheometer. On one hand, with a conventional rheometer it is possible to analyze the rheological behaviour of the debris flow material considering a 70% of the whole grain size distribution, to study the changing of the rheological parameter with the variation of the solid fraction and to investigate the influence of the shear rate. On the other hand, with a large scale annular rheometer it is possible to analyze the rheological behaviour of a large particles mixtures (i.e., the monogranular-sand suspensions) and the influence of the grain size and of the interstitial fluid viscosity on different

characteristic flowing parameters. The rheological interpretation has been kept in order to assess the possibility of a simple evaluation of rheological parameters for natural material and to evaluate the possibility to use rheological parameters in numerical simulation for a practical hazard assessment [14].

2. MATERIALS

The debris flow material analyzed has been sampled from the source area of debris flows occurred in Nocera, southern Italy, on March 2005 [8]. The soil type, in a thickness of about a meter, depends on the most recent pyroclastic deposits deriving from the volcanic activity of Mount Somma/Vesuvius. The grain size distributions of the collected sample are reported in Fig. 1: the soil is sandy silt with a small clay fraction. The bedrock underlying the soil is limestone, the specific gravity of soil particles is 2.61, the dry and total weight of soil per unit volume are respectively 9.08 and 11.35 kN/m³ and the porosity is 0.66. With the debris flow material, it has been decided to perform tests on the soil fraction with a particle diameter less than 0.5 mm, in order to respect at best the continuum assumption (it is necessary to have sample thickness in the rheometrical apparatus much larger than the particle size in the material). Doing so retains about 50–70% of the whole grain size distribution, as shown in Fig. 1. In fact, according to the mixtures involving debris flow material and water, it is not possible to determine exactly how much of the dry material contributes to the formation of interstitial fluid (i.e., composed by water and smaller particles) and how much of the material set up the solid phase of the mixture (see Fig.2). All the experiments involving debris flow materials have been carried out with mixtures of dry soils with different amounts of water. The solid concentration is described with the help of the solid volume fraction Φ , that is, the ratio of the volume of solids, V_s , to the total volume V_T (volume of water V_w plus volume of solids) of the sample, as reported in the following:

$$\Phi = V_s / (V_s + V_w) \quad (1)$$

For each material tested, material mixtures of about 500 ml have been prepared, mixing soils and distilled water with an electronic mixer (at about 30 rev/min) for 15 min. Then a sample volume of about 30 ml has been used for each test at a constant temperature (23°C). The natural sand analyzed (Fig. 2) have uniform granulometric distribution ($d=1.4-1.68$ mm). The shape of the grains is irregular and the density is equal to 2670 Kg/m³.

All experiments have been carried out with mixtures of dry sand remixed with different fluids: clear water (low viscosity interstitial fluid, 0,001 Pa·s), Glycerine B (medium viscosity interstitial Newtonian fluid, 0,394 Pa·s) and Glycerine C (medium viscosity interstitial Newtonian fluid 0,598 Pa·s). The combinations of fluid and grains lead to mixtures of fluid and irregular grains having solid-fluid density ratios ranging from 1 to 3. According to [3] the linear concentration λ , i.e. the ratio between particle diameter and their relative distance, related to the actual concentration Φ and to reference concentration Φ_0 (i.e. the concentration at which all particles are in reciprocal contact) has been used as reported following:

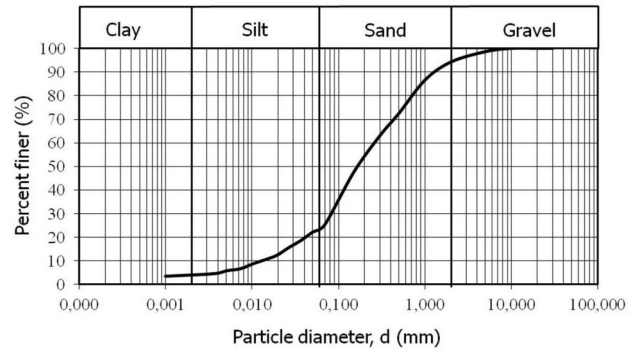


Figure 1 Grain size distribution of the collected debris flow material.



Figure 2 Tested materials. a) debris flow material; b) natural sand.

$$\lambda = \left[\left(\frac{\Phi_0}{\Phi} \right)^{\frac{1}{3}} - 1 \right]^{-1} \quad (2)$$

As reference concentration Φ_0 , the maximum packing concentration $\Phi_m=0.56$ has been used. It is important to note that in the case of the natural sand has been possible to accurately determine the maximum packing concentration (for the detailed procedure see [7]) while for the debris flow material it has been simply deduced (for the detailed procedure see [6]).

3 EXPERIMENTAL SETUP AND PROCEDURES

A rotational rheometer CVOR (Bohlin Instruments) equipped with a vane rotor geometry system had been used in order to analyze the debris flow material mixtures. It consists of four thin blades arranged at equal angles around a small cylindrical shaft. The blade radius is $R_1=13$ mm, and the blade height was $L=48$ mm. The vane rotor has been immersed in the sample (the sample volume was roughly 27 ml) contained in a cylindrical cup of radius $R_2=18.5$ mm. During the test, a part of the material is trapped in the blades so that as a first approximation the flow characteristics are similar to those between two solid coaxial cylinders, with the inner radius equal to that of the blade [10]. Under usual assumptions (no inertia effects, negligible normal stress differences) one can estimate the shear stress τ and the shear rate $\dot{\gamma}$ within the material from the following formulae:

$$\tau = T / (2\pi R_1^2 L) \quad (3)$$

$$\dot{\gamma} = \Omega R_1 / (R_2 - R_1) \quad (4)$$

Where T is the torque (N·m) and Ω is the angular velocity (rad/s). It should be noted that although these equations neglect stress heterogeneity. It has been also possible to

define the deformation undergone by the material from the initial time. At time t , the deformation γ is equal to:

$$\gamma = \int_0^t \dot{\gamma} dt \quad (5)$$

Stress sweep tests have been carried out, which consist in measuring the apparent flow curves by applying an increasing shear stress ramp. The shear stress has been continuously increased in a logarithmic way from 0.1 Pa to a large (maximum) value, and the corresponding shear rate has been measured. The maximum stress value has been determined for each sample from independent (rheometrical) tests under similar technical conditions: getting a rapid flow in the liquid regime without fluid expulsion out of the geometry. The total duration of this sweep is 60 s. The complete procedure consists of setting up the material inside the geometry, immediately imposing a pre-shear at the maximum stress value above described for 30 s, and then starting the sweep test. This pre-shear homogenizes the sample. Also some creep tests have been carried out, which consisted of imposing a constant stress and measuring the induced deformation of the material over time. The deformation is expressed in terms of the angle of rotation of the inner cylinder since the initial application of the stress. A complete test consists of imposing various values of stress, preparing each sample in the same initial state before each new stress value. A large scale annular rheometer has also been used, which consists of two concentric horizontal aluminium circular disks assemblies mounted on a vertical shaft fixed on the basement of the apparatus as showed in Fig. 3. The lower disk assembly is mounted on the shaft with two roller bearings allowing rotation but no vertical motion. The lower disk is restrained from rotating by a torque arm connected to a load cell. This lower part has an annular trough 100 mm wide and 35 mm deep and has a mean radius of 200 mm; it is therefore called channel. The channel is closed above by a heavy rotating upper disk assembly mounted on the same vertical shaft through two roller bearings allowing both rotation and vertical movements. In the lower part of the upper disk assembly there is a horizontal plate which lodges in the cavity of the lower disk and thus forms the ceiling of the channel. On the outer part of the top disk assembly there is a cogged wheel coupled to the gear of a d.c. variable speed servomotor that can induce any velocity of the upper disk in the range 0-2.0 m/s. The rotation rate of the motor is monitored by means a disk having 90 mm of diameter which is coaxial to the axis of the motor. The disk has many equidistant holes on its outer circumference and it is coupled to a photodiode; a pulse is generated each time a hole passes in front of the photodiode. The angular velocity is obtained by recording the pulse rate and, knowing the size of the gear and of the cogged wheel, the rotation speed of the upper plate of the shear cell is easily obtained. The vertical displacement of the upper disk is measured, with respect to the channel bottom, via a cable linear position transducer. The normal stress applied to the granular was obtained via a system of counterweights balancing the upper disk. It is possible exerting any pre-assigned mean vertical pressure in the range $0-3 \times 10^3$ Pa. The surfaces of the upper (i.e. the ceiling of the channel) and of the lower disk (i.e. the bottom of the channel) were made rough with a glued sand paper sheet having a roughness of about 1.2

mm.

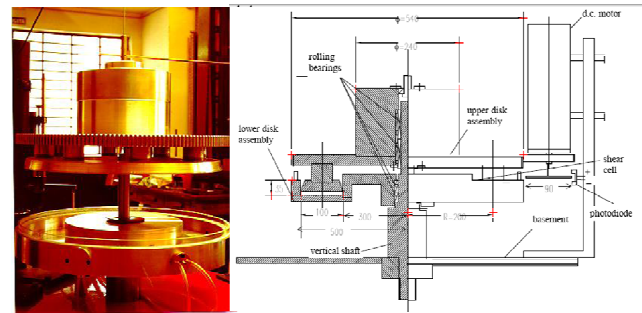


Fig. 3 Large scale annular rheometer: apparatus and section (from [7]).

The stress transmitted to the lower disk, the velocity and the vertical displacement of the upper disk are monitored during a test, while pre-assigned vertical pressure remains constant. The channel is also provided in the external sidewall with two glass windows (having an angular distance of 90° with respect to the rotational axis) in order to allow visual observations and video recording of the shearing layer and velocity measurements. A support was made for the laser optic unit with a mechanism for it to move vertically and forward towards the centre of the channel to perform measurements at different vertical position near the wall and inside the shearing layer by a LDA equipment (Laser Doppler Anemometer). Before starting a run, the shearing channel is filled with a known amount of granular material, carefully mixed with the liquid (special attention is paid to removing any trapped air). After a few rotations aiming to settle the material (the lower plate remaining at rest), the vertical position of the disk is measured. The counter weight strictly necessary to balance the disk weight is determined and, by unloading the counterweight, a fixed vertical pressure is caused. The disk is then let turn and a run is performed according to one of the two following procedures: one or more assigned velocities of the upper disk are reached, and the corresponding upper disk displacements are measured; the velocity is increased until a desired displacement of the rotating disk is reached; the velocity of the upper disk is increased step by step and subsequently decreased as well. During the test several desired velocities are reached. Torque T , angular velocity Ω and displacement are anyway monitored and a video record is taken. The shear stress τ and the shear rate $\dot{\gamma}$ within the material have been calculated from the following formulae:

$$\tau = \frac{3T}{2\pi(R_0^3 - R_i^3)} \quad (6)$$

$$\dot{\gamma} = \frac{\Omega R_m}{\delta_m} \quad (7)$$

In which R_0 and R_i are the radius of outer annulus and the radius of inner annulus. R_m is equal to $(R_0 + R_i) / 2$ and δ_m is the measured depth of the channel. In order to better investigate and to quantify stratification effects, measurements of grain velocity profiles were performed by Laser Doppler Anemometer equipment. The used system is made up of a Flow Lite integrated laser-optics unit with a Flow Velocity Analyzer signal processor (FVA). The optic

unit is mounted on a specific support, and it is manually driven in order to perform measurements at different point inside the shearing channel. Typical run was performed in analogy with the former procedure i.e.: the channel is filled by a known amount of grains and fluid; by a counterweight a normal load is applied to the rotating upper disk; after few rotations the upper disk remains at rest aiming to settle the material and extrude any trapped air; the vertical displacement of the upper disk is measured; the upper disk is set into rotation at the fixed velocities and measurements are then accomplished. In every run, the entire channel depth is visible through the window mounted on the external wall. Velocity measurements are performed inside the shearing gap along a vertical at different levels (about 10 levels for every run). The first set of measurements deals with a vertical just close to the wall. Afterwards, the measuring volume of LDA is moved inside the channel and a new set of measurements is carried out along a different vertical. Measures along different verticals, located at different positions apart from the wall, were repeated as many times as possible depending on the optical characteristics of the mixture. The most remote measuring point was usually located 3-4 mm apart from the sidewall towards the core of the channel (about 2-3 grain diameter). In this way any boundary effect related to the presence of the wall could have been evaluated; both velocity profiles and actual shearing zone could have been extrapolated. Measurements were carried out during several runs, reproducing with strict approximation the experimental condition of the corresponding rheometer tests; velocity profiles were measured along few verticals from the external wall towards the centre of the channel.

4 EXPERIMENTAL RESULTS

4.1 Creep and sweep tests

Creep tests were carried out imposing a constant stress to the debris flow material mixtures and measuring the induced deformation over time. A complete test consists of imposing various values of stress, lower and larger than a critical stress, called static yield stress (i.e. the value of stress after that the mixture starts to flow like a fluid) [9]. The value of the static yield stress for each debris flow material mixtures analyzed was determined with some stress sweep tests carried out using the rotational rheometer. The stress sweep tests consist in measuring the apparent flow curves by applying an increasing shear stress ramp. The shear stress was continuously increased in a logarithmic way from 0.1 Pa to a large (maximum) value, and the corresponding shear rate was measured. The maximum stress value was specifically determined for each sample from independent (rheometrical) tests under similar technical conditions so as to get a rapid flow in the liquid regime without fluid expulsion out of the geometry (for the complete procedures and results see [6]). Before each creep test performed, the material was set up inside the geometry, immediately imposing a pre-shear at the maximum stress value above described for 30 s, and then starting the test in order to homogenize the sample. Fig. 4 shows the experimental results obtained with a creep test on debris flow material mixture at solid volumetric concentration Φ of 42%. It is observed that for stresses lower than critical stress the deformation's curve remains concave, with a

slope continuously decreasing in time on a logarithmic scale, and exhibits an apparent horizontal asymptote. The deformation is limited, and the instantaneous shear rate decreases continuously to lower values, so that no steady state is reached. Finally, the material apparently stops moving and this should correspond to the solid regime of the material (the apparent shear rate $\dot{\gamma}$ is close to zero) [11]. For stress values higher than the critical value, the initial slope of the curve is similar to that under smaller stresses, but after some time there is an inflection point, and the curves gradually tend to reach an inclined straight line, with a slope equal to 1. In this case the deformation increases at a constant rate, which means that the apparent shear rate is constant, and a steady-state flow has been reached. These curves correspond to the liquid regime of the material. However, the transition from the solid to the liquid regime is abrupt (see Fig. 4): for a stress just above the yield stress, the material rapidly reaches a shear rate level that is relatively high (typically of the order of or larger than 1 s^{-1}). This suggests some viscosity bifurcation effect [9], again associated with a critical shear rate ($\dot{\gamma}_c$) below which no steady flow can be observed, as has already been observed from the results obtained in the sweep test on the same material mixtures. Note that the apparent critical shear rate may depend on the flow history, which can explain a slight difference between the value deduced from Fig. 4 and that found from the specific procedure used for sweep tests, showed in Fig. 5. A recent work [11], focused on the behaviour of concentrated granular suspensions exhibiting similar characteristics, showed that this material exhibits a critical shear rate below which they cannot flow steadily. This could be an effect leading to shear-banding when an apparent shear rate is imposed below this value. The same trends occur here with the debris flow material mixtures analyzed: the static yield stress corresponds to the stress needed to unjam the locally settled structure, and then the dispersed suspension flows more easily. Consistent with this scheme, along the stress plateau associated with the static yield stress the material shear-bands and, increasing shear rate beyond the critical value, the material flows as a homogeneous fluid (see Fig. 5). As a consequence we have an unstable behaviour: when a stress is imposed while the mixtures are at rest they will not flow until the static yield stress has been reached, and just beyond this value suddenly flow at a shear rate larger than the critical shear rate. It is interesting to analyze the flow curve obtained from the experimental data recorded with the annular rheometer. In Fig. 6, the torque vs. the rotational velocity for the steady flows of sand-water suspension ($\Phi=42\%$ - $\lambda=7$) has been reported. As observed in the experiments on debris flow materials (see previous section), it has been observed a quasi static regime (i.e., the solid regime of the material) followed by a viscous regime (i.e., the liquid regime of the material). It has been found a shear torque plateau at low velocities and a linear increase of torque with the velocity above a critical velocity Ω_c (Fig. 6). The data can be well fitted to a Bingham law $T=T_c + \alpha\Omega$ with $T_c=3.86 \text{ Nm}$ and $\alpha=0.53 \text{ Pa}\cdot\text{s}$: this suspension seems to exhibit a yield stress and to behave macroscopically like yield stress fluids. In the following, the regime for which the torque increases linearly with the rotational velocity will be called the "macro-viscous" regime (as in [12]). It has been noted that,

in the absence of sedimentation and with very small particles, the material behaves like a Newtonian fluid up to a critical shear rate [9]-[11]-[12]. This behaviour is strictly related to the characteristics of these mixtures, i.e. particle type and interstitial fluid viscosity, which are strongly related to the solid volumetric concentration of the mixtures as showed in section 2. In fact it is especially interesting to look at the variations of the static yield stresses and the critical shear rate with the solid fraction (see Fig. 7). It can be seen that the yield stress and the critical shear rate increase in a similar way with solid fraction and they increase by two orders of magnitude over the very narrow range of concentration analyzed (less than 10%) in which the debris flow material mixtures tested behave as homogeneous fluids (for more details on the identification of the range of concentrations in which this type of material may be considered as fluids and thus can be characterized with the usual rheological tools see [6]). It is important to note that if the critical shear rate increases more or less like the yield stress when the solid fraction increases, then the material strength increases, and its apparent velocity when it starts to flow increases proportionally.

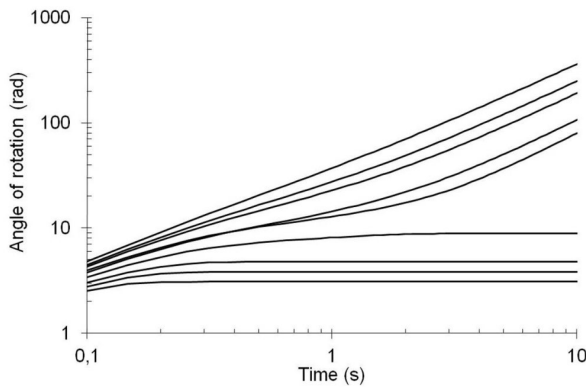


Figure 4 Creep tests for debris flow material (42%). Deformation against time for different stress levels (from bottom to top): 90, 110, 120, 140, 142, 160, 170, 180, 200 Pa.

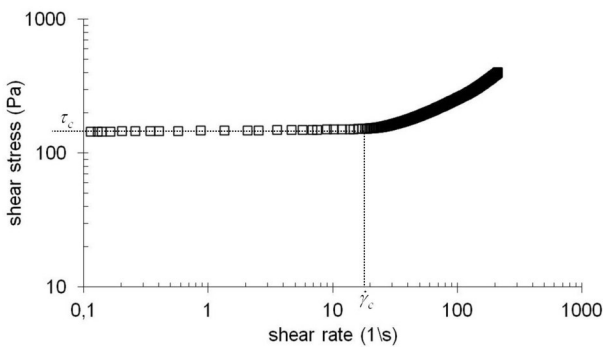


Figure 5 Sweep tests with debris flow material 1 at 42% (Representative test).

4.2 Velocity profile

Accounting for the experimental set up and for the test procedure (described in section 3) it has been expected a roughly constant shear stress inside the mixture whereas normal stress increases downward because of specific gravity (i.e., the normal stress applied by the rotating upper disk). Because of the granular density, stratification occurs and it leads to an almost locked lower layer and an actually shearing upper layer as it is also evident from the

video records made during the tests. If the granular material is denser than the interstitial fluid the vertical pressure in the granular phase increases downwards starting from the value we evaluate at the ceiling of the shearing cell.

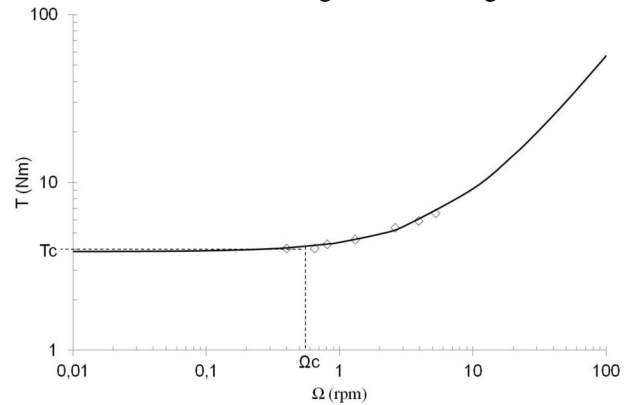


Figure 6 Torque vs. the rotational velocity in the steady state of a water-sand suspension ($\Phi=42\%-\lambda=7$). The line is a fit to a Bingham model: $T=T_c + \alpha\Omega$ with $T_c=3.86$ N m and $\alpha=0.53$ Pa•s.

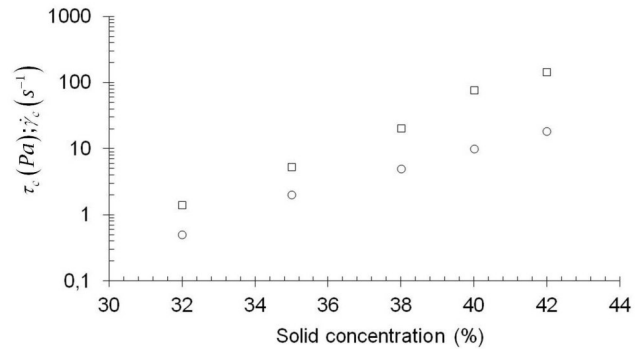


Figure 7 Rheological characteristics of debris flow material as a function of solid fraction: static yield stress (empty squares symbols) and critical shear rate (empty circles symbols).

The shear stress remains instead almost constant, or more precisely, decreases slightly because of the friction on the sidewalls. As a consequence, the concentration of the granular increases downwards and the granular is eventually blocked below a certain level. This level should be below the shearing cell bottom, in order to produce a reasonably uniform condition in the cell itself. This is practically not possible for granular substantially denser than the fluid. For the present study, in every run the whole channel depth was visible through the windows and the video records made evident that the shearing cell is characterized by the presence of an actual shearing upper layer and of a quasi-static lower layer. The principal effect of stratification is a strongly concave velocity profile. Therefore the average velocity gradient, which can be crudely estimated by the upper disk velocity and the total channel height, is substantially smaller than the velocity gradient in the upper shearing part of the flow, to which any stress measurement refers. Assuming no-slip condition of the grains in contact with the upper rotating disk, theoretical profile may be derived avoiding any boundary effects of the external wall [5]. Measurements of velocity profiles were performed by Laser Doppler Anemometer equipment

mounted on the large scale annular rheometer [7]. Typical measured velocity profiles obtained are plotted in Fig. 8, Fig. 9 and Fig. 10: the dimensionless velocity profiles for the steady flows for various rotational velocities have been represented for water-sand suspension, Glycerine B-sand suspension and Glycerine C-sand suspension respectively. As it is evident, the measured velocity profiles are similar in shape regardless of interstitial fluid. Measurements show that the velocity profiles are roughly exponential and that they occupy the whole gap for the considered rotation velocities. Moreover the curving of the velocity profiles strongly inward and this trend is more pronounced for the Glycerine-sand mixtures. These velocity profiles show the mixture in the called macro-viscous regime [3]-[7], in which typically the applied shear rate is higher than the critical one. In fact, in this regime (i.e., at high rotation velocities), the mixture inside the gap is all sheared. In the case, the whole sample is sheared, and all the reduced velocity $V(z_i)/V(z)$ profiles plotted vs. the radius fall along the same curve. It is noted that the critical velocity below which the shear flow is localized is as the same order of magnitude of the one associated with the torque plateau in Fig. 6. The velocity profiles obtained confirmed the non Newtonian character of these mixtures: indeed the velocity profiles in the macro-viscous regime are very different from those expected for a Newtonian fluid; i.e. a quasi-linear velocity profile. In Fig. 11 and in Fig. 12, it has been plotted the dimensionless velocity profiles of sand in suspension with different interstitial fluids at equal rotational velocity (respectively, 20 rpm and 30 rpm). These rotational velocities belong to the macro-viscous regime of these three suspensions, in which the mixtures analyzed behaviour like a fluid and easily flow. In the case of the water-sand suspension, it has seen that in the macro-viscous regime all the gap is sheared. In the case of glycerine-sand suspensions, it has been observed that the gap cannot be fully sheared: there still is a 1 mm region where the material is not sheared. In this case, when the rotational velocity increases, the thickness of the sheared layer does not increase anymore for $\Omega_i > \Omega_c$, and it remains smaller than the gap size.

4.3 The shearing zone

Analyzing velocity profiles and video records, it seems reasonable to assume an active shearing layer z_m , which extends from the ceiling of the channel to the level corresponding to 10% of the higher velocity (see Fig.13). Below this level we assumed that the quasi-locked lower layer z_s is at rest. It has been thus observed that the thickness of the sheared layer in the macro-viscous regime (i.e., for $\Omega_i > \Omega_c$), does not depend on the velocity and cannot exceed a maximum value z_m , which decreases when the suspension's viscosity increases. A value of 7.5 mm was found for the water-sand suspension, whereas 7 mm for the glycerine-sand suspensions. In Fig. 14 has been shown an ideal representation of the probable flow regimes occur in the sample thickness.

The flow spans from the frictional regime (bottom layer) to the fully developed collisional regime (top layer) through a transition zone characterized from the intermittence of the two regimes. Actually, we observe that viscous flows at low velocities are not stable (i.e., for $\Omega_i > \Omega_c$ and $\dot{\gamma} > \dot{\gamma}_c$), and that the flow localizes.

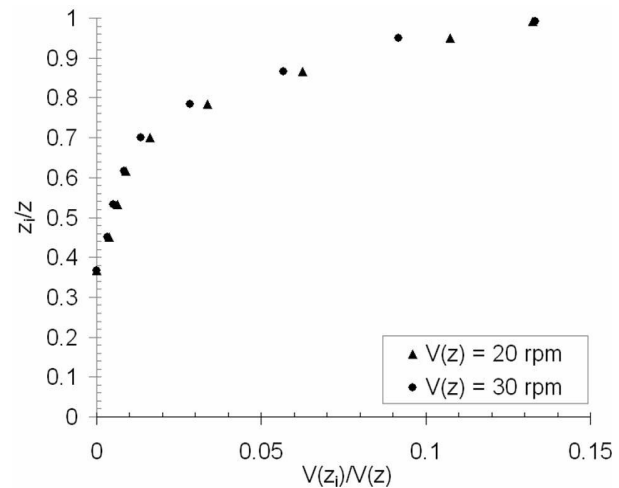


Figure 8 Dimensionless velocity profiles in the steady state of a water-sand suspension ($\Phi=42\%-\lambda=7$), at various rotational velocities.

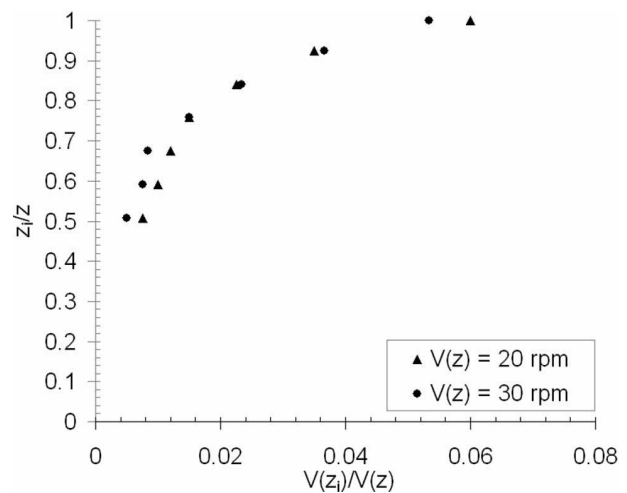


Figure 9 Dimensionless velocity profiles in the steady state of a Glycerine B-sand suspension ($\Phi=40\%-\lambda=5$), at various rotational velocities.

The mechanical origin of localization was evidenced by [7]: there is no steady flow for a shear rate below a critical shear rate $\dot{\gamma}_c$ that depends on the material's properties. When the rotational velocity is lower than Ω_c , the apparent shear rate in the gap is lower than $\dot{\gamma}_c$. Therefore, the flow has to localize so as to ensure that in the flowing material $\dot{\gamma} > \dot{\gamma}_c$ and during localization, the shear stress increases while $\dot{\gamma}$ tends to $\dot{\gamma}_c$: the stationary shear stress at the walls is then approximately $\tau > \tau_c$. Shear localization thus leads to a shear stress plateau τ_c at low velocities (Fig. 7); however the flowing behaviour of the sand mixtures analyzed is always a purely viscous behaviour, even when the flow is localized, in the range of velocities studied. Finally, it has been noted that the mixtures behaviour dependences on the volume fraction: there may be no flow for Φ_m . The macro-viscous regime of dense suspensions then starts when the sheared region has reached a region where $\Phi=\Phi_m$: the thickness of the sheared layer cannot increase anymore, and now the torque has to linearly increase with the rotational velocity since the local shear rate now increases

linearly with the velocity and since the flowing material behave like a purely viscous material. It is finally showed in Fig. 15 the comparison between the variations of the yield stresses with the solid fraction for every material mixtures tested in this study. Regarding the water-sand suspensions, it has been considered two experimental points measured for mixtures having respectively solid concentration of 42% ($\lambda=7$) and 44% ($\lambda=9$). For the Glycerine C-sand suspension, it has been considered the data points measured for mixtures having respectively solid concentration of 39% ($\lambda=5$) and 54% ($\lambda=18$). It can be seen the same trend regardless the material: yield stress increases with solid fraction in exponential way. The yield stress for debris flow material mixtures and water-sand suspensions increases in a similar way with solid fraction. This means that solid content strongly influences the characteristic rheological parameters of the mixtures: when the amount of solid increases, the flowing resistance of the mixtures also increases. The slight slope difference between the two curves is probably due to the different grain size distribution of the soils. Also for the Glycerine-sand suspension, yield stress increases with solid fraction in exponential way but the slope curve is quite different from that obtained for the water-sand mixture. This trend is probably done to the influence of the interstitial fluid, which is much more viscous than the simple water.

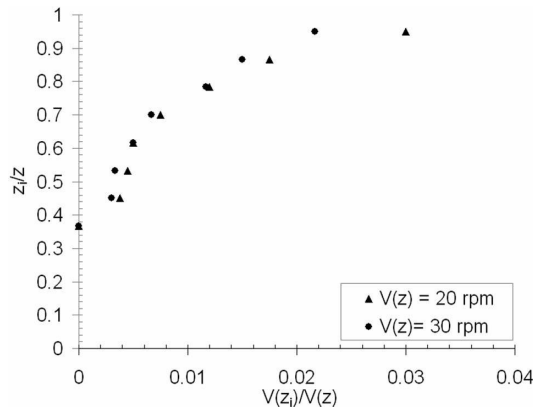


Figure 10 Dimensionless velocity profiles in the steady state of a Glycerine C-sand suspension ($\Phi=42\%-\lambda=7$), at various rotational velocities.

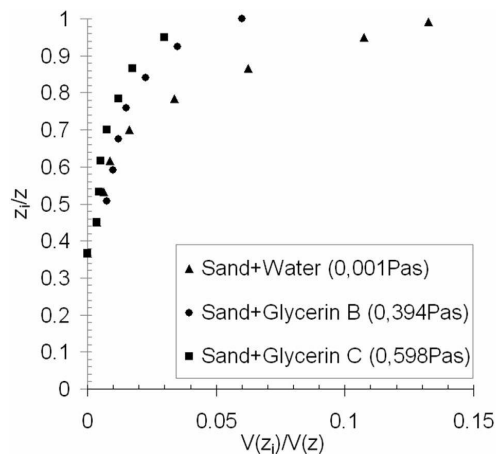


Figure 11 Dimensionless velocity profiles in the steady state of sand in a suspension with different interstitial fluids at equal rotational velocity (20 rpm).

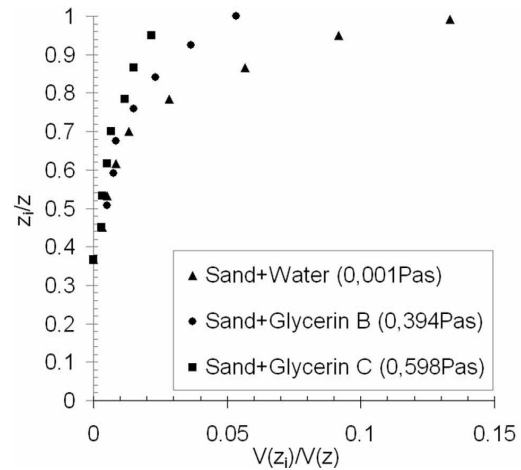


Figure 12 Dimensionless velocity profiles in the steady state of sand in a suspension with different interstitial fluids at equal rotational velocity (20 rpm).

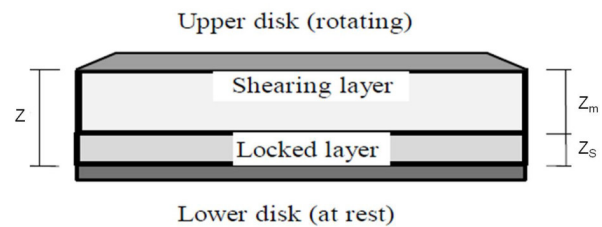


Figure 13 Sketch of shearing and quasi-locked layer in the shearing gap.

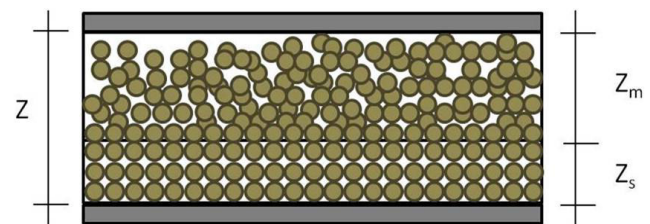


Figure 14 Ideal representation of the probable flow regimes occur in the sample thickness.

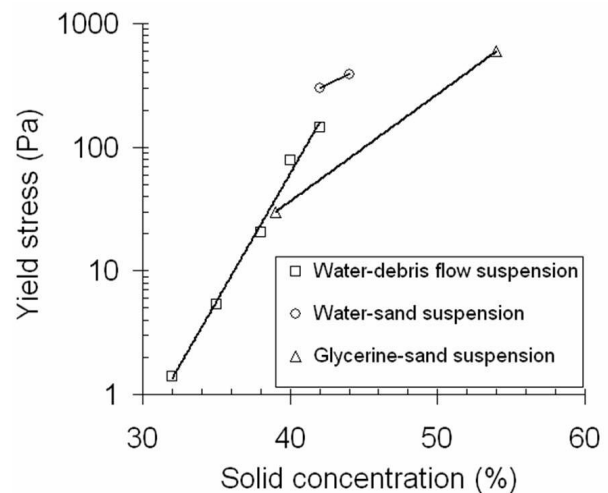


Figure 15 Static yield stress as a function of solid fraction for all the material mixtures tested: comparison between debris flow material and mono-granular sand.

5 CONCLUSION

In this paper it has been studied the flowing behaviour of debris flow material-water mixtures and natural sand water and glycerine suspensions by coupling local velocity and concentration measurements through large scale annular rheometer and macroscopic rheometrical experiments in a vane geometry. From rheometrical experiments performed and with the help of the velocity profile measurements, it has thus been shown that the local material behaviour is a purely viscous behaviour. Creep tests and sweep tests have been shown that the typical rheological behaviour of these suspensions is that of a yield stress fluid exhibiting a static yield stress. The flow of such materials is usually unstable: they will start to flow beyond a critical stress, but just beyond this value will reach a high shear rate associated with a high flowing velocity. Then, the yield stresses and the critical shear rates are strongly influenced by solid fraction: if the solid fraction increases they increase in an exponential way. Analyzing velocity profile has been possible to identify and quantify the actual shearing layer and deriving the related parameters. Velocity measurements have confirmed that these kind of mixtures are non Newtonian (they can flow only if a critical value of velocity has been reached, i.e., critical shear rate) and that the grain characteristics does not appear to affect the macroscopic rheological behaviour of both mixtures. Moreover in the velocity profiles it has been clearly seen the influence of the interstitial fluid viscosity on the mixtures behaviour: the shared material layer decrease when the viscosity of the interstitial fluid increase and the relative velocity also decrease. These results suggest that, in the field, a small change in solid fraction will cause a slight decrease of the static yield stress, inducing a flow rapidly reaching a shear rate larger than the critical shear rate associated with a rapid flow.

These results raise many questions: first, the physical mechanism associated with critical shear rate; second, the cause leading to the formation of two distinct layers within the material: the lower quasi-locked layer and the upper fully sheared layer; third, the characterization of the suspension at very low velocities in the quasi-static regime.

6 REFERENCES

- [1] GDR MiDi. On dense granular flow. *The Eur. Phys. J. E* No. 14, 2004, pp. 341-365.
- [2] Rajchenbach J. Granular flows. *Adv. Phys.*, No 49(2), 2000, pp. 229-256.

- [3] Bagnold RA. Experiment on a gravity-free dispersion of large solid sphere in a Newtonian fluid under shear. *Proc. R. Soc. London Ser. A* 225, No. 1160, 1954, pp. 49-63.
- [4] Ancey C. Plasticity and geophysical flows: A review. *J. Non-Newtonian Fluid Mech.*, No. 142, 2006, pp. 4-35.
- [5] Coussot P & Piau JM. A large-scale field coaxial cylinder rheometer for the study of the rheology of natural coarse suspensions. *J. Rheol.* 39, No. 1, 1995, pp. 105-124.
- [6] Scotto di Santolo et al. Rheological behaviour of reconstituted pyroclastic debris flow, *Geotechnique Journal*, Vol 62, Issue 1, 2011, pp. 19-27.
- [7] Schippa L & Lamberti A. Experiments on the rheology of a dense granular flow. Final report of EC Research. June 1999, pp. 1-34.
- [8] Budetta P. Rockfall-induced impact force causing a debris flow on a volcanoclastic soil slope: a case study in southern Italy. *Nat. Hazards Earth Syst. Sci.*, No 10, 2010, pp. 1995-2006
- [9] Fall et al.. Yield stress and shear-banding in granular suspensions. *Phys. Rev. Lett.* 103, No. 17, 2009.
- [10] Coussot P. Rheometry of pastes, suspensions and granular materials: Application in industry and environment. New York: John Wiley & Sons, 2005.
- [11] Ovarlez G, Bertrand F & Rodts S. Local determination of the constitutive law of a dense suspension of noncolloidal particles through MRI. *J. Rheol.* 50, No. 3, 2006, pp. 259-292.
- [12] Huang et al.. Flow of wet granular materials. *Phys. Rev. Lett.* 94, No. 2, 2005.
- [13] Nguyen QD & Boger DV. Direct yield stress measurement with the vane method. *J. Rheol.* 29, No. 3, 1985, pp. 335-347.
- [14] Schippa L & Pavan S. Numerical modelling of catastrophic events produced by mud or debris flow. *Int. J. of Safety and Security Eng.*, Vol. 1, No. 4, 2011, pp.

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Corresponding Author: Anna Maria Pellegrino

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