NUMERICAL SIMULATIONS OF LOW-SPEED IMPACT CRATERING INTO GRANULAR MATERIALS USING A HIGH-PERFORMANCE PARALLEL GRAVITY TREE CODE INCLUDING BOTH THE SOFT- AND HARD- SPHERE DISCRETE ELEMENT METHOD.

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Introduction: The impact process plays a major role in the formation and evolution of planetary systems, including our own Solar System. In particular, the impact cratering process is important because impact craters are the geological features that are most commonly observed on the surface of solid Solar System bodies. Crater shapes and features are crucial sources of information regarding past and present surface environments, and can provide us indirect information about the internal structures of these bodies as well.

In this study, we consider the effects of low-speed impacts into granular materials, such as the regolith that covers most of the solid bodies of our Solar System. In principle, if the cratering process involves solid rock and/or if the impact speed is larger than the sound speed of the material, hydrocode simulations that take into account large plastic deformations and phase changes of particles are the most adapted to model the process [1]. However, if the cratering process involves a low-speed impactor into regolith material, then the discreteness of particles as well as the different contact frictional forces between them must be taken into account. Sophisticated constitutive equations may be implemented in hydrocodes to study these types of cases, but numerical codes capable of directly simulating the evolution of particles and the contact forces between them during such a cratering event are probably best suited.

We use our implementation of both the Soft-Sphere Discrete Element Method (SSDEM) [2] as well as the Hard-Sphere Discrete Element Method (HSDEM) [3,4] into the parallel N-body code PKDGRAV [5] to model the impact cratering process into granular materials. Studies of low-speed impact events are suited for understanding the cratering process leading, for instance, to secondary craters. Such craters result from the ejecta of material from a large crater formed by a high-speed impact, which fall back onto the regolith at the surface of the considered body. Our simulations can be used to investigate the morphologies, shapes, and sizes of such low-speed impacts as a function of the impact conditions and regolith properties, and can therefore help in the interpretation of images of solid-body surfaces sent by space missions. We can also investigate the effect of boundary conditions by placing granular material into shells of two different sizes: one small relative to the zone in which the entire process takes place, and one where the boundaries affect less strongly the outcome of the simulation. The first case may represent a cratering event into a small layer of regolith that covers bare rock at a depth still large enough that the rock does not fragment. The second case can be used to better understand the process in a fully granular medium.

Numerical Model: Our numerical code is a modified version of the original parallel collisional *N*-body tree-code PKDGRAV that uses HSDEM. In HSDEM, gravitational interactions between hard spherical particles are calculated, and collisions are computed in advance by extrapolating from their motion. Each collision is treated as an instantaneous transfer of momentum, parameterized by normal and tangential coefficients of restitution. HSDEM is well suited for the dilute regime and/or for cases when taking collisions to be instantaneous is an appropriate approximation. In this study, we primarily use the SSDEM implementation. In this collisional routine, spherical particles, despite being indestructible, can overlap during collisions, which can be seen as a representation of their deformation during contact. While particles are in overlap, a host of contact forces arise, including restoring forces in both the normal and tangential directions, along with other contact frictional forces (due to, e.g., rolling, sliding), etc., which is especially needed in dense regimes and for simulations where interparticle contacts can last for long durations.

Numerical Simulations: We performed preliminary simulations using the SSDEM version of our numerical code. For the reasons mentioned above, this version is the one best suited to simulate the cratering process during its early stage when contact frictional forces have a strong influence on the outcome. For the later phases, e.g., during the excavation when particles escape from the surface, the HSDEM method is probably more adapted as it allows for a larger timestep, but this stage is not considered here.

Simulation with spherical shell boundary condition. We first simulate the impact of a projectile in a granular material placed into a half-spherical shell whose diameter is significantly smaller than the distance at which the wave generated by the impact would attenuate. As a consequence, the presence of the boundary will affect the outcome (e.g., by generating a reflective wave). The granular material consists of close to 100,000 particles of radius 1 cm and density 2.7 g/cm^3 in a half-shell of radius 65 cm. First, a simulation is made to fill the shell with this granular material. This is done by suspending several groupings of particles over a large funnel, which under the influence of gravity, empties into the shell. The projectile, which consists of one spherical particle a few times the size of those that constitute the target, has a vertical impact speed of ~100 m/s. Figure 1 (top-left) shows the initial conditions of the target prior to impact. As a result of the impact, material is excavated and redistributed atop other material or outside the shell (results to be presented).

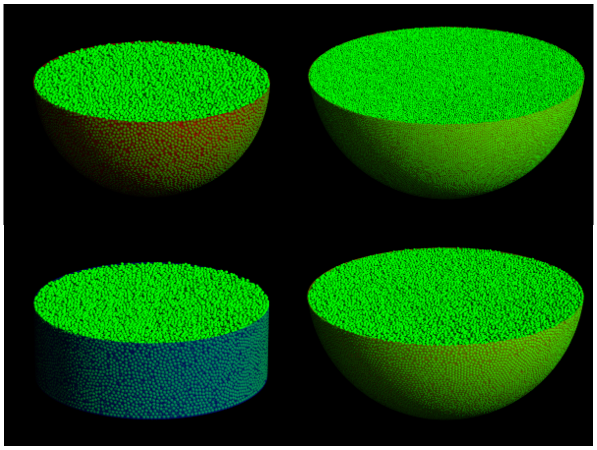

Figure 1: Initial conditions prior to impact simulations. Top row: spherical half-shells of radius 65 cm (left) and 155 cm (right, zoomed out) filled with spherical particles of radius 1 cm; bottom row: cylindrical container of radius 65 cm (identical in volume to simulation shown in top-left) filled with spherical particles of radius 1 cm (left), and spherical half-shell of radius 155 cm filled with spherical particles of radius 1.71 cm (right, zoomed out).

Simulations with different boundary condition effects. The second simulation, and each subsequent simulation, uses the same process as the first to fill the shell, however, this time, the shell size is 155 cm and uses the same size particles, thus the number of particles is increased by a factor of about 14 (Figure 1, top-right). The wave generated by the impact will have had more time and distance to attenuate before running into the boundary (shell wall). For the third simulation, the half-shell from the first simulation is substituted with a cylinder of the same radius and total volume bounded by a disk at the bottom (Figure 1, bottom-left). A comparison of the results from these first three impact simulations will be presented, which provide insight into boundary effects.

Simulation using target comprised of larger grains. The fourth simulation (Figure 1, bottom-right) uses the larger shell size (155 cm), but with particles of five times the mass (all particles in all simulations use the same density). Comparing the outcome of this simulation to those of the first two can shed light on the influence of the sizes of grains that comprise the target. Preliminary results will be presented.

Conclusions and Perspectives: We performed 4 simulations of low-speed impact cratering into granular material using our numerical SSDEM code. Boundary and grain-size effects were explored by simulating over a small variety of confinement conditions and particle sizes in this preliminary study. We show the importance of boundary effects in the outcome in a qualitative way. Future steps will be to investigate in more detail these processes and to implement a hybrid approach that will use the appropriate collisional routine, SSDEM or HSDEM, at each of the different phases of the impact. Once this more sophisticated treatment is implemented, we will compare the outcome of our simulations with experiments and/or simulations with other validated code, to demonstrate the reilability of our numerical model for cratering events.

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