Cratering experiments on a boulder buried in quartz sand: Dependence of boulder’s depth on armoring effect

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The Hayabusa spacecraft observed that the surface of the asteroid Itokawa was covered with pebbles and boulders ranging from several centimeters to several meters in diameter, making it the first direct observation of a rubble-pile object. In addition, Itokawa has very few small craters compared to the Moon, and holes and cracks can be seen on the boulder surface, suggesting that an armoring effect is working in Itokawa’s crater formation process. Previous laboratory impact experiments using targets simulating boulder-covered asteroids have studied the armoring effect on the crater formation process. But when focusing on a single boulder, the behavior of boulders during impact and the accompanying crater formation process are still unclear. Several estimates have been made about the strength of boulders on asteroids. Analysis of craters found on Bennu’s boulders indicates the impact strengths ranging from 0.44 to 1.7 MPa (Ballouz et al., 2020). Additionally, thermal inertia data estimated the tensile strength of Ryugu’s boulders to be 0.20 to 0.28 MPa (Grott et al., 2019). However, previous studies using coarse-grained targets have used particles with an order of magnitude greater strength and have not been studied in the boulder strength range of actual asteroid’s boulders.

Therefore, the purpose of this study is to conduct cratering experiments using targets simulating rubble-pile asteroid surfaces and investigate the influence of boulders on and below the surface on the crater formation process. In particular, we focus on the armoring effect on the burial depth, the strength of boulder, and impact velocity of the boulder.

To simulate a boulder on rubble-pile asteroids, the boulder simulant was prepared by mixing quartz sand with a diameter of 100 μm and gypsum at a mass ratio of 2:1 to 20:1. The strength is 770 kPa at 2:1 and 19 kPa at 20:1. The diameter of the mixing sphere was 40 mm (low-velocity) and 60 mm (high-velocity), and it was placed in the center of a basin filled with 100 μm quartz sand. The depth of the mixing sphere was defined by the burial depth divided by the boulder diameter, d/D_B, and the d/D_B changed from 0 (above the target surface) to 1.25 (below the sand surface). Cratering experiments were conducted using a vertical single-stage light gas gun at Kobe University (low-velocity) and a vertical two-stage light gas gun at ISAS (high-velocity). A nylon sphere with a diameter of 10 mm (low velocity) and a polycarbonate sphere with a diameter of 4.7 mm (high-velocity) were used as a projectile. The impact velocities were ~150 m/s (low-velocity) and ~1.8 km/s (high-velocity). We observed collisional phenomena by a high-speed camera to check the position of the impact point, the shape of the ejecta curtain, and the disruption of the mixing sphere.

When a mixing sphere was placed, a large difference was observed in the crater formation process depending on the depth. At $d/D_B = 0$, no crater was formed, and the sphere’s fragments were disrupted catastrophically and scattered radially from the impact point, forming some radial traces on the target surface around the impact point. At $d/D_B = 0.5$, a crater was formed, but several irregular crater shapes were observed around the impact point. The largest fragment of the mixing sphere was buried in the center of the crater, and the ejecta curtain was very thin. At $d/D_B = 1$, a cone-shaped crater was formed, similar to the case of homogeneous sand targets. The degree of disruption of the mixing sphere was smaller than that at $d/D_B = 0$, and the largest fragment remained buried. The difference in crater shape with burial depth did not vary significantly with the strength of the mixing sphere. However, the degree of destruction of the mixing sphere was greater with decreasing strength, resulting in smaller fragment sizes

and greater numbers of fragments. Therefore, the lower the strength, the more roughness and more distorted shape were observed on the crater rim.
Comparing the crater rim diameter at each depth, two distinct trends were found. In the low velocity range, the diameter was almost 0 mm at d/D_B = 0 to 0.25. On the other hand, at d/D_B = 0.5 to 1, the crater diameter was larger than those at d/D_B = 0 to 0.25, but there was no significant difference in the data between these depths, and the crater diameter was 80 to 90% of that for homogeneous target. When the strength decreased, there was no significant difference in the data at d/D_B = 0.5 to 1.25. On the other hand, below d/D_B = 0.5, the fragments were fine, suggesting that the excavation flow might be similar to that of quartz sand targets, resulting in a larger crater diameter.

Keywords: asteroids, crater formation processes, armoring effect, boulders, buried depth, tensile strength