

Chapter 11

Rubble-Pile Near Earth Objects: Insights from Granular Physics

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11.1 Introduction

Most Near Earth Objects (NEOs) are composed of fractured rock, sometimes highly fractured and porous, and they have come to be known as rubble piles (Britt 2001; Fujiwara et al. 2006). The constituent particles, ranging from millimeters up to tens of meters, are weakly held together as an aggregate by a combination of both gravitational and van der Waals forces, which can be of comparable strength (Scheers et al. 2010). Future missions to these rubble NEOs, whether human or robotic, will need to operate in such a way that they can safely and successfully probe a fragile object. Of key importance is the ability to predict and control the circumstances under which the NEO material will remain intact or become unstable during activities such as digging, sample-collection, anchoring, or lift-off.

Rubble-like materials are members of a broader class of what have been named granular materials (Jaeger et al. 1996). These are commonly defined as a collection of macroscopic particles that interact through classical mechanics: force balance, collisions, friction, inelasticity, etc. Natural and industrial examples include sand/gravel, agricultural grains, and pharmaceutical powders; idealized particles such as glass spheres are also frequently considered as laboratory models. There are extensive laboratory experiments and computer simulations on these materials (both with and without gravity), all of which are leading towards an improved theoretical understanding of their dynamics. However, a comprehensive theory of granular materials remains elusive, and most techniques have a limited range of validity within a large parameter space. This chapter reviews the current state of knowledge of granular materials, and provides guidance about how to apply this knowledge to rubble-pile asteroids.

On any mission to collect samples from a NEO, it will be necessary to design both reliable techniques for anchoring to the surface, and methods for collecting and retrieving samples. A sense of the challenges is given by the following representative examples, which begin with the approach of the mission hardware. As a human or robotic explorer attempts to slow its approach to the surface of the NEO,

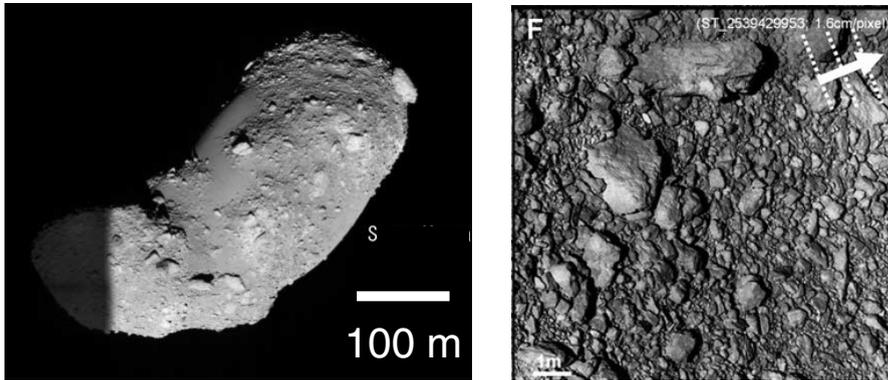


Fig. 11.1 Images of rubble pile asteroid 25143 Itokawa, observed by spacecraft Hayabusa, the first mission to return asteroid samples to Earth, illustrating size and granular texture at two different scales. Sources: Fujiwara et al. (2006) (left) and Miyamoto et al. (2007) (right).

any firing of thrusters will disrupt the surface material. Without strong gravitational forces to return the material to the NEO, the dislodged particles will remain in the vicinity of the explorer as a hazard. Even once the explorer is located at the surface, further movements can similarly dislodge particles. Furthermore, if the explorer needs to anchor to the fragile surface, any thrust into the surface will cause it to move in the opposite direction: away from the very surface that it is trying to probe. If the explorer requires digging (whether for the purposes of anchoring or sample-collection), this will necessarily disrupt the surface material (Miyamoto et al. 2007; Tsuchiyama et al. 2011), again creating a population of dislodged, hazardous particles in the vicinity.

The granular materials that comprise rubble NEOs have much in common with the geological granular materials studied in Earth's gravity, but with the key distinction that gravitational forces do not as easily return disturbed particles to the ground. For example, asteroid 25143 Itokawa (shown in Fig. 11.1), has a mass of 3.5×10^{10} kg (Fujiwara et al. 2006). At a distance of 150 m from the center of mass, the gravitational acceleration is only $10^{-5}g$; this means that any dislodged particles that travel faster than 17 cm/s will escape the asteroid; this speed is known as the escape speed.

No motion on or near the NEO surface will be simple, and although one mission has already been successful (Fujiwara et al. 2006), no established protocols yet exist for this new class of explorations. Ongoing studies of lunar and martian regolith (Rickman et al. 2012) and blast protocols (Metzger et al. 2009) will provide some guidance, but the much-lower gravitational forces are likely to limit their transfer of knowledge. In this chapter, we describe the current state of knowledge as it relates to the problem of digging and anchoring on rubble NEOs, drawing on studies performed both within Earth's gravity and in zero gravity. Finally, we close with some concrete recommendations for safe, successful exploration and mining operations on NEOs.

11.2 Resisting Applied Forces: Force Chains

Dry granular materials differ from conventional solids in that cohesion due to interatomic and intermolecular forces plays little role in determining the bulk and shear response of the aggregate. Instead, the material resists deformation via the friction and elasticity at each interparticle contact, together with the impossibility of two particles passing through each other. The interparticle contacts have long been known to create a highly heterogeneous distribution of forces, first visualized in the 1950s using the photoelastic (birefringent) properties of glass (Dantu 1957). Figure 11.2 shows a modern implementation of the same effect, using 2,500 disks cut from Vishay PhotoStress supported by a plastic floor and subjected to biaxial stresses: either isotropic compression or pure shear. In both cases, chain-like structures carry the majority of the force in the system, but this force network is far more isotropic in the compressed sample than in the sheared sample. The sheared sample is strongly anisotropic and shows a clear signature of the principal stress axis.

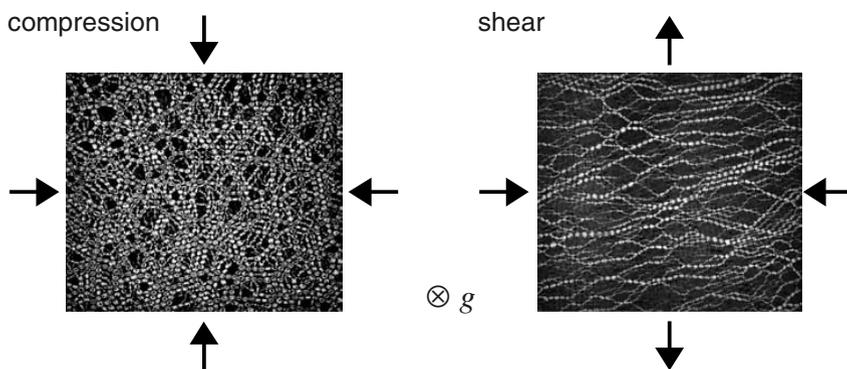


Fig. 11.2 Images of a quasi-two-dimensional granular material composed of disk-shaped, birefringent particles arranged in a singular, horizontal layer and subject to (left) isotropic compression and (right) pure shear in a uniform gravitational potential. By viewing the particles with polarized light, particles subject to larger stresses are brighter and show more optical fringes. Figure adapted from Majmudar and Behringer (2005)

The properties of this force chain network have been the subject of much recent research. Notably, the probability distribution function of individual forces within a static system can be highly non-Gaussian (Liu et al. 1955) and depends strongly on the type of loading (see Fig. 11.2 and Majmudar and Behringer (2005)). While circular/spherical particles have been the focus of much of the quantitative research on force distributions, the existence of such heterogeneous networks is a robust feature that holds even for non-circular particles (Geng et al. 2001). Furthermore, the weaker gravitational potential within asteroids will not destroy the effect: the images in Fig. 11.2 were obtained within a constant gravitational potential, resting upon a horizontal surface. Through the use of an air-table that gently

floats flat particles (Lechenault and Daniels 2010; Puckett and Daniels 2013), it would be possible to investigate dynamics within a two-dimensional version of a zero-gravity environment. When the load on a granular material is increased, for instance by a digging or anchoring process, the force and contact network will necessarily rearrange. As long as all particles maintain torque and force balance, the granular material can remain intact. However, even for small changes this typically cannot be accomplished through linear (elastic) processes alone, and particle and force rearrangements are necessarily present (Cates et al. 1998). If the disturbance is sufficiently large, as in the case of a high-energy impact, then the material can become “fluidized” and transiently exist in a collisional, flowing state (Asphaug et al. 1998; Daniels et al. 2004; Pica Ciamarra et al. 2004; Clark et al. 2012). In each of these studies, whether laboratory or simulated, the propagation of stress or failure within the material is observed to have a branching structure reminiscent of the underlying force chain network.

The degree to which a granular material is in a gas-like (collision-dominated) vs. liquid-like (sustained contacts) state can be described by the non-dimensional inertial number $I = \dot{\gamma}d(P/\rho)^{-0.5}$. Here, $\dot{\gamma}$ is the imposed shear rate, d is the particle diameter, P is the confining pressure, and ρ is the mass-density of the particle material. This can be thought of as a competition between two time-scales: $\dot{\gamma}^{-1}$ is the macroscopic timescale over which shear-deformation takes place (creating gaps), and $d/(P/\rho)^{-0.5}$ is the microscopic timescale describing the time it takes for a particle to fall into a gap of size d (Campbell 2005; Forterre and Pouliquen 2008). In the context of rubble-pile asteroids, the downward pressure on particles arises from gravitational acceleration ($10^{-5}g$) and this microscopic timescale would instead be $(d/g)^{-0.5}$. For particles ranging in size from 10 cm to 10 m, this corresponds to timescales of 30 sec to 5 min. Therefore, under all but the slowest of shear rates, I will tend to take large values, corresponding to the gas-like, rapid-flow limit. Each of these situations (solid-like, liquid-like, gas-like), and the transitions between them, will be discussed in more detail below.

11.3 Solid-to-Fluid Transition

In order to explore a granular asteroid, it will be important to control its response: whether the surface material remains solid-like (good for anchoring, bad for digging), or transitions to a fluid-like state (good for digging, bad for anchoring). Several frameworks have been developed in recent years that address both the two regimes (solid-like, fluid-like) and the transition between them. Because flowing granular materials are always compressible, the term fluid-like will be used when both gas-like (collisional) and liquid-like (sustained contacts) materials are under discussion. Below, we review several key approaches and indicate which are applicable to NEOs in microgravity and which will require further research in order to be applicable.

One key descriptive variable underlying many of these studies is the extent to which the granular material fills the available space. In the physics literature, this is commonly referred to as the packing fraction or packing density ϕ , defined as the fraction of space occupied by particles. Within the geotechnical community, it is more common to report the inverse ($1 - \phi$), called the void fraction or porosity. Below, we will use the convention from the physics literature and refer to ϕ . Conceptually, ϕ is important because a loose packing (low ϕ) has fewer inter-particle contacts to stabilize particles (Wyart 2005), and more possibilities for particles to rearrange than does a dense packing (high ϕ) (Edwards and Oakeshott 1989, Song et al. 2008). In a survey of 26 asteroids, Baer et al. (2011) found that for asteroids with effective diameters below 300 km, bulk porosities in the range of 50% to 70% are quite common; this corresponds to $\phi = 0.3$ to 0.5 . As will be discussed below, these values fall below what is needed to constrain the motion of particles relative to each other.

The connection between applied stress and changes in packing density dates back to a classic paper by Reynolds (1885). When a dense granular material is subjected to shear, the individual particles cannot pass through each other; instead, the material must be allowed to dilate in order to make space for the shear to occur. Conversely, a very loose granular material will collapse under shear, due to gravity. Within the geotechnical community, this relationship has been formalized as critical state soil mechanics. In particular, the point at which the internal friction between the particles can no longer support a load is referred to as the Mohr-Coulomb criterion (Schofield and Wroth 1968, Nedderman 1992). There exist both continuum models that account for either dilation or compaction as averaged properties of a granular flow (Campbell 2005), and experiments that quantify the transition at a particle scale by using x-ray radiography and tomography (Kabla and Senden 2009, Métyayer et al. 2011) in Earth's gravity. In a microgravity environment, there will be no restoring force to drive compaction, so these behaviors may be significantly modified.

A sheared NEO will likely not self-compact, and instead the constituent particles will only be slowed by dissipative effects (inelastic collisions, friction). Further investigation using simulations (Baran and Kondic 2006) or experiments (Murdoch et al. 2013) are necessary to know what the dominant effects will be as gravity is reduced. Understanding the transition between unstable and stable configurations has been a particular focus in recent years, a process that has come to be known as jamming (Liu and Nagel 1998). Two recent reviews (Liu and Nagel 2010, Hecke 2010) provide details about this approach, which takes as its starting point studies of frictionless spheres in zero gravity, interacting only when in contact. The central idea is that the average number of constraints (contacts) per particle, the natural vibrational modes of the aggregate, and the rigidity of the system are all fundamental manifestations the same physics. This has allowed for the understanding of such features as how the shear modulus of a jammed material changes as a function of its packing density. As a spherical material is packed denser than its critical (lowest stable) packing fraction ϕ_c , its shear modulus G

increases according to the function $G \propto (\phi - \phi_c)^\alpha$. The scaling exponent α is set by the exponent in the functional form of the contact force law between two particles, and $\phi_c \approx 0.64$ for disordered, frictionless, spherical particles (Hern et al. 2003). Similar scaling relations are known for other quantities such as the bulk modulus, pressure, and the mean number of particle contacts (Liu and Nagel 2010, Hecke 2010).

More recently, the jamming approach has been extended to frictional (Somfai et al. 2007, Henkes et al. 2010) or elliptical (Mailman et al. 2009, Zeravcic et al. 2009) particles, for which ϕ_c takes a different value. Two important complications are the fact that friction always introduces history-dependence (the frictional force opposes the direction of motion), and non-spherical particles can have more complicated relationships between ϕ and the number of interparticle contacts. Therefore, the scaling relations between the bulk/shear modulus and the packing density are no longer the simple power laws known for the frictionless, spherical particle case. Promising new directions are studies that investigate when shear rigidity is either enhanced or degraded as a function of the preparation protocol or the choice of shear-direction (Bi et al. 2011; Dagois-Bohy et al. 2012). Ultimately, it may be possible to use the vibrational modes of the system as an empirical measure (Owens and Daniels 2013) of how near a granular system is to the point at which the material yields to external stresses and begins to flow.

11.4 Granular Gases

When sufficient energy is injected into a granular system that the individual particles have enough kinetic energy to overcome dissipative and attractive forces, they can exist in a gas-like state in which the behaviors are collision-dominated instead of contact-dominated. Such a situation can quite readily occur in and near NEOs during probing or capture, particularly as material becomes dislodged from the surface. For packing densities low enough that the material is collision-dominated, it is possible to understand the dynamics of the granular material using extensions of the kinetic theory of ordinary gases. A review article (Goldhirsch 2003) and book (Brilliantov and Pöschel 2004) detail the methods used to provide a quantitative theory, although this has been most commonly considered without gravitational attractions and between spherical particles.

One predicted feature is that granular gases undergo a clustering instability as they ‘cool’ through collisions in free space (Goldhirsch and Zanetti 1993), each pair of particles losing kinetic energy during each collision. The mechanism for this instability is that particles located within any small density fluctuation will (due to the increased density) suffer more collisions than neighboring regions. This causes that region to lose energy at a greater rate than the neighboring regions. Therefore, any initial density fluctuation will grow rather than decay; this effect has been observed in numerical simulations (Goldhirsch and Zanetti 1993).

Were it to also be present in real granular materials, it would predict a highly heterogeneous environment once any granular material was dislodged on a NEO.

To date, there have been relatively few experimental studies of granular gases in zero- or micro-gravity, due to the difficulty and expense of obtaining high-quality environments for long enough duration. While expensive, Earth-based experiments are possible through the use of parabolic flights, drop-towers, and sounding rockets. In studies of a dilute gas of steel spheres, Leconte et al. (2006) found significant differences with theoretical predictions from kinetic theory that remain unresolved. Murdoch et al. (2013) found that an important effect on Earth, the presence of convective-like flows in sheared granular materials, is strongly suppressed in microgravity, and Harth et al. (2013) made quantitative measurements of the translational and rotational motions of particles in a dilute rod-like granular gas. Intriguingly, unlike what was predicted for spherical particles, no clustering effect was observed. Each of these experiments illustrates the limitations of the current theoretical predictions. Further experiments probing the collisional dynamics of frictional, non-spherical particles in a microgravity environment would provide new information about what to expect once an asteroid is fluidized by impacts or digging.

11.5 Simulation Techniques

While continuum models of granular materials (Goldhirsch 2003, Jop et al. 2006, Kamrin and Koval 2012) only span narrow regions of parameter space, discrete numerical simulations are able to span the full range of solid-like to gas-like behavior. The classic Cundall and Strack (1979) method established the discrete (or distinct) element method (DEM), which models individual particles according to Newton's laws; these techniques are analogous to molecular dynamics simulations, but with macroscopic interactions instead of microscopic. Several reviews of up-to-date DEM methods have been published (Pöschel and Schwager 2005, Vermeer et al. 2001), and most typically allow for the modeling of spherical particle with interparticle friction, Hertzian (elastic) contact forces, and inelastic losses during collisions. Inherent in the design of such simulations is a choice between event-driven protocols, which are fast but only permit instantaneous binary collisions, and fully-resolved soft-sphere models which permit multiple sustained contacts. While event-driven simulations work well for dilute (low- ϕ) systems, densely-packed aggregates require the inclusion of sustained contacts. More recently, DEM simulations have been extended to permit a super-set of sphere-like shapes that includes ellipses (Zeravcic et al. 2009, Mailman et al. 2009) or conjoined circles/spheres (Gravish et al. 2012, Phillips et al. 2012), but angular shapes remain a challenge due to difficulties in modeling contact force laws for arbitrary curvatures. It is important to distinguish DEM techniques from smoothed-particle hydrodynamics (SPH) (Asphaug et al. 1998), in which a continuum fluid is divided into a set of discrete elements whose properties are smoothed over a pre-determined lengthscale that need not correspond to a granular lengthscale.

In order to capture the dominant interactions, simulations of granular materials on asteroids require not only sustained, elastic contacts, but the inclusion of both long-range gravitational forces and cohesion. Numerical simulations on the stability of and collisions between asteroids have begun to include all of these effects (Scheeres et al. 2010, Sánchez and Scheeres 2011, Richardson et al. 2011, Ringl et al. 2012, Schwartz et al. 2012), but such advances are quite recent. To date, such studies have primarily focused on asteroid-scale dynamics, rather than localized disturbances appropriate to digging and anchoring applications.

To judge the need to include various of these terms in simulations, it is helpful to consider the magnitude of various key energies, particularly as compared with any kinetic energy imparted to either individual particles or the collective (e.g. centripetal effects). The magnitude of the gravitational energy for two identical particles of mass m is Gm^2/r , where r is the distance between them and G is the gravitational constant. If both particles have a mass density ρ and a radius R , then this energy is proportional to R^5 ; this predicts a significant particle-size dependence. In contrast, the kinetic energy grows proportional to R^3 . The elastic energy stored between two spherical particles compressed by an amount δ is given by the Hertzian contact law (Johnson 1985), and is of magnitude $ER\delta$, where E is the Young's modulus of the particle material. While dry, convex granular materials can sustain shear or compressive loading, they cannot support a tensile load without the presence of cohesive forces between the particles. Because asteroids are observed to have a tensile strength that resists breakup under rotation (Trigo-Rodríguez and Blum 2009), some type of cohesive force can be inferred. While the energy associated with van der Waals adhesion may seem small – the magnitude is set by the Hamaker constant (10^{-19} to 10^{-20} J for typical materials) – Scheeres et al. (2010) showed that it can dominate over electrostatic or radiative-pressure effects for small objects. In addition, this paper provides scaling arguments that illustrate how to use experiments on Earth-based powders to simulate and infer behaviors in rubble-pile asteroids.

11.6 Particle Properties

The granular material studied in many of the above examples has most commonly been composed of hard (little deformation), frictional, dry (non-cohesive), and smooth (often circular/spherical) particles. In numerical simulations, the choice of smooth, frictionless, cohesionless particles facilitates computations, since the Hertzian contact forces are known analytic functions of the interparticle force in the limit of small deformation (Johnson 1985). Within this framework, governing properties such as particle size and elastic modulus are easily non-dimensionalized for comparison. Experiments have often chosen similarly-idealized particles, both to facilitate direct comparisons and to make experiments more repeatable. Nonetheless, recent numerical and laboratory studies have begun to investigate the roles of deformation (Saadatfar et al. 2012), polydispersity (distribution of particle sizes) (Tsoungui et al. 1998, Wackenhut et al. 2005, Muthuswamy and Tordesillas 2006, Voivret et al.

2009), particle shape (Azéma and Radjai 2010, 2012; Torquato and Jiao 2012), and cohesion (Nowak et al. 2005, Richefeu et al. 2006, Herminghaus 2005, Strauch and Herminghaus 2012). In all cases, the results differ in nontrivial ways from experiments/simulations on monodisperse spherical particles.

Rubble pile NEOs are composed of hard, dry, polydisperse (see Fig. 11.1), non-spherical particles (Fujiwara et al. 2006, Michikami and Nakamura 2008, Yano et al. 2006), so comparison to the granular physics literature must proceed carefully. Regolith samples returned from the surface of 25143 Itokawa were also found to be highly polydisperse, with grain sizes ranging from micro- to millimeter scales (Tsuchiyama et al. 2011). It remains an open question how particle size and shape distributions (Herrmann et al. 2004, Pena et al. 2007, Saint-Cyr et al. 2012) influence the point at which a granular material transitions from solid-like to fluid-like behavior.

11.7 Interacting with a Rubble NEO

Safely interacting with rubble NEOs will require engineering within the properties and constraints described above. While self-gravitational and van der Waals effects have so far seen little investigation in Earth-based studies due to the inaccessibility of the regime, enough is known about general properties to point the way towards promising, and away from dangerous, modes of interaction.

As noted above, the escape speeds for rubble NEOs can be quite low: cm/s is typical. For comparison, the 17 cm/s speed calculated for asteroid 25143 Itokawa is about half a km/hr, two orders of magnitude lower than a child playing softball can pitch. Importantly, all motions at the surface of the asteroid must move at speeds below this limit if both the constituent particles and the probe hardware are to remain gravitationally bounded.

There is a second speed scale, set by the speed of sound within the asteroid body, the consequences of which are less clear. Since the rigidity of the fragile aggregate vanishes on approach to the jamming point (Liu and Nagel 2010, Hecke 2010), the speed of sound vanishes as well. Thus, for an asteroid only slightly above the jamming point (compressed slightly by gravitation), even very small perturbations will likely create supersonic shocks which propagate through the asteroid body (Gomez et al. 2012). As the material is compressed behind the propagating shock wave, the speed of sound in that region will increase. Meanwhile, collisions between the particles are dissipating energy; as discussed in the context of granular gases, it remains unclear to what degree clustering instabilities are to be expected for frictional, non-spherical particles. Whether this combination of effects leads to a stable (local damage) or unstable (propagating damage) situation is unknown. SPH simulations (Asphaug et al. 1998) of an 8 m sphere impacting an intact, non rubble-pile asteroid, suggest that damage propagates within (but not between) intact bodies. Laboratory or DEM simulations would be able to model the dynamics of an impinging probe and thereby estimate how large of an impact

would be sustainable in the presence of real particle-contacts. There is likely a speed or energy threshold associated with the transition to local or global failure.

It has been commonly advocated that quickly firing a harpoon into a NEO would be an effective way to either tether it or produce ejecta to be collected. However, it remains to be determined whether fast or slow insertion is safer, more efficient, or more effective. For example, one goal might be to insert a probe or anchor into the asteroid while imparting as little momentum and breakup as possible. Therefore, it is illustrative to consider what distinguishes fast (firing) insertion from slow (digging). Fast firing would be defined as any speed at which the gravitational relaxation time $(dl/g)^{0.5}$ exceeds the reciprocal shear rate $(\dot{\gamma}^{-1})$. For a 10 cm particle at the surface of 25143 Itokawa, this timescale would be approximately 30 seconds. As such, all but the slowest of insertion speeds will be too fast for any relaxation of particle positions to take place during insertion, and will meet with significant resistance. From experiments, it is known that the resistance the projectile encounters is strongly dependent on how tightly-packed the material is (how difficult it is to rearrange) (Albert et al. 1999, Geng and Behringer 2005, Constantino et al. 2011). Therefore, one should additionally consider slow/digging techniques. Recent experiments (Wendell 2011) on flexible diggers have shown that that in Earth's gravity, thin/flexible objects can be more-efficient diggers than thick/stiff ones (see Fig. 11.3). For a given maximum digging force, probe flexibility was observed to allow for deeper digging. Similar optimization-style studies could examine what shape/flexibility/speed of a probe displaces the fewest particles in a zero gravity or self-gravitating environment.

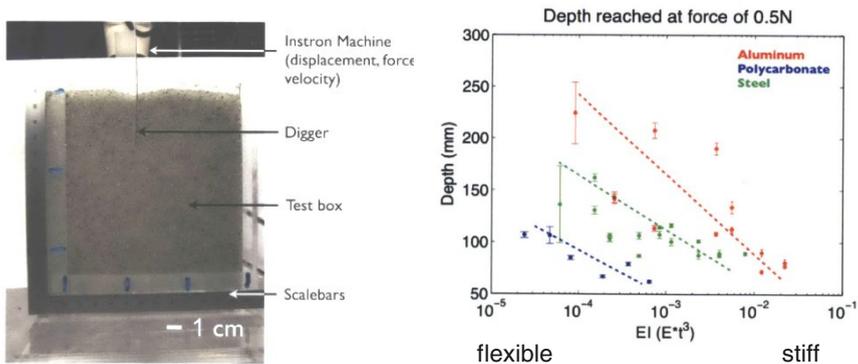


Fig. 11.3 In tabletop experiments in Earth's gravity (Wendell 2011), flexible diggers made of thin (0.1–1 mm) strips of polycarbonate, aluminum, steel were driven into a bed of dry 1–2 mm glass beads until a force threshold was reached. The maximum obtainable depth for 0.5 N of force is plotted at right; this depth was observed to decrease with the strip stiffness EI , where E is the material-dependent Young's modulus and I is the thickness-dependent bending moment.

Once a probe is inserted, it may be desirable to use it as an anchor, either to tether a spacecraft or to drag the asteroid through space. In this case, the engineering goal would be to design a system that can resist the largest force before failure of its hold. Because a dry, convex granular aggregate has no tensile rigidity of its own, it would be necessary to induce such behavior by a change in material properties. Two possibilities, already explored on Earth, are liquid films and magnetism. It is known that even very thin fluid layers can dramatically change granular collisions (Donahue et al. 2010), and this dissipative effect may be beneficial to anchoring. Furthermore, the presence of even microscopic fluid layers on the surface of particles would lead to liquid bridges which would further stabilize the granular material and provide tensile strength (Herminghaus 2005). A key difficulty in utilizing liquids would be to find a material that was not volatile on the timescales required for its use. A magnetically-induced rigidity would rely on using an electromagnet as the probe, so that the magnetic cohesion could be turned on and off as desired, by analogy to ferromagnetic shock-absorbers and valves. However, such a solution would require that the asteroid be composed of magnetically susceptible material (for instance, in M-type asteroids). Reliable identification of a particular asteroid's composition would of course be definitively settled by a sampling mission: a classic chicken and egg problem! A final concern is that any jamming of the surface particles on a NEO which aids the anchoring, would at the same time hinder digging efforts.

11.8 Conclusion

While this chapter has focused on rubble-pile asteroids that are thought to be completely granular in character, other asteroids such as Eros (Veverka 2000, Robinson et al. 2002, Li et al. 2004) are thought to have solid cores with a surface regolith composed of a granular material. Exploration of either type of asteroid will require working with granular materials in a microgravity environment. We have already sent one successful mission (Hayabusa) to asteroid 25143 Itokawa, and future missions for asteroid sample return are in various stages of planning. NASA is preparing for the 2016 launch of the Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission to study a carbonaceous (C-type) asteroid. As part of this mission, they plan to obtain and return a regolith sample. Similarly, JAXA is considering a second Hayabusa mission, this time to visit an C-type rocky asteroid and return samples from the surface. Finally, ESA is currently assessing the feasibility of the MarcoPolo-R mission, which also aims to visit a NEO. Eventually, it is likely that NASA (KISS 2012) or another organization will plan a mission to entirely capture a NEO; this would be altogether more challenging to successfully complete.

Because the population of NEOs is heterogeneous and largely uncharacterized, advance planning for particular asteroid or regolith materials will only partially predict the observed dynamics. The design (and ultimate success) of robust

interaction protocols for digging, sample-collection, anchoring, and lift-off will depend on laboratory experiments and simulations which take place ahead of time.

Controlled experiments on granular materials in microgravity remain quite limited in both number and scope (Leconte et al. 2006, Chen et al. 2012, Murdoch et al. 2013, Harth et al. 2013). It is notable that two of these studies (Murdoch et al. 2013, Harth et al. 2013) were funded by European programs in which students apply to perform experiments using existing microgravity facilities. This means that while there is a population of young scientists ready to address many of the problems laid out in this chapter, there has been not yet been a sustained research program to address these issues. While drop-towers, catapults, sounding-rockets, and parabolic flights can all provide platforms for short experiments, developing tools for slow, gentle manipulation of space-based granular materials (both idealized and realistic) will require longer access to microgravity. The International Space Station is well-suited to host long-term experiments, and the burgeoning commercial spaceflight industry can provide intermediate timescales in a suborbital environment. Facilities and funds with which to perform future investigations will determine whether we are able to improve our ability to understand and predict the dynamics of rubble-pile asteroids, but the ground is laid for opportunities to make significant advances.

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