EXPERIMENTAL STUDIES ON CRATER SCALING LAW APPLICABLE TO UNDULATING SURFACES AND CRATER COLLAPSE.

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Introduction: Impact craters are one of the major geological features on solid bodies such as asteroids and satellites. The crater morphology is expected to be affected by target surface topography. For example, a crater formed on a flat surface is observed to be a circle. On the other hand, a crater formed on a slope is ellipse [1]. Recent explorations by Hayabusa2 and OSIRIS-REx have revealed that the asteroids Ryugu and Bennu have a huge bulge at the equatorial region. Large craters are recognized to be concentrated on the bulge of Ryugu, which may show different surface characteristics and/or surface ages from other regions [2]. Smooth regions extending downslope around large craters on Bennu have been observed, suggesting that avalanches were caused by ejecta deposit during the crater formation [3]. However, the crater formation process on such undulating surfaces is still unknown. In this study, we conduct crater formation experiments on a target that simulates the undulating topography of an asteroid surface, and construct a scaling law applicable to craters on undulating topography. It may improve the accuracy of estimating the mechanical properties of the celestial surface layer and the surface age.

Experimental methods: We prepared targets to simulate the surface topography of asteroids: It was a granular target having the shape of a mountain range. This target was made of quartz sand with the diameter of 100 μm and simulated the regolith surface on asteroids. The angle of repose of the quartz sand was ~31°. The inclination (θ) of the mountain range target was set to be 20° and 30°. We also prepared the target having the flat surface (that is, $\theta = 0°$). We changed the distance d for the mountain range target, where d was defined as the horizontal distance between the impact point and the summit, and it was changed from 1 to 22 mm. Figure 1 shows the definition of each parameter.

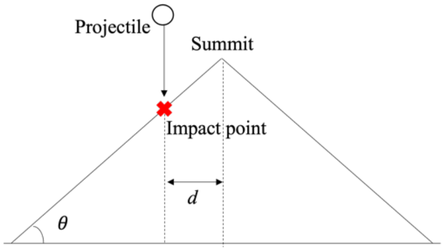

Figure 1. Schematic diagram showing the definition of each parameter.

We conducted impact experiments by using a one-stage vertical gas gun at Kobe University. The targets were set in a vacuum chamber and evacuated below 1000 Pa. We used an alumina spherical projectile with the radius, a, of 1.5 mm.

The impact velocities, v_i, ranged from 63 to 202 m/s at $\theta = 30°$, 3.8 to 89 m/s at $\theta = 20°$, and 76 to 187 m/s at $\theta = 0°$. In order to analyze the crater morphology, we constructed a 3D shape model by using the software of Metashape. The length of ellipse in the ridge direction D_{ma}, that in the slope direction D_{mi}, depth, and the crater volume were measured on the shape model. We observed the impact phenomena by using a high-speed camera with the frame rate of 1,000–20,000 FPS and the exposure time of 10 μs.

Results: Fig. 2 shows an example of 3D shape model for the mountain range target. We found that the crater had an elliptical shape: The length of this ellipse along the ridge direction (D_{ma}) was always larger than that along the slope direction (D_{mi}).

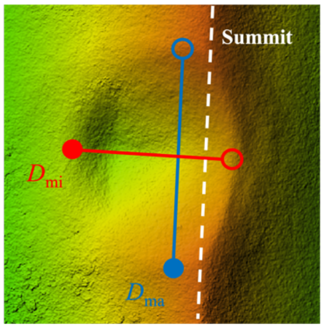

Figure 2. Example of 3D shape model for the mountain range target.

The crater volume was found to depend on d/D_{ma}. The volume was significantly smaller at $d/D_{ma} > 0.3$ because the transient crater did not cross over the summit and the transient crater was almost collapsed: The cavity was deformed and filled by collapsed wall. At $d/D_{ma} < 0.3$, the transient crater grew beyond the summit and the crater wall of the ridge direction collapsed toward the crater floor. But the crater wall of the slope direction collapsed outward of the crater. Then the burial of the crater cavity was limited due to these two mechanisms. We found that d/D_{ma} controls the aspect ratio (the ratio of the ridge direction length D_{ma} to the slope direction length D_{mi}) and the depth to diameter ratio (h/D_{ma}). Fig. 3 shows the relationship between the aspect ratio and d/D_{ma}, and it can be expressed as $D_{ma}/D_{mi} = 1.29 \exp(-0.61\ d/D_{ma})$. Fig. 4 shows the relationship between h/D_{ma} and d/D_{ma}, and it is written as $h/D_{ma} = 0.122 \exp(-1.81\ d/D_{ma})$.

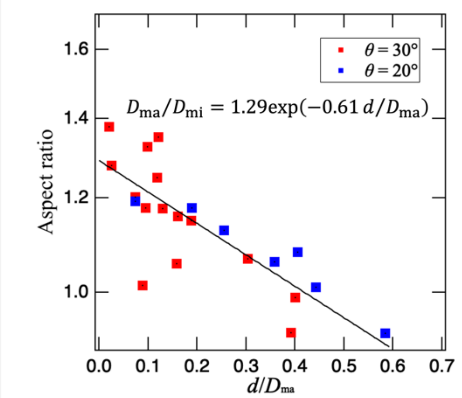

Figure 3. Relationship between aspect ratio and d/D_{ma}.

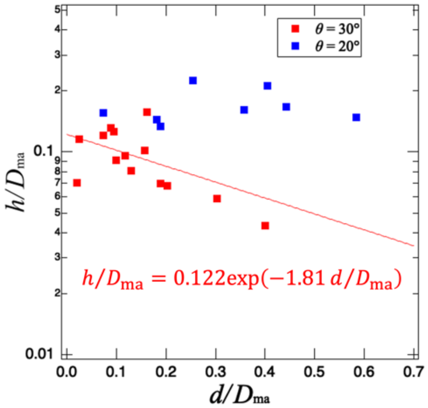

Figure 4: Relationship between depth-diameter ratio and d/D_{ma}.

Note that Urashima crater on Ryugu has a small depth-diameter ratio of 0.07. Our experimental results on simulated bulge with the slope angle of 30° indicate that $d/D_{ma} = 0.2$ for h/D_m=0.07 in Fig.4. Since this d/D_{ma} is < 0.3, the shallow crater with h/D_m=0.07 could be mainly caused by collapse of the crater wall of the ridge direction. Moreover, the crater profile obtained at d/D_{ma} = 0.2 experimentally is found to be in good agreement with the characteristics of Urashima crater.

Fig. 5 shows the relationship between π_R and d/D_{ma} at θ = 30° at constant π_2 of $3.6\times10^{-7} < \pi_2 < 5.7\times10^{-7}$. It is written as

$$\pi_R = \pi_{R^*} \exp(-0.45\ d/D_{ma}),$$

where $\pi_R = R(\rho/m)^{1/3}$; R is crater radius, ρ is target density, m is projectile mass [4]; π_{R^*} is π_R at d/D_{ma}=0 and a constant π_2, where $\pi_2 = ag/v_i^{\ 2}$, g is gravity. We obtained that π_{R^*} =10.2 for the constant π_2 of ~4.6×10^{-7}. The D_{ma} was used to calculate the π_R instead of the crater radius for the conventional circular crater.

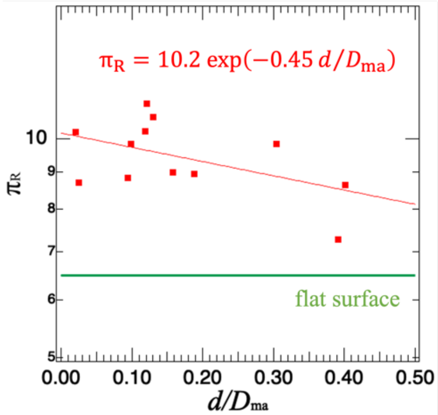

Figure 5: Relationship between π_R and d/D_{ma}.

π_R derived at various d/D_{ma} for the mountain ridge target is normalized by $\exp(-0.45\ d/D_{ma})$ to obtain π_{R^*} at each π_2. Fig. 6 shows the relationship between π_{R^*} and π_2. Thus, the crater size scaling law for the mountain range target is described as follows,

$$\pi_R = 0.88 \exp(-0.45\ d/D_{ma})\pi_2^{-0.17}. \qquad (1)$$

We compared Eq. (1) at d/D_{ma}=0 with the crater size scaling law for the flat surface as follows,

$$\pi_R = 0.52\ \pi_2^{-0.17}. \qquad (2)$$

Comparing Eq. (1) with (2), the crater formed on the top of bulge is always found to be larger than that formed on the flat surface. Therefore, this result may suggest that the surface age of the bulge on Ryugu should be reconsidered.

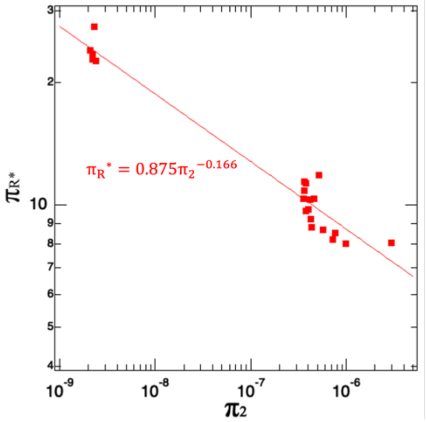

Figure 6: Crater size scaling relationship for the mountain range target.

References: [1] K. Hayashi & I. Sumita (2017) *Icarus, 291,* 160–175. [2] Y. Cho (2021) *Journal of Geophysical Research : Planets, 126,* e2020JE006572. [3] M. E. Perry (2022) *Nature Geoscience, 15,* 447–452. [4] K. R. Housen & K. A. Holsapple (2011) *Icarus, 211,* 856–875.