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Laboratory Determination of the Viscosity of Soils for Debris Flow Analysis

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Abstract. To correctly analyze debris flow events a rheological approach is necessary, through constitutive modelling the descendent moving mass. Bingham's model is widely employed in the debris flow literature, its input parameters being plastic viscosity and yield stress. Such rheological approach is important in the evaluation of the propagation of the downhill motion, not only by determining its velocity, but also to aid the delimitation of areas to be affected by such catastrophic type of movement. The present study presents a proposal for the assessment of soil viscosity by laboratory testing on a modified set-up of the well-known slump test. Through the definition of shearing rates in the slump tests, viscosity is determined on a plate–plate rotational rheometer. It was studied one natural soil from Rio de Janeiro, Brazil. Correlations were obtained concerning to soil moisture and shear rates, defined in the slump tests, and also between shear rate and plastic viscosity, the latter defined in the rheometer tests. As a result, good relationships between water content and viscosity were established. Comparing the obtained data with other results available in the literature it is concluded that the developed experimental methodology may provide a simple way to evaluate soils viscosity for debris flow analysis.

Keywords. Debris flow, soil rheology, yield stress, viscosity.

1. Introduction

Debris flow comprises one of the most damaging movements among landslides [1]. Its propagation along drainage channels is associated with high velocities and wide areas of deposition (e.g. [2-3]). Few researches have been taken to provide rheological parameters to such phenomena analyses and appropriate design of contentions, such as the flexible barriers widely employed nowadays.

Some studies have been taken in the last decades on analyses of the viscosity and the yield stress of soil-water mixtures (e.g., [1, -6]), usually correlating one or the two parameters with the solid volumetric concentration of the mass, which, for saturated soils, is defined by expression 1.

$$C_v = \frac{V_S}{V} = \frac{1}{1+w.Gs} \tag{1}$$

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where C_v is the solid volumetric concentration, V_s is the solid volume, V is the total volume, w is the water content and G_s is the specific gravity of the grains. It should be noted that water content and solid concentration present an inverse relation.

This study intends to improve the understanding of the rheological behavior of tropical soils over an experimental study of the plastic viscosity of a colluvium from Rio de Janeiro/Brazil, through determination of the shear rate developed in an own-weight motion in a modified set-up of the slump test and the corresponding viscosity determined in a rotational plate-plate rheometer. Moreover, it is intended to evaluate the efficiency of the test as an alternative to expensive rheometric equipment.

2. Rheological behavior of mass-flowing soils

In a flow curve of fine-grained sediments (Figure 1), there is a yield transition from creep regime (rapid increase of shear stress due to low increments of shear rate) to the flow regime (where flow is established and shear stress develops less considerable variations along time). This transition from solid-type material to fluid-type is denoted by the yield stress.

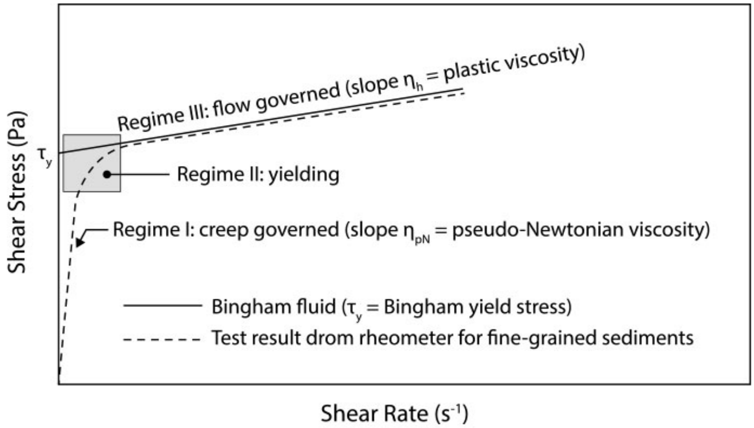

Figure 1. Typical flow curve for soil-water mixtures (adapted from [2]).

The viscosity is defined as the stress-strain moduli, being the slope of the flow curve in its various stages. In the creep regime, soils present high viscosities as they behave as a solid. After yielding, viscosity decreases as a consequence of the flow regime. Hence, the slope is referred as a plastic viscosity.

Studying polymeric fluids, [7] observed a linear relationship between shear stress and rate of shear after reaching τ_0. Drawing a parallel between polymeric liquids and clay soils under high water content (for example, with liquidity index above 1.5), it could be said that clay slurries may behave as Bingham fluids. Investigations related to debris flow indicate that η and τ_0 increase exponentially with sediment concentration (e.g. [6]) confirming that soils behave as non-Newtonian fluids, but not necessarily as Bingham fluids. The authors studied soils with natural water contents well above their liquidity limits, showed that the occurrence of a Bingham fluid behavior would depend on the rate of shearing employed in rotary rheometric tests.

3. Studied geomaterial

The analyzed geomaterial comprises a widely studied colluvium from a natural slope within the main campus of Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), denoted MCP. The material has no background of relevant mass movement and it was unsaturated under its original condition [1].

Figure 2 and Table 1 show the physical and mineralogical characterization of MCP soil. Conventional geotechnical characterization tests were performed in the Brazilian standards. Mineralogical analyses were performed using both differential thermal analysis and X-ray diffraction (Table 2). The soil is a clayey-sand, and is classified as a high-plasticity clay according to USCS. The sand, silt and clay fractions are as follows: 34.9, 10.2 and 54.9 %.

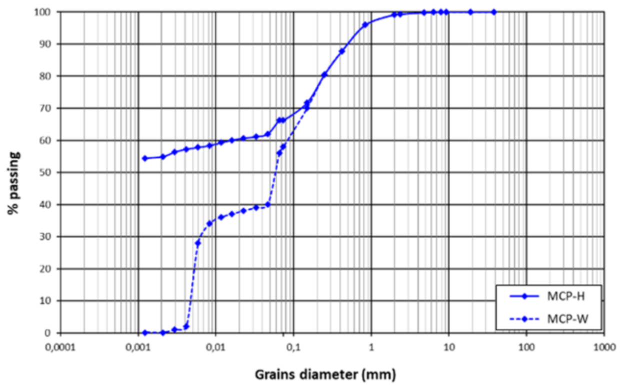

Figure 2. Grain size distribution of the MCP soil. Sedimentation tests performed with both sodium hexametaphosphate (H) and water (W) as deflocculant.

The sedimentation test was realized in presence of sodium hexametaphosphate deflocculant, thus it is important to note that it has been observed changes in the grain size distribution when the test was realized using water. The clay fraction disappeared and its particles formed silt to fine sand sized clusters [1]. This finding is relevant in the sense that all mechanical tests in this study were realized with water, and debris flow mechanisms may change depending on the grain size of the moving mass (e.g. [4], [5]).

Table 1. Physical and mineralogical characterization of the MCP soil.

LL (%)	PL (%)	PI (%)	A_c	G_s	Clay mineral	USCS
68.0	28.3	39.7	0.72	2.723	Kaolinite	CH

4. Equipment and techniques

4.1. Slump test

The modified slump test set-up used in this study is shown in Figure 3 and its particularities are well explained in [8]. Tests consists in uplifting the truncated cone by loading an extra weight to the counter weight (located in the left size of the equipment), as shown in Figure 3.

In order to minimize surface friction effects between the mass and the internal cone surface, it was used a thin layer of glycerin as lubricant. Furthermore, the counter weight was loaded with 20kg to speed the cone uplift, hence the mass-cone contact was minimized during the test. Tests were performed in an environmental controlled room at a temperature of 22ºC.

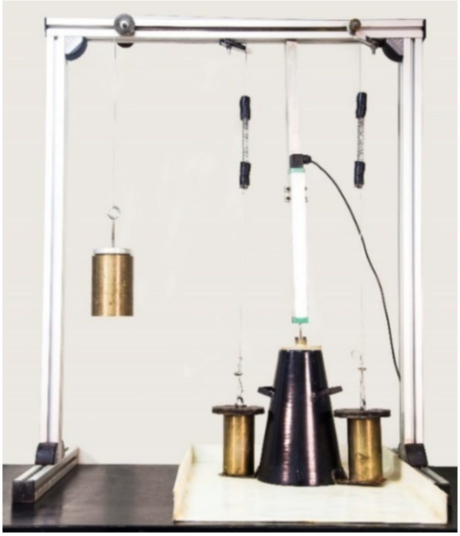

Figure 3. Modified slump test set-up.

4.1.1. Shear rate interpretation

The methodology used to define the shear rates developed in the slump tests is explained in [9]. Such methodology consists in analyzing the ratio between horizontal (runout) velocity and vertical (slump) displacement during a flow event, considering results of triplicated slump tests performed at four differing moisture contents, and assuming that shear rates resulting from slump tests would be equivalent to applied shearing strain rates in rheometer devices.

Considering that in a debris flow event, the rate at which a flowing mass moves is associated to acceleration – once the descendent movement predominantly concerns to acceleration due to gravitational-kinetic energy transfer mechanisms – it was investigated shear rates associated with acceleration, by evaluating the runout acceleration time interval. To do so, vertical and horizontal displacements were measured with, respectively, a LVDT and a camera [9]. Polynomial fitting was applied in the displacement experimental points, and then velocity and acceleration were obtained as the first and second function derivative, respectively.

Figure 4 shows typical kinematical results obtained in the slump tests. As it is described, the shear strain rates were defined in the runout acceleration interval ($t_0 - t_f$), and so, runout velocities were obtained in the $v_0 - v_f$ and slump discplaments in the $y_0 - y_f$ intervals. Finally, it is shown in Figure 5 the shear rate interpretation as the velocity-displacement ratio in such acceleration interval.

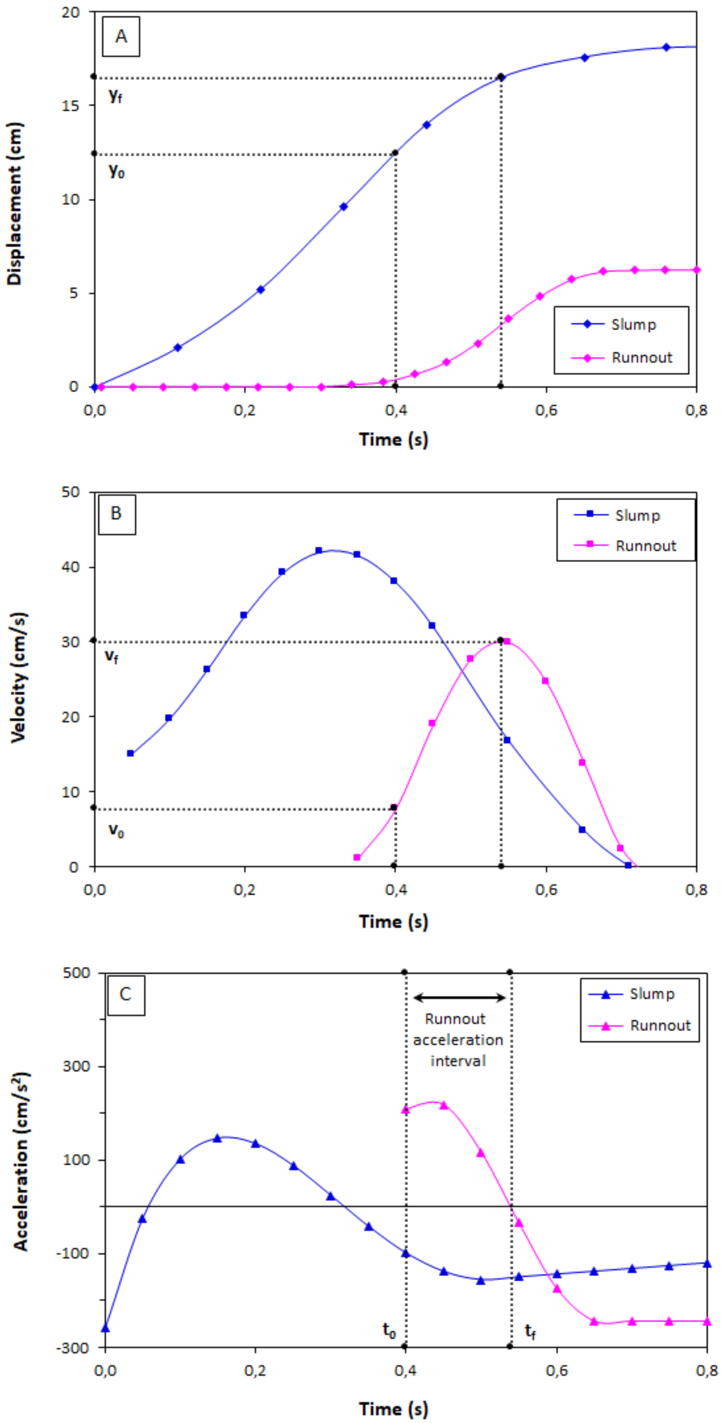

Figure 4. Typical kinematical curves, for both runout and slump movements, obtained in the slump test. (A) Displacement-time curves. (B) Velocity-time curves. (C) Acceleration-time curves.

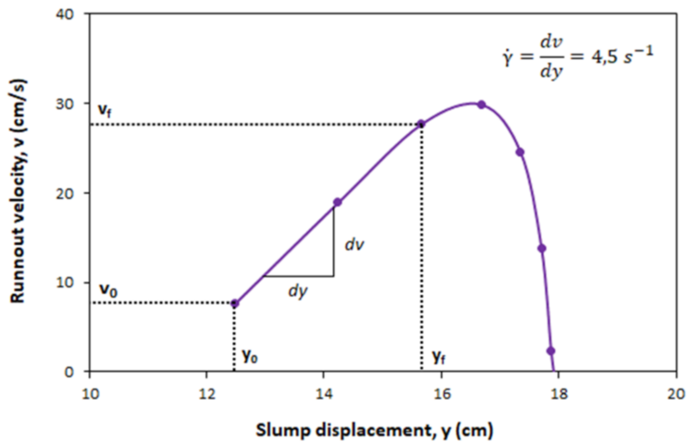

Figure 5. Shear rate interpretation by graphical analysis of a typical velocity-displacement curve.Rheometric tests

Flow tests were performed in a rotational rheometer Discovery. Figure 6 shows the device and its coupled software data acquisition system. Flow ramp tests (or sweep tests) were executed. Such tests are deformation-controlled type, where shear rates are incrementally increased, and the shear stress is determined with the devices' motor applied. As it is suggested in [6], tests were executed in a shear rate range commonly observed in debris flows materials (1 to 100 s^{-1}).

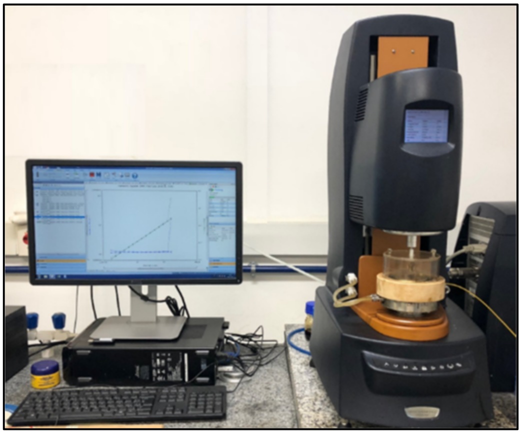

Figure 6. Discovery rotational rheometer and its coupled computer for data acquisition.

The rheometer was equipped with a crosshatch plate-to-plate geometry. Such geometry was chosen as its grooves avoids material sliding during the test. Furthermore, it provides a simpler sample preparation for very viscous materials and soft solids. The device has a diameter of 49.96 mm and samples thickness were set to 2.0 mm.

Figure 7 shows the flow curves obtained for the MCP soil in the rheometer. As mentioned earlier, the shear rates obtained in the slump tests were used to determine the corresponding viscosity.

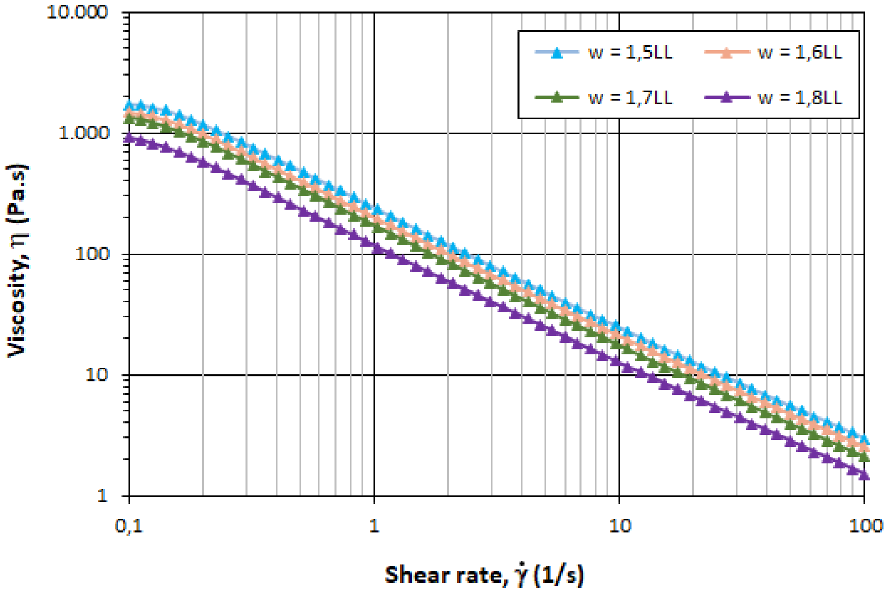

Figure 7. Flow curves obtained within the rheometer, for the MCP soil.

5. Results

Table 2 shows average physical indexes (water content and solids concentration) of the MCP soil samples used in the rheometer and in the modified slump tests, as well as the shear rates and plastic viscosities obtained in the slump tests and rheometer, respectively.

Table 2. Slump and rheometer test results for the MCP soil.

Water content w (%)	w/LL	Solid concentration C_v (%)	Shear rate $\dot{\gamma}$ (1/s)	Plastic viscosity η_p (Pa.s)
98.7	1.5	27.0	4.5	53.8
106.6	1.6	25.6	5.1	37.8
114.2	1.7	24.5	5.6	27.7
119.6	1.8	24.1	6.7	20.0

As slump tests resulted in essentially low strain rates, it could be said that they are representative of pseudo-Newtonian viscosities (creep regime). However, it can be seen in Figure 7 that the slump tests' shear rates interval is associated with the plastic regime, as the viscosity-shear rate relation is linear in the log-log scale. Thus, it is considered that the results of the present study refer to plastic viscosity.

The relationship between plastic viscosity and water content is presented in Figure 8. An exponential relation is observed, which is in agreement with the suggestion by [7]. The higher the water content or the lower the solids concentration, the lower the viscosity of the material, appointing to a relevant sensitivity to soil moisture.

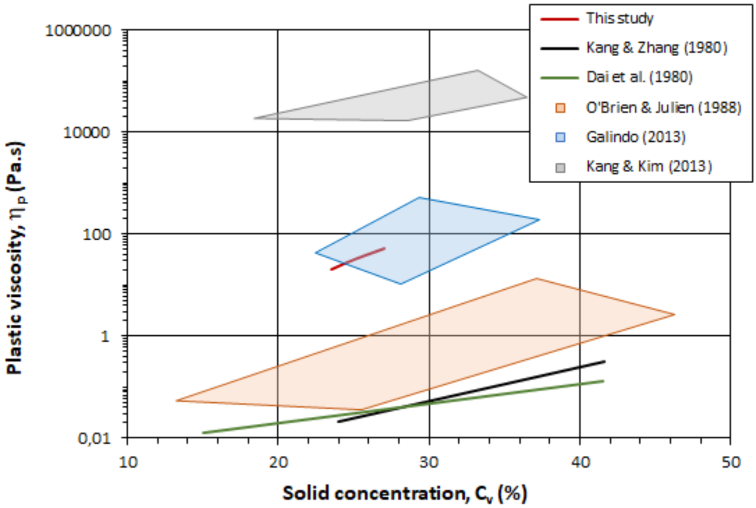

Figure 8. Comparison with data gathered from the literature.

Results herein obtained are in quite good agreement with data from other studies, which can be observed in the overlay of regions presented in Figure 8. These studies involve predominantly rheometers and viscometers devices. [7] studied natural mudflow materials in a concentric cylindrical rotational viscometer. [10] refer to a silty soil (more than 80% silt) with variable sand content.

Indeed, this conclusion indicates that the slump test is an efficient and cheap alternative methodology for soils viscosity measurement, once the test leads to similar results compared to expensive rheometric equipment, such as rheometers and viscometers.

6. Conclusions

The combined results obtained from the rheometer tests, performed at a shear rate range observed in flow events, and with shear rates obtained in slump tests, showed to be a good methodology viscosity determination. Indeed, the average shear rate interval observed in the slump tests is related to the plastic flow regime of the materials, which was observed in the rheometer. As a consequence, slump test shear rates are representative of yield stress and plastic viscosity.

Results obtained for two different tropical soils indicated that exponential curves provide fairly good relationships between water content and both yield stress and viscosity, for the tested materials. Such findings indicate that the use of a fairly simple and cheap testing technique can provide a direct estimate of soil viscosity.

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