Evaluation of Model Parameterization through Laboratory Investigations

Roland KAITTNA\(^1\), Dieter RICKENMANN\(^2\) and Johannes HUEBL\(^1\)

\(^1\) Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Vienna
(Peter Jordanstrasse 82, 1190 Vienna, Austria)
E-mail: roland.kaitna@boku.ac.at
\(^2\) Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Zuercherstrasse 111, 8903 Birmensdorf, Switzerland)

Engineering simulation tools for predicting the flow and deposition behavior of debris flows make use of simple rheologic flow laws describing flow resistance. In this contribution we test the possibility to parameterize simple flow models by laboratory investigations. We estimate parameters for the Bingham model from a suite of laboratory experiments in different setups. Material samples were taken from fresh deposits of a muddy debris flow and analyzed over a range of volumetric sediment concentrations and maximum grain sizes. Our results are relatively consistent between most setups. Estimated rheologic parameters show an exponential dependence on volumetric sediment concentration and a systematic variation for mixtures of different maximum grain sizes. Though a rheologic interpretation of bulk flow behavior seems feasible at the laboratory scale, extrapolation of rheologic parameters to prototype flow situation for direct use in numerical simulation tools is not recommended.

**Key words:** rheologic parameters, laboratory investigation, simulation tools

1. INTRODUCTION

To assess potential debris-flow hazard areas, often numerical simulation tools solving depth-averaged mass and momentum balance equations are used (e.g. Flo2D, DAN3D, RAMMS-DF, RASH3D, ...). By treating these two-phase mixtures of sediment and water as homogeneous media (cf. equivalent fluid concept as outlined by [Hung, 1995]), relatively simple concepts for describing the bulk flow resistance are available, including a simple basal Coulomb friction model or the Voellmy model [Voellmy, 1955]. Some simulation tools make use of a simple rheologic constitutive equation, relating shear stress with shear rate [e.g., O’Brien et al., 1993], the Bingham model [Bingham, 1922], which reads

\[
\tau = \tau_y + \mu \dot{\gamma}
\]

where \(\tau\) = shear stress [Pa], \(\tau_y\) = yield stress [Pa], \(\mu\) = viscosity [Pa.s], and \(\dot{\gamma} = du/dz\) = shear rate [Pa.s], with \(u\) = velocity [m/s] in flow direction \(x\) and \(z\) = bed normal coordinate. Though the applicability of such simple flow laws for describing the flow and deposition behavior of grain-fluid mixtures is limited [Coussot, 1997; Hashimoto and Hirano, 1997; Ancey, 2006; Boyer et al., 2011; Mueller et al., 2009], they are often still standard in engineering applications.

With this comes the problem of determination of the magnitude of model parameters \(\tau_y\) and \(\mu\) for the case study in question. There are typically three options: (1) back-calculation of a past event in the same or similar watershed using a numerical simulation model, (2) determination from field observations using relations outlined e.g. by [Johnson and Rodine, 1984], or (3) carrying out laboratory tests on samples from deposits or expected source areas. There are only few studies comparing model parameterization by back-calculation, field evidence and laboratory experiments [e.g., Sosio et al., 2007]. Options (1) and (2) are often limited by the lack of observations. Laboratory experiments with standard rheologic setups are typically restricted to grain sizes not larger than silt (\(10^{-5}\) m; e.g. [O’Brien and Julien, 1988]). Few studies on the relation between shear stress and shear rate have been conducted with
sediment-fluid mixtures including grain sizes up to sand and gravel (10^2 m; e.g. [Phillips and Davies, 1991; Major and Pierson, 1992; Coussot and Piau, 1995; Ancey and Jorrot, 2001; Schatzmann, 2005; Kaitna et al., 2007]. However, the applicability of the results for model parameterization seems questionable due to several reasons: first, a limited fraction of the total grain size distribution may not be representative for the prototype flow, which may include boulders of several meter in diameter (“sample bias”). Secondly, dynamic similarity between small scale experiments and natural flows is expected to be violated since some forces might be over- or under-represented in experimental flows (“scaling bias”; e.g. [Iverson, 1997 and subsequent papers].

In this contribution we focus on quantifying the first limitation, investigating the effect of different maximum grain sizes on the rheologic behavior of debris mixtures as proposed by [Coussot et al., 1998]. The material used stems from deposits of a monitored debris-flow event. The investigations are conducted for different mixture sediment concentrations (C_i) and using different setups, which are explained in section 2. In section 3 we present an overview of the results and in section 4 we discuss the applicability for model parameterization.

2. METHODS

2.1 Material

The debris flow material used in this study was taken from deposits of a debris flow event at the Lattenbach creek, Austria, which occurred on June 20th, 2007. Due to video recordings at a monitoring station in the lower reach of the creek, information on flow depth and surface velocity is available. During this event a total of about 20,000 m³ of sediment and fluid was delivered in 14 surges to the receiving river Sanna. Details of the monitoring station and an analysis of the dynamics of the event are reported by [Arai et al., 2013]. Since only a relatively low fraction of the total event volume was deposited outside of the channel, about 400 kg of material was sampled with an excavator from a lobe at an outer channel bend close to the monitoring station, where the flow overtopped the channel boundary. The muddy appearance of the debris flow is supported by subsequent grain size analysis of all material, which was carried out by means of hand count of grains > 63 mm, sieve analysis and sedimentation analysis (Fig. 1). In total silt and clay accounts for about 8% of grain sizes and sand for about 27% [Olbort, 2009].

Subsequently four partial samples with maximum grain sizes d_max of 0.13 mm, 1 mm, 8 mm and 32 mm were prepared.

2.2 Experimental setups and analysis

We used rheometric shear experiments with a standard desktop viscometer to derive the relation between shear stress and shear rate for grain sizes < 1 mm, a tilted board to conduct deposition experiments for all partial samples, and a rotating drum to carry out steady free-surface flow experiments with partial samples > 1 mm [Olbort, 2009]. Additional experiments with a conveyor belt setup did not yield replicable results due to technical difficulties (material loss).

The viscometer used was a co-axial cylinder viscometer (model Bohlin Visco 88) with a gap of 1.5 mm. Bingham parameters were derived in a shear rate range between 14 and 200 s⁻¹.

The tilt-board tests to derive bulk yield stress were guided by a procedure outlined by [Coussot and Boyer, 1995], and using the well-known equation

\[ \tau_y = \rho g h_0 \sin \theta \] (2)

where \( \rho \) = bulk density [kg/m³], \( g \) = gravity [m/s²], \( h_0 \) = deposition depth [m], and \( \theta \) = inclination [°].

Determination of Bingham parameters from steady flow experiments in a rotating drum follows a procedure outlined by [Kaitna and Rickenmann, 2007]. The rotating drum has a diameter \( R \) of 2.46 m and the rectangular channel a width of 0.45 m. Measured parameters include the longitudinal distribution of flow depth and basal normal stress in the centerline of the flow, mean and surface velocity, and total torque at the axis, which is needed to keep the flow at different pre-defined constant speed levels. To derive a relation between bulk shear stress and shear rate, and subsequently parameters for the Bingham model, we assume steady, uniform flow conditions. Bulk shear stress is calculated from the measured torque \( T \) with
3. RESULTS

A general observation from the experiments is that volumetric sediment concentration for debris-flow like sediment-fluid mixtures below the geotechnical liquid limit differs between partial samples having different cutoff grain sizes. E.g. the partial sample with \( d_{\text{max}} = 0.1 \text{ mm} \) “flows” below a \( C_y \)-value of about 0.35, and behaves plastic above 0.35. A partial sample with \( d_{\text{max}} = 8 \text{ mm} \) is liquid up to a \( C_y \)-value of 0.6.

As expected our results show that Bingham yield stress and viscosity are strongly dependent on sediment concentration (Fig. 2 and Fig. 3). For all experiments Bingham yield stress ranges between 4 Pa and 290 Pa, with increasing values with increasing \( d_{\text{max}} \). For samples \( \leq 0.1 \text{ mm} \) there is a reasonable agreement of yield stress derived from viscometer measurement and tilt-board test (Fig. 2, diamond symbols). Similarly, for samples \( \leq 1 \text{ mm} \) yield stress predicted from three independent experimental setups, including the drum, show a similar exponential dependence of yield stress on \( C_v \) value (circles). Increasing \( d_{\text{max}} \) increases data scatter. For mixtures \( \leq 8 \text{ mm} \) and \( \leq 32 \text{ mm} \) the dependence of yield stress on sediment concentration seems to increase, but still there is a reasonable agreement between setups. Here highest values are in the range of 200-300 Pa.

For the Bingham viscosity data from the viscometer tests and the drum experiments are available (Fig. 3). As for the yield stress we find an exponential dependence of viscosity on volumetric sediment concentration, but in this case values range over three orders of magnitude, from 0.06 to about 5 Pa.s. Viscosity values for partial samples \( \leq 1 \text{ mm} \) span over about one order of magnitude for both setups, the viscometer and the drum experiments.

Fitting an exponential equation of the form

\[
\tau_y = \alpha_y \cdot e^{d_{\text{max}}^\beta C_v}
\]

we derive fit parameters and coefficients of determination for the data of Bingham yield stress and Bingham viscosity for different partial samples (Table 1 and Table 2). We see relative high coefficients of determination for all mixtures except for the yield stress with \( d_{\text{max}} = 32 \text{ and viscosity with } d_{\text{max}} = 8 \). Neglecting these mixtures, coefficient \( \alpha \) tends to exponentially decrease with increasing maximum grain size and coefficient \( \beta \) is relatively constant around 22 and 27 for yield stress and Bingham viscosity, respectively.

4. DISCUSSION

4.1 Rheologic interpretation
The exponential dependence of yield stress and viscosity on sediment concentration found in our experiments fits well to observations made earlier [e.g., O’Brien and Julien, 1988; Coussot, 1997; Ancey, 2006]. In our study we find evidence that this relation systematically changes with increasing maximum grain size. Consequently rheologic parameters derived from partial samples are not representative for the full mixture. This supports the finding of [Sosio et al., 2007], who could not replicate deposition pattern of a documented debris flow solely relying on analysis of fine slurry rheology.

Using the data given in Table 1 and Table 2, and neglecting results with low coefficients of determination, assessment of $\alpha$ and $\beta$ for the prototype debris flow with a maximum grain size of 250 mm seems possible. When extrapolating $\alpha$ using an exponential function of form $\alpha = m d_{\max}^n$ yields $\alpha_{\max} = 1.04 \times 10^{-4}$ for yield stress and $\alpha_{\max} = 2.05 \times 10^{-8}$ for Bingham viscosity. Since both values of $\beta$ do not change significantly we pragmatically choose mean values $\beta_{\text{yp}} = 21$ and $\beta_{\text{yp}} = 27$, for yield stress and viscosity, respectively. Hence, rheologic parameters for the prototype flow with a $C_v$ value between 0.6 and 0.8, would range between 36 Pa and 2520 Pa for the yield stress and between 0.24 and 53 for Bingham viscosity.

A verification of these values with a numerical simulation model is not feasible here, because neither reference deposition patterns are available (the debris flow event did not leave the channel), nor further parameters of the flow dynamics along the reach were measured.

4.2 Limitations

There are several severe limitations concerning the presented analysis:

- Applicability of the Bingham model: several studies showed that the Bingham model represents a strong simplification of the true rheologic behavior of fine grain-fluid mixtures [e.g., Coussot, 1997; Ancey, 2006; Hashimoto et al., 2006; Mueller et al., 2009]
- Experimental shortcomings: true rheometric flows including particles $> 1$ mm are hard to establish due to settling, slip or other processes. Data often show hysteresis effects, inaccuracies or limited replicability [e.g., Phillips and Davies, 1991; Major and Pierson, 1992; Coussot and Piau, 1995]. Similarly, free surface flows are connected to uncertainties due experimental difficulties (e.g. sorting processes, solid-fluid segregation, and loss of material). All these limitations are expected to be important for experiments presented herein.
- Rheologic interpretation: the above described experimental problems as well as the design of the laboratory setups may pose difficulties for a rheologic interpretation, since the stress and strain field is not exactly known [e.g., Parson et al., 2001; Kaitna et al., 2007].
- Scaling: for a flowing mixture of sediment and water different sources of flow resistance can be identified: particle-particle interactions including friction and collision, fluid resistance (probably including fine sediment suspended in the fluid), as well as particle-fluid interactions [e.g., Iverson, 1997; Ancey, 2006]. Using dimensional analysis, Iverson, 2015, argues that in small scale experiments viscous effects, yield strength and grain inertia may be over-represented, whereas the effect of pore fluid pressure mediating grain contact forces may be disproportionally small. In our experiments we did not measure pore fluid pressure that would give an insight on the internal dynamics of the mixture. Similar experiments where fluid pressure was measured [Kaitna et al., 2014; 2016] showed high fluid pressures when the content of fine sediment was high, as in the current study.

5. CONCLUSION

In this contribution we investigated the rheologic behavior of debris flow material which was sieved to different maximum grain sizes (partial samples). The range of volumetric sediment concentration where a rheologic analysis is possible differs for partial samples and increases with increasing maximum grain size.
We find that Bingham model parameters derived with different methods are relative consistent between experimental setups.

Bingham parameters increase exponentially with volumetric sediment concentration and this relation depends on maximum grain size of the samples investigated.

For the material tested in this study it was not possible to overcome the “sampling bias” by extrapolating Bingham parameters derived in the lab for partial samples to the prototype mixture (debris flow mixture found in the field). Even if all experimental difficulties were solved, there is still a limitation due to scaling considerations (“scaling bias”), which need further investigations.

ACKNOWLEDGMENT: We thank Matthias Olbort and Andreas Macho for experimental data and Friedrich Zott for technical support.

REFERENCES


Received: 8 July, 2015
Accepted: 15 February, 2016