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Effect of material strength and heterogeneity on small asteroid cratering events

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Introduction: Impacts can modify the physical state of a substantial fraction of a target body. Studying the hypervelocity impact process and outcome is crucial in the interpretation of the history of a planetary body (Jutzi et al., 2015) and the design of asteroid deflection strategies based on the kinetic impactor technique (Raducan et al., 2019). Images returned by space missions show that small asteroids have complex surface morphologies with heterogeneous distributions of fine regolith and large boulders (e.g., Watanabe et al., 2019). To properly decipher the crater imprints on asteroid surfaces, we carried out numerical investigations to understand the effect of surface material properties (i.e., friction, cohesion) and the presence of large boulders on cratering processes.

Methods: We used a hybrid SPH-SSDEM framework to model the high-speed impact cratering (Zhang et al., 2021). The Smooth Particle Hydrodynamics (SPH) is used to simulate the initial shock propagation and fragmentation stage (Jutzi & Michel, 2015). The outcome is then transferred into a Soft-Sphere Discrete Element Method (SSDEM) code (Zhang et al., 2018), which solves the ejecta evolution and crater growth in the later stages. This modeling framework is capable of simulating impacts from the beginning to the later stages when all ejecta are settled down, allowing capturing the final morphology of the resulting crater.

To make comparisons with the first impact experiment performed on an asteroid by the Hayabusa2 Small Carry-on Impactor (SCI; Arakawa et al., 2020), we conducted SCI-like cratering tests using the same impact condition (except using an impact angle of 0°) and Ryugu's gravity field. The target is modeled as a 15-meter-radius granular bed held by a hemispherical ball. The particle-ball contact parameters are the same as those used for particle-particle contacts.

Results: As the SCI cratering analyses show consistencies with a very low-strength scaling law (Arakawa et al., 2020), we considered modeling the surface properties with three types of low cohesion (i.e., 0 Pa, 0.01 Pa, and 0.1 Pa) and four types of low to moderate friction angles (20°, 25°, 30°, and 33°). The results show that, in a monotonic manner, the diameter and depth of the resulting crater and rim decrease with a larger friction or cohesion (Fig. 1). Compared with the crater morphology of the SCI impact (i.e., crater diameter 14.5 ± 0.8 m and depth ~ 2.3 m, rim diameter 17.6 ± 0.7 m and depth 0.4 m), the case with $C = 0.1$ Pa and $\mu = 30^\circ$ provides the best

match. This suggests that the surface fine regolith on Ryugu near the SCI impact site would be likely to have a small amount of cohesion on the order of 0.1 Pa and moderate friction.

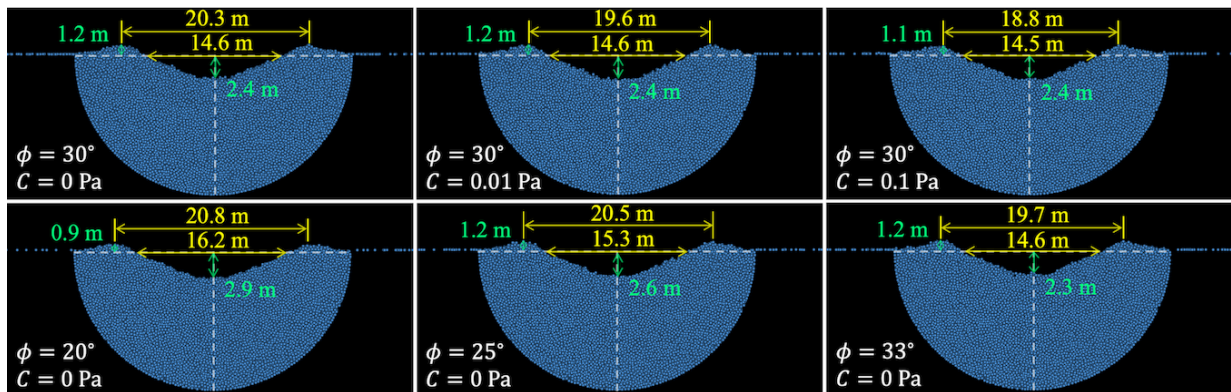


Figure 1 Crater morphology of SCI-like cratering tests. The material friction angle ϕ and cohesion C are indicated in the left bottom for each case. The crater/rim diameter and the crater/rim depth are highlighted by the yellow and green measurements, respectively. The dashed lines indicate the reference of the original surface and the central axis.

Nonetheless, the crater growth was undoubtedly affected by the surface morphology as observed during the SCI impact (Arakawa et al., 2020). To test the effect of the presence of boulders, we constructed a target with four boulders imbedded on its cohesionless granular material (Fig. 2d, e). As shown in Fig. 2, the velocity field of the target is significantly affected by these boulders. The growth of the left region was inhibited by the large block on the left side. The small boulders were elevated by the impact and displaced over 20 m. As the granular bed was mobilized by the impact and the movement of the large boulders, at the end, some granular materials were pushed out and the two large boulders sank into the bottom of the container. This sinkage behavior was not seen at the SCI impact site. This inconsistency may suggest that the subsurface area of this site could have large strength that inhibited the downward movement of large boulders, which is consistent with the formation of the small pit at the bottom of the SCI crater. However, the boundary effect of the simulations cannot be ruled out, and further tests are required.

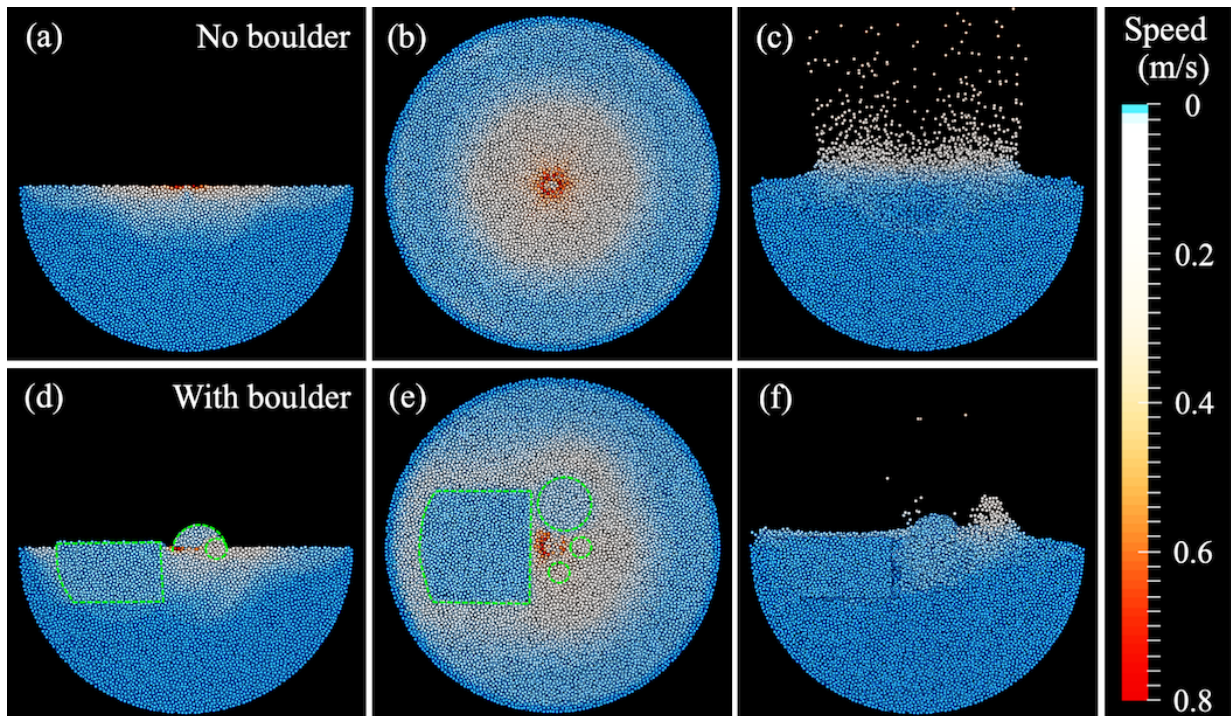


Figure 2 Velocity field at the beginning of the SSDEM-stage simulations (no boulder: **a.** side view of a cross-section , **b.** top view; with boulder: **d.** side view of a cross section, **e.** top view, where boulders are highlighted by the green dashed curves) and at 100 s (**c.**no boulder; **f.** with boulder).

Conclusion: Here we present the first step towards modeling impacts into realistic asteroid surface environments using well validated codes. These impacts are challenging to model and only limited number of impact scenarios have been studied so far. We found that the cratering outcome is very sensitive to the target material properties. Further tests against laboratory and in-situ experiments will be carried out to establish the relation between crater morphologies and surface properties, and understand the regolith and boulder dynamics in low-gravity environments. Moreover, comparisons to direct SPH calculations carried out to long times (Raducan & Jutzi, 2021) will allow to assess the differences between continuum and particle-based codes in the modelling of late-stage crater growth.

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