EPSC Abstracts
Vol. 6, EPSC-DPS2011-887, 2011
EPSC-DPS Joint Meeting 2011

Simulating Regoliths in a Microgravity Environment

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Abstract

The dynamics of granular materials are involved in the evolution of solid planets and small bodies in our Solar System, whose surfaces are generally covered with regolith. An understanding of granular dynamics appears also to be critical for the design and/or operations of landers, sampling devices and rovers to be included in space missions. The AstEx experiment uses a microgravity modified Taylor-Couette shear cell to investigate granular motion caused by shear and shear reversal forces under the microgravity conditions of parabolic flight. The results will lead to a greater understanding of the mechanical response of granular materials subject to external forces in varying gravitational environments.

1. Introduction

From solid planets to small bodies of our Solar System surface gravities vary by many orders of magnitude. The surfaces of all such bodies are covered by granular materials that can range in size from a few microns (dust) or few hundreds of microns (sand) to a few centimetres or metres (gravels, pebbles, boulders). This superficial layer extends to variable depths and essentially results from impact processes via excavation, fragmentation and ejection of material. Granular materials (regolith) may also be produced via other geological processes such as volcanic activity, erosion and transport. Therefore, given that they are extremely common at the surface of all solid bodies, understanding the dynamics of granular materials is vital to interpret the surface geology of these bodies and is also critical in the design of any device planned to interact with their surfaces.

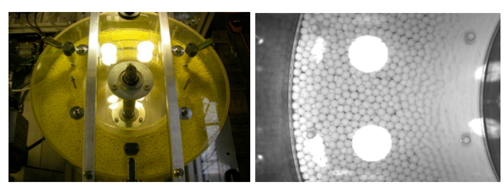
Constitutive equations linking stress and strain involve a wide range of forces but are empirically known for most granular interactions on Earth. However, the inferred scaling of these equations to the gravitational and environmental conditions on other planetary bodies such as asteroids, as discussed in Scheeres et al. (2010) [6], is currently untested.

Recent research, in Earth gravity conditions, has shown that the direction of prior shear influences how granular matter starts to flow [7]. The dynamics of granular materials on asteroid surfaces could also depend on the direction of shear that they have undergone. For instance impact phenomena [3][5], tidal forces from planetary encounters [2], and YORP spin up [4] could apply shear forces to the surface.

2. The AstEx Experiment

The AstEx experimental aim is to characterise the response of granular material to rotational shear forces in a microgravity environment. A particular emphasis has been put on investigating the memory effects of sheared glass beads in a Taylor-Couette shear cell in microgravity.

In an AstEx shear cell (see Fig. 1a) there are two concentric cylinders (200 mm and 100 mm diameter). The outer cylinder is fixed and its inside surface is rough with a layer of glued on particles; the outer surface of the inner cylinder is also rough but it is free to rotate. The floor between the two cylinders is smooth and fixed in place. The gap between the two cylinders is filled with granular material (to a height of 100 mm) on which the rotating inner cylinder applies shear stresses. Velocity gradients are produced near the rotating inner cylinder as the energy input into the granular system is dissipated by friction in a narrow band. This localised region of shearing is known as a shear band (see Fig. 1b).



(a) (b)

Figure 1: (a) An AstEx microgravity shear cell. (b) The narrow band where shearing occurs can be seen on the right of this stacked image of the granular surface during constant shearing.

3. AstEx Experimental Method

The gravity regime during each parabola is $0 \pm 0.05\ g$ for 22 secs, where g is the Earth's gravity. During this period of microgravity a granular flow was initiated by applying rotational shear forces to the granular material. Both constant shear rate and shear reversal experiments were performed at three different shear rates (0.025, 0.05 and 0.1 rad s^{-1}). During the experiments high-speed cameras imaged the surface layers of the granular material. After the flight the individual particles were tracked using a particle-tracking algorithm [7].

4. Results

The normalised angular velocities are given by $V_\theta{*}(r) = V_\theta(r)/\omega$, where $V_\theta(r)$ is the mean measured tangential particle velocity and ω is the rotational velocity of the inner cylinder. The normalised radial coordinates are given by $r* = r/d$ where r is the distance from the shearing surface and d is the particle diameter. For constant shear rate experiments $V_\theta{*}(r)$ is found to be independent of the inner cylinder rotation rate. $V_\theta{*}(r)$ is also largely unchanged by the gravitational environment, reducing only slightly close to the shearing surface in ~0 g (see Fig. 2). In shear reversal experiments regions of particles that normally do not move under steady shear move more during reversal of the shear direction. This is probably due to the shear displacements required to break and re-form the contact network [1]. This effect is quantified by considering the extra displacement, $l_e(r)$, travelled by the particles for a given strain just after shear reversal compared to during steady state shear. For a strain of $5d$ there is a larger extra displacement of particles far from the shearing surface in ~0 g compared to that in 1 g. This implies that the transient shear band after reversal of shear direction is wider in ~0 g than on the ground. Close to the shearing surface the reversal of the shear direction causes a larger extra displacement in 1 g than in ~0 g. See Figure 3.

5. Conclusions

These initial results indicate that the effect of constant shearing on a granular material in a direction perpendicular to the gravity field does not seem to be strongly influenced by gravity. Transient weakening of the granular material is observed upon reversal of the shear direction both in 1 g and in ~0 g. Far from the shearing surface the extra displacements of particles after shear reversal appear to be larger in ~0 g than in 1 g. This implies that the spatial extent of the transient weakening is enhanced in the microgravity environment. However, close to the shearing surface the transient weakening may be reduced by the microgravity environment.

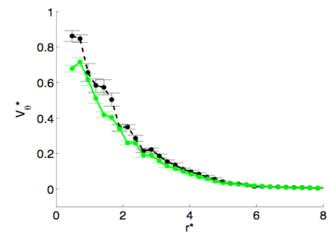


Figure 2: The mean steady state velocity profiles for constant shear rate experiments in 1 g (dotted, black line) and in ~0 g (solid green line). V_θ* is the normalised angular velocity and r* is the normalised radial distance from the shearing surface.

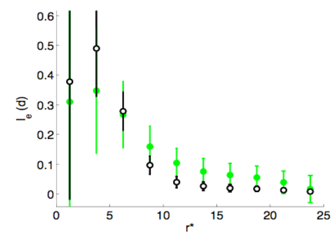


Figure 3: Extra displacement, *le*, of particles for a strain of 5*d*. Shown are mean results of experiments performed in 1 g (black, open circles) and ~0 g (green, solid circles).

Acknowledgements

Thanks to the OU, TAS, the STFC, the RAS and the french PNP for providing financial support. Thank you also to ESA 'Fly your Thesis' for giving us the opportunity to be part of the 51st ESA microgravity research campaign, and for the financial support. Finally, thanks to the workshop of the PSSRI for constructing our experimental hardware. Part of this study was done as part of the International Team (#202) sponsored by the ISSI.

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