Submitted 01/19/04 to the International Journal of Earth Sciences

Rock-avalanche dynamics: Insights from granular physics experiments

S. JULIO FRIEDMANN[1], N. TABERLET[2], W. LOSERT[3]

[1†] *Dept. of Geology, Univ. of Maryland, College Park, MD 20742-4211,* 1-301-405-4087 *(off),* 1-301-314-9661 *(fax),* juliof@geol.umd.edu

[2] *GMCM, Université Rennes I, Bat 11a, 35042 Rennes, France*

[3] *Dept. of Physics, IPST and IREAP, Univ. of Maryland, College Park, MD 20742-3511*

†Present Address: Lawrence Livermore National Laboratory, 7000 East Rd., Livermore, CA

Abstract

Rock avalanches are known to behave in extraordinary ways unlike other landslides, and their deposits in part reflect their unusual physical behavior. Recent experiments in granular physics suggest that many phenomena and features simply reflect the non-linear nature of granular flows, although some behavior cannot simply be reproduced in lab scale experiments. In a static configuration, grain-grain contact networks dominate the distribution of forces and stresses within a granular mass. During flow, granular collisions damp the system through energy dissipation, while gravitational potential drives the system. The energy distribution between static and collisional stresses within the system can change very rapidly. Threshold events dominate system response, and the challenge is to find which characterization of the static phase helps to predict failure (and thus flow) resistance. Once flowing, many "unusual" rock avalanche phenomena are entirely consistent with the physics of flow of large granular masses, but the low energy dissipation rate required for long run-out events requires the presence of physical processes that are not involved in experimental flows in the current parameter range or in the assumptions of current models.

Keywords: Rock avalanche, granular physics, landslides, geological hazards, surface processes

Introduction

Recently, a great deal of research and attention has focused on the physics of granular materials. The theoretical challenge is to find characterization for a system of purely repulsive particles that are at rest in equilibrium and thus flow only under non-equilibrium conditions. Systems of repulsive particles pose a challenge for descriptions of stress transmission – stresses within granular matter are strongly inhomogeneous and dependent on the network of particle contacts. The far from equilibrium nature of granular flows allows unusual behavior such as segregation of particles by size, shear banding, avalanching and memory effects. For recent reviews see Behringer (*et al.* 1996) and Shinbrot and Muzzio (2000).

Figure 1

One particularly spectacular manifestation of granular physics is the initiation, transport, and deposition of rock avalanches. These are very large (> 10^6 m^3) geostrophic flows, commonly triggered by seismic shaking, volcanic activity, or undercutting (Keefer 1993; Friedmann et al. 2003; Eberhard-Phillips et al. 2003). They have been found in many mountainous regions, particularly semi-arid or arid settings, as well as undersea and on other planetary bodies (Fig. 1). They commonly occur in clusters, and often have unusually long run-outs relative to their drop heights (e.g., Heim 1932; Shreve 1968; Hsu 1975).

These features, along with others (see below), have prompted geological investigators to hypothesize unusual modes of transport and deposition. These hypotheses remain largely unresolved and controversial, despite many decades of focused research. However, recent advances in granular physics suggest that no special mechanisms are needed to explain many physical characteristics of these flows and their deposits. However, the central characteristic and main hazard factor, the long run-out, requires either an unusual and yet to be accessed region of phase space for current models, or additional physical principles.

Rock-avalanche characteristics

A suite of characteristic features common to most rock-avalanche deposits serve to constrain the physics of transport and deposition (e.g., Yarnold 1993; Friedmann 1997). These can be separated into two groups: ones that suggest grain-local or microscopic processes, and those that suggest bulk, distributed, or macroscopic processes.

Microscopic features included the following: jigsaw breccias, or locally shattered coherent blocks; fitted fabrics, or blocks with only minor dislocations; and the preservation of inherited geometries (e.g., stratigraphic order, faulted relationships). These features suggest that individual particles did not move significantly relative to each other (Shreve 1968; Yarnold 1993). Other microscopic features suggest intense local deformation, including the following: a significant component of matrix entirely formed from finely comminuted parent rock; local zones of intense deformation and comminution, usually interpreted as shear zones; and inverse grading (coarsening upwards), suggesting a kinetic sieving process (e.g., Friedmann 1997). Both sets of microscopic features imply plug-like flow and a strongly non-linear (e.g., thixotropic) velocity profiles (e.g., Hsu 1975; Friedmann et al. 2003).

Macroscopic features involve an array of scales and implications. The most important and enigmatic is the exceptionally long run-out of large flows. This suggests either very low internal angles of friction (25 to 3 degrees) or some sort of basal lubrication (e.g., air lubrication, frictional melting) (Heim 1932; Shreve 1968; Howard 1973; Erismann 1979; Melosh 1979; McEwan 1989). Additional features include the following: well developed frontal and lateral raised edges like levees (figure 1a), large relief transverse ridges (figure 1a); low-relief longitudinal ridges (figure 1b,c); a basal zone of mixing. (Figure 1d). These features suggest complex internal processes, such as internal thickening through imbrication or incorporation of basal material through shear. Finally, rock avalanches can be classified by a small set of distinctive morphological types (e.g., Blackhawk style), commonly linked to local configurations (e.g., substrate, degree of confinement). These morphologies and configurations are correlated to different degrees of run-out, suggesting that they reflect the physics of transport for all cases (Shaller 1991).

Experimental techniques

Fundamental studies of flow of granular matter have been greatly aided by new imaging and image processing techniques. We use high resolution, fast cameras (up to 16,000 frames per second, or 1280 x 1024 pixels at 500 frames/sec) to follow the motion of grains on the surface of a granular flow. Such images had been possible before, but digital high-speed imaging permits the crucial second step of automatic tracking of the motion of up to 4000 individual particles through sequences of up to about 10,000 images. From a typical experiment, we gather 1Gb of imaging data. This allows for direct computations of velocities, velocity fluctuations, and particle densities on the imaged flow surface. These quantities can then be directly compared to modeling efforts. If the flow profile in interior of a granular assembly is needed, other research groups have used NMR techniques, though the spatial and time resolution of that technique is inferior to direct imaging (Mueth 2000). Direct imaging of particle motion helps separate models with spurious agreement to experiments from models that capture correctly both the macroscopic properties of the flow, and the microscopic detail, i.e. the dynamics of particle motion. For example, in studying segregation during flow of a mixture of two particle sizes we found that large particles flow more slowly than small particles, an effect that is not incorporated in models of segregation to our knowledge. Currently, we characterize this velocity difference and its possible role in driving segregation. Only a model that describes particle motion correctly should be trusted in predictions of bulk properties such as segregation or shear strength.

Numerical simulations have been widely used in the study of granular flows (for a review see Herrmann and Luding 1998). We developed a program based on the Molecular Dynamic (MD) principles (a.k.a. Discrete Element Method) in which soft (but stiff), frictional, rotating spheres interact with one to another through multiple collisions. Since the particles are soft they overlap during a collision and a repulsive force can be computed from that overlap. Friction forces follow the laws of solid friction (Coulomb's laws). There are three useful features of this method. First, simulations allow one to choose and vary the values of all physical parameters that are difficult or impossible to vary independently in experiment (such as the density of the material, the Young modulus, the frictional properties, the restitution coefficient). Second, some physical properties that cannot be measured in an experimental system (such as the average duration of contacts, the internal pressure, or the stress anisotropy) can be easily computed throughout the granular medium. Last but not least, the simulation can serve as a good test for the validity of a purely mechanical approach. For example, the fact that recent MD simulations (Campbell *et* al 1995) have produced long run-out avalanches, indicates that mechanical collisions alone, for some range of initial conditions and parameters, may lead to long run-out.

Finally, new tools have been developed to image the 3D structure of dense granular matter. The driving force is that some key materials properties such as shear strength cannot be predicted from particle number density and particle properties alone, instead, the subtle changes in the 3D arrangement of grains can e.g. cause significant strengthening as described below. Our lab uses confocal imaging to analyze the 3D structure of a granular assembly immersed in an index matching fluid. Similar efforts using x-ray microtomography (Richard *et al* 2003) are underway in our group and in several laboratories worldwide.

Static rheology

A static granular mass contains a network of repulsive grain-grain contacts. The number, geometry, and spatial distribution of these contacts are the primary controls on the granular material properties, especially strength. The network is not a random network: Large and small forces between particles are more common, which increases comminution of rock. In addition, the network may be anisotropic, e.g. if the material is jammed through shearing. For this reason, the bulk properties of a granular mass are tensor, not scalar, properties.

Figure 2

Due to geometric and spatial dependence, one might anticipate that the strength tensor within a granular framework is history dependent. Recent experiments have revealed this effect, showing that unidirectional shear can create contact network anisotropies (Radjai 1999). Strong chains of particles form in the direction of applied shear. When shear is reversed, particles reorganize to disrupt these strong chains, producing collapse and densification of the granular mass. This is consistent with the well known Reynolds dilatancy that granular matter has to dilate in order to allow shear flow. Hence, if the shear direction is reversed, the material may at first compact before shear in the opposite direction is reestablished. This compaction involves the destruction of the contact network, as can be seen in the shear strength of the material: The sheared mass is demonstrably weaker during reversal of the shear direction, despite the greater density and larger number of particle contacts. It takes shear strain by several particle diameters for these anisotropies to reestablish themselves (Fig. 2).

These phenomena, wherein anisotropies are retained within the particle framework even after shear has ceased, indicates that the history of a granular mass in part determines its response to future deformation. This granular “memory” effect may help explain the local occurrence and spatial clustering of rock avalanche deposits in modern and ancient systems (Friedmann et al. 2003). It may also help to improve the predictions of rock avalanche failure distribution.

Similar memory effects appear to be a generic feature of jammed granular matter: In tapping experiments, where a column of grains is compacted through vertical tapping, the compaction rate depends on the intensity of prior taps, i.e. two heaps at the same density respond differently to tapping, depending on the magnitude of prior tapping (Josserand 2000). Similarly, a heap of granular matter will have a peak in the normal force exerted on the center of the base if the material was poured onto the heap from a sieve, but will have a local minimum of force if the heap was created by pouring from a point source (Vanel et al. 1999).

Measurements of anisotropic configurations may also be possible in natural settings with comparatively noninvasive techniques such as ultrasound. Proper analysis of the anisotropic configuration of the granular network may reveal the history of shear in the sample, and provide a way to predict the failure direction and flow rheology after failure. In order to obtain results representative of the state of the bulk material, it is important that the granular mass that is being measured remains in the "natural" state of stress and strain since small strain can significantly alter the network.

Flowing rheology

Although contact networks are critical to the stress and force distribution within granular flows, they are rather dominated by energy dissipation and entrainment. Grains collide within the flow, changing kinetic and potential energy into sounds and heat. When enough energy is lost, jamming occurs and flow ceases. However, during flow, gravitational accelerations acting on the mass add kinetic energy. Similarly, seismic accelerations can add energy early to the system to help encourage flow (e.g., Keefer 1993; Eberhardt-Phillips et al. 2003). Within the flow, different particles of different size have different energies, greatly complicating intergranular dynamics. This is a basic manifestation of the fact that granular flows are not in thermal equilibrium, so that concepts from equilibrium thermodynamics such as uniform distribution of energy do not apply.

Segregation by size

One persistent consequence of the non-thermal nature of granular flows is grain size segregation. It may be related to the energy difference between particles, or simply characterized by various physical processes such as sieving. This is a universal character of polydisperse granular flows and can occur very rapidly. Much research has focused on vertical segregation, in which small grains move to the flow base and large grains to the top (inverse grading) (Savage 1988). Many experiments have characterized this phenomenon, and many workers have described this segregation effect in rock avalanches (e.g., Heim 1932; Mudge 1965; Shaller 1991; Yarnold 1993).

Lateral segregation, however, also occurs during flow, and populations of grains will separate into bands of discrete particle size (Oyama 1939; Newey *et al* in review). The bands have subtle but demonstrable relief, and those containing the coarsest grains stand physically above the other bands in the direction parallel to flow. This lateral segregation might explain the longitudinal, low-relief ridges seen in many rock avalanche deposits, including the Blackhawk and Sherman Glacier events (Fig. 1).

Velocity flow profiles

The occurrence of shear bands, jigsaw fabrics, and inherited stratigraphic and structural geometries within rock avalanche deposits suggests that during transport, the rock mass undergoes very little internal deformation. As a corollary, most of the deformation appears to occur near the base, as suggested by the presence of shear zones, concentrated comminution, and incorporation of substrate into thin basal layers (Yarnold 1993; Friedmann 1997). These features suggest a non-linear velocity profile, possibly thixotropic, and have prompted a range of explanations in the literature, including air gliding (Shreve 1968), frictional melting (Erismann 1979; 2001), acoustic fluidization (Melosh 1979), powder incorporation (Hsu 1975), and other phenomena.

Observations of several experiments suggest that sheared granular material under pressure deforms in this fashion. In Couette cell experiments on single grain-sized populations where grains are sheared between two concentric cylinders, unidirectional shear produces strongly non-linear flow profiles (Losert 2000). Particle tracking yields a vector field in which very little relative motion occurs between particles, and where deformation is concentrated in shear bands at the flow boundary. Deformation falls off profoundly across small distances, commonly no more than 5 particle diameters, suggesting a non-Newtonian response. This effect is independent of material or grain shape (it occurs for sand, model fault gauge, soft birefringent plastic disks), and occurs for a large range of pressures, from Pascals (Losert 2000) to 10^8 Pascals (Karner 1998) The flow profile also does not change significantly with shear rate, as long as the granular material remains dense.

Figure 3

In avalanche flows various velocity profiles have been observed. Often, a linear flow profile on the surface of a stable mass is observed. However, if the bottom surface on which the avalanche flows is smooth and low friction, a plug flow develops (Fig 3a). This flow is gradually destroyed as the material flows through a curve onto a flat section. As material reaches the flat region, a gradual transition to a linear velocity profile is seen. This indicates that shear bands develop if there are anisotropies in the flow geometry: They confine gradients to regions of low friction, or to regions or larger stress (for the Couette shear flow). Changes in flow geometry can destroy the shear band.

Flow Products

Eye witness accounts of rock-avalanche events are few (Heim 1932; Daly 1912; Voight 1978). This can be attributed to their short life-cycle and remote locations. As such, much of the inferences regarding rock avalanches and their behavior come from analysis of their deposits. Some of these conclusions (e.g., the effects of confinement) are relatively robust. However, others are problematic due to the non-linear nature of the material, their dynamic flow, and history dependence. Recent experimental results confirm the difficulty in such interpretations, which can lead to spurious or non-unique conclusions.

Long run-out and momentum effects

The long run-out seen in many rock avalanches is known to increase with mass and volume (Hsu 1975; Shaller 1991). Although this varies with local conditions, the volume/run-out relationships are observed regardless of substrate, confinement, gravitational acceleration, triggering mechanism, and material (e.g., Campbell *et al.* 1995). This suggests that the absolute momentum of the granular mass plays a role in long run-out.

Since shear-zone localization and deformation during flow appears common to rock-avalanche deposits, it is reasonable to assume that this phenomenon occurs during long run-out flows. However, the effect is notoriously difficult to replicate in the lab. Despite numerous attempts to initiate shear flow by triggering a stable granular mass on an incline (Fig 3b), shear flow only occurred in two circumstances. First, shear flow occurred when triggering was initiated through large amplitude, low frequency, horizontal shaking, although these flows were intermittent and occurred only during part of the driving oscillation. Second, shear flow occurred when the mass accelerated to a high velocity along a long incline after gravitational triggering (Fig. 3d). In all other cases, a linear flow profile was observed, most commonly a surface flow only, reaching zero velocity at some depth.

How could long run-out be recreated? Since vibrations reduce the *static* angle of repose of a sandpile into the regime of effective friction angles (5-23 degrees) found in long run-out avalanches, one might expect shaking to increase the run-out of an avalanche. We designed a horizontally vibrated granular avalanche experiment, shown in Fig 3c to investigate vibration driven avalanches. One important aspect in our effort to recreate long run-out avalanches in the lab is proper scaling of the model system. We built a chute with all parameters scaled down according to scaling laws based on ideal inelastic spheres (Poeschel 2000).

However, for the range of frequencies (up to ~120Hz) and shaking amplitudes (up to 5g) we investigated and for a range of materials (sand, glass beads, rubber), we did not observe changes in the dynamic angle of repose. The static angle of repose changed as observed in a gradual flattening of the heap at the base of the chute, but on a much longer timescale than the initial flow. This indicates that higher frequency shaking is necessary to obtain a flattening of the heap on the same timescale as the initial run-out. While sufficiently fast changes in the angle of repose may lead to long run-out avalanche flows, it is quite possible that the lower dynamic angle of repose of long run-out rock avalanches may be related to aspects of the physics of large rocks that cannot be recreated in lab scale experiments.

Two key observations were made in this model system: First, the transition from the sloped to the flat region strongly influences the flow dynamics. This is not entirely surprising since the momentum of the avalanche has to be redirected from downhill motion to horizontal motion with relatively minimal loss. In our model system, a smooth transition (as in Fig 3d) enhances the run-out. In geological systems that run out far, a large range of transition region properties are found. Whether those transition regions possess any common features deserves further investigation. The second observation is that we were in general not able to generate plug flows if we started from a granular heap at the angle of repose (Fig 3b), even under horizontal vibration with a smooth, low friction bottom surface. In a system started at the angle of repose, steady-state plug-flow was not observed, and only intermittent plug-flow occurred at large amplitude shaking. Otherwise, linear flows exclusively occur, commonly as shallow flows only a few grain diameters deep.

Confined flows

Long run-out is a signature characteristic of many rock avalanches. However, when flows are initially confined, they do not run out as far given the same initial mass or volume of material (Shaller 1991; Friedmann 1997). This may reflect a dynamic transient associated with confined granular flows. Recent experiments involved a steady-state flow of material into a very narrow chute, with moderately sorted quartz sand as the granular medium.

Most granular physics phenomena scale with particle diameter. As such, several workers suggested that there was a critical depth within a channel that was explained as the ratio between particle diameter and channel width. If so, then the only important scaling parameter would be particle size independent of other boundary effects, and laboratory results could be simply exported to natural systems.

Figure 4

This relationship was not observed in the experiments. Rather, the critical depth reflecting a change in flow behavior did not scale with particle diameter, but rather with the height of the flow itself (Fig. 4). The narrowness of a chute thus has to take the depth of the flow into account and, for deep enough flows, friction with the sidewalls will add to the frictional dissipation and increase the angle of repose (Hutter 1991 Taberlet 2003).

This signature may be seen in natural systems, where the degree of confinement is high. Frictional forces with the wall, as well as increased numbers of inelastic collisions, may dissipate the driving energy more rapidly than in unconfined systems, producing smaller observed run-outs. It is also possible that very high flow rates can produce a stable heap arrangement. In very large extraterrestrial and submarine events (e.g., Figure 1c), blocks of material pile near the base of slope, perhaps a physical manifestation of stable heap dynamics.

Deposit Morphology

The morphology of rock-avalanche deposits has served as the basis for interpretation for years (e.g., Shaller 1991). This is understandable given the ability to discriminate between behavior based on commonly recurring shapes (e.g. Luchitta 1979). Certain disciplines (e.g., planetary or marine geology) often have little other information, requiring interpretation based on shape characteristics (Moore 1989; McEwan 1989).

Laboratory flows cannot reproduce natural flows entirely, and thus rely on scaling and morphological relationships to extrapolate results. Indeed, many laboratory flows showed morphologies strikingly similar to natural deposits (Figs. 3, 4). These included both lobate and digitate forms, transverse ridges, and raised front and lateral ridges. However, interpretation is highly problematic. These experimental flows varied as a function of shaking frequency, initial thickness, subtle topographic asperities, and initial flow channel geometry details and surface properties. They did NOT, however, vary with substrate composition, volume, or initial drop height; these are the most commonly inferred parameters based on form. Moreover, none of these flows showed plug-like flow behavior, but rather clearly were surface avalanches that flowed only a few grains deep with a linear profile. This suggests that observed horizontal and transverse instabilities appear generic and not restricted to long run-out avalanche flow properties.

The properties of the flows we observed did not vary with the shape or roughness of the substrate. A wide variety of substrates (ranging from smooth Plexiglas to rough sand paper) was tested but did not produce any difference in the properties of the flow. We also used corrugated cardboard (about 10 particle diameters deep) to test whether substrate geometry influences flow dynamics, but flow properties and deposit morphology did not change regardless of the orientation of the grooves (parallel, perpendicular or oblique to the flow direction).

As such, the deposits' similarity to natural systems may signal that these range of shapes and forms seen in natural systems are in themselves generic. Upon closer inspection, even archetypical events have features reminiscent of more than one style. For example, the Blackhawk landslide has longitudinal ridges and some small, digitate fronts to the flow, features most commonly associated with the ice/snow substrates (Fig., 1). Another possibility is that these forms are actually quite close together in a multidimensional phase space, and that it takes little to move from one morphological class to another. If so, great care should be exercised when interpreting flow conditions from large-scale deposit morphology alone.

Discussion

Rock avalanches exhibit many features strikingly different from ordinary fluids or solids. Features such as inherited stratigraphy, jigsaw breccias, non-linear velocity profiles, surface waves, lobate and digitate forms, longitudinal striae, shear-zone occurrence, and inverse grading are common. Many of these "exotic" or unusual features seen in the field have prompted other workers to provide new transport mechanisms. However, recent experiments on systems of many inelastic particles – the simplest model of granular matter – recover all of the features listed above. This suggests that many aspects of rock avalanches and their deposits may simply be a consequence of their granular nature, rather than, for example, frictional melting or air lubrication producing jigsaw breccias or inherited stratigraphy.

Since the physical parameters of idealized experiments and rock avalanches differ significantly, a true quantitative comparison is not yet possible. Instead, the idealized experiments (a) point to which parameters of a granular material (e.g. stiffness, shape) would most strongly influence the avalanche flow, if it was governed by "granular physics"; and (b) point to additional parameters that should be quantified; for example, the direction of prior shear or the spatial distribution of grain sizes.

Long run-out remains enigmatic. In contrast to other features it cannot simply be reproduced in experiments or simulations on inelastic hard spheres. There are several possible explanations. The first is that long run-out IS a generic feature of granular materials, but only within a rare set of boundary conditions outside current laboratory experiments and simulations. In essence, the basic rheology of granular flows (linear, Bingham, work-softening, glassy) may vary naturally within some multi-dimensional phase space. It is permissible, then, that long run-out occupies some yet unmapped corner of regular granular phase space. The energy dissipation profile and time-dependent behavior would also vary, ultimately into a field characterized by very low dissipation rates and a low effective friction coefficient. It is not yet clear how such low friction angles could be achieved.

However, it is equally viable that long run-out behavior does not occur in strict granular networks under any conditions. Instead, one or more other physical interactions may decrease the intergranular friction or energy dissipation kinetics. Several possibilities have been suggested, such as acoustic fluidization, lubrication with clay-sized particles, frictional melting, or air lubrication. Further experimental work is needed to quantify how these effects would change the bulk frictional character of the flow, in isolation or in combination. Of note, our experiments on horizontally vibrated avalanches demonstrate that changing the effective *static* friction coefficient is not sufficient to produce and maintain dynamic friction reductions and rapid long run-out flows.

The experiments described here and elsewhere in the literature suggest caution in the physical interpretation of rock-avalanche deposits. It may be that unique interpretations are difficult to fully circumscribe, and behavior characterization is the end point of interpretation. This interpretive limit is common to many non-linear systems, due to the dependence of the final system configuration on small, time-dependant perturbations. This may be thought of again in terms of phase space descriptions. The granular behavior may map into two different fields given only two-dimensional considerations, but may completely overlap in other settings (e.g., lower gravity, under water). Caution is recommended in making strong, first-order interpretations in these large granular systems.

Conclusions

Relating the physics of simple granular model systems to rock avalanches showed that stratification and shear banding are generic and may not reveal much about the specifics of historic landslides. Long run-out has not yet been successfully recreated in the laboratory, and it is not clear whether it is related to the basic physics of flowing grains, or whether one or more additional physical phenomena – separately or taken together are necessary to explain long run-out.

While the physics of long run-out flow remain mysterious, insights into the microstructural arrangement of sheared grains may be usefully applied to geological problems. Granular physics experiments have shown that granular structures contain a "memory" of the excitation history of the material, and shows strongly anisotropic flow behavior. It may be worthwhile to try to apply these insights to investigate granular structures for materials subjected to different magnitude earthquakes, or materials subjected to different shear deformations.

Acknowledgements

This research was carried out as part of NASA research grant NAG32736. Thanks to M. Toiya, D. Britti, M. Newey, J. Harp, E. Schemm, and R. Pizzarro who carried out the granular experiments. Special thanks to Don Martin for help in designing and assembling the experiments. Thanks to Renaud Delanney for input and expenses.

References

Barrat A, Loreto V (2001) Memory in aged granular media. Europhys. Lett. 53: 297

Baumberger T, Berthoud P, Caroli C (1999) Physical analysis of the state- and rate-dependent friction law. II. Dynamic friction Phys. Rev. B 60: 3928

Campbell CS, Cleary P, Hopkins M (1995) Large scale landslide simulations: global deformation, velocities, and basal friction. J. Geophys. Res. 100: 8267

Daly RA, Miller WG, Rice GS (1912) Report of the Commission appointed to investigate Turtle Mountain, Frank, Alberta. Can. Geol. Survey Memoir 27, Ottowa

Eberhart-Phillips D, et al. (2003) The 2002 Denali Fault Earthquake, Alaska: A Large Magnitude, Slip-Partitioned Event. Science 300: 1113

Edwards SF, Grinev DV, (2001) Transmission of stress in granular materials as a problem of statistical mechanics. Physica A 302: 162

Erismann TH (1979) The mechanics of large landslides. Rock Mechanics 12: 5

Erismann TH, Abele G (2001) Dynamics of rockslides and rockfalls. Springer-Verlag, Secaucus, NJ

Friedmann SJ, Kwon G, Losert W (2003) Granular memory and its effect on the triggering and distribution of rock avalanche events. J. Geophys. Res. 108

Geng J, Longhi E, Howell DW, Behringer RP (2001) Memory in two-dimensional heap experiments. Phys. Rev. E 64: 060301

Heim A (1932) Bergsturz und Menschleben. Fretz & Wasmuth, Zurich, p. 1-218

Herrmann HJ, Luding S (1998) Modeling granular media on the computer. Continuum Mech. Thermodyn. 10: 189

Hsu KJ (1975) Catastrophic debris streams (sturzstroms) generated by rockfalls. Geol. Soc. Am. Bull. 86: 129

Howard K (1973) Avalanche mode of motion: implications from lunar examples. Science 180: 1052

Hutter K, Koch T (1991) Motion of a granular avalanche in an exponentially curved chute: Experiment and theoretical predictions. Phil Trans Royal Soc. London A 334: 93

Josserand C, Tkachenko AV, Mueth DM, Jaeger HM (200) Memory effects in granular materials. Phys. Rev. Lett. 85: 3632.

Karner SL, Marone C (1998) The effect of shear load on frictional healing in simulated fault gouge. Geophys. Res. Lett. 25: 4561

Keefer DK (1993) The susceptibility of rock slopes to earthquake-induced failure. Bull. Assoc. Eng. Geol. 30: 353

Knight JB, Fandrich CG, Lau CN, Jaeger HM, Nagel SR (1995) Density relaxation in a vibrated granular material. Phys. Rev. E 51: 3957

Komatsu TS, Inagaki S, Nakagawa N, Nasuno S (2001) Creep motion in a granular pile exhibiting steady surface flow. Phys. Rev. Lett. 86: 1757

Liu AJ, Nagel SR (1998) Jamming is not just cool anymore. Nature 396: N6706, 21

Losert W, Geminard J-C, Nasuno S, Gollub JP (2000) Mechanisms for slow strengthening in granular materials. Phys. Rev. E 61: 4060

Losert W, Kwon G (2001) Transient and steady state dynamics of granular shear flows. Advances in Complex Systems 4: 369

Luchitta BK (1979) A Large Landslide on Mars. Geol. Soc. Am. Bull. 89: 1601

McEwan AS (1989) Mobility of large rock avalanches: Evidence from the Valles Marineris, Mars. Geology 17: 1111

Melosh HJ (1979) Acoustic Fluidization: a new geological process? J. Geophys. Res. 84: 7513

Moore JG, Clague DA, Holcomb RT, et al. (1989) Prodigious submarine landslides on the Hawaiian Ridge. J. Geophys. Res. 94: 17,456

Mudge MR (1965) Rockfall-avalanche and rockslide-avalanche deposits at Sawtooth Ridge, Montana. Geol. Soc. Am. Bull. 76: 1003

Mueth DM, Debregeas GF, Karczmar GS, Eng PJ, Nagel SR, Jaeger HM (2000) Signatures of granular microstructure in dense shear flows. Nature 406: 385-389 p.

Newey M, Van der Meer S, Ozik J, Ott E, Losert W (in press) Band-in-band segregation of multidisperse granular mixtures. submitted to Europhys. Lett.

O'Hern CS, Langer SA, Liu AJ, Nagel SR (2001) Force distributions near jamming and glass transitions. Phys. Rev. Lett. 86: 111

Oyama Y (1939) Bull. Inst. Phys. Chem. Res. Japan. Rep. 18: 600 (in Japanese).

Radjai F, Roux S, Moreau JJ (1999) Contact forces in a granular packing. Chaos 9: 544

Richard P, Philippe P, Barbe F, Bourlès Thibault X, Bideau D (2003) Analysis by x-ray microtomography of a granular packing undergoing compaction. Phys. Rev. E 68: 020301

Savage SB, Lun CKK (1988) Particle size segregation in inclined chute flow of dry cohesionless granular solids. J. of Fluid Mechanics 189: 311

Shaller PJ (1991) Analysis and implications of large Martian and terrestrial slides. unpub. Ph.D. thesis, Cal. Inst. of Tech., p. 1-451

Shinbrot T, Muzzio FJ (2000) Nonequilibrium Patterns in granular mixing and segregation. Physics Today, 25 p.

Shreve RL (1968) The Blackhawk Landslide. Geol. Soc. Am. Spec. Paper 108, Boulder

Silbert LE, Ertas D, Grest GS, Halsey TC, Levine D (2002) Geometry of frictionless and frictional sphere packings. Phys. Rev. E 65: 031304

Toiya M, Stambaugh J, Losert W (in press) Transient and oscillatory granular shear flow, Phys Rev Lett.

Vanel L, Howell DW, Clark D, Behringer RP, Clèment E (1999) Phys.Rev. E 60: R5040

Voight B. (ed.) (1978) Rockslides and Avalanches 1: Natural Phenomena. Developments in Geotechnical Engineering 14a: Elsevier, Amsterdam

FIGURE CAPTIONS

Figure 1. Three examples of rock-avalanches. (a) The Blackhawk Landslide, CA, initiated due to seismic shaking. Note the prominent raised rim or snout and well developed transverse ridges. This flow ran out 9 km for a 1200 m drop at 235 km/hr and segregated large blocks towards the flow top (b) The Sherman Glacier Landslide, Alaska, initiated due to the M9.0 1964 earthquake and ran out over ice. Note the prominent fingering termination, absence of raised rim, and longitudinal ridges. (c) Rock-avalanche deposit in Ganges Chasma, Mars, age unknown. Note the prominent fingering termination, absence of raised rim, and longitudinal ridges like the Sherman slide. This has led some workers to propose an ice substrate for this flow, which ran out 119 km from a 7000 m drop at ~300 km/hr. (d) Cross-section through the base of an ancient rock avalanche deposit, CA. Between the dark substrate and the pale upper material lies a zone of intermediate color, which is a zone of basal mixing. Mixing occurred in part through shear and injection of substrate material (center).

Figure 2. Memory of the prior shear direction (a) compaction and (b) shear forces. Note the significant decrease in flow height, suggesting densification of the sheared granular mass upon reversal. That change is associated with overall weakening of the material for several rotations of the shear cell.

Figure 3. Results from simple avalanche experiments on relatively deep flows (>100 part. diameters). (top left) Map-view image of unconfined avalanche experiment with coarse sand. The bright lines are multiple laser-sheet reflections on the flow upper surface. Note incipient undulose, digitate front and topographic step near flow front (top right) Schematic diagram of experimental set-up. (lower left) Velocity profiles of sand passing down an inclined channel. Velocity decreases through time while height increases. Initial plug-like flow (red & orange) give way to strong internal gradients and linear profiles. A stable heap develops , above which linear flow continues. This effect may be due to the early material jamming, producing a wedge of stable material. (lower right) Schematic

diagram of the expeimental set-up. Note steeper supercritical ramp and laterally confined chute and run-out area

Figure 4: Super stable heaps (from Taberlet et al., 2003) (a) snapshot of flowing sand. The darker, blurred zone corresponds to flowing grains whereas the lighter, sharp part is static. (b) Sketch of the experimental set-up. Granular material is poured from a hopper onto a rough substrate between two vertical planes. (c) Experimental results using polydisperse (poorly sorted) sand. The angle of the flowing mass (tan ϕ) increases linearly as the height of the flow increases relative to the width, intepreted as a solid friction law on the experimental walls. This shows that not all physical responses scale simply with particle diameter.

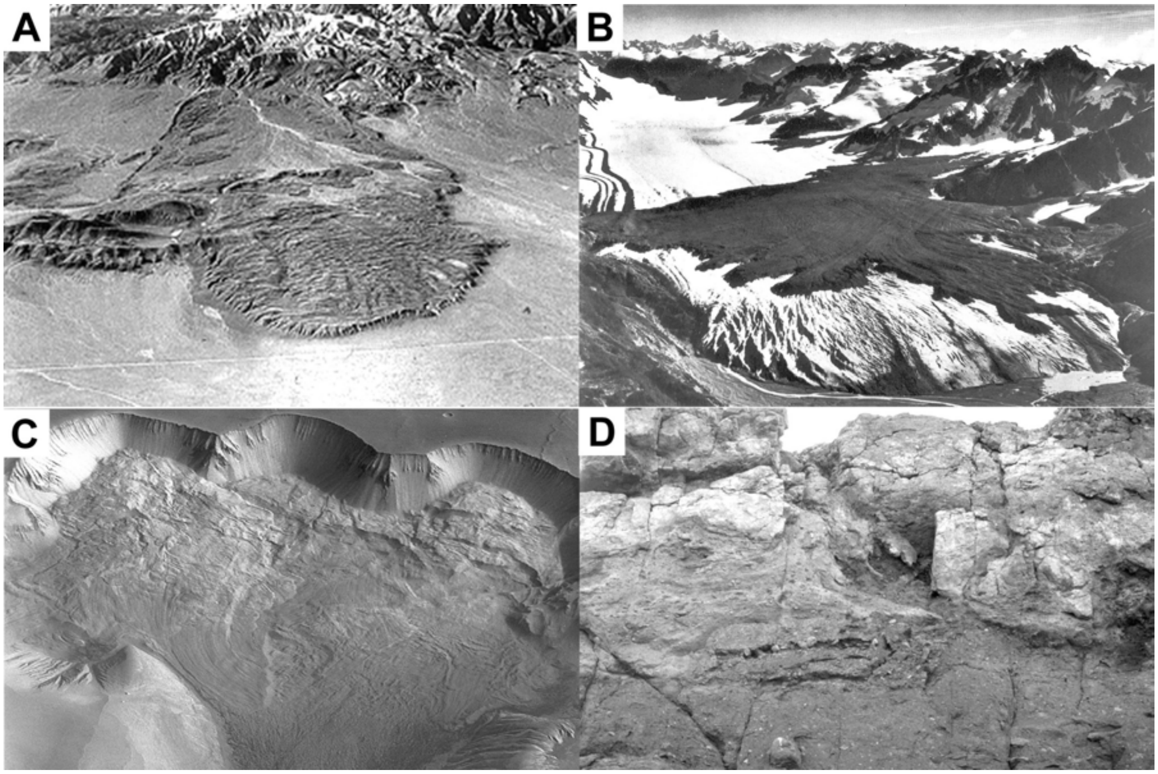

Figure 1. Three examples of rock-avalanches. (a) The Blackhawk Landslide, CA, initiated due to seismic shaking. Note the prominent raised rim or snout and well developed transverse ridges. This flow ran out 9 km for a 1200 m drop at 235 km/hr and segregated large blocks towards the flow top (b) The Sherman Glacier Landslide, Alaska, initiated due to the M9.0 1964 earthquake and ran out over ice. Note the prominent fingering termination, absence of raised rim, and longitudinal ridges. (c) Rock-avalanche deposit in Ganges Chasma, Mars, age unknown. Note the prominent fingering termination, absence of raised rim, and longitudinal ridges like the Sherman slide. This has led some workers to propose an ice substrate for this flow, which ran out 119 km from a 7000 m drop at ~300 km/hr. (d) Cross-section through the base of an ancient rock avalanche deposit, CA. Between the dark substrate and the pale upper material lies a zone of intermediate color, which is a zone of basal mixing. Mixing occurred in part through shear and injection of substrate material (center).

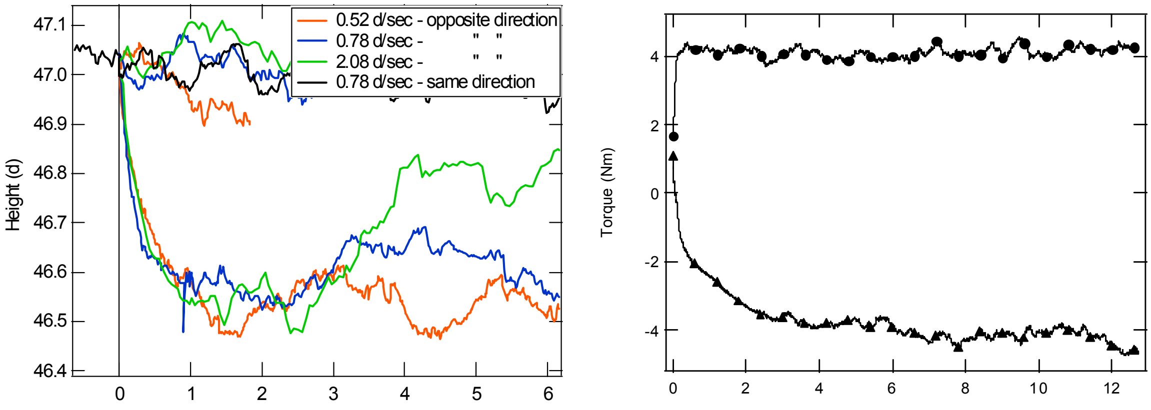

Figure 2. Memory of the prior shear direction (a) compaction and (b) shear forces. Note the significant decrease in flow height, suggesting densification of the sheared granular mass upon reversal. That change is associated with overall weakening of the material for several rotations of the shear cell.

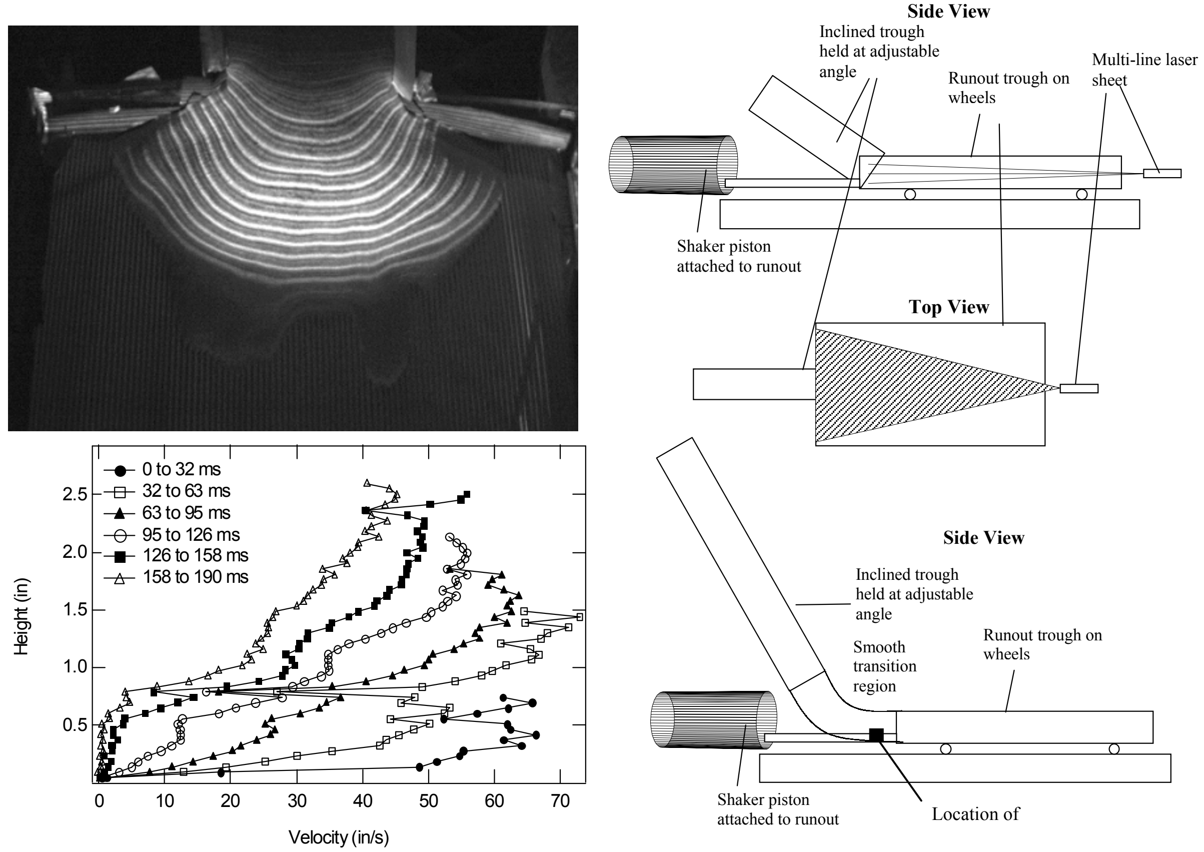

Figure 3. Results from simple avalanche experiments on relatively deep flows (>100 part. diameters). (top left) Map-view image of unconfined avalanche experiment with coarse sand. The bright lines are multiple laser-sheet reflections on the flow upper surface. Note incipient undulose, digitate front and topographic step near flow front (top right) Schematic diagram of experimental set-up. (lower left) Velocity profiles of sand passing down an inclined channel. Velocity decreases through time while height increases. Initial plug-like flow (red & orange) give way to strong internal gradients and linear profiles. A stable heap develops , above which linear flow continues. This effect may be due to the early material jamming, producing a wedge of stable material. (lower right) Schematic diagram of the expeimental set-up. Note steeper supercritical ramp and laterally confined chute and run-out area

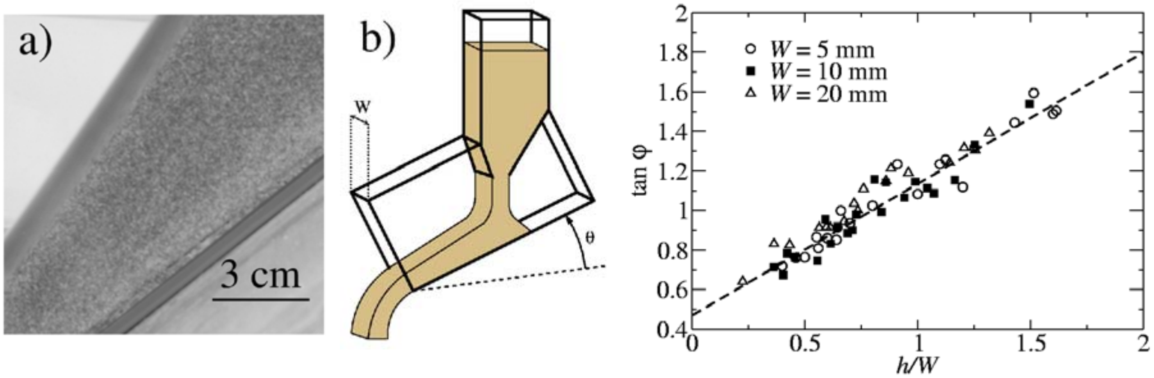

Figure 4: Super stable heaps (from Taberlet et al., 2003) (a) snapshot of flowing sand. The darker, blurred zone corresponds to flowing grains whereas the lighter, sharp part is static. (b) Sketch of the experimental set-up. Granular material is poured from a hopper onto a rough