The significance of fundamental granular materials research to space exploration.

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1 Background

Granular materials are ubiquitous on Earth and in space. Because condensed planets and their satellites are chiefly made up of solids, any mission landing on their surface must establish how to deal with the technological obstacles they present [1]. Sample return missions to distant objects require a strategy for extracting solids, and possibly processing them to liberate valuable components such as hydrogen, helium-3, or oxygen, so the spacecraft musters enough fuel to return to Earth within a reasonable time.

Human exploration implies landing large crafts on a bed of dispersed solids, resulting in a violent supersonic upsurge of solids, called rocket blast [2], toward the craft or its neighborhood. The protection of astronauts from cosmic radiation and the establishment of a colony require construction of berms, tunnels and spaceports, all involving massive solids handling.

Because bulk properties of granular materials, such as mechanical strength, depend on such microscopic details as packing, chemical composition and size distribution, they are largely unpredictable without access to a sample. On Earth, science-based progress in powder technology benefits from availability of the actual solids. For example, the industrial processing of granular materials is mainly refined by trial and error. Mining of ores, chemical processing, agriculture and infrastructure construction all derive practices from centuries of experience that is only beginning to emerge in planetary exploration, for which complicating physics, such as massive electrostatic buildup in dry atmospheres or in vacuo, present unforeseeable factors [3].

Minimizing astronaut risk makes it likely that robots will always precede human exploration for advance reconnaissance, habitat construction, and harvesting/processing resources prior to astronauts' arrival. However, delays in signal transmission require robotic autonomy, thus requiring that on-board software incorporates realistic models of soil and ore behavior.

Granular materials also concern planetary geophysicists. For instance, an understanding of Martian slides [4] requires better insight of the dynamic behavior

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of granular materials found at or near future settlements, including their constitutive stress-strain relations and physical properties like particle size distribution and material density.

2 Perspectives

Having elicited considerable interest from the Engineering and Physics communities, rapid progress has been made on understanding the mechanics of granular materials. Briefly put, grains behave as a solid, a liquid or a dense gas, depending whether they flow locally with sufficient agitation (e.g., rapid avalanches), or not (e.g., a static sand heap).

For static grain assemblies under stress, theories derived from continuum mechanics treat the complicated force network to predict how these assemblies can support a load, such as the foundation of a building [5]. At the other end of the solid-liquid-gas spectrum, the Maxwell-Boltzmann kinetic theory of dense gases captures flow behavior, if grains move fast enough to sustain sufficient agitation despite collisional energy dissipation [6].

Unfortunately, because gravity causes grain flows to lose agitation and "condense" into a static heap, real applications undergo a transition between these two extremes of static and dynamic behavior within the same system. This transition constitutes the principal challenge of granular mechanics. Examples of this conundrum abound: how does a sand bed behave in an earthquake? Why did the MER B Mars Rover get stuck on a sand heap? How do Martian landslides differ from their counterparts on Earth?

Because the behavior of granular materials is crucially affected by details of microscopic contacts between individual grains, predictions of practical systems are complicated by surface physics, which, as Wolfgang Pauli once mused, "is the invention of the devil." Electrostatics, friction, and cohesion all play an important role, in addition to surface chemistry, if stress or thermal effects are large enough.

Another important challenge in granular media is their interaction with a continuous phase, such as a gas or liquid. Industrial solids processing technologies include fluidized beds, which bring finely divided solids (fuels, catalysts, etc) in close contact with gases for chemical reactions; solid transport and storage systems, such as chutes, conveyors, hoppers, and pneumatic lines; "wet" processors separating solids from waste streams or valuable ores from mine tailing; etc. In space exploration, a need for massive solids processing requires most of these industrial methods, all of which are adjusted by trial and error, for a lack of basic understanding of the underlying non-linear physics.

Science can contribute to illuminating these issues, and facilitate space exploration, as past reports of the National Academies have noted [7]. A program in granular physics was sponsored by the NASA-Glenn Research Center until 2004, when the agency refocused its priorities away from fundamental physics, and toward engineering development of a successor to the Shuttle and a vision for human exploration of the Moon and Mars.

Fundamental experiments were addressing the key challenges mentioned earlier:

transmission of forces along networks of grain contacts; interaction of agitated grains and gases; and size segregation in granular flows. To interrogate them without obscuring the physics with local gravitational condensation, these experiments were to exploit long-term microgravity on the International Space Station.[1]

Planetary space exploration, whether by humans or robots, must deal with granular materials and the challenge they pose – from uncertainties in landing large crafts, to processing massive amounts of material for in-situ-resource utilization.

Fortunately, a solid technology and intellectual base exist in the US, so that understanding can improve to where granular systems may be designed with minimal prior trial and error. Because many planets and their satellites are made up of condensed granular matter, it it is timely to resurrect research efforts on granular materials.

References

[1] Wilkinson, R.A., Behringer, R.P., Jenkins, J.T., and Louge, M.Y. (2005), Granular Materials and the Risks They Pose for Success on the Moon and Mars, *Space Technology and Applications International Forum-STAIF05* **76**, Albuquerque NM, M.S. El-Genk, ed., AIP Conference Proceedings.

[2] Donahue, C.M., Metzger, P. T., and Immer, C. D. (2006), Functional Scaling for the Cratering of a Granular Surface by an Impinging Jet, *Earth & Space*, doi 10.1061/40830(188)20, pp. 1–6.

[3] Grard R. (1995), Solar photon interaction with the Martian surface and related electrical and chemical phenomena, *Icarus*, *114*, 130–138.

[4] Gerstell, M.F., Aharonson, O., and Schorghofer, N. (2004), A distinct class of avalanche scars on Mars, *Icarus*, *168*, 122–130.

[5] Jaeger, H.M., Nagel, S. R., and Behringer, R. P. (1996), Granular solids, liquids, and gases, *Reviews of Modern Physics*, *68*, 1259–1273.

[6] Goldhirsch, I. (2003), Rapid granular flows, *Annu. Rev. Fluid Mech.*, *35*, 267–293.

[7] Voorhees, P. W. (chair), et al. (2003), Assessment of Directions in Microgravity and Physical Sciences Research at NASA, *Committee on Microgravity Research Space Studies Board, Division on Engineering and Physical Sciences*, ISBN 0-309-50848-7.

[8] Xu, H. M. Louge, M., and Reeves, A. (2003), Solutions of the kinetic theory for bounded collisional granular flows, *Continuum Mech. Thermodyn.*, *15*, 321–349.

[1] The SiGMA experiment – "Solids interacting with a Gas in a Microgravity Apparatus," and MugSEG – "Microgravity Segregation of Energetic Grains" had been successfully tested on the KC-135 microgravity aircraft [8], and waited for final design of flight hardware. A third, the "μ-SiGMA" experiment, was ready for the Microgravity Science Glovebox; its flight hardware is now mothballed at Cornell.