Laboratory rheology measurements of natural debris material

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Abstract Debris flows are fast-moving masses of debris material that often occur in mountainous regions. Due to high velocity, they endanger the local population. To predict the time of arrival and the extent of hazard zones, the rheological properties of debris flow material, among others, are needed. This study presents the rheological investigation of debris flow materials in Slovenia. The rheological parameters were measured at different sediment concentrations using two shear-rate controlled coaxial cylinder rheometers (Brookfield DV3T HB and ConTec Viscometer 5) and standard tests for determining the workability and flowability of construction materials (e.g., funnels, V-funnel, flow channel, flow table, L-box). The measured data were evaluated by using the Bingham rheological model. The study was conducted in two separate stages. Firstly, the rheological parameters were measured only on fines (0-0.063 mm). These tests were used to determine the correctness of the rheological parameters measured in the rheometer by predicting their behaviour in standard tests. Afterwards, an attempt to predict rheological properties from these tests was made. In the second stage of this study, debris materials up to 16 mm were tested. A comparison of the rheological parameters obtained from the two coaxial cylinder rheometers was made. The study shows that the rheological parameters measured with the coaxial cylinder rheometers give reasonably good predictions of standard tests results, while the vice versa, i.e., from these standard tests estimation of rheological parameters is not possible. Although fines predominate the behaviour of a debris flow, the rheological properties are not only defined by fines, and thus should be tested in large rheometers with a wide grain-size distribution.

Keywords BING model, debris flow, debris material, laboratory test, rheology, rheometers

Introductions

Debris flows are natural disasters that pose a great threat to life and infrastructures around the world. Numerical simulation of debris flow is very important element of potential hazard zones determinations. An important part of numerical models is estimation rheological parameters. The rheological behaviour of debris flow is depended on grain size distributions, fines and sediment concentration. In the past decades considerable work has been carried out to provide rheological parameters for debris material using different types of viscometers and rheometers (e.g., Contreras and Davies 2000, Schatzmann et al. 2009, Bisantino et al. 2010, Maček et al. 2017). Many authors have pointed out, that there is a need to determine the rheological behaviour of debris flow with as large particle size as possible (Jeong 2006).

This study presents rheological measurements of debris flow materials from four Slovenia landslides – Stože, Stogovci, Čikla and Urbas. Measurements were executed using two coaxial cylinder rheometers and standard tests for determination workability and flowability of construction materials. Two coaxial cylinder rheometers were used to evaluate influence of geometry and maximum grain size of specimens. The low-cost standard test for determination workability and flowability of construction materials were used to investigate the determination possibility of rheological parameters from these tests.

Development of debris flow research in Slovenia

Practically one-third of Slovenian's territory is highly susceptible to landslides. Furthermore, susceptibility model reveals that about 15% of Slovenia is highly susceptible to debris flows events (Komac et al. 2009). Interest on debris-flow hazard has increased in Slovenia after the catastrophic debris-flow event from the Stože landslide in November 2000. Various studies have been performed in order to better understand this type of natural hazard (Mikoš, 2020).

Majes et al. (2002) reported first rheological parameters of three Slovenian landslides – Stože, Slano blato and Strug, measured on fines. These parameters were than used by Četina et al. (2006) for back analysis of the Stože debris flow. They found that a different set of rheological parameters is needed.

Later Maček et. al. (2017) analysed influence of rheometer size and grain distribution on rheological parameters of debris flow using larger rheometer. A new back analyse was made by Sodnik (2017) using these rheological parameters. Again, there were differences between material parameters and model prediction.

Bezak et. al. (2021) also used rheological parameters obtained from large rheometer to calibrate a debris flow model for the Koroška Bela landslides.

Rheological behaviour of debris material

Debris materials display non-Newtonian flow behaviour, which could be described by the Bingham model. The Bingham model is one of the simplest and most popular rheological models for pseudoplastic materials. This model preserves linear relationship between shear stress (τ) and shear rate ($\dot{\gamma}$) including yield stress (τ_y) and plastic viscosity (η_p).

$$\tau = \tau_y + \eta_p \dot{\gamma} \qquad [1]$$

The rheological parameters of debris material are usually expressed depending on sediment concentration (O'Brien and Julien 1988). The sediment concentration (C_v) in this study was calculated from the measured water content assuming full saturation of specimen.

$$C_V = \frac{V_S}{V} = \frac{1}{1+\frac{w\,\rho_S}{S_r\,\rho_W}} \qquad [2]$$

where V_s is the volume of particles, V is the volume of soil, w is the water content, S_r is the degree of saturation (1 for fully saturated soil), ρ_s is the density of particles, and ρ_w is the density of water.

Rheometers

Physical problem of soil deformation in rheometers is very complex (Schramm, 2000). The mathematical solution is acceptable with some basic assumptions – laminar flow, steady state flow, no slip at the cylinder surface, no end effect, homogeneity of soil and no chemical or physical changes during testing (Jeong, 2006).

From the measurements by coaxial cylinder rheometers, the properties of the Bingham model were determined considering the possibility of plug flow (Feys et al. 2013, Smolar et al. 2016). In the plug flow regime not all material flows, and the boundary between the sheared "fluid" and the un-sheared "solid" is called the plug radius (R_p).

$$R_P = \sqrt{\frac{T}{\tau_y\,2\,\pi\,h}} \;\leq\; R_0 \qquad [3]$$

where T is torque, h is height of the inner cylinder and R_o is radius of container.

Rheological parameters were determined by using proper mathematical equation (Eq. 1) considering boundary conditions (Eq. 3). The Eq. 4 is obtained by integrating shear rates between inner and outer cylinders.

$$T = \frac{4\,\pi\,h\,ln\left(\frac{R_S}{R_i}\right)}{\left(\frac{1}{R_i^2}-\frac{1}{R_S^2}\right)}\,\tau_y + \frac{8\,\pi^2 h}{\left(\frac{1}{R_i^2}-\frac{1}{R_S^2}\right)}\,\eta_p\,N \qquad [4]$$

where $R_S = \min(R_P, R_0)$ defined after Fig. 1 and R_i is inner cylinder radius. From the measured sets of rotational velocity (N) and corresponding torque (T), the Bingham rheological parameters can be calculated by using least-squares method.

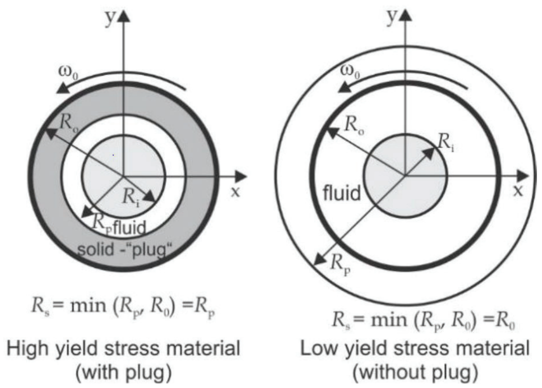

Figure 1 Top view of coaxial cylinder left – with plug flow, right – without plug flow (Feys et al. 2013).

Standard laboratory tests

There are numerous standard tests for determination workability and flowability of construction materials. Furthermore, such determination of rheological properties frequently enables only measurements of material response to test (e.g., material spreading, time needed to flow) without determinations of rheological parameters. However, in this study the possibility of determination Bingham rheological parameters by using standard tests (funnels, V-funnel, and flow channel) were also carried out.

Funnels

The Bingham rheological parameters were determined according to outflow time from funnels using semi-analytical approach introducing by Nguyen et al. (2006). The outflow times were calculated by numerical integration. Rheological parameters were obtained by comparing measured data with calculated ones.

V-funnel and flow channel

The possibility of rheological parameters determination from V-funnel and flow channel measurements was performed by using parametric analysis. However, after initial measurements on fines were concluded that V-funnel is not suitable for rheological investigation of debris material. Debris material at low volume concentrations flowed from the V-funnel rapidly (about in 1 second), while material at higher volume concentration did not flow (dripping). Due to this only flow channel was used afterwards.

Materials investigated

Investigated materials are from 4 different Slovenian landslides – Stože, Stogovci, Urbas and Čikla landslides. Grain size distribution curves of debris materials are shown in Fig. 2 and index properties of fines are shown in Tab. 1.

Testing equipment and methods

Rheometers

Two types of shear rate controlled coaxial cylinder rheometers were used in this study – Brookfield DV3T HB (DV3T HB) and ConTec Viscometer 5 (CTK 5). The main differences between these rheometers are the volume and maximal grain size of the specimen.

DV3T HB Rheometer

Smaller DV3T HB rheometer is suitable for measurements on fine-grained debris material (0-0.063 mm) at different sediment concentrations (Fig. 3). Tests in this rheometer were conducted by using different size of vain and smooth spindles. However, spindle was found not suitable for rheological investigation of debris material due to problems with slippage at the contact of material and spindle. Same problem is reported by Smolar et al. (2016) on marine clays.

Measurements were performed by decreasing shear rate from 250 to 10 RPM (revolutions/ minute) in stages of 10 RPM. Each step lasted until the vane had rotated at least one revolution (360°). During the investigation the outer cylinder was fixed, while vane was rotating. The resulting torque was calculated for each step as the average of measured values after equilibrium was reached.

ConTec Viscometer 5

Larger ConTec Viscometer 5 is primary designed for rheological testing fresh mortars and concrete (Fig. 4). It enables measurements on material with maximum grain size of 22.4 mm.

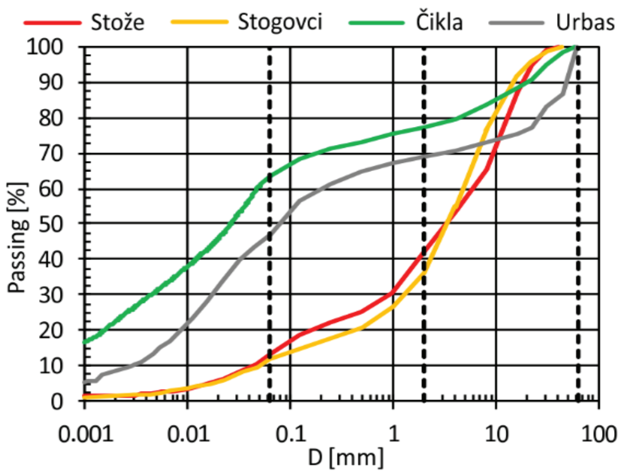

Figure 2 Grain size distribution of tested samples.

Table 1: Index properties of fines.

Material	w_L [%]	I_P [/]
Stože landslide	16.2	11.6
Stogovci landslide	20.4	9.1
Čikla landslide	20.0	39.3
Urbas landslide	31.7	23.3

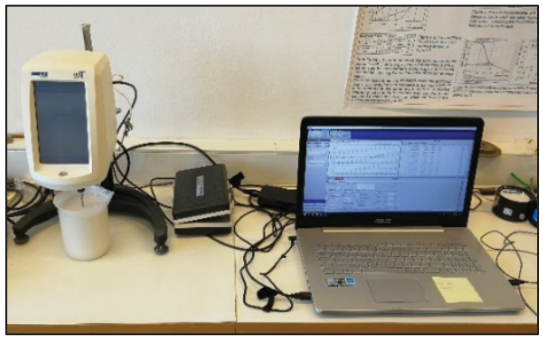

Figure 3 DV3T HB rheometer.

Figure 4 ConTec Viscometer 5.

In this study grain size of debris material was reduced to 16 mm as elongated particles could jam the gap between the inner and outer radius (Maček, 2017). After the initial pre-shear period of around 6 seconds the measurements were performed by decreasing shear rate from 1.1 RPS (revolutions/ second) to 0.1 RPS in steps of 0.1 RPS. The last stage of the test was shearing at rotational velocity of 0.7 RPS to check segregation of the material. The resulting torque for each step was calculated from the 10 lowest measured values in 15 seconds of measurement, after an equilibration time of 1 second.

Standard laboratory tests

Funnels

Rheological measurements using funnels were performed on fine-grained debris material at different sediment concentration (Fig. 5). The time of specimen flow through different nozzle diameter (4.75, 8, 9, 10, 11, 13 mm) in step by 200 ml was measured. Measurements were performed while flow was continuous. In case of segregation or dripping specimens out of nozzle, the measurements were terminated.

Flow channel

By using the flow channel, the impact of rheological properties on the time and length of spreading 1 L fine-grained debris material at different sediment concentration were investigated. The test started by opening valve and the material started to spread along the channel. After 30 second the spread was measured.

The entire measurement was enhanced by recordings with GoPro Hero 4 camera with an accuracy of 25 images per second. The recordings were afterwards equipped with image counter (Fig. 6). The rate of spreading was determined from these images.

Test results

Fine-grained debris material

Rheometer and funnels

Measured data from DV3T HB rheometer was analysed by using Eq. 4. Furthermore, the rheological parameters were estimated from funnel measurements by using semi-analytical equations by Nguyen et al. (2006). It was found that one rheological parameter was close to rheometer measurements while the other exhibit significant uncertainties. Best results were obtained if rheological parameters from funnel measurements were fitted using initial approximation of yield stress as remoulded undrained shear stress (c_{ur}). Additionally, analysis could be improved by considering relationship between rheological parameters and volume concentration (O'Brien and Julien, 1988) as presented in Fig. 7.

Remoulded undrained shear stress of fine-grained debris material was measured separately with laboratory vane at 0.25 RPM.

Flow channel

The results of flow channel measurements are presented in Fig. 8.

Figure 5 Funnel with different nozzle diameter.

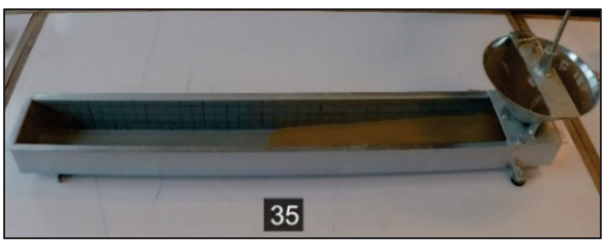

Figure 6 Flow channel.

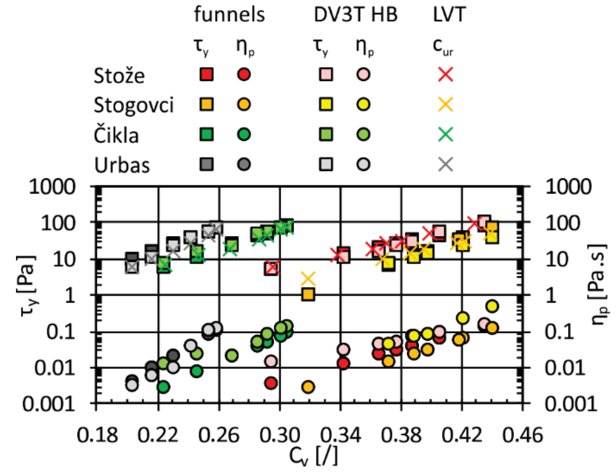

Figure 7 Rheological parameters and remoulded undrained shear stress of fine-grained debris material.

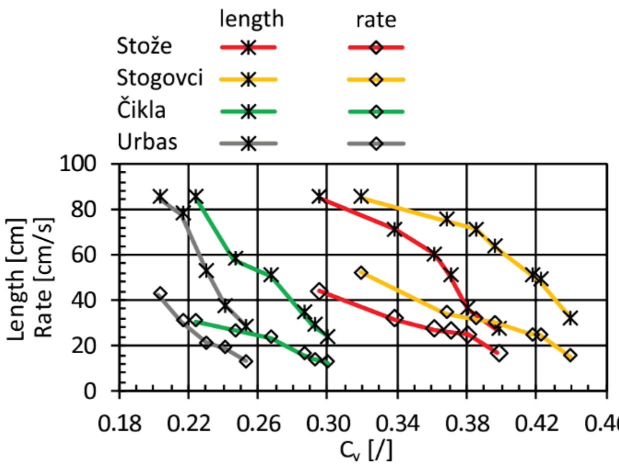

Figure 8 Length and rate of spreading fine-grained debris material in flow channel.

Coarse-grained debris material

Rheometer

Measured data from CVT 5 rheometer was analysed by using Eq. 4 (Fig. 9). Rheological measurements on coarse-grained debris material from the Čikla landslide were performed in twice within the interval of 3 months. Yield stresses were close while plastic viscosity were approximately two times different.

Analysis of results and discussion

Rheometers

Rheological parameters obtained by rheometers were compared considering grain composition and relationship between shear stress and plastic viscosity. In case that rheological properties would be predominately defined by nature and consistency of fines, then rheological parameters would be only consistency of fines dependent. In Fig. 10 sediment concentration of fines was calculated by assuming that water is only bonded on fines (i.e., coarse grains floats in fine-grained matrix). However, the results show significant differences between tests on fine-grained fractions or on material 0-16 mm, thus measurement only on fine-grained fractions cannot describe the flow behaviour of debris material.

Flow channel

A parametric analysis was performed to investigate a relationship between rheological parameters of fine-grained debris material and length/speed of spreading material over the channel. Fig. 11 compares the measured and estimated length and rate (Eq. 8 and 9). The accuracy of prediction is ± 5 cm for length or ± 5 cm/s for rate. By inversing the problem, it was found that only yield stress could be reasonably estimated by measuring length and rate of spread, but not plastic viscosity.

A better prediction was trying to obtain by using one-dimensional BING model for simulating the flow of debris flows in subaqueous or subaerial environment. The input parameters of the model are the longitudinal profile of the bed, the initial shape of debris source (parabolic), the density of debris material and rheological parameters. The output produced by BING includes runout distance and frontal velocity of material.

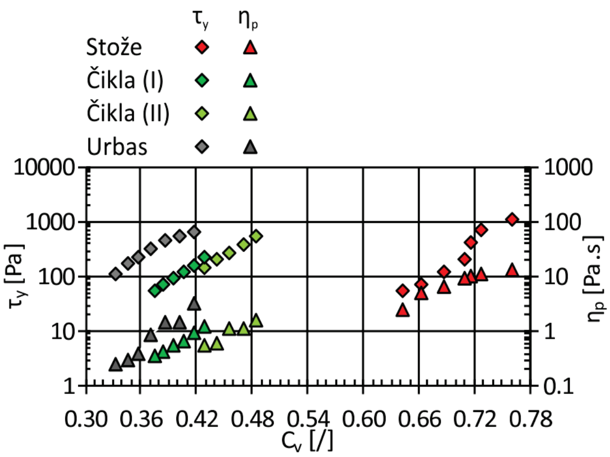

Figure 9 Rheological parameters of coarse-grained debris material.

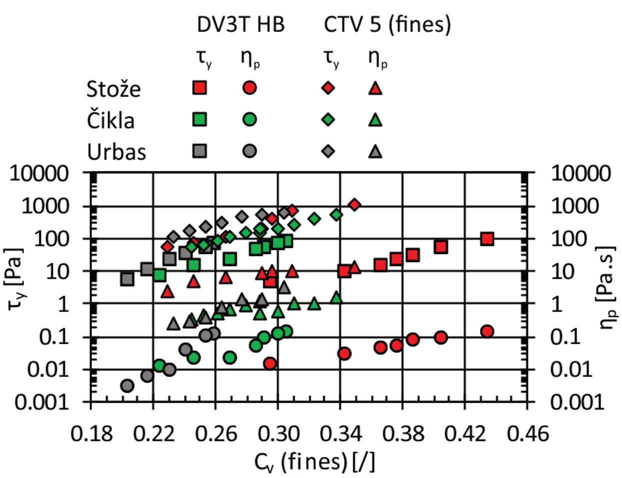

Figure 10 Yield stress, plastic viscosity and sediment concentration (for fines) from DV3T HB and CTV5 rheological measurement.

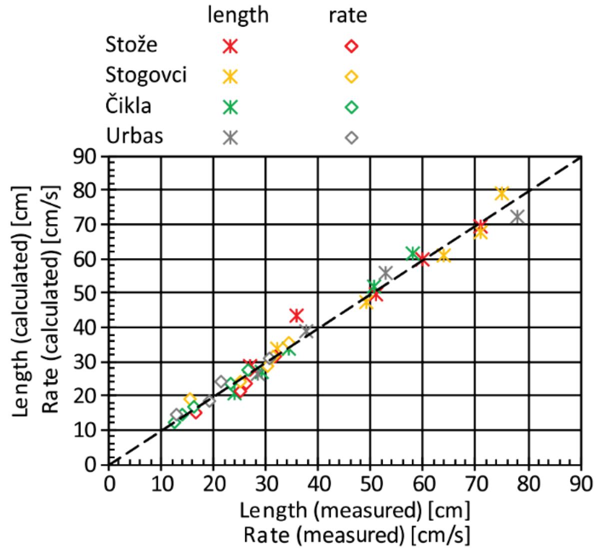

Figure 11: Measured and calculated (parametric analysis) length and rate of spreading.

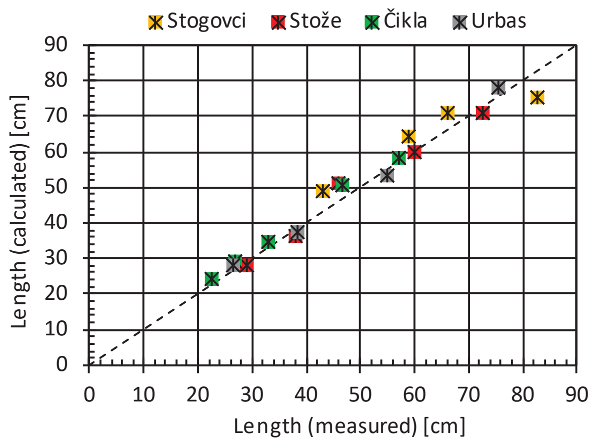

Figure 12 Measured and calculated (BING model) length and rate of spreading.

The funnel flow measurements were calculated based on rheological parameters from DV3T HB rheometer. The initial material shape (parabola) was such that potential energy was approximately the same. The model describes well the influence of each type of fine-grained debris material on the behaviour (runout distance) of the flow (Fig. 12), although the velocities were significantly overestimated The same is also reported by Remaire et al. (2005) and Jeon (2014).

Conclusions

The main conclusions based on this study are:

- The debris materials behave as Bingham viscoplastic fluid.
- The rheological parameters depend on sediment concentration and grain size distribution. The increase of sediment concentration or maximal grain size increases both yield stress and plastic viscosity.

- The rheological properties of debris flows are not defined only by fines.
- The rheological parameters measured in coaxial cylinder rheometers give reasonably good predictions of standard test results, while from these standard tests estimations of rheological parameters are not possible. Standard tests are suitable for quality assessment of rheological measurements.
- For real field cases, rheological properties of debris materials should be tested in large rheometers with as wide grain-size distribution as possible.

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