CRATER SIZE SCALING LAW AND IMPACT-INDUCED SEISMIC SHAKING ON RUBBLE-PILE ASTEROIDS.

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Introduction: Impact crater formation on a non-cohesive regolith layer of asteroids is widely accepted to be controlled by gravity. Impact cratering experiments in the gravity regime have been carried out for a non-cohesive granular target simulating a regolith layer under various impact conditions, and several scaling laws were proposed [e.g.,1]. Recent planetary explorations show that rubble-pile asteroids are covered with boulders with size distributions [2], and low strength [3]. Therefore, a detailed study to elucidate the effects of the size distribution and the boulder strength would be necessary to investigate the impact craters observed on rubble-pile asteroids.

However, a conventional crater size scaling law in the gravity regime is not enough to include these effects, and so we focus on the following effects: one is a projectile to target grain size ratio, another is a weak strength of boulders. Güttler et al. (2012) [4] and Barnouin et al. (2019) [5] studied the effects of the projectile to target grain size ratios on the cratering efficiency and they found that the large deviation of the cratering efficiency from that expected from the gravity scaling. Furthermore, Tatsumi and Sugita (2018) [6] found that the cratering efficiency was reduced by energy dissipation due to the disruption of the first-contacted target grain of the impactor.

Seismic shaking induced by a high-velocity impact is one of the most important surface geologic processes that occurs on an asteroid surface. Such shaking could modify the asteroid surface topography and dissipate small impact craters. Miyamoto et al. (2007) [7] reported the evidence of regolith migration on the 25143 Itokawa. 433 Eros was revealed to have surface areas at which the crater number density differed considerably [8]. To study seismic shaking, numerical simulations and experimental studies have been carried out [e.g.,9,10,11], however, the effects of size distribution and weak strength of target grains on the impact-induced seismic shaking remain to be poorly understood.

Therefore, we conducted impact experiments on granular targets composed of low strength and coarse-grains to study the effects of size distribution and strength on the crater size scaling law and the impact-induced seismic shaking processes on asteroids.

Experimental methods: Cratering experiments were conducted by using vertical gas gun sets at Kobe University and ISAS. Granular targets were prepared by using weathered tuff granules with the size of 1 to 4 mm (small particle) and the size of 1 to 4 cm (large particle). The crush strength of these tuff particles was measured to be about 60 kPa and 30 kPa, respectively. A spherical projectile with the size of 3mm (stainless steel, zirconia, alumina, glass, and nylon) was launched at the impact velocity from 40 to 200m/s, and a spherical projectile with the size of 2mm (tungsten carbide, copper, stainless steel, zirconia, titan, aluminum, and nylon) was launched at the impact velocity from 1.2 to 4.5 km/s. These projectiles were impacted on the target surface at the normal direction. Impact cratering phenomena were observed by a high-speed camera at the frame rate of 10^3-10^5 fps. After each shot, the crater morphology was observed by using the 2D laser displacement, and the diameter and the depth were measured. Impact-induced seismic waves were measured by using three accelerometers (a specific frequency is 30kHz) at different positions from the impact point, and a data logger was used to record the seismic data through charge amplifiers (the data acquisition rate was 100 kHz).

Results: *Crater size scaling law*. Fig. 1 shows the relationship between the crater radius and the kinetic energy of projectiles for different targets and projectiles.

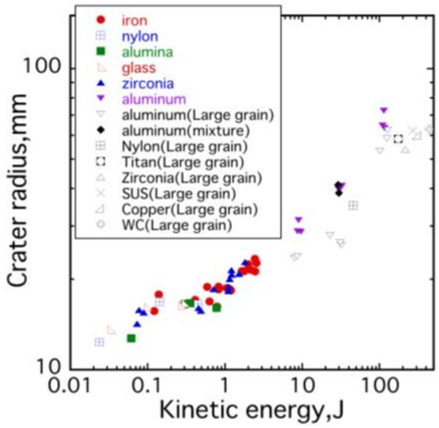

Fig1: Crater radius vs kinetic energy of the projectile. The colored and black plots show the results of small particle targets and those of large particle targets, respectively.

As a result, the crater radius increases with increasing kinetic energy of a projectile (E_k), except for the region of the E_k between 0.1 and 0.7 J, the crater radius was almost constants in this region. This trend did not depend on the projectile materials but the crater radius of the large particle target was smaller than that of the small particle target at the same E_k.

The π-scaling law [1] was applied to our experimental results to study the effects of the target particle size and the strength on the cratering efficiency. Fig. 2 shows the relationship between the normalized radius and the normalized gravity.

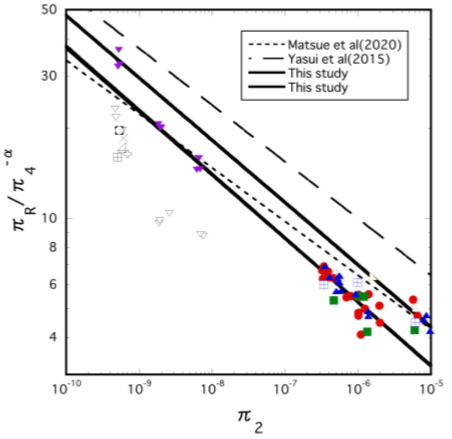

Fig2: Normalized crater radius π_R vs normalized gravity π_2 for various projectiles and two types of targets. The two solid lines show the fitting lines shown by Eqs. (1) and (2). The dashed and dotted lines show the previous results of glass beads and quartz sand [10,11]

We noticed that the cratering efficiency for the large particle targets is lower than the large particle target at first. Secondary, we found that the data of the small particle targets was separated into two regions with a clear offset, depending on the impact velocity and the projectile material. This offset might be caused by the dissipation of the projectile kinetic energy due to the disruption of tuff particles. The disruption should be caused by the impact pressure calculated from the impact velocity and the projectile density. These data of small particle targets can be fitted by the different empirical equations as follows:

$$\pi_R \pi_4^{-0.20} = (0.39 \pm 0.07)\ \pi_2^{-0.21\pm0.01}\text{(up)}, \quad (1)$$

$$\pi_R \pi_4^{-0.20} = (0.27 \pm 0.02)\ \pi_2^{-0.21\pm0.003}\ \text{(down)}, \quad (2)$$

These results in Fig. 2 showed that the cratering efficiency of weak coarse grain targets was affected by not only the particle size but also the disruption of tuff particles by the impact pressure. Large particles dissipate larger impact energy to reduce the cratering efficiency, and the impact pressure less than the particle strength might reduce the energy dissipation during the impact to increase the cratering efficiency.

Impact-induced seismic wave. We obtained the relationship between the maximum acceleration (g_{max}) and the distance from the impact point shown in Fig. 3, where the distance of the accelerometer is normalized by the crater radius.

The g_{max} decreased exponentially with increasing the normalized distance for all targets, irrespective of projectile material and impact velocity. The empirical equations for the attenuation of the acceleration are obtained to be for the small particle targets, and for the large particle targets.

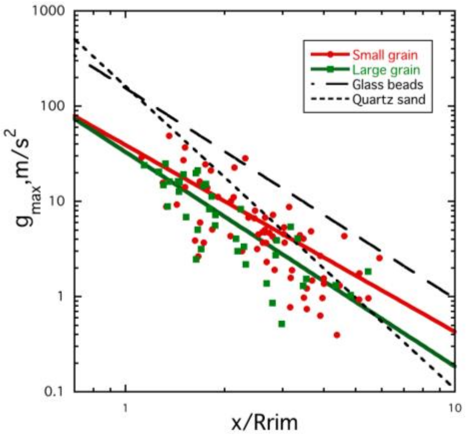

Fig3: Maximum acceleration vs distance normalized by the crater radius obtained in our study and previous works [10,11].

For small, $g_{max} = 10^{1.81} \times (x/R)^{-1.98}$

For large, $g_{max} = 10^{1.77} \times (x/R)^{-2.21}$

The g_{max} at the crater rim and the attenuation rates were similar in both targets. Compared with the previous studies [10,11], our g_{max} was about 1/3 - 1/4 times of those of glass beads and quartz sand, but the attenuation rates of the acceleration were almost comparable to those of glass beads, about -2.

Discussions: Our results showed that the crater size of the large particle targets was smaller than that of the small particle targets at the same π2, while g_{max} at the crater rim is comparable for the two targets. So, we can speculate that the crater size is not determined by only the maximum acceleration, and we then focus on the duration of the impact-induced seismic wave, T_{half}. The T_{half} of the small particle targets was found to be larger than that of the large particle targets. The ejection velocity of a particle at the rim was roughly estimated by the product of the maximum acceleration and the duration of the wave. The ejection velocity at the rim is proportional to the square root of the crater radius according to the π-scaling theory [1], so, the difference in the crater size between small and large particle targets could be caused by the difference in the duration of the impact-induced seismic wave.

References: [1] Holsapple & Housen (2011) *Icarus, 211,* 856–875. [2] Michikami et al. (2019), *Icarus, 331, 179-191.* [3] Grött et al. (2019), *Nature Astron, 3, 971-976.* [4] Güttler et al. (2012) *Icarus, 220,1040-1049.* [5] Barnouin et al. (2019) *Icarus, 325, 67-83.* [6] Tatsumi & Sugita (2002) *Icarus, 300, 227-248.* [7] Miyamoto et al. (2007), *Science, 316, 1011-1014.* [8] Robinson et al. (2002), *Meteorit. Planet. Sci.37, 1651-1684.* [9] Richardson Jr. et al. (2005), *Icarus, 179, 325-349.* [10] Matsue et al. (2020), *Icarus, 338, 113520.* [11] Yasui et al. (2015), *Icarus, 260, 320-331.*