IMPACT CRATERING EXPERIMENTS ON GRANULAR TARGETS SIMULATING SURFACE LAYER ON ASTEROID 162173 RYUGU: CRATER SCALING LAW AND IMPACT-INDUCED SEISMIC SHAKING. M. Yasui[1], M. Arakawa[1], H. Okawa[1], and S. Hasegawa[2], [1]Graduate School of Science, Kobe University, Japan (minami.yasui@pearl.kobe-u.ac.jp), [2]ISAS, JAXA

Introduction: On April 2019, the Japanese spacecraft Hayabusa2 conducted an artificial impact experiment on asteroid 162173 Ryugu, and it succeeded to form an impact crater. The diameter of this artificial impact crater (SCI crater) was 14.5 m[1] and it was almost consistent with the estimate from the crater size scaling law of typical dry sand in the gravity regime[2]. This result was unexpected because Ryugu is globally covered with many large boulders with the size from > 100 m to a few meters[3] and so the SCI crater was expected to be much smaller than the actual value. Furthermore, we found that some boulders within a region of 2 × SCI crater radii from the impact point might move due to the impact-induced seismic shaking[4]. From these observations, the crater size scaling law and the propagation processes of the impact-induced seismic shaking on Ryugu should be clarified to discuss the physical properties of the surface layer on Ryugu.

In this study, we focus on the size frequency distribution of boulders on Ryugu. We conducted impact cratering experiments on grains having various sizes to study the effect of the grain size frequency distribution on the crater size scaling law. Furthermore, we measured the impact-induced seismic wave in situ and examined the properties of impact-induced seismic shaking on targets having the size frequency distribution.

Experimental Methods: We used glass beads with the diameter of 0.1, 1, 3, and 10 mm as a target: they were mixed evenly with equal mass fraction. We prepared two types of mixed beads target, 4 mixed beads target composed of 0.1 to 10 mm-sized beads (bulk density of 1.97 g/cm^3) and 3 mixed beads target composed of 1 to 10 mm-sized beads (1.68 g/cm^3). We also prepared 0.1 mm-sized beads target (1.42 g/cm^3).

We conducted cratering experiments by using one-stage light gas gun at Kobe University and two-stage light gas gun at ISAS. At Kobe University, we used 9 types of projectiles having different densities with the diameter of 2 or 3 mm and the impact velocity ranged from 40 to 213 m/s (low velocity). At ISAS, we used 4 types of projectiles with the diameter of 1 or 2 mm and the impact velocity ranged from 1.1 to 4.4 km/s (high velocity). The impact phenomena were observed by using the high-speed video camera, and the frame rate was set to be 3×10^3–2×10^4 fps at low impact velocity while it was 10^4–10^5 fps at high impact velocity. For high-velocity impact experiments, impact-induced seismic waves were measured by using 2 or 3 accelerometers with the specific frequency of 30 kHz setting at different positions from the impact point. To record the seismic data, a data logger was used with the sampling rate of 100 kHz.

Results:

Crater morphology and size scaling law. The crater profile was measured by using the 2D laser displacement meter after each shot. The crater morphology depended on the target materials. In the case of 0.1-mm beads target, the crater had a conical shape, irrespective of the impact velocity. In the case of mixed beads targets, the crater had a hemispherical shape and furthermore, the crater depth was a little larger than that of 0.1-mm beads target at same impact velocity.

Next, we applied our results to the crater size scaling law in the gravity regime[2]. The crater size scaling law related to the crater radius, R, is described as follows:

$$\pi_{\rm R} = K_1 \cdot \pi_2{}^{-a} \cdot \pi_4{}^{b}, \qquad (1)$$

$$\pi_{\rm R} = R\left(\frac{\rho_{\rm t}}{m_{\rm p}}\right)^{1/3}, \ \pi_2 = \frac{g r_{\rm p}}{v_{\rm i}{}^2}, \ \pi_4 = \frac{\rho_{\rm t}}{\rho_{\rm p}}, \qquad (2)$$

where $\rho_{\rm t}$ is the target density, $m_{\rm p}$, $r_{\rm p}$, and $\rho_{\rm p}$ are the projectile mass, radius, and density, $v_{\rm i}$ is the impact velocity, and g is the gravitational acceleration. The parameters, a, b, and K_1, are constants. Fig. 1 shows the relationship between the ratio of $\pi_{\rm R}$ to $\pi_4{}^b$ and the π_2. The b could be calculated from the relationship between the $\pi_{\rm R}$ and the π_4 at same π_2 for 4 mixed beads targets, and it was obtained to be 0.011. At the π_2 larger than 10^{-7} (low velocity), the $\pi_{\rm R}$ of the 0.1-mm beads target was a little bit larger than that of the mixed beads targets while they were almost consistent with each other at the π_2 smaller than 10^{-8} (high velocity). The $\pi_{\rm R}$ of the 4 mixed beads and the 3 mixed beads targets were almost same in the whole range of the π_2 in our study. Furthermore, our results of the mixed beads targets were almost consistent with that of sintered glass beads target with the diameter of 10 mm and the polycarbonate projectile with the diameter of 10 mm[6]. However, the $\pi_{\rm R}$ of the mixed beads targets shown as "fractured" which means that the projectile impacted on 10-mm sized bead was much smaller. The data of our 0.1-mm glass beads target (Eq. 3) and 4 mixed glass beads target (Eq. 4) could be fitted by one power law equation and we could obtain their empirical crater scaling laws as follows:

$$\pi_{\rm R} = 10^{-0.08} \cdot \pi_2{}^{-0.17} \cdot \pi_4{}^{0.011} \quad (3)$$

$$\pi_{\rm R} = 10^{-0.19} \cdot \pi_2{}^{-0.18} \cdot \pi_4{}^{0.011} \quad (4)$$

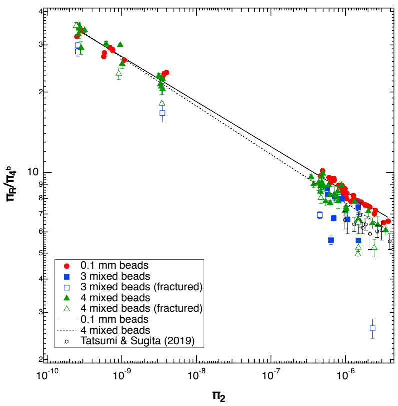

Fig. 1: Relationship between the ratio of π_R to ${\pi_4}^b$ and the π_2. The "fractured" means that the projectile impacted on the 10-mm sized glass bead on the target surface. The solid and dashed lines represent the fitting lines shown by Eqs. (3) and (4).

Impact-induced seismic waves. Fig. 2 shows the examples of the impact-induced seismic waves obtained in this study. The x means the distance of the accelerometer from the impact point, and the time "0 s" means the impact time. All waveforms were very similar: the acceleration had a sinusoidal wave and the first peak was positive. This means that the glass beads pushed upward near the crater rim just after the impact. However, in the case of the 4 mixed beads target, the first peak showed negative near the crater rim. Furthermore, when the distance normalized by the crater rim radius (x/R_{rim}) increased, the arrival time of the acceleration increased while the maximum acceleration of the first positive peak decreased.

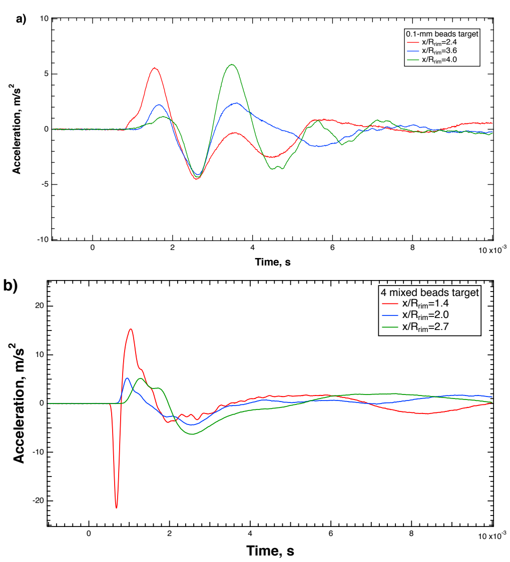

Fig. 2: Impact-induced seismic waves of 0.1-mm beads target (a) and 4 mixed beads target (b) at various normalized distances. The projectile was a stainless steel sphere with the diameter of 1 mm and the impact velocity was 1.2 km/s.

Maximum acceleration on a first positive peak. We analyzed the maximum acceleration on the first positive peak of the seismic wave, g_{max}, to examine the attenuation process of the seismic waves. Fig. 3 shows the relationship between the g_{max} and the normalized distance, x/R_{rim}. The g_{max} decreased with the increase of the x/R_{rim} for all target types. In the case of the 0.1-mm beads target, the data was a little bit scattered but they were almost consistent, irrespective of the projectile size and material. Furthermore, our data was almost consistent with the previous result of quart sand in the same range of the impact velocity [5]. The empirical equation for 0.1-mm beads target could be obtained as follows:

$$g_{\mathrm{max}} = 10^{2.08}(x/R_{\mathrm{rim}})^{-2.86}, \qquad (5)$$

The power law index means the attenuation rate of the acceleration and it was obtained to be -2.86; it was smaller than that of quartz sand, -3.31[5]. In the case of the mixed beads targets, the relationship between the g_{max} and the x/R_{rim} appeared to be independent of the target and the projectile material, the projectile size, and the bead size under the impact point. Furthermore, the g_{max} became smaller than that of 0.1-mm beads target at large x/R_{rim}. However, the data was somewhat scattered and this might be caused by the difference of the arrangement of various sized beads for each shot.

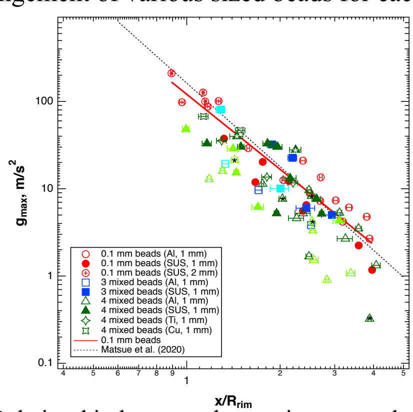

Fig. 3: Relationship between the maximum acceleration of a first positive peak (g_{max}) and the normalized distance (x/R_{rim}). Same symbol with different colors (Al & SUS projectiles for the mixed beads targets) means that the first peak is negative. The star (*) shows the same meaning of the "fractured" on Fig. 1. The solid and the dashed lines represent the fitting line shown by Eq. (5) and the previous result of quartz sand at same impact velocity range[6].

References: [1] Arakawa M. et al. (2020), *Science*, *368*, 67–71. [2] Housen K. R. & Holsapple K. A. (2011), *Icarus*, *211*, 856–875. [3] Michikami T. et al. (2019), *Icarus*, *331*, 179–191. [4] Honda R. et al., *Icarus*, in submission. [5] Matsue K. et al. (2020), *Icarus*, *338*, #113520. [6] Tatsumi E. & Sugita S. (2018), *Icarus*, *300*, 227–248.