Field and laboratory observations of bedrock erosion by granular flows

H53D-0658

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1. Motivation:

Granular flows (debris flows, rock avalanches) are geomorphically frequent in steep landscapes. What is their effect on the topography? A distinct slope-area signature is found in many areas dominated by granular flows (generally above 10-15% slope), suggesting that these mass flows erode by different processes from fluvial flows. After granular flow events in the field, we observe scoured bedrock channels and eroded concrete dams. As a step towards understanding the role of granular flows in long-term landscape evolution, we aim to quantify bedrock erosion by granular flows.

Questions

- Which mechanism causes greater erosion – impact or sliding of grains on the bed?
- How does erosion by the coarse-grained snout differ from the more fluid body?
- How can we distinguish erosion by granular flows from that by fluvial flows?

Goals

- Observe the mechanistic processes of bedrock erosion by granular flows in the field and the laboratory.
- Measure the rates of bedrock erosion in erodible substrates (real and synthetic bedrock) of different strength.
- Explore the effects of measurable variables: characteristic grain size, water content, clay content, velocity, channel slope.

Fig. 1. Bedrock channel in the San Bernardino Mountains, southern California, after a debris flow event.

Fig. 2. Wave of boulders during a debris flow event in the Illgraben torrent (photo C. Gwerder).

2. Hypotheses for bedrock erosion by granular flows

Erosion of the bed depends on the mechanism of grain-boundary interaction. Two end-members of boundary interaction are impact and sliding, which may have varying importance at the coarse-grained front and more-fluid body of the flow.

Impact: The largest boulders tend to accumulate at the front of the flow, where they are seen bouncing, rolling, and sliding on the bed. Following Stock and Dietrich (2006), we propose that the erosion rate varies with the normal stresses caused by the bulk inertial stress of the flow, and that these stresses are greatest at the bouldery snout.

Sliding: Grooves have been observed in bedrock beds, and sliding particles are observed in field video and lab experiments, indicating that sliding may be significant.

Even when slip occurs, the amount of material removed in grooves and scratches may be much less than those removed by plucking of fractured blocks caused by impact. Therefore we hypothesize that under a no-slip condition, erosion is proportional to inertial stresses in the flow, scaled by the tensile strength of the erodible substrate (Eqn. 1).

$$e' = k\left[\upsilon_s\rho_s D^2\left(\frac{\partial U}{\partial z}\right)^2 \frac{Y}{T_o^2}\right]$$

(Eqn. 1)

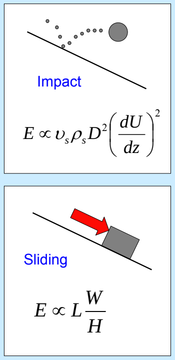

Fig. 3. Schematics of the impact and sliding end-members of grain-bed interaction.

D: characteristic particle diameter
E: eroded volume
e′ : dimensionless erosion
H: substrate hardness
k: constant
L: sliding length
T_0: tensile strength
U: velocity
W: applied load
Y: elastic modulus
z: depth
ρ_s: solid density
υ_s: volume fraction solid

3. Field Experiments in the Illgraben Torrent

We installed natural bedrock slabs (marble and granite) to document wear patterns and rates by successive flows in the Illgraben torrent (Valais, Switzerland), where debris flows events occur annually (Figure 4).

Two debris flows occurred in 2006 across our rock samples. The soft marble slab was extensively worn by two events, exhibiting elongate grooves several centimeters long and centimeter-scale impact marks (Figure 5). The granite slab endured small cm-scale scratches but retained its polished surface.

Other measurements at the Illgraben include:

- Front Velocity
- Flow Height
- Normal Load
- Shear Stress
- Precipitation
- Video

(See poster H53D-0657)

We plan to find the relationship between the amount of material eroded and the flow characteristics, particularly the bed stresses measured at the normal load plate. In summer 2007 we will return to measure the amount of erosion in the slabs by making a mould of the surface topography.

Fig. 4. The erodible slabs are secured by a heavy steel frame, upstream of a check dam. After a debris flow event, they are uncovered and photographed.

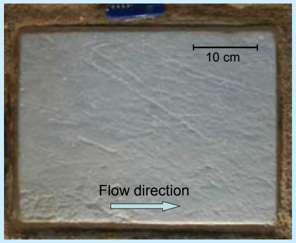

Fig. 5. Photograph of the marble slab after two debris flow events. Erosion occurred by both grooves and knicks, indicating sliding and impact. The grooves are oriented roughly 20 to 45 degrees towards the nearest bank, indicating lateral movement of boulders towards the bank.

4. Laboratory Experiments in a Small Rotating Drum

In the laboratory, we use rotating-drum flumes to measure the amount and nature of bedrock erosion by granular flows. The flume beds have synthetic bedrock samples with weak tensile strength for recording erosion on laboratory timescales. In the 56 cm diameter drum, we used single-grain-size flows and measured erodible sample mass loss while estimating inertial stress to test Equation 1.

Small Rotating Drum:
Diameter: 56 cm
Channel Width: 15 cm
Grain size: clay- to gravel-sized (1 cm) particles

Experiments completed in a small rotating drum suggest that the erosion rate of homogeneous bedrock varies with one-dimensional, average inertial stress values. Slip occurs, more commonly in water-saturated than dry flows, and surprisingly seems to cause more wear despite the reduction in the shear velocity (Fig. 8).

Our data indicate that erosion had a strong dependence on grain diameter, a moderate dependence on the shear rate of the flow, and an inverse dependence on the bed tensile strength squared.

Fig. 6. Small rotating drum flume.

Fig. 7. Schematic velocity field in a dry granular flow in the drum with no slip at the bed.

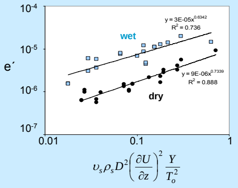

Fig. 8. Dimensionless erosion, e′, vs. strength-normalized inertial stress for dry and water-saturated single-grain-size granular flows.

5. Laboratory Experiments in a Large Rotating Drum

In the large 4-meter diameter drum, we are currently studying natural-scale particle-size distributions while directly measuring the bed normal stress and sample incision rate.

Big Wheel:
Diameter = 4 m
Width = 80 cm
Grain size = 20 cm

Measurements:

- **Erosion Rate**: Laser sheet camera system measures the topography of the erodible slab.
- **Longitudinal Profile**: Laser with rotating mirror sweeps longitudinal profiles to measure dynamic changes in the height, length, and position of the flow.
- **Normal Stress on Bed**: 230 cm^2 square load-plate measures at 200,000 Hz and averages to 1000 Hz.
- **Grain Accelerations and Orientation:** A wireless sensor ball uses accelerometers, magnetometers, and angular rate sensors in 3 axes in a wireless sensor ball.
- **Surface and front particle tracks:** digital video

The figure to the right shows five different single profiles of height (red line) and normal stress (pink line) for different drum speeds and slurry compositions. Note that the position of the flow depends on the flow composition and the drum speed. Excursions in the normal stress indicate impacts on the load plate, and are sometimes (but not always) concentrated near the front of the flow.

Initial experiments in the large rotating drum with natural-scale grain-size distributions demonstrate significant three-dimensional behavior (lateral convection), and show that the flow is strongly influenced by small changes in water content, abundance of fines, wall roughness, and drum speed.

a. Drum speed: 0.8 m/s: sand, cobble, water
b. 0.8 m/s sand, cobble, clay (10% by mass), water
c. 1.25 m/s sand, cobble, clay (10% by mass), water
d. 1.25 m/s sand, cobble, clay (10% by mass), water

Fig. 9. 4-meter rotating drum flume.

Fig. 10. Wireless sensor ball measures acceleration and orientation.

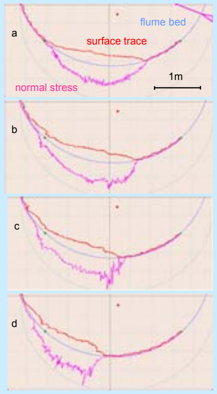

Fig. 11. Surface profiles (red) and normal stresses (pink) measured in the big drum for different speeds and flow compositions. (See text at left.)

6. Summary

We are making measurements of bedrock erosion by granular flow and measuring coincident normal stresses and flow properties over a wide range of spatial scales. Small scale experiments support the hypothesis that bedrock erosion scales with 1-D average inertial stress in the flow. However, field observations and large scale experiments suggest that we must account for lateral accelerations and slip on the bed.

	Field, Illgraben	Large Drum	Small Drum
Total flow volume	47,000 m^3	1 m^3 per rotation	0.001 m^3 per rotation
Height of flow	2.5 m	0.3 m	0.05 m
Front velocity	4.7 m/s	1.5 m/s	0.75 m/s
Boulder size	200 cm	20 cm	1 cm
Erodible sample tensile strength	~10 MPa	0.2-1 MPa	0.2-1 MPa
Bagnold Number	$\sim 10^4$	$\sim 10^3$	$\sim 10^4$
Savage Number	$\sim 10^{-1}$	$\sim 10^{-2}$	$\sim 10^{-1}$

For videos and more information: http://www.seismo.berkeley.edu/~Lhsu

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