NUMERICAL SIMULATIONS OF THE LANDING OF MASCOT DEPLOYED BY HAYABUSA2 ON A REGOLITH BED OR A BIG BOULDER. F. Thuillet[1], P. Michel[1], J. Biele[2], R.-L. Ballouz[3], S.R. Schwartz[3], E. Tatsumi[4], S. Sugita[4,5], T.-M. Ho[6], S. Kameda[7], H. Yano[8], S. Watanabe[9] [1]Lagrange Laboratory, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS (CS 34229, 06304 Nice Cedex 4, France; fthuille@oca.eu), [2]DLR_German Aerospace Center, Micro-Gravity User Support Center, 51147 Cologne, Germany, [3]Lunar & Planetary Lab, University of Arizona, Tucson, AZ, USA, [4]Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan, [5]Research Center for the Early Universe, University of Tokyo, Tokyo, Japan, [6]German Aerospace Center (DLR), Bremen, Germany, [7]Department of Physics, Rikkyo University, Tokyo, Japan, [8]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan, [9]Dep. of Earth and Planetary Sciences, Nagoya University, Nagoya, Japan

Introduction: JAXA's asteroid sample return mission Hayabusa2 was launched on December 3, 2014 and reached its target, the C-type near-Earth asteroid (162173) Ryugu on June 27, 2018. It will bring back samples from Ryugu's surface to Earth in 2020.

DLR/CNES lander MASCOT (Mobile Asteroid SCOuT) [1] on board Hayabusa2 reached the surface of Ryugu on October 3, 2018. It first bounced on or near a large boulder, and then bounced several times on the surface to finally settle upside down. It was then relocated to allow camera observations and in-situ measurements.

Thanks to MASCOT's onboard measurements and observations from Hayabusa2 optical navigation camera (ONC) system, the lander's trajectory can be at least partly reconstructed. A better understanding of the interactions between the lander and a low-g asteroid surface, applied to MASCOT's case, can therefore provide essential hints about Ryugu's surface properties.

For this purpose and because MASCOT possibly bounced on a boulder, we conducted several sets of simulations of MASCOT impacting a regolith bed representing Ryugu's surface, with and without a boulder.

Method: We performed simulations by using the parallel N-body gravity tree code *pkdgrav*, in which was implemented the soft-sphere discrete element method (SSDEM) in order to represent the dynamics and contacts between regolith grains [2].

Our simulation setup consists of a cylinder filled with spherical grains [3]. Concerning the grains, we considered a gaussian distribution with a 1-cm mean radius, a 33% standard deviation and a cutoff at 1 sigma. Two different frictions were considered in our simulations, a gravel-like one (high friction) and a moderate one, and the cylinder is either 30 cm or 40 cm deep.

MASCOT is modeled by a 10-kg cuboid made of inertial walls that react to the forces exerted by the grains. In most of our simulations, we made the lander impact at 19 cm/s, which was supposed to be the upper limit for the first impact, but we also investigated the influence of the impact speed.

We considered different orientations for MASCOT and five impact angles (from 0 to 60°, 0° being vertical) and the simulations were conducted in Ryugu's low gravity, considered to be $2.5 \times 10^{-4}\ m\ s^{-2}$ prior to arrival and measured to be about $1.2 \times 10^{-4}\ m\ s^{-2}$ near the first impact point.

When considered, boulders are made of aggregates of particles linked together and behaving as rigid bodies. We considered four different vertical positions for the boulder (see Figure 1), and three different horizontal positions. The boulder is roughly ellipsoidal with dimensions of $30\ cm \times 22.2\ cm\ \times 12.9\ cm$, and a weight of about 8 kg.

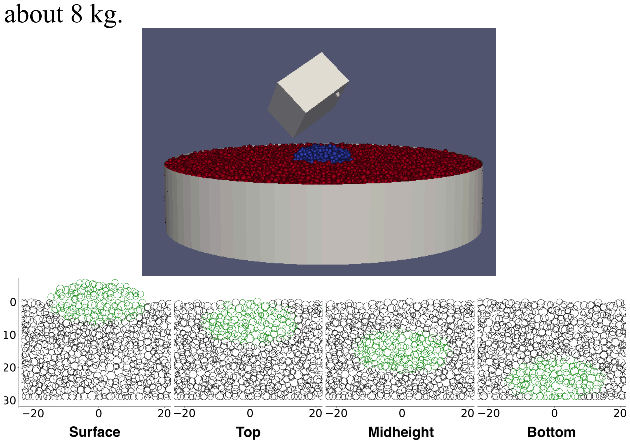

Figure 1. Top: Snapshot of a simulation of MASCOT impacting a boulder in a regolith bed. Bottom: Vertical positions considered for a boulder when present.

Concerning the outputs, we were particularly interested in the outgoing-to-incoming speed ratio, the outgoing angle (leading to the distance traveled by the lander after impact), the outgoing spin, the penetration depth, and the the traces left in the ground, and we looked at the influence of several parameters (impact geometry, physical properties…) on these outputs.

Results: *Presence of a boulder.* First, we looked at the influence of a boulder in the regolith bed just at the impact point or close to it. As expected, concerning the outgoing-to-incoming speed ratio, the higher and the closer to the surface the boulder, the larger the differences with the "no boulder" case. Variations in the speed ratio begin to appear with a midheight boulder, and can be as high as 0.2, corresponding to a variation of outgoing speed of about 4 cm s^{-1}. When the boulder is just under the surface or on the surface, speed ratios are in general much higher, and much more stochastic depending on the attitude of MASCOT when it hits the boulder. Moreover, as we found in previous studies, the speed ratio generally increases with the impact angle and the grain friction coefficients [3].

The outgoing energy partly comes from the rotation created at impact by the back corner encountering resistance [3]. With no boulder, when the lander impacts the surface, the energy can be transferred from particles to particles as they are mobile, leading to ejecta and compression of the bed under the impact point. In the presence of a boulder, the particles encounter a large resistance from the boulder and this energy is given back to the lander, increasing either its outgoing linear speed or rotation speed (or both). If the lander directly impacts the boulder, the energy given back to the lander is even higher. For the same reasons, the penetration depth usually decreases with an increased boulder height. Depending on the geometry of the impact, the speed ratio for an impact on a boulder can be as small as 0.3 even if the boulder is hard, as MASCOT can hits several times the boulder during the interaction (see Figure 2).

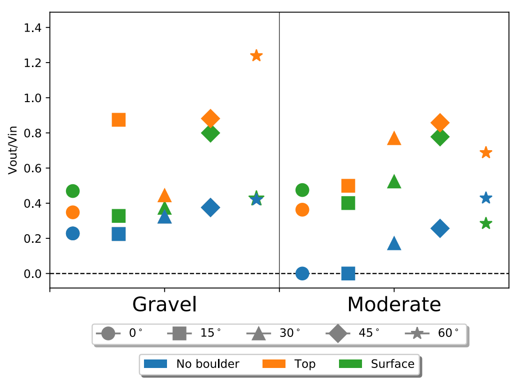

Figure 2. Outgoing-to-incoming speed ratio as a function of friction, impact angle, and vertical position of the boulder (with a 40 cm deep bed, and MASCOT landing on its back corner first).

Concerning the traces left on the ground, even a midheight boulder can be detected in the traces, as the patterns observed with boulders are different in the middle from the ones without boulders, with less ejecta.

We also investigated the presence of a boulder at about 1 to 5 cm from the edge of MASCOT to check if it could have an influence on the outputs even if MASCOT is not directly in contact with it. We found that its position do not play any major role, and that a midheight boulder buried under MASCOT's impact point has a higher influence on the different outputs (like the speed ratio) than a surface or a deeper boulder close to the impact but not in contact with MASCOT.

Influence of gravity and slopes. No variation is see, by considering Ryugu's actual gravity and modifying it from $2.5 \times 10^{-4}\ m\ s^{-2}$ to $1.2 \times 10^{-4}\ m\ s^{-2}$, the speed ratios and the penetration depths being the same.

Also, we investigated the influence of slopes, and therefore to the gravity angle. Between -25° and +25° (not exceeding the angles of repose of both considered materials), we find similar speed ratios and other outputs. Of course, for both variations of gravity (magnitude and angle), the traveled distances are different.

We think these results are at least partly due to the very low value of the gravity considered here, making modifications of the magnitude or orientation very tiny in absolute numbers.

Influence of impact speed. The impacting speed being loosely constrained, and to apply our results to the successive bounces, we checked the influence of the incoming speed. We ran simulations from 1 to 20 cm s^{-1}. For impacts of less than 2 cm s^{-1}, it is difficult to establish the speed ratio as the lander often does not completely bounce. We see a large discrepancy between gravel-like and moderate-friction regolith. For moderate friction, the speed ratio is roughly constant with the impact speed, whereas no trend can be established for a gravel-like impact, as it seems to depend on the impact angle and on the impact position (directly on a grain or between several ones). Gravel-like particles are represented as more angular in our codes (through a shape coefficient), and this angularity makes the bed more sensitive to any tiny change in the impact condition.

Conclusion. We continued expanding the parameter space for our simulations of MASCOT landing on a regolith bed, in order to interpret the actual landing. We particularly investigated the influence of a boulder as Ryugu's surface is composed of many boulders, and MASCOT possibly impacted one. In particular, we find that a low impact speed ratio does not necessarily indicate that the impacted boulder is soft, but can also be due to the actually geometry of the impact.

References: [1] Ho, T.M. et al. (2016) *Space Science Reviews, MASCOT—The Mobile Asteroid Surface Scout Onboard the Hayabusa2 Mission.* [2] Schwartz, S. R. et al. (2012) *Granular Matter, 14:363-380.* [3] Thuillet, F. et al. (2018) *A&A, 615: A41.*

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