Crater scaling laws in low speed impacts

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Regolith-covered small bodies have numerous craters in varying sizes across their surfaces. The long-established scaling laws have been successful in large craters arising from astronomical impacts, which occur in orbital speeds of several km/s (Housen et al., 1983). Moreover, it has also recently been observed during OSIRIS-REx mission that material ejection from the active asteroids may be originated through micrometeoroid impacts that occur at similar velocities, but should produce much smaller craters (Lauretta et al., 2019). In that case, the ejecta velocity field of a crater would contain materials with velocities less than the escape speed of small-body, i.e. typically below m/s. Such material would eventually fall back to surface after orbital motion, creating new craters at lower-speed impacts. In a similar case, small lander spacecraft, e.g. the MASCOT and MINERVA rovers onboard Hayabusa2, impact small-body surfaces at cm/s-level speeds and bounce across the surface, essentially making new craters (where regolith is available) at low speeds, before settling on the surface (Thuillet et al., 2018). These two seemingly different phenomena highlight the relevance of understanding low-speed cratering process that primarily occurs in low gravity environments through the interaction of natural and artificial objects with regolith-covered small body surfaces. However, it is currently not known whether the scaling laws developed for high-speed astronomical impacts would hold for impacts of orders of magnitude lower speed.

To test this question, a literature survey was performed on impact experiments in high- and low-speed and under different gravity levels to demonstrate that the scaling law holds for impact speeds from km/s to m/s (Fig. 1). A full study of the applicability of the crater scaling laws to lower-speed impacts is currently a gap in the experimental literature. This is because performing impacts at below-m/s speeds is difficult on Earth in terms of data resolution due to high gravitational acceleration. On the other hand, currently available low-speed impact data under low-gravity only provides phenomenological explanations due to these challenges in measurements (Brisset et al., 2018). To overcome these limitations and bridge the aforementioned gap in literature, this study instead makes use of discrete-element method (DEM) granular mechanics simulations in order to test the crater scaling laws quantitatively. The DEM simulations avoid limited low-gravity time and test conditions, as well as vibration-caused noisy data in drop towers and parabolic flights while allowing to perform “experiments” in virtually any small-body environment. The DEM code employed in the study is called pkdgrav, a state-of-the-art parallelized granular mechanics code, which treats particle collisions through a soft-sphere discrete element method (SSDEM). Through SSDEM implementation, pkdgrav handles multi-contact and frictional forces using dissipative and frictional parameters that allow mimicking the behavior of angular and rough particles. The code has been tested extensively and calibrated for a variety of materials to represent the actual granular behaviour realistically throughout different studies.

Impact simulations of a spherical impactor in the study are performed in local vertical at speeds between 1 cm/s and 1 m/s in a regolith bed under asteroid level gravity that is created in the simulation environment. As each particle’s state is recorded during the simulations, the collected data are post-processed to compute not only crater size but also velocity field and ejected mass during the process. This would then yield a complete test of the theory under given conditions which is typically not

available in experimental studies. The tested theory can then be applied to a variety of problems that relevant to current small-body exploration framework, e.g. estimating coefficient of restitution on regolith-covered portions of asteroids, which would subsequently be used in designing landers, sampling spacecraft as well as explaining the reimpact behaviour of ejected materials.

Keywords: Small body, Low speed impact, Cratering, Scaling laws, Regolith science, Discrete element method