Digging on Asteroids: A Laboratory Model of Granular Dynamics in Microgravity

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ABSTRACT

As NASA prepares to visit asteroids and other poorly-consolidated near-earth-objects (NEOs), it will be important to safely interact with the granular materials at the surface of these objects. A particular concern is the low elastic modulus of granular materials: rubble-pile asteroids are only held together by weak gravitational and van der Waals forces. This means that both the escape velocity and the sound velocity are low compared to their values on earth. To better predict the dynamics of the granular flows resulting from surface explorations such as digging, sample-collection, anchoring, or lift-off, we develop microgravity experiments which are able to predict the circumstances under which the NEO material will remain intact or become unstable. In our experiments, we insert a flexible probe into a granular material under simulated conditions of low gravity. We show that low-speed interactions reduce the effects of shock wave creation and observe that thinner diggers allow the grains to rearrange and minimize the possibility of ejecta.

INTRODUCTION

Recently, a number of missions to so-called rubble pile asteroids have been conducted (Hayabusa) or proposed/planned (OSIRIS-REX, Hayabusa 2), and space agencies around the world are showing a great interest in sampling or even redirecting them [NASA (2014a)]. However, caution is necessary when landing on such an asteroid due to uncertainties in how the poorly-characterized asteroid material will respond to external perturbations. This comes from the fact that these asteroids, including the regolith at their surface, are composed of granular materials: collections of macroscopic particles.

The mechanical properties of granular materials are highly dependent on the degree of gravitational or external compression, the features of which are often understood in terms of force networks, shown in Figure 1. In contrast to a bulk material or liquid, the load on a granular material is not distributed uniformly, but is instead focused in force chains. While only a fraction of the particles that make up the loaded granular system take part in these chains, they bear the majority of the load. The network of force chains in turn has been shown to control the sound propagation in a granular system [Bassett (2012)].

As an example take the case of landing a probe on an asteroid surface and collecting a sample. What is the elastic response of the surface to the probe landing? Can the surface reliably bear the weight of the probe? How difficult is it to penetrate the surface to take a sample, without creating ejecta? What can we learn about the granular structure from geological measurements such as sound propagation? Finally, how does all of this scale with gravity, i.e. size and density of the asteroid. Similar granular challenges are also present on other low gravity bodies. During the recent landing of the Philae probe on the rocky ground of comet 67P during the Rosetta mission, significant bouncing was observed. These effects could even be relevant for scenarios such as in-situ-resource utilization on the Moon [Wilkinson (2005)].

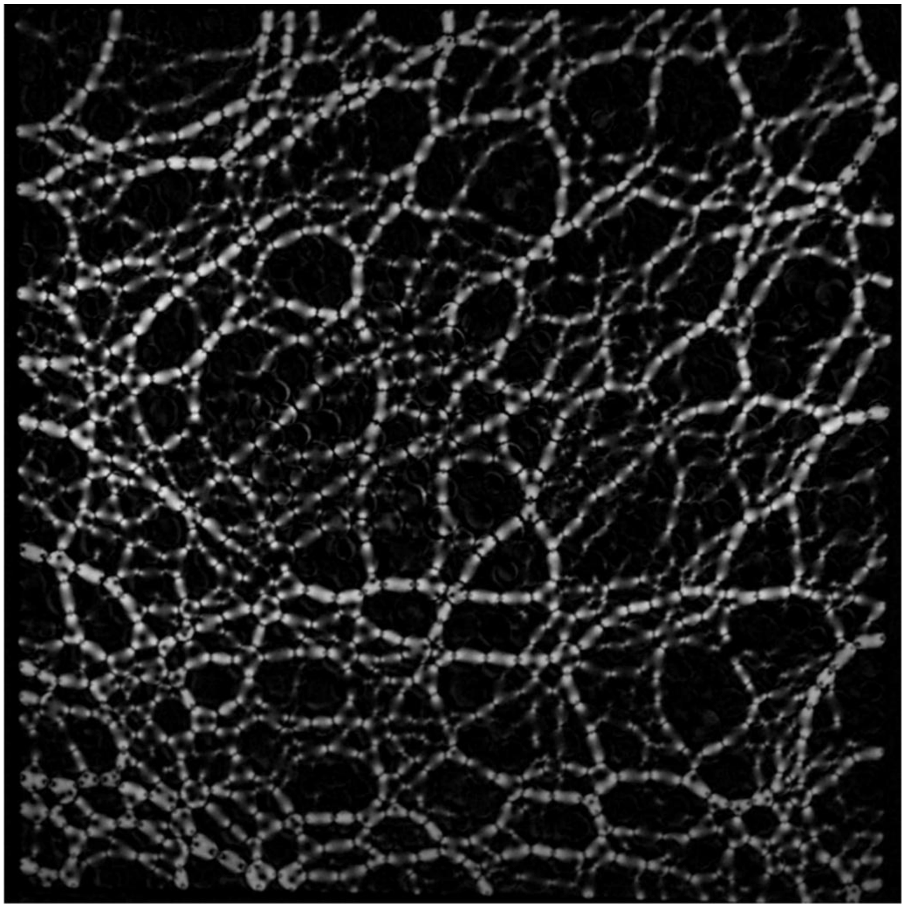

Figure 1: Image of force chains. A single layer of disk-shaped photoelastic granular materials under biaxial compression on the apparatus (horizontal, θ = 0°). Particles are viewed through a polariscope: bright particles are those carrying more force than the dark particles. (Source: James Puckett, raw data from [Puckett(2012)])

Zimber et al. have recently shown that the stability of a granular system is greatly influenced by its orientation relative to the direction of gravity [Zimber (2013)]. Furthermore, the magnitude of the gravitational acceleration will also have an influence on the force network. In the case of an asteroid, the surface gravity can easily be as low as 10^{-5} g (where g is earth's gravitational acceleration) [Daniels (2013)], and decreases towards the interior. In such small gravitational fields, the confining pressure from the particles' own weight is also small and therefore only a weakly compressed granular packing is formed. The granular material is therefore in a barely jammed state [Liu (2010)] and it requires little effort to rearrange the packing. In addition, barely-jammed packings have anomalous mechanical responses such as a vanishing rigidity and speed of sound [Gomez (2012)].

It remains an open question how the presence of weak gravity affects not just the elastic response, but also the yielding conditions which mark the onset of flow. For example, what is the minimum load at which the surface breaks apart, and how much force is needed to drive a penetrator through the packing [Schröter (2007)]. Pacheco-Vázquez (2011) performed experiments quantifying how an intruder's penetration depth depends on the magnitude of the gravitational acceleration. One observation was that the intruder experiences acceleration oscillations on its way through the material. These oscillations are not fully understood, but likely arise due to rearrangements in the force network and/or packing structure as the intruder moves through the material [Clark (2015)].

A final consideration is that the kinetic energy required to achieve escape velocity for a particle in the top layer of the packing is similar or small compared to other typical energies in the system. Therefore, if the asteroid material is pushed past the yield criterion and particles are dislodged, it will only slowly (or not at all) settle back into a stable configuration.

Therefore, there is a need to develop microgravity experiments which are able to predict the circumstances under which the NEO material will remain intact or become unstable during activities such as digging, sample-collection, anchoring, or lift-off. Prior research has shown promise in the use of flexible diggers [Wendell (2011)] in order to facilitate penetration into granular material with minimal deformation. In this work, we create a low cost experimental setup capable of addressing the granular challenges above, by simulating microgravity in a two dimensional granular packing. In ongoing work, we perform experiments to test the viability of flexible diggers for penetrating asteroid surfaces through a controlled parameter sweep. By varying the size and aspect ratio (flexibility) of the diggers, we provide insight into the optimal properties to enhance/suppress particle rearrangements.

EXPERIMENTAL SETUP

Our experiments utilize a two-dimensional microgravity analog: flat particles levitated on a gentle layer of air pumped through a porous medium. This cushion of air levitates the particles into a single flat layer with negligible substrate friction. The airflow is carefully adjusted to just support and levitate the particles, without being strong enough to overturn them or disturb their motion. This apparatus is shown in Fig.2 and is described in technical detail in [Puckett (2012)]. In the original design, the particles are interacting in a zero gravitational field within the horizontal plane ($\theta = 0°$).

To create a laboratory analog of microgravity, we incline the surface of the air table by a small amount. Effective gravities can be computed from

$$g_{\text{eff}} = g \sin\theta,$$

where θ is the inclination of the table above the $\theta = 0°$ horizontal plane. These values can be orders of magnitude lower than earth's gravity. The following table gives a few sample values for g_{eff} that can be achieved with this apparatus as well as its corresponding celestial body. We calculate the surface gravity with the following:

$$g_{\text{surf}} = \frac{GM}{r^2},$$

where r and M are, respectively, the body's radius and mass and G is the gravitational constant.

The simulated regolith is idealized to aid in comparisons with discrete element simulations [Pöschel (2005)]. It is composed of 750 centimeter-scale disks in a 1:1 mix of 11.0 mm and 15.5 mm diameters. To capture the position of the particles, a camera is mounted directly above the air table. The captured images are processed to extract particle positions for each frame. Furthermore, each of the side walls is equipped with force sensors to record wall-pressure. The choice of smooth walls allows particles to slip instead of being pinned; this particle motion is more consistent with large scale systems than rough walls would provide.

Table 1: Required table inclination to create an effective gravity analogous to the surfaces gravities of the Moon, dwarf planet Ceres, and asteroid Vesta. g_{eff} for Vesta is an approximation derived from the data given in [Russell (2012)].

g_{eff}	0.17 g	$2.9\ 10^{-2}$ g	$2.6\ 10^{-2}$ g
Air table inclination	9.8°	1.7°	1.5°
Corresponding celestial body	Moon	Ceres	Vesta

To permit the visualization of particle-scale forces, we have the option to use photoelastic particles (raw material is Vishay PhotoStress PSM-4). When illuminated with polarized light, these particles show light and dark fringes which indicate the amount of force acting upon them, as shown in Figure 1. A flexible probe is mounted onto a translation stage at the uphill side of the apparatus. It can be inserted into the packing to simulate a digging device. The translation stage and digger can be connected via a force sensor allowing for the measurement of the digging force.

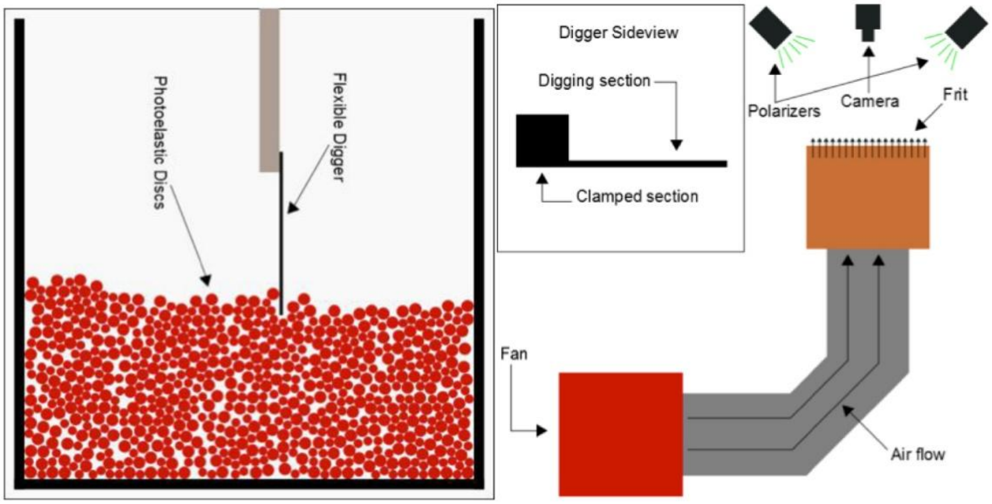

Figure 2: (Left) Schematic drawing of the flexible digger being inserted into the simulated regolith packing, as seen from above. (Right) The whole experimental setup consists of an air-table on which the particles float on a cushion of air, eliminating substrate friction. To measure forces acting on the photoelastic particles, they are illuminated by polarized light from above, and their positions are tracked with an overhead camera.

RESULTS

At the beginning of each experiment, we consolidate the regolith into a “labsteroid” surface against the downhill wall. We then drive the digger into the granular packing in quasistatic steps, moving the translation stage forward by 3 mm and then waiting for the material to come to rest before making the next step. We repeat this procedure until the penetration depth has reached 95% of the digger’s length. We found that using this quasistatic approach eliminated the effects of shock wave creation.

Each wall force sensor records the change in pressure due to each digger displacement step. This reading measures the average pressure redistribution within the labsteroid. By considering the total of theses changes over the course of an experiment, we can deduce the effect of digger thickness and flexibility. Large pressure changes correspond to increased load on the digger.

To understand how digger thickness controls the total pressure redistribution, we measured the response of the system as a function of the thickness of the probe. We penetrated the system with probes of varying thickness (millimeter scale), and found that as the probe's thickness is increased, the total horizontal pressure redistribution decreases (see Figure 3). Beyond these thicknesses, the diggers were no longer flexible. As the thickness increases, the digger has a more localized effect and does not redistribute the force of the impact as effectively. Therefore, thinner diggers allow the grains to rearrange and minimize the possibility of ejecta.

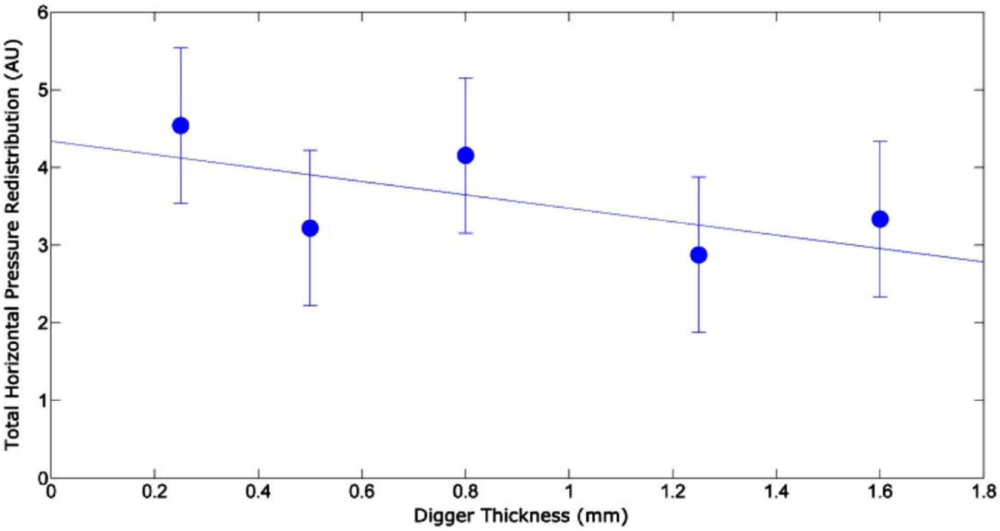

Figure 3: Change in side wall pressure summed cumulatively for each step in an entire experimental run versus differing digger thicknesses. The solid line is a best fit of the data and the results are averaged over at least twenty experiments.

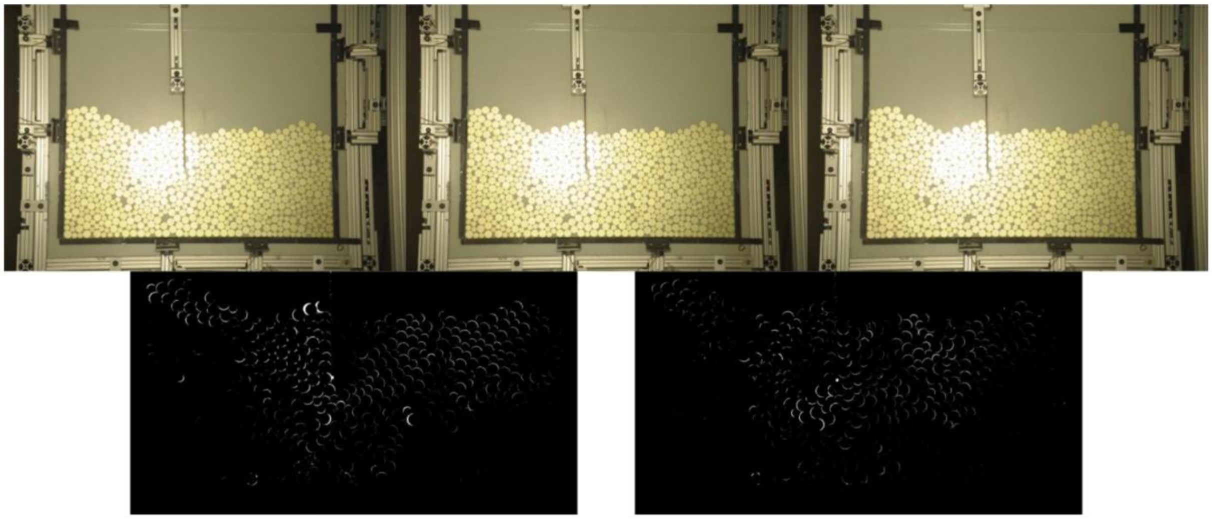

Figure 4: (Top) Sequential images as the digger makes 2 quasistatic steps into the labsteroid surface. (Bottom) Corresponding difference images, with white representing the differences between the subsequent images.

To quantify the effect the digger has on rearranging the packing, we take a pair of images, one immediately before a driving step and one after the packing has come to rest. We then subtract these two images from each other to highlight the internal displacements within the labsteroid. Figure 4 shows a short sequence of images from the digger insertion with the corresponding difference images. Although the digger is small as compared to a single particle, the changes in particle configuration can be seen throughout the whole system. We observe that even small steps of the intruder can lead to global packing rearrangements.

In addition, we observe that regolith rearrangement is suppressed through the use of the thinnest (most flexible) digger. As the digger thickness increases, the force applied becomes more localized to the impact site. This could have important implications for the production of ejecta.

For the present configuration, forces were too small to provide a photoelastic response. Therefore, no force chains were visible in the labsteroid during the quasistatic digger steps. This is in stark contrast to the strong force chains which form at higher velocity impacts [Clark (2015)], and strengthens the case for the use of small flexible diggers to avoid forming force chains which resist further deformation of the material.

CONCLUSIONS & OUTLOOK

We have developed a new type of laboratory-microgravity apparatus that allows for a broad range of experimental techniques relevant to developing interactions with rubble-pile asteroids. These include the measurement of the digging force, interparticle forces, and particle-displacements in a two-dimensional simulated regolith. We presented results which examine the insertion of thin, flexible diggers. As expected, we find that low-speed interactions reduce the effects of shock wave creation, helping maintain the continuity of the granular material. We measured the response of the system as a function of the thickness and length of the probe, and observed that the localization of pressure is minimized through the use of a thin, flexible digger, thus suppressing the likelihood of particle ejecta. There is a trend of increased pressure on the side walls as the probe steps further into the bulk material. Additionally, as the probe’s thickness is increased, the total pressure redistribution of a complete run lessens. Thus, we find that considering the use of slowly moving, thin flexible diggers would be advantageous when designing sampling missions to rubble pile asteroids.

Looking ahead, similar techniques are likely applicable to the insertion of anchoring devices. While the digger designs presented here might pull out as easily as they were inserted, it would be possible to design thin diggers which are composed of a hierarchy of thin structures that fan out when loaded in the reverse direction, in the manner of a ratchet or fishhook. Even though the constituent structures might be individually weak, a network of such structures could hold fast like a plant root, grown between the grains of soil.

It will also be possible to evaluate a wide range of digging/anchoring strategies using the same apparatus. For example, examining the fast-insertion limit could reveal strategies which capitalize on the system being transiently stabilized (densified) by a shock wave. This could be important for real missions in which the quasistatic approach might not always be feasible, for instance in the need of quick anchoring.

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