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Friction in Debris Flows: Inferences from Large-scale Flume Experiments

Richard M. Iverson and Richard G. LaHusen[1]

Abstract

A recently constructed flume, 95 m long and 2 m wide, permits systematic experimentation with unsteady, nonuniform flows of poorly sorted geological debris. Preliminary experiments with water-saturated mixtures of sand and gravel show that they flow in a manner consistent with Coulomb frictional behavior. The Coulomb flow model of Savage and Hutter (1989, 1991), modified to include quasi-static pore-pressure effects, predicts flow-front velocities and flow depths reasonably well. Moreover, simple scaling analyses show that grain friction, rather than liquid viscosity or grain collisions, probably dominates shear resistance and momentum transport in the experimental flows. The same scaling indicates that grain friction is also important in many natural debris flows.

Introduction

Progress in predicting the behavior of debris flows has been hampered by a dearth of data suitable for testing hypotheses. The capricious timing, location, and magnitude of most debris flows make systematic field measurements both difficult and dangerous. Consequently, in 1991 and 1992 the U.S. Geological Survey constructed a flume to conduct controlled experiments on debris flows. Located on a hillside about 70 kilometers east of Eugene, Oregon, near the headquarters of the H.J. Andrews Experimental Forest, Willamette National Forest, the flume provides research opportunities available nowhere else. This paper describes the rationale for flume design and operation and presents some results and interpretations of preliminary experiments. The interpretations focus on a key question that must be addressed in debris-flow modeling: what are the relative contributions of liquid viscosity, grain collisions, and grain friction to shear resistance and momentum transport in debris flows?

[1]U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA 98661

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Flume Design and Operation

Three considerations guided the flume design. (1) We wished to study flow of finite debris masses from initiation to deposition. This dictated the choice of a non-recirculating flume with a sediment-loading area at its head and a run-out area at its toe. (2) We wished to study flow of realistic geological debris, which can include large particles with the potential for strong inertial interactions. (Miniature, laboratory debris flows provide inadequate similitude of coarse-grained, natural debris flows owing to the low inertia of small particles and the difficulty of scaling the peculiar physico-chemical properties of interstitial water and clay.) This dictated that the flume would be large. Cost restrictions consequently necessitated an outdoor location and a fixed bed slope. (3) We wished to study both water-saturated debris flows and relatively dry flows such as rock avalanches and pyroclastic flows. This dictated a flume slope steeper than 30° -- steep enough for some dry mixtures to flow. This slope also typifies steep hillsides where natural debris flows originate.

These considerations resulted in construction of a reinforced concrete flume 95 m long, 2 m wide, and 1.2 m deep that slopes 31° throughout its upper 88 m and flattens gradually to $2\frac{1}{2}$° over the last 7 m (Figure 1a). Ten meters downslope from the flume head, steel gates attach with hinges to the flume walls. Up to 20 m^3 of sediment can be loaded behind the gates and saturated with water applied via subsurface channels and surface sprinklers. To initiate a debris flow, a hydraulic piston unlatches the gates, which swing fully open in about half a second. Alternatively, a sloping mass of sediment can be placed behind a low retaining wall and watered until slope failure occurs. In either case the ensuing debris flow descends the channel and forms a deposit on a concrete run-out pad at the flume base (Figure 1b). The deposited sediment can be studied and then recycled by excavating it with a loader and trucking it to the head of the flume.

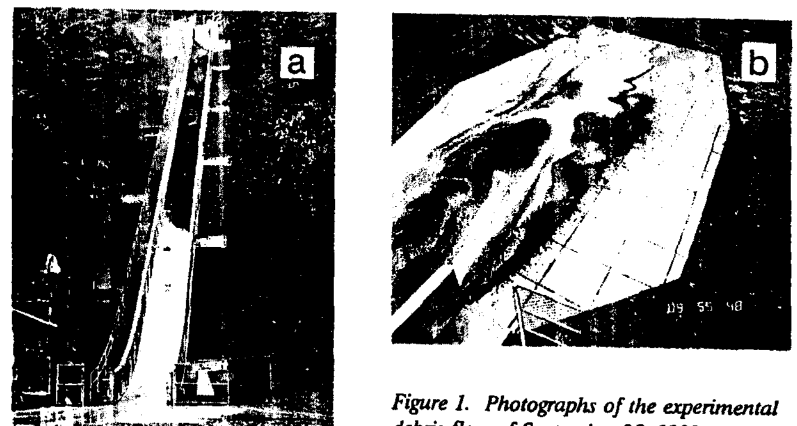

Figure 1. Photographs of the experimental debris flow of September 25, 1992.

Opening of the flume gate triggers a clock that synchronizes digital data acquisition. Collection of flow-dynamics data is focused at three cross sections, located 33 m and 67 m below the gate and 3 m above the gate. The cross sections include ports in the flume bed, glass windows and steel panels in the flume wall, and booms for suspending instruments above the flow. Load cells and piezoelectric sensors mounted in the ports measure normal stresses at the bed over areas of 1, 22, and 500 cm^2 and at frequencies up to 4000 Hz. Transducers that measure shear stresses or pore-fluid pressures also can be installed in the ports. Windows permit cross-sectional viewing and videotaping of flows as they pass, and steel panels provide a low-attenuation environment for making active and passive acoustic measurements. Booms facilitate placement of cameras and ultrasonic flow-depth meters directly above the flows.

Other data-collection efforts focus on refinement of an automated debris-flow detection system, quantitative interpretation of deposit morphology and sedimentology, and testing of formulae for estimation of flow velocities, discharges, and impact forces.

The Coulomb Flow Hypothesis: An Experimental Test

Preliminary experiments during the spring and summer of 1992 emphasized development and refinement of experimental techniques, but also yielded useful data. Simultaneous, high-speed measurements of flow depth and normal stress on the flume bed permitted calculation of the dynamic bulk density of a flowing sand-gravel-water mixture. The data (see Iverson et al., 1992, figure 4) yielded a dynamic bulk density close to 2000 kg/m^3, indistinguishable from the static bulk density of the uncompacted material. This indicated that sediment grains in the flow may have contacted one another almost continuously. Accordingly, we hypothesized that solid grain friction dominated shear resistance and momentum transport in the experimental flow.

Solid friction is only one possible mechanism of shear resistance and momentum transport in debris flows. Liquid viscosity, the mechanism in viscoplastic or viscous models, and particle collisions, the mechanism in inertial grain-flow models, may also be important (Iverson and Denlinger, 1987). Evaluation of key dimensionless scaling parameters for open-channel flows of sediment-liquid mixtures helps quantify the relative importance of these three mechanisms. Three key scaling parameters may be labeled the Bagnold number, B, Savage number, S, and friction number, F, and defined as

$$B = \frac{\dot{\gamma}\rho_s\delta^2}{\mu}\lambda^{1/2} \qquad S = \frac{\dot{\gamma}^2\delta^2}{\nu g h} \qquad F = \frac{\rho_s \nu g h}{\dot{\gamma}\mu}$$

where $\dot{\gamma}$ is a typical shear-strain rate, ρ_s is the sediment density, δ is a typical grain diameter, μ is the liquid viscosity, ν is the mean volume fraction of the granular phase, h is a typical flow depth, and g is the gravitational acceleration.

The factor λ depends on ν and the maximum (close-packed) grain volume fraction, ν^*, in the manner $\lambda = \nu^{1/3}/(\nu^{*1/3} - \nu^{1/3})$. For a range of hypothetical debris flows, with $0.5 \le \nu \le 0.7$ and $0.7 \le \nu^* \le 0.9$, λ is typically of order 10.

The definitions of B and S derive from the work of Bagnold (1954) and Savage (1984) and represent ratios of the characteristic shear stresses due to grain collisions, $\dot{\gamma}^2\rho_s\delta^2$, liquid viscosity, $\dot{\gamma}\mu$, and solid friction, $\nu\rho_s gh\tan\phi$. (To match the usage of Savage, the definitions of S and F omit $\tan\phi$, the solid bulk friction coefficient, which typically ranges only from 0.5 to 1.0.) Shear-cell experiments performed by Bagnold (1954) and subsequently replicated by others demonstrate that stresses due to grain collisions dominate viscous fluid stresses if $B > 450$, whereas viscous effects dominate if $B < 40$. Similarly, inferences drawn by Savage and Hutter (1989) from a variety of data indicate that grain collisions probably dominate grain friction if $S > 0.1$. Experimental data that define the value of F at which grain friction dominates liquid viscosity are not available. However, because $F = \lambda^{-1/2}B/S$, a plausible estimate is that friction dominates viscosity if $F > 10^{-1/2} \cdot (450 \div 0.1)$, that is, $F > 1400$.

Table 1 summarizes evaluation of B, S, and F for a water-saturated sand-and-gravel debris flow released in the flume on Sept. 25, 1992, and for larger, muddier, stonier, hypothetical debris flows. Values of B, S, and F for the experimental flow indicate that Coulomb friction probably dominated both grain collisions and liquid viscosity as a mode of shear resistance and momentum transport. This reflects the low viscosity of the liquid (water) and small size of the grains (median diameter ~0.007 m) in the flow. The values of B, S, and F for the hypothetical debris flows are more equivocal and indicate the importance of collisions and viscosity in addition to solid friction.

Table 1. Estimation of scaling parameters B, S, and F for debris flows.

	Flume flow, 9/25/92	Hypothetical flow 1	Hypothetical flow 2
h (m)	0.1	1	2
δ (m)	0.007 (median)	0.1 (cobbles)	1 (boulders)
$\dot{\gamma}$ (s^{-1})	20[@]	5[*]	5[*]
μ (Pa-s)	0.001 (water)	1 (dense slurry)[#]	0.1 (dilute slurry)[#]
ρ_s (kg/m^3)	2700	2700	2700
g (m/s^2)	9.8	9.8	9.8
ν	0.6	0.6	0.6
ν^*	0.75	0.75	0.75
B	10,000	500	500,000
S	0.03	0.04	2
F	80,000	3000	60,000

[@]Employs estimate (from videotapes) that bed slip accounted for 2/3 of mean motion.
[*]Typical of natural debris flows as inferred by Phillips and Davies (1991).
[#]Typical of clay-silt slurry tests by O'Brien & Julien (1988) and Major & Pierson (1992).

As a test of the Coulomb hypothesis, we used the model of Savage and Hutter (1989, 1991) to predict the velocity and depth of the Sept. 25 flume debris flow. The model employs depth-averaged equations of motion to simulate unsteady, nonuniform flow of a finite mass of Coulomb material. The flow begins and ends with the mass at rest. The model contains only two material parameters, an internal friction angle, ϕ_i, and a bed friction angle, ϕ_b. We independently measured quasi-static values of these parameters and obtained $\phi_i = 42°$ and $\phi_b = 27°$ for input to the model. To account for pore-water pressure effects, which are not included in *B*, *S*, and *F* as defined above, we added the term $-\overline{\partial p/\partial \eta}(\tan\phi_b)/\rho_s g$ to the right-hand side of Savage and Hutter's (1991) normalized momentum equation, 2.39. Here $\overline{\partial p/\partial \eta}$ is the depth-averaged pore-pressure gradient in the debris flow. In making model predictions, we estimated that $\overline{\partial p/\partial \eta} = -\rho_w g \cos\theta$; thus we assumed that the vertical pore-pressure gradient is hydrostatic and that the pore-water head gradient parallels the flume bed, which slopes at an angle θ. This represents the simplest, uncoupled, quasi-static pore-pressure effect. More complex, dynamic and coupled pore-pressure effects (e.g., Iverson and LaHusen, 1989) undoubtedly arise in debris flows and should be predicted, not estimated, as part of a more comprehensive model.

Figure 2 illustrates a comparison between model predictions and measured behavior of the experimental debris flow. The model over-predicts

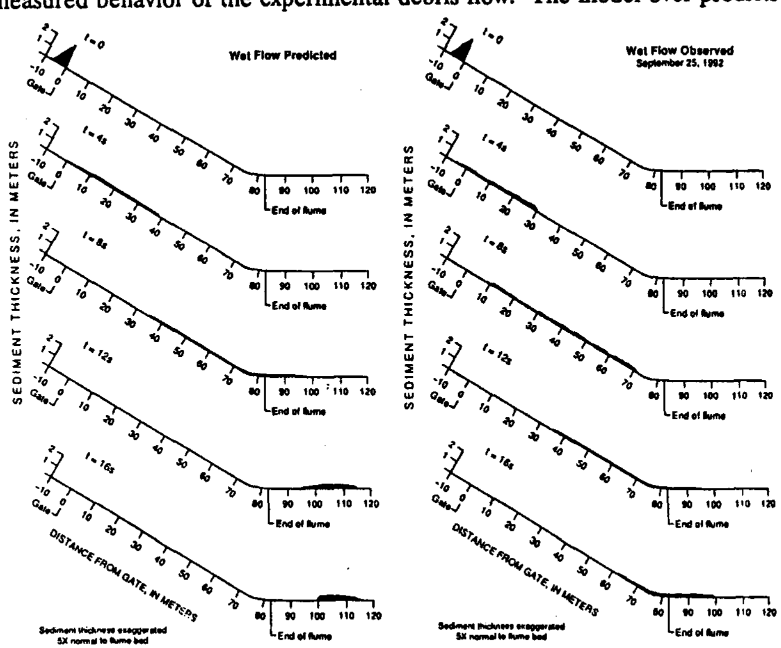

Figure 2. Predicted and observed debris-flow motion from initiation to deposition.

flow-front speed and flow depth, but typically only by a few tens of percent. The error can be reduced somewhat by accounting for sidewall friction, finite opening speed of the flume gate, and lateral spreading of sediment that occurs when the flow discharges from the flume. Moreover, if we calibrate the model by adjusting friction angles or the estimated pore-pressure gradient, the error can be can be made almost zero. However, we emphasize instead that the predictions of the *uncalibrated* model are quite good, given the complexity of debris flows and the simplicity of the model.

Conclusions

Results from preliminary experiments in a recently constructed hillside flume support the hypothesis that Coulomb friction dominates shear resistance and momentum transport in rapid debris flows that consist of water-saturated sand and gravel. Simple scaling analyses show that solid friction may also dominate in some natural debris flows, although grain collisions or liquid viscosity may dominate in others. Because pore-fluid pressures can strongly mediate both grain friction and collisions, improved models of debris flow should incorporate solid-fluid coupling that generates pore-pressure gradients.

Acknowledgments

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