A HYBRID SPH-SSDEM FRAMEWORK FOR END-TO-END IMPACT CRATERING MODELING.

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Introduction: Impacts can modify the physical state of a substantial fraction of a target body. Studying the impact craters on small bodies imaged by space missions can provide an insight into their geophysical properties, estimate their surface age and compositional heterogeneity, elaborate evolutionary scenarios from their parent body formation to their current states, and trace back to the planet-forming process [1]. In addition, understanding the hypervelocity impact process and outcome is crucial in the design of mitigation strategies based on the kinetic impactor technique.

Numerical modeling with shock physics codes has been widely used to study the impact process on small bodies [e.g., 2, 3]. However, the low strength of surface granular materials and the low-gravity environment raise many challenges for the impact modeling. Such cratering events requires high numerical resolution to resolve ejecta and a relatively long time to settle down (typically $\gtrsim$ 10 min on km-sized small bodies). Therefore, the late stage of crater growth and the evolution of low-velocity ejecta are often ignored in current impact cratering modeling, which may bring a substantial error in estimating the final morphology of the crater and the amount of ejecta blanket.

Direct shock-physics code calculations of the late stage have been carried out recently in the context of the DART impact [4], but these are very challenging and numerically expensive simulations. Here we use an alternative approach. With a combination of two numerical schemes, Smooth Particle Hydrodynamics (SPH) and Soft-Sphere Discrete Element Method (SSDEM), we developed a novel hybrid framework to achieve self-consistent and high-efficiency end-to-end impact cratering modeling. Here we present the concept of this framework and validation tests.

Hybrid framework:

SPH method: The SPH method is appropriate to study the shock propagation and large deformation and ejection of material under hypervelocity impacts. We use Bern's SPH code, which includes material models suitable to simulate geological materials [2, 5].

SSDEM method: The SSDEM method is able to model unfractured collisions and flow of granular materials. We use the parallelized hierarchical tree SSDEM code, *pkdgrav*. A granular physics model including 4 dissipation/friction components in the normal, tangential, rolling, and twisting directions is applied for computing particle contact interactions and controlling the material shear strength [6, 7].

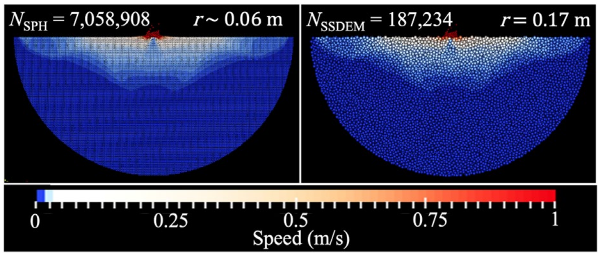

***Figure 1** SPH-SSDEM handoff illustration (a cross-section): particle velocity field of the SPH-stage output (left); particle velocity field of the SSDEM-stage input (right). The number of particles and typical particle radius are given on the top.*

Combination of SPH and SSDEM: Extensive studies have used the combination of these two methods to simulate small body impact process [e.g., 8, 9]. The SPH code is used to simulate the initial shock propagation and fragmentation stage. The outcome is then transferred into the SSDEM code, which solves the fragments' evolution in the later stages. The particle-based description of these two methods allows direct information transition at the particle level, which is the common handoff procedure used in these studies. However, this direct particle-particle transition has several issues in handling the particle overlaps and maintaining linear and angular momentum constant [9]. Furthermore, since SPH simulations use very high particle resolution for properly solving the damage propagation and energy dissipation, the direct transition with comparable particle resolution in the subsequent SSDEM simulations leads to unachievable computational time to complete the crater growth modeling [10]. All these issues impede achieving a reliable end-to-end cratering modeling.

To solve these issues, we propose a velocity field SPH-SSDEM transition procedure for impact cratering modeling based on a shape-construction algorithm [9]. The procedure consists of four steps: (1) a granular bed with a predefined particle size distribution is produced and settled down using the SSDEM with a boundary geometry, gravity conditions, and material parameters that are consistent with the SPH simulation; (2) with the given SPH output, we use the α-shape-construction algorithm to construct a surface that isolates the compact material from the fast-moving ejecta whose speeds exceed a given limit; (3) the isolated surface is then used to carve out the surface of the SSDEM granular bed, and a nearest neighbor search is conducted to map the linear and angular momentum from the SPH compact material data to the SSDEM bed; (4) finally,

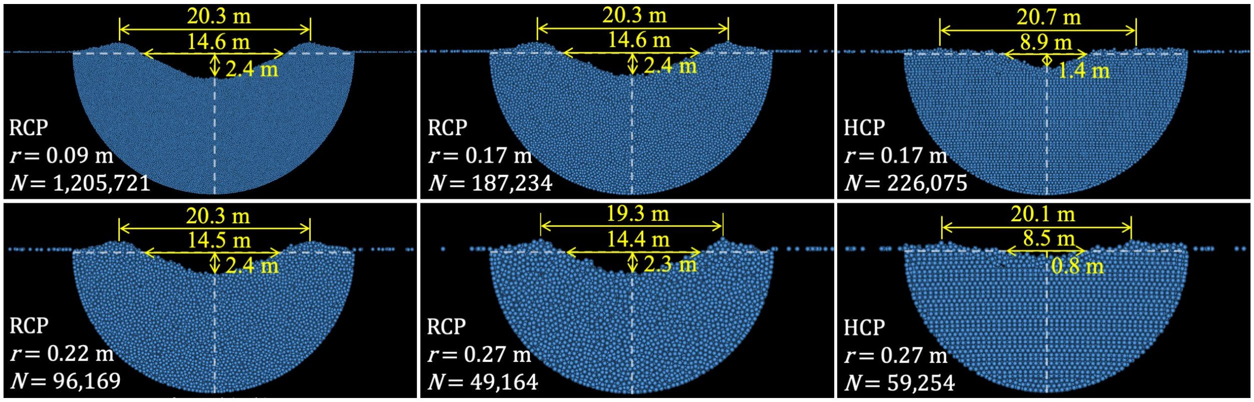

Figure 2 *Crater morphology of the SCI-like cratering tests. The packing (RCP/HCP), particle radius (r), and total particle number (N) of SSDEM models are indicated in the left bottom for each case. The rim diameter and the crater depth and diameter are highlighted by the yellow measurements. The dashed lines give the reference of the original surface plane and the central axis.*

the fast-moving ejecta is added into the SSDEM simulation scenario as individual particles.

Figure 1 shows an example of the particle velocity field before and after the transition. We verified that the new procedure can accurately reproduce the particle velocity field of the SPH output with the given SSDEM bed and therefore provide a high-fidelity transition.

Modelling of a SCI-like crater: The experiment performed by the Hayabusa2 Small Carry-on Impactor (SCI) on asteroid Ryugu in April 2019 offers the first opportunity for a direct confrontation of cratering on small bodies with numerical modeling [11]. To validate our hybrid modeling framework, we conducted SCI-like cratering tests using the same impact condition (except using an impact angle of 0º) and Ryugu's gravity field. The speed limit to isolate the ejecta is set to 1 m/s (three times the escaped speed of Ryugu). For consistency, granular material properties with a friction angle of 30º and zero cohesive strength are used for both SPH and SSDEM simulations. To minimize the boundary effect, the modeling uses a hemispherical domain to hold the granular bed. The particle-ball contact parameters are the same as those used for particle-particle contacts.

Figure 2 shows the crater cross-section morphology of our SCI-like cratering tests. To examine the robustness of the transition procedure, we have considered different particle resolution and arrangements in preparing the SSDEM granular bed (i.e., in the 1st step). When a random close packing (RCP) is adopted (the left and middle columns in Fig. 2), the effect of particle resolution is negligible, and the impact outcomes converge when the particle number $N \gtrsim 100{,}000$. The particle resolution has a more pronounced effect on the results using a hexagonal close packing (HCP). More notably, the particle packing plays a significant role in the crater growth and final morphology. Owing to the geometrical effects of particle interlocking, the HCP granular bed can resist much higher shear stress than the RCP bed, and therefore results in a shallower and smaller crater. The rim is also less prominent in the HCP tests. The RCP craters are slightly larger but very close to the crater morphology of the SCI impact (i.e., rim diameter ~18 m, crater depth ~2.3 m and diameter ~14.5 m; [11]). This is consistent with the fact that regolith and boulders are randomly distributed on small body surfaces.

Conclusions and future work: The preliminary but successful comparison with the SCI impact shows that the proposed modeling framework is capable of reproducing the morphological features of the resulting crater. Our study also highlights the importance of granular properties in the cratering process. We will continue to explore a larger parameter space with the consideration of cohesion and polydisperse size distribution. Moreover, comparisons to SPH calculations carried out to long times [4] will allow to assess the differences between continuum and particle-based codes in the modelling of late-stage crater growth.

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