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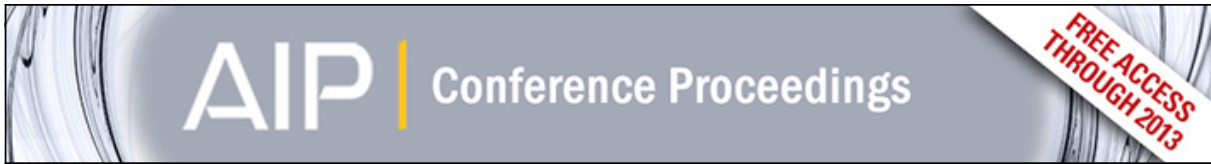
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Erosion Rate and Instability of a Wet/Dry Granular Interface

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Abstract. Liquid may give strong cohesion properties to a granular medium, and confers a solid-like behavior. We study the evolution of a fixed aggregate of wet granular matter subjected to a flow of dry grains. In the confined geometry of a thin cell, the aggregate is held by the walls, and the dry matter flowing around will pull grains out of the aggregate. Thus, by granular erosion, the shape of the interface is modified. Image treatment allows us to retrieve the interface of the wet area, and analyze the phenomenon. Two different configurations are set up for erosion study. In a rotating drum, we follow the diameter of a circular aggregate remaining at the center. This provides an erosion rate, related to the liquid and grains physical properties. In an open cell between vertical plates, we can form a heap-shaped aggregate. Then, with a funnel of constant outlet, we inject dry grains, flowing on top of the cohesive heap. We observe destabilization of an initial flat profile in certain conditions. The coupling between the flow stress and the shape of the heap creates periodical structures, which propagate to the top through the erosion process.

Keywords: Granular matter, capillary bridges, instability, erosion.

PACS: 81.05.Rm, 68.08.De, 92.40.Gc

INTRODUCTION

Cohesion properties brought by liquid in a granular medium can make it behave like a solid substrate. When two phases, wet and dry, are flowing in contact, we can expect morphological evolution of the cohesive medium. This occurs through exchanges between the two areas. More precisely, dry grains will agglomerate on the existing aggregate if liquid is available to form new bridges. On the other hand, some grains will be extracted from the aggregate, if the stress applied on the bridges is high enough. We study this last mechanism here, from an experimental point of view, at the grain scale.

EROSION IN A ROTATING DRUM

We set up an erosion experiment in a rotating drum. This geometry is a usual one for granular flow, so we can rely on flow properties previously investigated [1].

Experimental set-up and results.

We used a Plexiglas cylinder with an inner diameter of 14.2 cm and a depth of 0.5 cm as rotating drum. This corresponds to an aspect ratio around 28, so the drum can be considered as 2-dimensional. Glass beads were the model material, with a size ranging from 200 to 400 micrometers. We have then a typical

Bond number of 10^{-2} , so cohesion from capillary bridges can easily overcome the gravity. Different liquids were used, as water, glycerol, ethylene glycol and silicon oils, in order to vary the surface tension γ , and viscosity η . We measured surface tension with the pendant drop method and the viscosity with a cone and plane rheometer.

In this configuration, we introduce wet material, of controlled liquid content, to form circular aggregate at the center of the drum. We have typically a liquid content of $W = 0.3\% - 2\%$, as the ratio of liquid volume on total pile volume. The cohesion forces that tie the aggregate will also make it stick to the drum walls, and remain at the center. Then, we filled half the place left with dry grains before closing the drum. During the rotation, shots are taken regularly, and the relevant information is retrieved by image analysis.

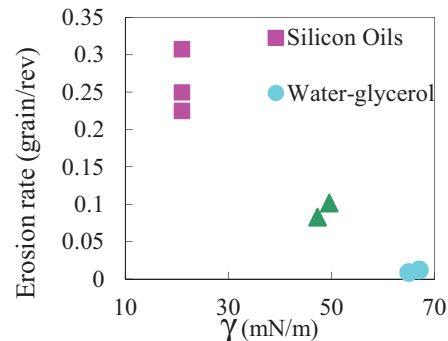


FIGURE 1. Evolution of the erosion rate with surface tension.

For liquid contents corresponding to the pendular regime, we observe an initial linear decrease from the initial aggregate diameter 2.8 cm, which remains circular. The slope measured represents a dimensionless quantified property of the erosion process that we call erosion rate E , in number of grain layers per revolution of the drum, the rotation speed being fixed. This parameter is the one we chose to follow to study the mechanism dynamics, regarding the liquid and flow properties. Figure 1 shows a strong influence of surface tension on the erosion rate, even on a small range of values. In Figure 2, we can see that the erosion rate scales with the η^{-1} over three decades, and has therefore a great influence.

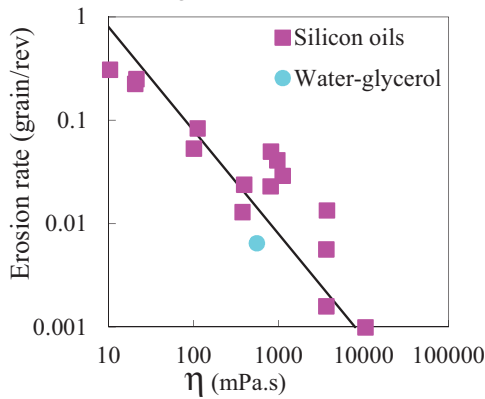


FIGURE 2. Evolution of the erosion rate with the viscosity.

Modelisation: stochastic approach

Shear stress distribution

An important fact to keep in mind in this system, is that the mean shear stress is weak compared to the capillary forces. One can evaluate the force undergone by one grain: $T = \tau R^2 \approx 3 \cdot 10^{-6} N$, τ being the mean shear stress at the bottom of the flow, and R the radius of the bead. Capillary forces are of order $10^{-4} N$ so erosion seems not possible to occur. This leads to consider the fluctuations in the granular flow, as a way to overcome the capillary forces. Only larger values present in the stress distribution can reach the threshold allowing the stretching of the bonds, until the rupture. Then, in order to build an erosion rate, we need the time for a bridge to reach the rupture, for each level of stress. Eventually, the erosion rate should follow:

$$E \propto \int_{F_{cap}}^{\infty} \frac{1}{t_{rupt}} P(f) df \quad (1)$$

Only forces greater than the static cohesion will contribute to the erosion. Distributions usually observed in that kind of system are exponential [2], and we chose to use this form, derived from the q-model:

$$P(f) = \frac{f^2}{2\bar{F}^3} \exp\left(-\frac{2f}{\bar{F}}\right) \quad (2)$$

\bar{F} being the mean force of the distribution. We expect the rupture time to depend on the stress level, as well as on the capillary bridge properties.

Capillary bridge dynamics

Evaluating the rupture time requires studying the bridge dynamics. Initially, the main force acting on the bridge is the capillary force. Then, as the bond is stretched, viscous forces will arise. We use a simple equation to model the bridge dynamics:

$$m \frac{d^2 s}{dt^2} = f - 2\pi\gamma R \cos \theta - \frac{3}{2} \pi R^2 \eta \frac{1}{s} \frac{ds}{dt} \quad (3)$$

We consider here a single capillary bridge, submitted to a constant traction force f . m is the mass of a bead, s the separation distance, and θ is the contact angle. Here we use first order expressions of the forces, the capillary forces, for instance, depends on the separation distance [3]. Two regimes can be distinguished, an inertial one, in which viscous forces are negligible, and a viscous regime, where inertia is safely neglected. Most of our experimental results are situated in the viscous regime, so we will consider this time to be dominant.

$$t_{rupt_visc} = \frac{\frac{3}{2} \pi \eta R^2 \ln \frac{s_c}{\delta}}{f - 2\pi\gamma R \cos \theta} \quad (4)$$

s_c is the pinch-off distance, and δ the rugosity.

Erosion rate

From here, we can obtain an expression for the main dependencies of the erosion rate. The integration of (1) gives:

$$E \propto \frac{1}{\frac{3}{2} \pi \eta R^2 \ln \frac{s_c}{\delta}} \frac{F_{cap}^2}{8\bar{F}} \exp\left(-\frac{2F_{cap}}{\bar{F}}\right) \quad (5)$$

F_{cap} is the capillary force, and \bar{F} the mean force.

In figure 3, we can see the data collapsed on a master curve, after fitting of the parameter \bar{F} . The best value is $\bar{F} = 4.3 \cdot 10^{-5} N$. Influence of the liquid content is also plotted on this graph. It acts mainly on the multiplicity of the bridges for each grain as reported in [3]. The mean number of capillary bridges

is approximated by $N_c = 6(1 + s_c/R)$, and multiplies both viscous and capillary forces. It is therefore included where stand η and γ .

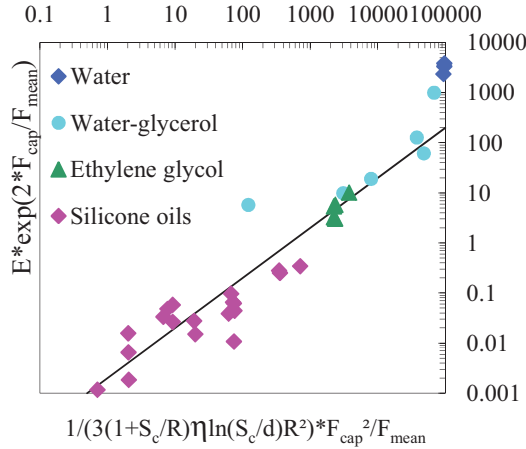


FIGURE 3. Master curve, for the three main variables: γ , η , and s_c .

Complimentary experiments have been carried out to confirm this model, by playing on the density of the flowing beads, with an identical aggregate. In this case, only the mean force is varied, as it scales with the density. The dependency with the density is again exponential, as shown in figure 4. The slope of the fit gives the mean force divided by the density, which enables to confirm the value of the mean force in the case of glass beads, $\bar{F} = 4.3 \cdot 10^{-5} N$.

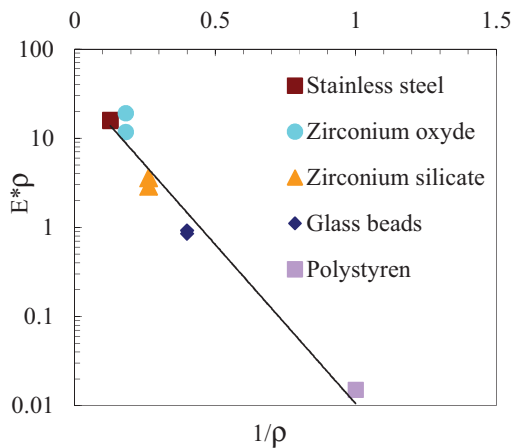


FIGURE 4. Evolution of the erosion rate with the density ρ , in log-lin representation.

This set of results seems to be in agreement with a statistical approach as we proposed for the erosion phenomenon. The viscosity acts then on the scaling

time of stretching of the capillary bridges, and the surface tension defines a threshold, for the efficient contribution in the stress distribution of the surrounding flow.

EROSION OF A WET HEAP

Erosion rate

Further study of the erosion mechanism has been carried out in a different configuration. We prepare a plane wet heap likewise between two glass plates. Dry grains are brought by a funnel, and exit the cell as it is open, after flowing on top of the aggregate. An original feature of this configuration is the destabilization of the interface. A typical run is shown in Figure 5. The experience has been repeated for different angles, from 31° to 51° , with identical heap properties and flow rate. Image treatment allows us to extract the evolution of the area of the wet heap, and the profile of the interface.

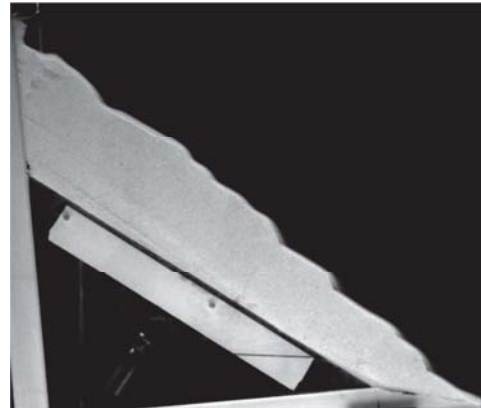


FIGURE 5. Lateral view of the heap erosion experiment, showing the destabilization of the shape of the heap.

The motivation for building this experiment was to control independently the shear stress of the flow, through the inclination of the heap. In this geometry, the wet heap acts like a rigid bottom for the dry granular flow, as the erosion is rather slow (< 5 cm/hr). During this quasi-static evolution, the effective friction coefficient between the flowing layer and the bottom is given by $\mu = \tan\theta$.

By the same means than in the previous experiment, we quantify erosion speed from the first steps of erosion, when the heap surface remains flat. The slope of the time evolution of the aggregate area gives an erosion rate by unit of length. As expected, we found a similar dependency with $\sin\theta$, confirming that the erosion is statistical, and governed by the mean shear stress: $\tau = \mu P = \rho g h \sin(\theta)$. In this

analysis, we neglected the influence of the additional shear stress due to the walls, which actually plays a role to allow the flow reaching a stationary state, otherwise accelerating in inclined plane configuration for such high angles.

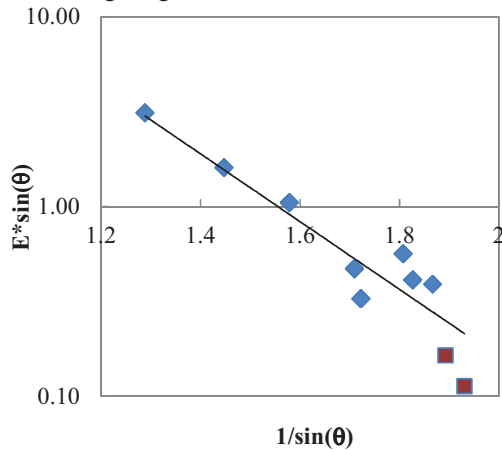


FIGURE 6. Evolution of the erosion rate with the initial slope of the wet heap.

Erosion instability

As shown in figure 5, the initial interface does not remain flat during the erosion, but structures appear. This instability has been observed for various angles, but does not occur for the lowest values we tested. This corresponds to the two red points in figure 6. Similar structures and destabilization have been observed in river beds [4]. In that case, a critical Froude number of 1 is the threshold for the instability. All the experiments we lead are situated around $Fr = 0.5 - 1$, so the critical Froude number here is also of order 1.

We observe an initial destabilization of the interface which grows and saturates in a non-linear regime. This phenomenon produces steep steps linked up by a gentle slope. The final sizes are distributed, with bigger steps for higher slopes, which seems to be a geometrical effect.

Propagation

From the evolution of the interface profile, we can follow the different step, and their characteristics. Figure 7 shows a correlation between the step speed and the step height. Only the small steps can reach the maximum speeds, and only the biggest steps have very small speed. This could be understood by a simple geometrical effect: assuming the erosion mechanism remain the same for different heights, as big steps need

more eroded area to be propagated than smaller ones, their velocities will be smaller. However, according to the variability of speeds observed, it is not the only parameter governing the propagation. This might be correlated as well with the previous geometrical effect mentioned, as the erosion rate increase also with the slope.

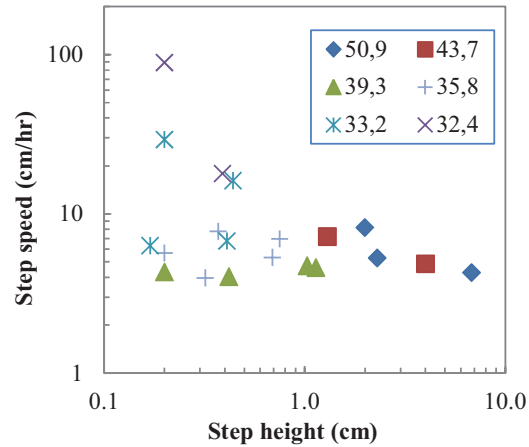


FIGURE 7. Step's speed versus step height, for different initial slopes.

CONCLUSION

We showed the different influence of surface tension and viscosity on the erosion process. The two erosion experiments we carried out give strong evidences in favor of a statistical model in two different geometries. This seems to be an important feature of erosion in the case of low shear stress level. The inclined plane configuration exhibits an instability relying on the interaction of the flow with the wet granular bed. More experiments are still to be done, but further details of this dynamic process should provide deeper insight about the erosion mechanism.

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