

CONSTRAINING ASTEROID RYUGU'S SURFACE PROPERTIES FROM NUMERICAL SIMULATIONS OF THE SCI IMPACT M. Jutzi¹, S. D. Raducan¹, Y. Zhang², P. Michel², M. Arakawa³. ¹Space Research and Planetary Sciences, Physikalisches Institut, University of Bern, Switzerland. ²Universite Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France. ³Kobe University, Japan. (E-mail: martin.jutzi@unibe.ch).

Introduction: The small carry-on impactor (SCI) experiment performed by the Hayabusa2 mission on asteroid Ryugu does not only provide important insights to the properties and collisional evolution of the small body populations, but also represents an ideal test case to validate impact cratering models. The results of this experiment suggest that the surface cohesion on Ryugu must be very small ($\lesssim 1$ Pa) and the impact might have taken place in the gravity-dominated regime [1]. This low-strength, low-gravity cratering environment has not yet been explored and it is not clear if traditional impact models and crater scaling laws are applicable. Another important question is how much the target inhomogeneities (i.e., boulders located close to the impact point) affected the cratering process and the impact outcome, such as the crater size and morphology. So far, because of the vastly different time-scales of the shock-wave propagation and of the crater formation, it has not been feasible for shock-physics codes to model the entire crater formation in the gravity-regime on small, ~ 100 m – 1000 m, asteroids.

Modelling approach: Here we use the Bern's SPH impact code [2–4] to study the sensitivity of the SCI impact outcome to target cohesion and target inhomogeneities (i.e., boulders). Bern's SPH is a shock physics code that includes material models suitable to simulate the behaviour of geological materials, various equations of state and a porosity compaction model ($P - \alpha$). To perform the long-term simulations, here we apply a recently developed numerical approach that allows for faster calculation times and for direct shock-physics code calculations of the entire process [5, 6].

We first use homogeneous targets to study the effects of material properties on the final crater and varied the initial cohesion ($Y_0 = 0$ –0.5 Pa) and coefficient of internal friction ($f = 0.4$ –1.0). We keep the target initial density constant throughout this study, at 1300 kg/m^3 and a fixed porosity of 50%.

Simulations with homogeneous targets: We find that the resulting final crater is very sensitive to our choice of cohesion and coefficient of internal friction (Figure 1) and that we do not have a unique solution. The same crater size can be produced by impacting targets with a combination of mechanical properties (represented by the friction coefficient and the cohesion). In order to match the observed size of the SCI crater, a cohesionless ($Y_0 = 0$ Pa) target requires a relatively high friction coefficient ($f >$

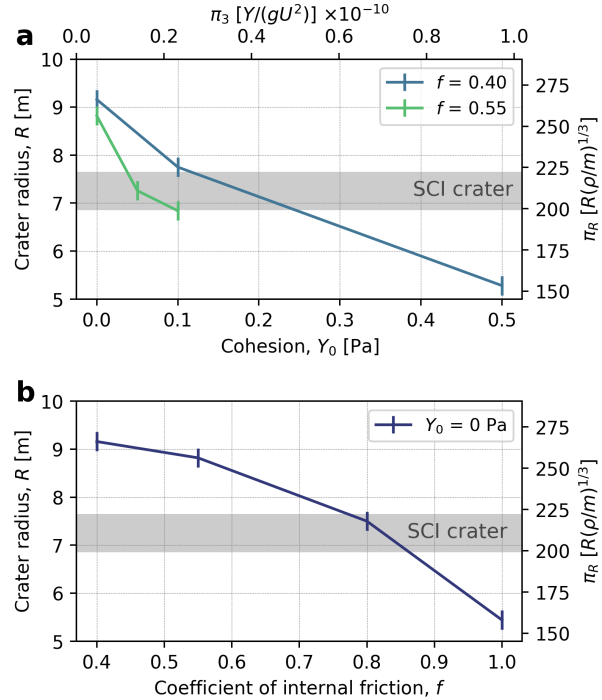


Figure 1: a) Crater radius as a function of cohesion Y_0 for different friction coefficients ($f = 0.4$ and $f = 0.55$). b) Crater radius as a function of the coefficient of internal friction for cohesionless targets ($Y_0 = 0$). The horizontal line shows the measured SCI crater size at the pre-impact level, with its associated error [1].

0.8). On the other hand, a cohesion of ~ 0.2 Pa with a small friction coefficient ($f = 0.4$) produces the required crater size.

Based on the available observations, it is not possible to constrain the cohesion at the required level, i.e., to distinguish between $Y_0 = 0.0$ Pa and $Y_0 = 0.2$ Pa. However, one can make reasonable assumptions regarding the friction coefficient. Because of the evidence for a very low cohesion (< 1 Pa) we consider cohesionless quartz sand [7] as best representative of Ryugu's subsurface material and define $f = 0.55$ as nominal friction coefficient. On the other hand, the friction coefficient for glass beads ($f \sim 0.4$) is regarded as lower limit for geological materials. Our results therefore suggest that the cohesion present on Ryugu at the SCI impact site cannot be higher than ~ 0.2 Pa (Fig. 1).

Simulations with boulders: For a subset of target material properties, boulders with varying sizes are distributed within the target (Fig. 2). The boulders have the same density as the matrix material and a cohesion of 100 MPa. The homogeneous matrix material was considered to be cohesionless ($Y_0 = 0$ Pa) and has $f = 0.55$. The sizes and positions of the boulders are representative of the ones present on Ryugu close to the SCI impact point.

Our simulations reproduce well the overall outcome of the SCI impact, including the displacement of the boulders (Fig. 2). The presence of the large block leads to an asymmetric crater, similar to the observed one. We find that the presence of the boulders within the target affects the resulting crater size by less than 5%.

Crater scaling law for low-strength low-gravity regime: Next, we investigate the dependence of the impact outcome to the impactor size scale for different values of cohesion, using homogenous targets and a nominal coefficient of friction ($f = 0.55$). By calibrating the general form of the impact cratering scaling [e.g. 8, 9] to our simulation results, we can determine the fitting constants ($K_1 = 0.60$, $K_2 = 0.25$ and $\mu = 0.44$). Our results suggest that for a fixed $f = 0.55$, a cohesion of $Y_0 = 0.05$ Pa is required to match the SCI crater size, and that the SCI impact most likely took place at the transition between the strength and gravity regime, where cohesive and gravitational forces determine the impact outcome concurrently.

Consequences for asteroid surface ages: Impacts into low-cohesion targets at small scales have a very large cratering efficiency. For the SCI impact, $D_{\text{crat}}/D_{\text{proj}} > 100$. High resurfacing rates are important consequences of a such a high cratering efficiency. Assuming that the cohesion of Ryugu is negligible and that the gravity controls the crater formation, absolute model ages of each geological unit on Ryugu have recently been shown to be in the range of ~ 2 -30 Myrs [10]. The observations also indicate variations in surface properties (e.g., strength) across the asteroids' surface, possibly leading to varying ages for the different geological units. The cratering efficiencies resulting from the crater scaling laws used here, which vary considerably with small variations in cohesion, might explain such differences in surface ages. Since the SCI impact probably occurred in the transitional regime, craters smaller than the one produced by the SCI are most likely strength dominated. This means that even a small amount of cohesion leads to a reduced cratering efficiency at small sizes, compared to craters produced in the gravity-dominated regime. This cratering effect may be responsible for the lack of observed small craters on Ryugu [10] and other small asteroids [11].

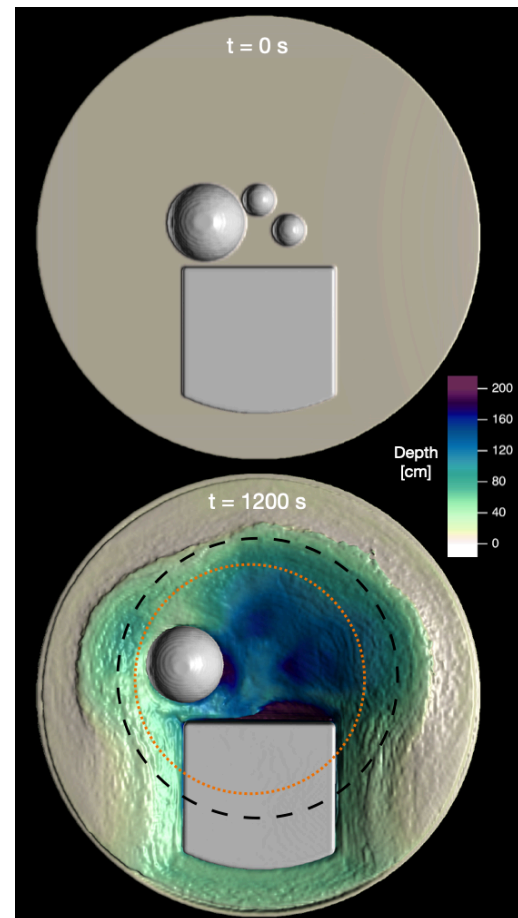


Figure 2: End-to-end SPH simulation of the SCI impact. Snapshots of the simulation are shown at $t = 0$ s and at $t = 1200$ s (showing the final crater). The observed dimensions of the crater are indicated by the dotted orange and dashed black lines. The overall outcome in terms of crater size and boulder displacement is well reproduced.

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