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Disruption and surface modification of asteroids modeled as self-gravitating granular aggregates

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Abstract

The dynamics of granular materials, such as regolith on asteroid surfaces, has become a field of high interest in planetary science, due to the recent images from spacecraft showing that granular materials are ubiquitous in the Solar System, and to the preparation of sample return space missions by major space agencies (OSIRIS-REx at NASA, Hayabusa 2 at JAXA, and MarcoPolo-R under study at ESA). We have implemented the Hard-Sphere (HSDEM) and Soft-Sphere Discrete Element Method (SSDEM) in the parallel *N*-body code *pkdgrav* ([1], [2]) and present here three of our investigations: low-speed collisions between rubble piles modeled as granular aggregates, low-speed impact cratering on regolith surfaces and landslides on small bodies.

1. Introduction

With recent interest in simulating granular processes, such as regolith on asteroid surfaces, new simulation techniques that treat collisions between grains using a "soft-sphere" approach (SSDEM), as opposed to the billiard-ball hard-sphere approach (HSDEM) have recently been developed [5, 6]. In SSDEM, particles experience a mostly spring-like repulsive force when they interact, parameterized at minimum by normal and tangential spring constants, but usually also with damping coefficients, and optionally including various friction forces that oppose relative sliding, rolling, and twisting motions. A disadvantage is that much smaller timesteps are needed to resolve the particle interactions with SSDEM than with HSDEM, but this can be offset by the fact that true parallelism can be achieved with SSDEM, permitting simulations with millions of particles. Such advantages have been exploited in our implementation into the *N*-body code *pkdgrav* ([1], [2]). In the following we present our investigations of three specific problems.

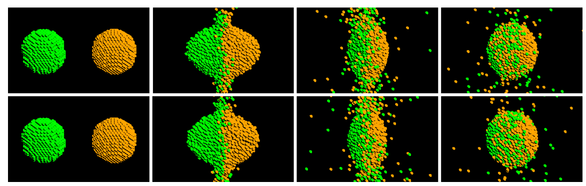

Figure 1: Snapshots from simulations of head-on rubble pile collisions at 2 km/s. Top: HSDEM; bottom: SSDEM. Both runs have mass ratios of $1:1$ with the spheres (randomly oriented) having a radius of ≈ 1 km, a density of ≈ 2 g/cm^3 and an initial separation between their centers of 3 km.

2. Low-Speed Collisions

Much of the evolution of small solar system bodies is dominated by collisions, whether from the initial build-up of planetesimals [3], or the subsequent impacts between remnant bodies that exist today (e.g., [4]). Some of the collisions occur at impact speeds that remain below the sound speed of the material. Since many small bodies may have low tensile/cohesive strength, the collisions can often be treated as impacts between rubble piles, the outcomes of which are dictated by the dissipation parameters and gravity.

We performed simulations of low-speed rubble pile collisions using either SSDEM or HSDEM, and compared the outcomes. This served both as a consistency check but also as a validation of the earlier hard-sphere approach. Our first simulations (Fig. 1, which is an updated version of [5]) did not include any frictional forces and the results from both methods are quite similar in general. SSDEM often, but not in all cases, shows a somewhat higher final ellipticity of the largest remnant of the collision, suggesting a higher shear strength that may arise from the more careful treatment of contact forces (recall there was no friction). New results that include the effects of interparticle friction will be presented.

3. Impact Cratering

Crater shapes and features are crucial sources of information regarding past and present surface environments on Solar System bodies, and can provide us indirect information about the internal structures as well. Here, we consider the effects of low-speed impacts into granular materials, such as those at the origin of secondary craters on the regolith that covers most of the solid Solar System bodies. We model numerically the impact cratering process, accounting for the contact forces between particles. We can investigate the morphologies, shapes, and sizes of low-speed impacts as a function of the impact conditions and regolith properties, and therefore help in the interpretation of images of solid body surfaces sent by space missions. Figure 2 shows an example of a simulation using SSDEM. Other simulations will be presented, showing the influence of various parameters contributing to the outcome, and some confrontations with experiments.

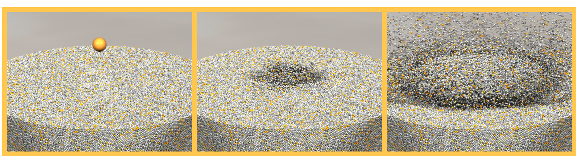

Figure 2: Cratering simulation into a target comprised of 1,137,576 particles. A 9 cm-radius projectile impacts perpendicular to the surface at a speed of 100 m/s into a 155 cm-radius half-shell filled with 1 cm-radius grains and with a coefficient of collisional restitution of 0.2. From left to right: 5 ms prior to impact; 15 ms and 375 ms after impact.

4. Landsides

We have begun an effort with Braunschweig University to build a controlled laboratory experiment specifically to serve as a testbed for calibrating our numerical simulations. The configuration was selected to provide a test environment where particle-particle interactions were dominant, to eliminate uncertainties about how to handle particle-wall interactions. Figure 3 shows an example of a simulation using the same conditions as the experiment: an entire box of particles is slowly tilted, and the flow of beads as a function of the angle of the box is measured. Given the simplicity of the configuration and the detailed laboratory measurements, we can explore a wide range of numerical parameters for detailed calibration. Preliminary results show that flow initiation requires a steeper angle as the static friction parameter is increased from 0.1 to 0.9 (high friction). We are exploring a range of static and rolling friction parameters in this preliminary study and results will be presented.

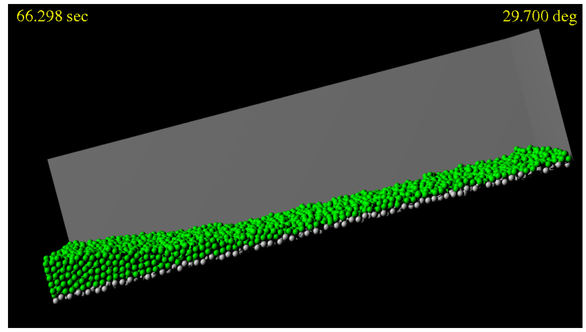

Figure 3: End-state of a simulation of a tilting bed with loose particles (green) on top of fixed particles (gray). Sustained flow initiates at a tilt angle of approximately 24 deg for this configuration that used about 14,000 monodisperse 5 cm radius particles (half free, half fixed) on a 6 by 9 m bed. For this simulation, the static and rolling friction parameters are both set to 0.1 (low friction).

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