MATERIAL DEPENDENCY OF CRATER SCALING IN LOW-SPEED IMPACTS UNDER MICROGRAVITY. O. Çelik[1], R. L. Ballouz[2], D. J. Scheeres[3], Y. Kawakatsu[4]. [1]University of Glasgow (onur.celik@glasgow.ac.uk), [2]The Johns Hopkins University Applied Physics Laboratory (ronald.ballouz@jhuapl.edu), [3]University of Colorado Boulder (scheeres@colorado.edu), [4]Japan Aerospace Exploration Agency (kawakatsu@jaxa.jp)

Introduction: The space missions thus far have shown that asteroids and comets are covered with loose granular material with variable depths. This regolith is observed to be capable of being easily mobilized, either by natural processes or during the surface operations of a spacecraft. An example to the former is the observed material ejection from the surface of Bennu [1], which may have occurred due to different potential contributing mechanisms [2, 3]. The latter is often intended and occurs through landings of small landers [4-6], sampling operations of their motherships or dedicated impact experiments [7]. In all of these events, either the impact or the speed of some of the ejected particles are on the order of escape speed of the body, i.e., a few tens of centimeter-per-second. As a result, some of the material would then re-impact and may ricochet after a brief of orbital motion [2], leading to further disturbance of the surface. These primary and secondary impacts can be seen as low-speed cratering events that potentially contribute to physical and dynamical evolution of the body.

It is difficult to test this impact regime in the Earth-based platforms. On one hand, under the terrestrial gravity, impacts at a few tens of centimeter-per-second speeds are very rapid and do not show the enhanced material ejection that is experienced under low-gravity environments [8]. On the other hand, artificial low-gravity platforms, such as the ISS, parabolic flights, drop towers or air-tables lack either necessary low-gravity level or duration and presents other challenges (e.g., accessibility) that make impact experiments at this regime very challenging [9-11].

We have recently utilized discrete element method (DEM) simulations to test impacts at this regime [12]. The DEM approach offers a quantitative framework to investigate the cratering process at a particle level in virtually any gravitational environment. The authors demonstrated that crater-scaling relationships developed for high-energy impacts [13] may also hold for normal impacts at 5-50 cm/s under the gravity level of Bennu and Ryugu [12]. While this was suggested previously in some level, for example in Refs [14, 15], the application of the DEM techniques allowed for a demonstration in power-law scaling for crater dimensions, ejection properties (speed, angle, mass), and the crater formation timescale. Furthermore, we observed no dependence of these crater-scaling properties with impactor density. For impacts into glass-bead type material, we found a scaling coefficient $\mu = 0.56$ [12], which is higher than the often-estimated value $\mu \approx 0.4$ for dry granular materials [16]. We attribute this result to the properties of glass-beads type material in the simulations that has high coefficient of restitution and low friction, leading to exaggerated cratering [12].

In this study, we extend our previous results by simulating gravel-like material, which has higher frictional properties and lower coefficient of restitution. The new impact simulations are again parallel to the surface normal at 5-10 cm/s under 9.81 x 10^{-5} m/s^2, or $10^{-5}g$, where g is the Earth's gravitational acceleration. The cratering process is discussed in comparison with the glass-beads simulations. The implications of the results for future small-body exploration missions will also be discussed.

DEM simulations: The simulations are performed in *pkdgrav* software. *pkdgrav* is a parallelized code to simulate the motion of granular materials due to gravity and collisions. The collisional interaction is modelled in the form of a spring model and resolved through a number of user-assigned material coefficients: the normal (ε_n) and tangential (ε_t) coefficients of restitution, and Coulomb (μ_s), rolling (μ_r) and twisting frictions (μ_t, assumed zero in this study). A spring coefficient also needs to be calculated a priori [17]. These parameters are presented in Table 1 below, alongside glass-beads parameters used in Ref. [12].

Table 1 Summary of DEM material parameters

Parameter	Gravel (GR)	Glass beads (GB)
ε_n	0.55	0.95
ε_t	0.55	1.0
μ_s	1.31	0.43
μ_r	3.00	0.1
k_n	75.25 kg/s^2	

Spherical, constant 1-cm size particles are used with 1600 kg/m^3 to avoid any particle size effects. The final granular assembly has a 39% porosity and bulk density of 975.4 kg/m^3. A spherical impactor of 5 cm radius is also used of different densities, from 100 kg/m^3 to 1910 kg/m^3 (i.e., a 1-kg impactor). All simulations are conducted in a microgravity environment. The covered parameter space is summarized in Table 2.

A total of 10 simulations were performed. The simulations are stopped after roughly 6 min of simulated time within which it was found that the particles have speeds less than 1 mm/s.

The collected data was later analyzed with a post-processing procedure that is previously outlined in Çelik et al. [12].

Table 2 Covered parameter space

Parameter	Value
Impactor radius, a [m]	0.05
Impactor density, δ [kg/m^3]	100, 260, 520, 1910
Impact speed, U [m/s]	0.05, 0.1
Bulk density, ρ [kg/m^3]	975.4
Particle density, ρ_p [kg/m^3]	1600
Particle radius, r_p [m]	0.01
Porosity, ϕ [%]	39.04
Gravity [m/s^2]	9.81 x 10^{-5}

Results: The qualitative simulation results are shown in Fig. 1.

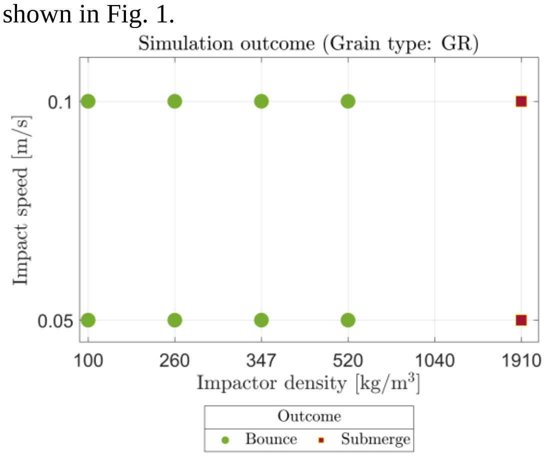

Figure 1 Qualitative simulation outcomes

The results show that all but the highest density object bounces off the surface at these low speeds. Impactor bounce has previously been observed in this regime and demonstrated by Çelik et al. (2022) [12]. In glass-bead type material, this is attributed to low energy of the impactors when they are low density. In gravel-type material, the impactor bounces at even higher densities, which suggests an increased surface resistance to penetration, likely due to low coefficient of restitution and high friction for the same mass object. As a result of this, crater sizes are also smaller with lower ejected mass and velocity. An example crater is shown in Fig. 2.

The crater radius in the presented case is 20 cm, nearly 40% smaller than the one occurred with glass-beads type material (33 cm) [12]. The impactor also appears to be stopped and bounced after a brief penetration and then stayed in the crater rim, instead of a full penetration as observed in by Çelik et al. (2022) [12], with the same impact and impactor properties. The partially buried impactor appears similar to the dimples observed on Itokawa [14].

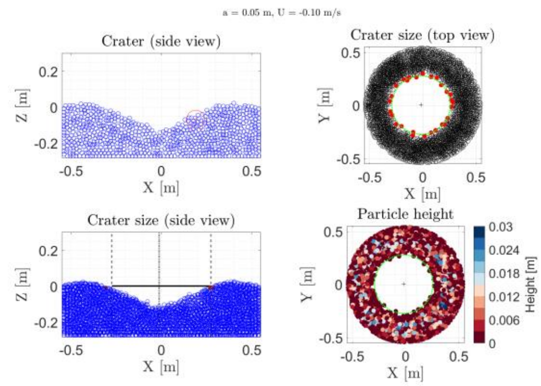

Figure 2 An example crater for the case of δ = 1910 kg/m^3 and U = 10 cm/s.

Smaller craters mean lower crater-scaling coefficients, i.e., closer to the values estimated by dry granular material, despite admittedly small number of simulations here. These aspects are discussed in more detail, including impactor-density dependency in crater scaling and the implications of the results for future small-body exploration missions.

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