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4 authors, including:

Sueng-Won Jeong
Korean Institute of Geoscience and Mineral R…

J.-P. Malet
CNRS / University of Strasbourg

RHEOLOGICAL PROPERTIES OF FINE-GRAINED SEDIMENTS IN MODELING SUBMARINE MASS MOVEMENTS: THE ROLE OF TEXTURE

S.W. JEONG, J. LOCAT, S. LEROUEIL
Laval University, Québec, Canada, G1K 7P4

J.-P. MALET
School and Observatory of Earth Sciences, Institute of Global Physics, UMR 7516 CNRS-ULP, 5 rue René Descartes, F-67084 Strasbourg Cedex, France

Abstract

The rheological behavior of soils depends on many factors, including their mineralogy and grain size distribution. This work comprises an extensive search of data collected from the literature, an experimental work on about 17 samples. These results, along with a compilation of existing data, have been used to show that, as a first approximation, the yield strength/viscosity ratio is about 1000, 100 and less than 10 for clayey, silty and sandy fine-grained sediments mixtures, respectively. Our research results on the rheological properties of fine-grained sediments indicate that they are very sensitive to the variation in grain size, shear rate, and geometry of the system.

Keywords: Rheological properties, grain size, shear rate, Bingham yield stress, plastic viscosity

1. Introduction

Submarine landslides are commonly observed on the continental margins, particularly becoming recognized as a potential source of damaging tsunamis. These submarine mass movements are distinguished by several characteristics: sediment concentration, sediment-support mechanism, flow rate, and sediment rheology (Locat and Lee, 2002; Niedoroda et al., 2006). Practically, the Bingham yield stress and plastic viscosity are often used to describe the modern deep-sea features and to estimate future debris flow runout behavior with a trial-and-error process. These rheological parameters are also influenced by soil types, solid concentration, salinity and liquidity index, not mention the effect of the geometry of rheometer. In particular, the influence of coarse-grained soils in fine-laden debris flow is essential. Debris flow materials with large size particles ranging from clay-size to boulder-size might have various rheological behaviors. As a result, a number of more or less complex rheological models to describe flow behavior may be found in the literature. However, the determination of rheological properties still faces the problem of the presence of large size particles in highly concentrated sediment-water mixtures (Coussot et al., 1998). In this paper we summarize the general flow behaviour and characteristics of fine-grained sediments encountered in the various environments. It is a very important topic when we are dealing with high speed mass movements such as subaqueous debris flows, because submarine landslides are much mobile and tend to involve larger volumes than subaerial slides. The aim of this paper is to examine a possible range of rheological properties with respect to the grain sizes.

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2. Materials and methods

The rheological behavior of selected soils was evaluated and separated into the three groups. The first group is natural clays taken from the Jonquière, St-Alban, Saguenay Fjord including Baie des Ha!Ha!, Pointe-du-Fort, and Confluence in Upper Saguenay Fjord, Adriatic, Mediterranean, Beaufort Sea, Cambridge Fjord, and Hudson Apron samples. As for the materials in Group 1, the liquid limit (w_L) and plasticity index (I_P) are approximately 35 - 75 % and 15 - 50 %, respectively. Group 1 is described as soft clays, i.e., inorganic clays of medium to high plasticity. The second group is two montmorillonite-rich materials in natural clays, i.e., the Black Sea sediments and the natural sodium-rich montmorillonite clay supplied by Black Hills Bentonite, LLC (Wyoming, USA). In Group 2 that contains highly plastic soils, the liquid limit and plasticity index are 100 - 360 % and 80 - 300 %. The third group is silt-dominated mixtures analyzed or examined for unflocculated/flocculated iron tailings samples. In Group 3, the liquid limit and plastic limit of a soil are less than 23 % and less than 19 %, respectively. The plasticity indices (I_P) are 3.7 and 6.2% for unflocculated and flocculated samples, respectively. They are typically classified as inorganic clayey silts of low plasticity. Group 3 is only limited here to the test results of iron tailings, because of more complex soil characteristics of more coarser mixtures and unclear determination of Atterberg limits of soils. In short, Group 1 has low to medium activities (i.e., $0.5 < A_c < 1.0$), Group 2 is classified as highly active (i.e., $1.3 < A_c < 4$), and Group 3 is inactive soils (i.e., $0 < A_c < 0.3$), reflecting the low content in clay minerals.

The rheological analysis were carried out using either a coaxial cylinder viscometer (Rotovisco RV-12) or a parallel plate rheometry on the <400 μm fraction. The latter is used for comparison: the rheological characteristics depending on shear rate and testing apparatus, using the complex debris flow in a clay-shale basin (Alpes-de-Haute-Provence, France). A detailed analysis of the rheological properties and complete methodology are explained by Malet et al. (2003). After proper sample preparation, the liquidity index was slowly increased at a constant salinity of the pore water by adding water with the same salinity. For each step the required geotechnical parameters, e.g., water content and remoulded undrained shear strength using the Swedish fall cone, were measured according to ASTM and BNQ (Bureau de normalisation du Québec) standards. The detailed procedures followed for viscometric measurements are described in Locat and Demers (1988). These procedures may include three types of tests: (1) constant shear rate; (2) dynamic response; and (3) hysteresis.

3. Results

3.1 RHEOLOGICAL BEHAVIOR OF FINE-GRAINED SEDIMENTS

Many studies showed that non-swelling natural clays present classically shear thinning and thixotropic behavior with a yield stress (e.g., Coussot and Piau, 1994; Locat, 1997). Typical viscometric results can be presented in a semi-logarithm or log-log diagram of rheological and geotechnical parameters with regard to liquidity index. Empirical relationships were presented by Locat (1997) for: (1) the apparent yield stress and plastic viscosity; (2) liquidity index and plastic viscosity; and (3) liquidity index and apparent yield stress. These relationships are much better for a sensitive soil, even if the scatter is important. Results given here may be useful for a preliminary numerical analysis for subaerial and submarine mass movements (e.g., Kvalstad et al., 2005). Assuming that the flow behaves as a Bingham fluid, there is the relationship between plastic viscosity (η_h, in mPa.s) and yield stress (τ_c, in Pa) measured at various liquidity indices. More detailed flow behaviors and characteristics for fine-grained sediments will be investigated in comparison with those of the previous data. As for sensitive clays, within given range of liquidity indices, the plastic viscosity only represents about 1/1000 of the total shearing resistance of the mixture (Locat, 1997).

A comparison of test results with those of the previous data is shown in Figure 1 with the relationships given by Locat (1997) as a reference. The representative materials in each group generally exhibited a shear thinning flow behavior: i.e., viscosity decreases with increasing shear rate. Even if the scatter is important, results are close to the empirical relationships presented by Locat (1997). Those described herein it seems reasonable to temporarily use at least for non-swelling fine muds. The results in Figure 1 can be used hereafter to provide a first estimate of the relationships between liquidity index and rheological parameters. There is also a positive relationship between liquidity index and pseudo-Newtonian viscosity (Jeong, 2006).

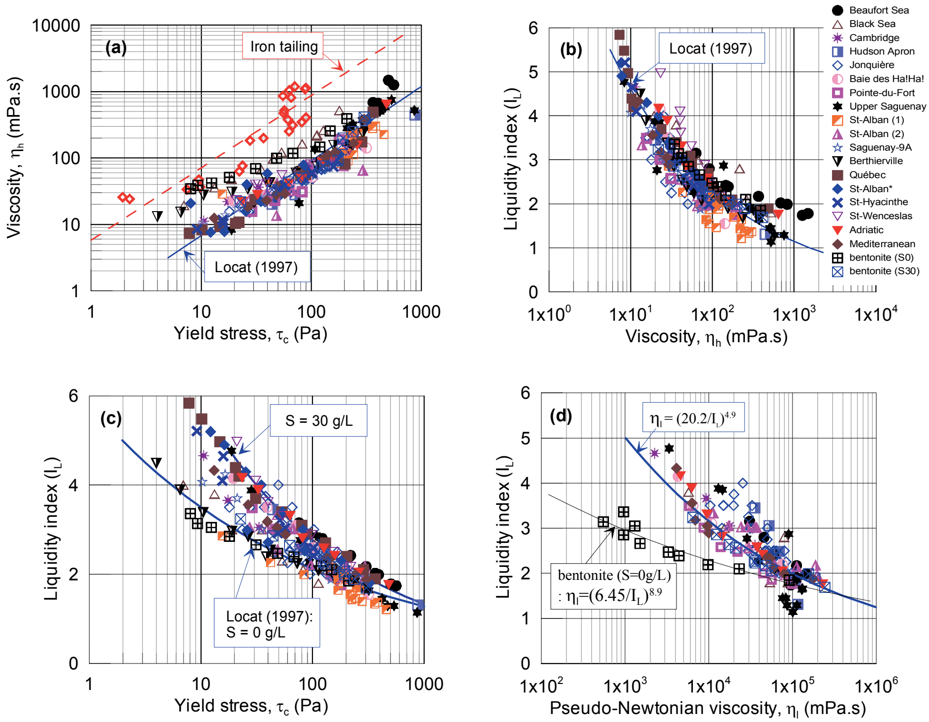

Figure 1. Rheological relationships among the yield stress, viscosity, and liquidity index. Lines correspond to the best power-law fit (equations presented by Locat, 1997; Jeong et al, 2004). Note that viscosity η_l and η_h are pseudo-Newtonian and Bingham viscosity, respectively.

3.2 POSSIBLE RANGE OF RHEOLOGICAL TRANSTION FROM FINE-GRAINED TO COARSE-GRAINED SOILS

It would be interesting to compare the rheological parameters of iron tailings with those obtained with a large-scale rheometer on coarser mixtures. The iron tailing has one of the largest grain sizes (i.e., silt-rich samples) in selected Groups of studied soils, as previously indicated. The plastic viscosity could represent about 1/100 of the total shearing resistance of the mixture (Jeong et al., 2004). Figure 2 shows the possible range of rheological transitions between grain sizes, often encountered in soil mixtures. It should be noted that the values of apparent yield stress and plastic viscosity presented here were approximately determined using ideal Bingham model. As far as the time-independent rheological behavior is concerned, a comparison of data obtained from conventional viscometer used in this study and the results presented in Figure 2 as a reference leads to similar results over a wide range of shear rates. Although there is data scattering with increasing grain size, on the basis of result of non-swelling natural clays, at the same yield stress, the viscosity increases stepwise with the same slope.

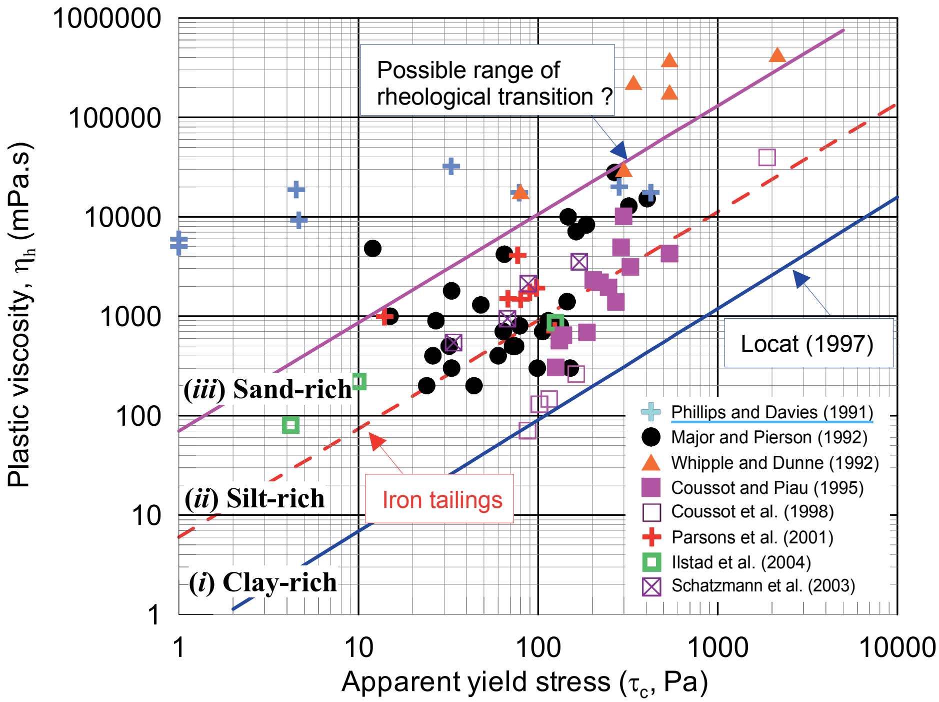

Figure 2. Relation of yield stress (τ_c) versus plastic viscosity (η_h): possible rheological transition in a variety of soil types.

Rheological properties presented by Schatzmann et al. (2003) and Ilstad et al. (2004) are similar to those obtained from test results of iron tailings. It is worth noting here that Ilstad et al. (2004) presented more coarser artificial mixtures, for examples, water (35%) - clay (28.7%) - sand (36.3%), with rheological properties appearing in the range of given values close to the limit of silt-rich materials. The rheological parameters obtained from Coussot and Piau (1995) are varied between the range of sand and clay sizes, but those obtained from Coussot et al. (1998) are getting closer to the limit of natural clays. The latter is evidently close to the behavior of fine-grained soils, but increasing large particles with solid concentration of 73% can result in the critical limit of silt-rich material. The rheological parameters determined in various flow types (e.g., Bingham, shear thinning and few dilatant) on artificial silt-and-sand rich materials presented by Major and Pierson (1992) are also shown with a similar range, even though the scatter is significant. Except for the parameters obtained from debris flows with large sand and gravel contents (e.g., Whipple and Dunne, 1992 and Parsons et al., 2001), the others fall well within the defined range between sand-rich and the fine-grained material. Consequently, the critical limits identified in Figure 2 can represent the possible range of rheological transition from clay to sand-size particle. It would be interesting to plot the ratio of plastic viscosity to yield stress as a function of the grain size. The ratio obtained from Locat (1997) and from the present study is 1 for clayey soils. The ratio for silt-rich material with low percentage of sands is 10. On the other hand, Phillips and Davies (1991) and Whipple and Dunne (1992) who tested gravelly soils found a ratio in the order of 200 - 2000 (see Figure 2). It results mostly from the fact that in cohesionless materials yield stress (τ_c, in Pa) is small compared to plastic viscosity (η_h, in mPa.s) and consequently η_h/τ_c ratio is large.

As shown in Figure 2, the influence of the grain size distribution on the flow curves is of paramount importance. The rheological characteristics of black marl slopes in the French Alps were examined in the same way. It is well known that these landslides, in most cases, show complex nature by changes in behavior in which the slides transform into various flow types (Malet et al., 2005). According to Malet et al. (2003, 2005), all natural and artificial mixtures have a higher silt and clay content and the textural classes vary from silty clay to silty sand. No swelling clays were detected. The mixtures were taken from deposits: earthflows (Super-Sauze, C1a, IND; La Valette, VAL; Poche, POC), muddy debris avalanches (Super-Sauze, COU), and debris flows torrents (Faucon, FAU; Riou-Bourdoux, RBX). In addition, several artificial mixtures of moraines, marls and sandstones were examined. The rheological characterization was conducted with two geometries: a coaxial viscometer (CO) on the < 0.075 mm and a parallel plate rheometer (PP) on the < 400 μm fraction. The rheological parameters were determined by the Bingham model. There are, of course, many experimental difficulties associated with the dynamic response with low liquidity index resulting in much scatter in data. Scatter may have partly resulted from the mineralogy of the clay fraction, the structure of the clay, uncertainty of steady state regime using a specific shear period, loss of material, and possible migration and sedimentation of the particles within the muds in a parallel plate rheometer.

For the mixtures tested in the coaxial geometry, results show a very good agreement between the ratios of yield stress to plastic viscosity obtained from black marls hillslopes and those obtained from the relationship presented by Locat (1997). This is mainly due to the samples are "clay-rich" mixtures, and they differ depending on the amplitude of the imposed shear rate. As shown in Figure 3, except for the limited number of cases that particularly for very low solid concentration the mixture behaves as a liquid, the difference is large between the ratios obtained from coaxial (CO) and parallel plate viscometer (PP). For the mixtures containing a low clay fraction, the imposed shear rate results in a higher viscosity for a given yield stress. However, at the yield stress of 100 Pa, CO/PP is about 1.2, even though the Bingham yield stress was determined in the similar ranges of shear rate (e.g., 500 - 1200 s^{-1}). The disagreement may be due to the difference in: (1) grain size, (2) shear rate (e.g., see Møller et al., 2006), and (3) geometry. Shear rate is considered as the main reason resulting in the inconsistency of results. Due to limitations in the experimental devices, the range of shear rates (e.g., γ = 0.01 - 20000 s^{-1}) is two or three times higher than that met with debris flows in the field (O'Brien and Julien, 1988). Thus, the smaller yield stresses are often estimated by rheometry due to a higher shear rate and smaller grain sizes in comparison with those based on field observations (Malet et al., 2005). More laboratory data and field observations needed to define the transition from viscous to granular debris flow-like behavior.

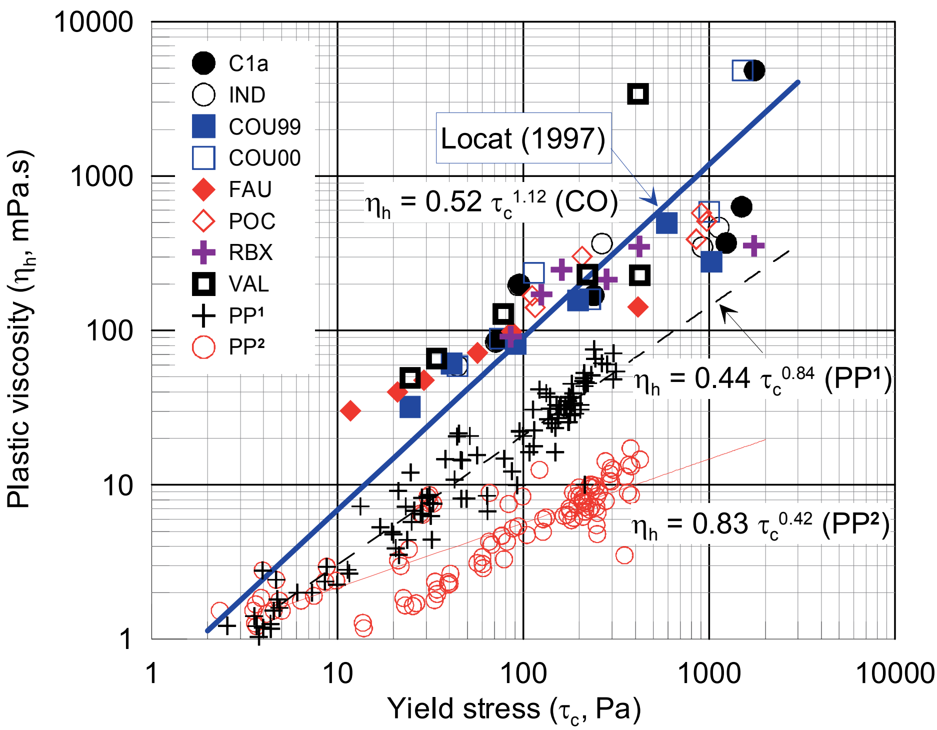

Figure 3. Relationship between yield stress and plastic viscosity depending on the geometry and imposed shear rate. The Bingham yield stress and plastic viscosity were determined in the (1) coaxial viscometric (CO) system having a maximum shear rate of 1200 (s^{-1}), (2) parallel plate (PP^1) rheometer having a maximum shear rate of about 20000 (s^{-1}), but the ratios were determined by the Bingham model in the similar range of coaxial viscometer; (3) parallel plate (PP^2) rheometer having a maximum shear rate of about 20000 (s^{-1}).

4. Conclusion

Rheological properties of fine-grained sediments and the possible rheological transition between viscous and granular flows were studied. The results are intended to provide guidance in selection of resistance parameters in those studies where numerical models are used to simulate the high speed deep-sea debris flows. Non-swelling and swelling materials have characteristics of a pseudoplastic (shear thinning) fluid, even in the case of the iron tailings. It is worth noting here that, for the non-swelling natural clays, the ratio of yield stress to viscosity is about 1 to 1000, whereas the ratio varies depending on the grain size distribution. Results suggest that it may be possible to estimate the rheological parameters, on the basis of result of non-swelling natural materials. The possible transitional ranges of rheological properties implemented by a linear relation of apparent yield stress (in Pa) and plastic viscosity (in mPa.s) are $\tau_c / \eta_h = 1000$ for clays (Group 1), 100 for silts (Group 3), and 10 for sands. Due to limitations in the experimental devices, the difference in ratio of yield stress to viscosity is related to the change in: (i) grain size, (ii) shear rate, and (iii) geometry. Shear rate is considered as the main reason resulting in the inconsistency of results. More laboratory data and field observations are needed to confirm the relationships proposed in this study.

5. Acknowledgements

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