THE THICKNESS OF THE LUNAR REGOLITH: COMPARISON BETWEEN ORBITAL MEASUREMENTS AND NUMERICAL SIMULATIONS OF IMPACTS. M. Joulaud¹,², V. J. Langlois¹, P. Allemand¹, J. Flahaut², E. Füri², ¹LGL-TPE (UCBL1-CNRS-ENS), France, (marine.joulaud@univ-lyon1.fr), ²CRPG (CNRS-UL), France.

Introduction: Impact cratering has shaped the surface of planetary bodies in the solar system and is a major geologic process involved in the production of regolith. Catastrophic large impacts increase the quantity of regolith formed while smaller impacts mix and garden the already existing regolith [1,2]. The layering of the target, with the weak regolith above the strong bedrock, affects the impact cratering process, and therefore influences the morphology of the resulting crater [2,3,4]. Previous laboratory experiments showed that a low energy impact in a fragmental layer above a more cohesive substrate can form four types of crater morphologies, depending on the regolith thickness at constant impact energy: bowl-shaped, flat-bottomed, central mound, concentric [4]. These results allow to use the morphology of planetary craters as an indirect way of estimating the regolith thickness.

Each crater morphology can be associated with a range of values for the ratio between final crater diameter (Dₙ) and regolith thickness (t): Dₙ/t < 4 corresponds to normal, bowl-shaped craters; Dₙ/t = 4–7.5 to central mound; Dₙ/t = 7.5–10 to flat-bottomed; Dₙ/t >10 to concentric. However, laboratory experiments are intrinsically limited in terms of their scaling and the values of control parameters: numerical models therefore appear to be a useful complementary approach to better understand the impact process in a layered target and predict the relation between regolith properties and crater geometries.

Launched in December 2022, the Emirates Lunar Mission (ELM) experienced an unsuccessful landing on the Moon at the end of April 2023. However, the craters of its prime landing site (floor-fractured crater Atlas) and of its three backup landing sites (located in the following maria areas: Sinus Iridum, Oceanus Procellarum, and Lacus Somniorum) have been extensively investigated [6,7]. This work proposes to compare these observations to the results of a novel numerical approach for modeling the impact of a projectile into a two-layer target.

Data and Methods: Traditional methods used to estimate regolith thickness are based on measuring the interior feature of craters presenting the specific morphologies mentioned above [4,5,8,9,10] (Figure 1). We previously estimated the regolith thickness at the four ELM candidate landing sites using the small crater morphology method through Geographic Information Systems (GIS) [10,11].

In this study, we use a two-dimensional (2D) Discrete Element Model to simulate the impact of a projectile and the resulting formation of a crater. This numerical approach was previously validated by successfully comparing the geometric properties of the craters formed in a uniform but brittle target with the results of classical hydrocode simulations [12].

Here, the target consists in a non-cohesive superficial layer (regolith) of adjustable thickness, lying on top of a strong layer (bedrock). The material is modeled as an assembly of 200,000 circular particles that interact through contact forces (inelastic repulsion, solid friction, and cohesion). When strained above a given threshold, this brittle granular material experiences spontaneous fragmentation.

The mechanical strength of each layer can be tuned by choosing the appropriate value for the dimensionless ratio S = Fᵣ / mg, where Fᵣ is the tensile strength necessary to break the cohesive bond between two particles, and mg is the particle’s weight [12]. We first limit ourselves to a unique set of values for the

![Figure 1: A concentric crater used to estimate the regolith thickness (11) and its topographic profile extracted from a LRO-NAC-based DEM (LRO NAC M1099022524; longitude -27.32°E, latitude 46.68°N).](image)
mechanical resistance of both layers, and to vertical impacts. We then study the influence of three control parameters: diameter of the projectile, impact velocity, and regolith thickness.

At the end of each numerical run, we measure the final rim-to-rim diameter and we study in detail the morphology of the final crater (see Figure 2) to identify it with one of the four types of specific morphologies observed in the ELM candidate landing sites using topographic profiles (example in Figure 1). The aim is to verify the validity of the empirical relationship established by [4] and [5], while also checking if the morphology of the final crater corresponds to the expected $D_A/t$ value.

**Results and discussion:** The regolith thickness estimated for the ELM landing sites ranges from approximately 1 to 40 m, with high spatial variability. The mean thicknesses calculated are 1.7 m (Atlas Crater), 2.1 m (Oceanus Procellarum and Lacus Somniorum), 3.5 m (Sinus Iridum) [10,11]. The same range (1 to 15 m) was used in our simulations in order to produce craters of comparable geometries. The variation of the crater diameter with impact velocity, impactor size and regolith thickness is investigated. Furthermore, the numerical simulation also allows us to follow the excavation of the transitional crater as well as its relaxation towards equilibrium, and to better understand the dynamical processes that lead to the formation of different geometries.

The $D_A/t$ ratios of modeled craters generally correspond to the empirical boundaries established by [4]. However, when comparing $D_A/t$ boundaries of actual lunar craters using the traditional approach (measurements on LROC NAC optical images), the $D_A/t$ values do not correspond to the morphologies observed. Only concentric craters present an accurate $D_A/t$ value ($>10$) without ambiguity. Meanwhile, central mound and flat-bottomed craters tend to have similar $D_A/t$ values and, thus, are more difficult to distinguish.

**Perspectives:** Since the inputs of the simulations are easily modified, the model will be adapted to tackle oblique impacts and study the influence of the density ratio between impactor and target as well as of the strength ratio between bedrock and regolith. Future work will also be focused on the same process at the surface of Mercury. In addition to the predictions of analog experiments, we expect that this numerical method will allow to improve the estimates of the regolith thickness based on the observations of crater geometries.

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**References:**