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Laboratory investigation of the frictional behavior of granular volcanic material

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Abstract

We report on detailed laboratory experiments designed to illustrate the frictional behavior of granular volcanic debris. The materials include pyroclastic flow debris from Soufrière Hills Volcano, Montserrat, and from Stromboli Volcano, Italy, and lahar deposits from Mount St. Helens. Experiments were conducted in a servo-controlled, double-direct shear apparatus under conditions of displacement-control and with monitored temperature and humidity. The effects of loading velocity, normal stress, grain-size range, and saturation state were examined for normal stresses from 0.75 to 8 MPa. The Soufrière Hills debris was sampled in the field using a 2 mm sieve. Samples from Stromboli and MSH represent the original bulk material. The influence of grain-size and size distribution were examined in detail for the Soufrière Hills material for 1) two narrow size ranges (3–4 ϕ, 0.063–0.125 mm; and 0–1 ϕ, 0.5–1 mm), 2) a wide size range (3–0 ϕ, 0.125–1 mm), and 3) the natural size distribution in the range 0–1 mm. These four data sets show remarkably uniform properties: coefficients of residual internal friction varied from 0.62 to 0.64 and coefficients of peak internal friction varied from 0.66 to 0.69, with zero cohesion in each case. For the natural grain-size distribution, we find a small but clear increase in residual sliding friction with increasing slip velocity in the range 10 to 900 μm/s, i.e. velocity strengthening frictional behavior. For Soufrière Hills pyroclastic material the coefficient of internal friction changes very little when water saturated. The frictional characteristics were remarkably similar for the three volcanoes. For the natural grain-size distributions, the coefficient of residual internal friction ranged from 0.61 to 0.63 and peak internal friction values ranged from 0.65 to 0.66. Pre-loaded and over-compacted materials sheared at reduced normal stress gave peak coefficients as high as 0.80. Our results imply that granular volcanic debris should often fail via stable creep, but may exhibit stick-slip instability under some conditions.

Keywords: friction; grain-size distribution; Soufriére Hills; Mount St. Helens; Stromboli

1. Introduction and motivation

Pyroclastic density currents (PDC's) and lahars are two examples of rapid and far-reaching hazards associated with volcanic eruptions. The flow behavior of PDC's and lahars is influenced by inter-particle friction associated with solid particles that come into contact during flow (Iverson, 1997; Cagnoli and Manga, 2004), affecting the velocity of travel and their reach. Inter-granular friction is of particular importance in understanding the behavior of PDC's as they become degassed and settle to a stop and lahars as they become dewatered. It is also of importance in defining the onset and triggering of instability in the failure of edifices and the failure of lava domes (Voight and Elsworth, 1997; Voight and Elsworth, 2000; Voight, 2000). The intention of this work is not to describe the complex behavior and processes taking place in lahars and pyroclastic flows while they are in full motion, but rather to specifically understand the frictional strength of the material as it might apply to the initiation of a slope failure, or as one of the factors influencing deceleration and stoppage of flows.

Here we present well-constrained experiments (Table 1) to investigate the frictional behavior of material from three

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Table 1
Experimental conditions and results for samples from Soufriére Hills, Mount St. Helens, and Stromboli volcanoes

Experiment #	Material type	Grain size	Normal stress (MPa)	Shear rate (μm/s)	Pre-shear porosity (%)	Relative density (%)	6.5 mm strength (MPa)	10 mm strength (MPa)	15 mm Strength (MPa)	Peak Strength (MPa)	Peak Shown?
p433	SHV P.F.	0.5–1.0	8	10	–	–	5.13	5.19	5.2		n
p504	SHV P.F.	0.5–1.0	2	10	40	150	1.26	1.31	1.34		n
p447	SHV P.F.	0.5–1.0	2	10	–	–	1.22	1.21	1.22	1.3	y
p448	SHV P.F.	0.5–1.0	0.75	10	–	–	0.46	0.45	0.43	0.54	y
p507	SHV P.F.	0.5–1.0	0.75	10	40	150	0.46	0.45	0.44	0.58	y
p467	SHV P.F.	0.063–0.125	8	10	30	200	5.04	5.12	5.12		n
p449	SHV P.F.	0.063–0.125	8	10	–	–	5.07	5.09	4.98		n
p450	SHV P.F.	0.063–0.125	2	10	–	–	1.25	1.19	1.21	1.36	y
p466	SHV P.F.	0.063–0.125	0.75	10	35	170	0.55	0.54	0.51		n
p513	SHV P.F.	0.125–1.0	8	10	30	170	4.93	4.99	5.09		n
p514	SHV P.F.	0.125–1.0	2	10	35	130	1.24	1.2	1.21	1.35	y
p517	SHV P.F.	0.125–1.0	0.75	10	–	–	0.5	0.49	0.45	0.58	y
p596	SHV P.F.	0–1.0	8	10	15	140	4.99	5.01	5.02	5.3	y
p523	SHV P.F.	0–1.0	2	10	20	130	1.21	1.19	1.19	1.27	y
p520	SHV P.F.	0–1.0	2	10	20	130	1.16	1.15	n/a		n
p521	SHV P.F.	0–1.0	0.75	10	20	130	0.49	0.48	0.49	0.56	y
p524	SHV P.F.	0–1.0	0.75 (pre-loaded)	10	20	130				0.6	y
p525	SHV P.F.	0–1.0	8	100	–	–	5.1	5.07	n/a	5.27	y
p529	SHV P.F.	0–1.0	2	100	25	110	1.3	1.25	1.26	1.35	y
p536	SHV P.F.	0–1.0	0.75 (pre-loaded)	100	–	–				1.08	y
p537	SHV P.F.	0–1.0	0.75	100	25	110	0.53	0.53	0.51		n
p528	SHV P.F.	0–1.0	8	900	25	110	5.23	5.15	5.19	5.38	y
p576	SHV P.F.	0–1.0	2	900	30	100	1.27	1.32	1.26		n
p577	SHV P.F.	0–1.0	0.75	900	25	110	0.5	0.5	0.47		n
p543	SHV P.F.	0–1.0	8 (saturated)	10	40	50	5.14	5.1	5.17		n
p545	SHV P.F.	0–1.0	2 (saturated)	10	45	30	1.28	1.26	n/a		n
p544	SHV P.F.	0–1.0	2 (sat, pre-loaded)	10	35	80				1.48	y
p578	SHV P.F.	0–1.0	0.75 (saturated)	10	45	30	0.46	0.44	0.43		n
p557	Stromboli P.F	0–1.0	8	10	35	160	4.88	4.93	4.89		n
p560	Stromboli P.F	0–1.0	2	10	35	160	1.22	1.22	1.26	1.31	y
p565	Stromboli P.F	0–1.0	0.75	10	40	70	0.43	0.42	0.42	0.54	y
p564	Stromboli P.F	0–1.0	0.75	~53	35	160				0.59	y
p566	MSH Lahar	0–1.0	8 (pre-loaded)	10	–	–				6.05	y
p567	MSH Lahar	0–1.0	8	10	–	–	5.06	5.08	5.09	5.23	y
p568	MSH Lahar	0–1.0	2	10	10	150	1.26	1.25	1.25	1.31	y
p569	MSH Lahar	0–1.0	0.75	10	20	120	0.47	0.47	0.46		n
p570	MSH Lahar	0.5–1.0	8	10	25	–					n
p574	MSH Lahar	0.5–1.0	2	10	25	–					n
p575	MSH Lahar	0.5–1.0	0.75	10	40	–				0.51	y

Relative density was calculated using a technique similar to ASTM test designation D-2049 (1999) (see Appendix A). Only shaded values of peak strength are used for Coulomb failure envelopes.

locations worldwide: pyroclastic debris from Soufrière Hills volcano (SHV), Montserrat, and from Stromboli, Italy, and lahar material from Mount St. Helens (MSH) (Fig. 1). These results provide detailed constitutive data to characterize the evolution of failure and to understand parameters that determine frictional strength. We measure the coefficient of internal friction as a function of mean grain-size and size range, normal stress, shearing rates, and water saturation state.

The control variables used in this analysis: grain-size, saturation state, shearing velocity, and provenance, were chosen in order to explore a wide array of conditions under which granular volcanic material can be expected to fail. Variations in grain size were investigated to understand potential effects of site-source distance. Saturation of the grains was studied to determine if sub-aqueous or rain saturated deposits have different frictional properties than dry deposits. The dependence of frictional strength on shearing rate and transients in rate was studied to investigate whether the volcanic sediment could host unstable sliding.

2. Geologic background

Stromboli volcano has been erupting almost continuously for thousands of years, and is characterized by frequent mild explosive activity typically taking place every 10–20 min (Guest et al., 2003). Less frequently, small pyroclastic flows also occur in the Sciarra del Fuoco sector collapse scar (Guest et al., 2003), and slope failures and associated tsunami present additional hazards. Much of the Sciarra slope was involved in a large but limited collapse (~10–15 m) in 28–29 December 2002. The submarine part of this body (~10x10^6 m^3) failed on 30 December 2002 in a massive slide, which generated a tsunami with an 11-m wave run-up over nearby inhabited areas (Marsella et al., 2004). The slide mass consisted of slabs of