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# Low-speed impact simulations into regolith in support of asteroid sampling mechanism design I: Comparison with 1-g experiments

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This study is carried out in the framework of sample-return missions to asteroids that use a low-speed projectile as the primary component of its sampling mechanism (e.g., JAXA's Hayabusa and Hayabusa2 missions). We perform numerical simulations of such impacts into granular materials using different projectile shapes under Earth's gravity. We then compare the amounts of ejected mass obtained in our simulations against what was found in experiments that used similar setups, which allows us to validate our numerical approach. We then investigate the sensitivity of various parameters involved in the contacts between grains on the amount of mass that is ejected. For the targets, we consider 2 different monodisperse grain-diameter sizes: 5 mm and 3 mm. The impact speed of the projectile is 11 m $s^{-1}$, and is directed downward, perpendicular to the surface of the targets. Using an implementation of the soft-sphere discrete element method (SSDEM) in the *N*-body gravity tree code `pkdgrav`, previously validated in the context of low-speed impacts into sintered glass bead agglomerates, we find a noticeable dependence of the amount of ejected mass on the projectile shape. As found in experiments, in the case of the larger target grain size (5 mm), a conically shaped projectile ejects a greater amount of mass than do projectiles of other shapes, including disks and spheres. We then find that numerically the results are sensitive to the normal coefficient of restitution of the grains, especially for impacts into targets comprising smaller grains (3 mm). We also find that static friction plays a more important role for impacts into targets comprising the larger grains. As a preliminary demonstration, one of these considered setups is simulated in a microgravity environment. As expected, a reduction in gravity increases both the amount of ejected mass and the timescale of the impact process. A dedicated quantitative study in microgravity is the subject of future work. We also plan to study other aspects of the ejection process such as velocity distributions and crater properties, and to adapt our methodology to the conditions of sampling mechanisms included in specific mission designs.



## 1. Introduction

The impact process plays a major role in the formation and evolution of planetary systems, including our own Solar System. It is particularly important because impact craters are the most commonly observed geological features on the surfaces of solid Solar System bodies. Crater shapes and features are crucial sources of information regarding past and present surface environments, and can provide us indirect information about the internal structures of these bodies as well. Piecing together the chronology of these surfaces relies on our ability to measure the size distribution of craters and to discriminate between primaries and secondaries, the latter the result of low-speed impact ejecta falling back upon the surface. Low-speed impact mechanisms are also being purposefully implemented into the design of robotic spacecraft missions as a way to collect samples from the surfaces of small bodies such as asteroids and comet nuclei. Specific mechanisms have been incorporated, for instance, by JAXA's Hayabusa and Hayabusa2 missions (Fujiwara et al., 2006; Tachibana et al., 2013). The Hayabusa2 mission is targeted for launch in late 2014, and aims to collect surface and sub-surface samples from the primitive near-Earth (C-type) asteroid 1999JU$_3$ (Vilas, 2008) by firing a small, low-speed, semispherical projectile, similar to the projectile aboard the previous Hayabusa mission (Fujiwara and Yano, 2005; Yano et al., 2006). The Hayabusa2 sample is scheduled to be returned to Earth in 2020.

In this paper we investigate the influence of various projectile shapes, for use in performing low-speed impacts, on the amount of

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ejected mass from coarse granular material targets. This allows for the determination of the optimal shape for maximizing the amount of material ejected (and thus collected) from surfaces comprising granular material for purposes of collector design aboard sample-return missions. Moreover, the outcomes are also relevant to the study of secondary cratering, the result of re-impaction of ejecta following a larger impact event, since the outcomes of such processes may be sensitive to the projectile shape.

The rationale in the assumption that asteroid surfaces consist of granular material is based on the results of several observations. First confirmed by space missions that have visited asteroids in the last few decades (Veverka et al., 2000; Fujiwara et al., 2006), it appears that all encountered asteroids thus far are covered with some sort of granular material, usually referred to as "regolith." To date, this includes a large range in asteroid sizes, from the largest one visited, by the Dawn spacecraft, the main belt asteroid (4) Vesta, which measures ~500 km across, to the smallest one, sampled by the Hayabusa mission, the NEA (25143) Itokawa, which measures ~500 m across (Russell et al., 2012; Yano et al., 2006; Miyamoto et al., 2007). Thermal infrared observations support the idea that most asteroids are covered with regolith, given their preferentially low thermal inertia (Delbó et al., 2007). Thermal inertia measurements also point to a trend based on the asteroid size: larger objects are expected to have a surface covered by a layer of fine regolith, while smaller ones are expected to have a surface covered by a layer of coarse regolith (Delbó et al., 2007; Müller et al., 2013).

In previous studies, we have satisfactorily reproduced the experimental results of low-speed impacts into sintered glass bead agglomerates (Schwartz et al., 2013). We have also demonstrated the ability to simulate the evolution of millions of granular particles in the context of both flow from a granular hopper (Schwartz et al., 2012b) and low-speed cratering events (e.g., Schwartz et al., 2012a); the latter included an evaluation of ejecta speeds and trajectories, and a preliminary analysis of resulting crater sizes and morphologies at the site of the impact (see Fig. 1).

In principle, if the cratering process involves monolithic rock and/or if the impact speed is in the hypervelocity regime (i.e., is larger than the sound speed of the material), then hydrocode simulations that take into account large plastic deformations and phase changes of particles are the most adapted to model the process (Barr and Citron, 2011). However, if the cratering process involves a low-speed impactor into granular material, then the discreteness of particles as well as the different contact frictional forces among them must be taken into account. Sophisticated constitutive equations may be implemented into hydrocodes to study these types of cases, but numerical codes capable of directly simulating the evolution of particles and the contact forces between them during such impact events are probably best suited.

We use an implementation of the Soft-Sphere Discrete Element Method (SSDEM), as developed in Schwartz et al. (2012b), to model the impact cratering process into granular materials to predict the amount of ejected mass. The numerical study presented here is based on the experimental results found by Makabe and Yano (2008) in preparation for the Haybusa2 mission, investigating the effects of different projectile shapes on the amounts of collected mass. We then perform simulations of their experiments, to compare the outcomes and provide results for a wider parameter space. Throughout this paper, when particle or projectile sizes are given, they can be assumed to represent their diameters, unless explicitly stated otherwise.

In the current study, our primary aim is to focus on the same measured outcomes from the Makabe and Yano (2008) experiments: the amount of ejected mass. We leave for future study the investigation of other interesting aspects of low-speed impacts (e.g., crater size, morphology, etc.). For this initial study, certain adaptations to the numerical code had to be made in order to simulate projectiles with shapes other than spheres (see Section 3). As will be explained, the shapes of the projectiles need to be modeled explicitly.

Many laboratory studies analyzing different aspects of the cratering process caused by low-speed (sub-sonic) impacts into loose granular material have already been performed. These include studies into the properties of crater growth and ejecta fate, and their correlations to impact conditions such as the impact speed, target material, projectile material, and the gravitational environment (see, e.g., Uehara et al., 2003; Yamamoto et al., 2006, 2009, who consider crater depth and morphology; Yamamoto et al., 2005; Housen et al., 1983, who investigate particle ejecta speeds; Nakamura et al., 2013, who consider the reaction force on the projectile as the impact process progresses; and Wada et al., 2006, for a numerical study of the excavation stage of low-speed impacts into regolith).

In Section 2, we give an overview of the experiments performed by Makabe and Yano (2008). We then describe our numerical method used to perform the simulations of the low-speed impacts with specific projectile shapes in Section 3. In Section 4, the simulations are presented, and their results are given. And finally, in Section 5, discussions, conclusions, and perspectives are presented.

## 2. Laboratory impacts into granular material

Makabe and Yano (2008) performed low-speed impacts into containers filled with coarse glass beads by shooting projectiles of approximately the same mass as the projectiles designed for the sampling mechanism aboard the Hayabusa spacecraft (i.e., ~5 g in mass) but considering a variety of shapes (Fig. 2). The primary purpose of this experiment was to look for substantial improvement of this impact sampling mechanism, in particular, for surfaces of coarse-grained regolith. A good example of such a surface is the smooth terrain of the MUSES-C region on Itokawa,

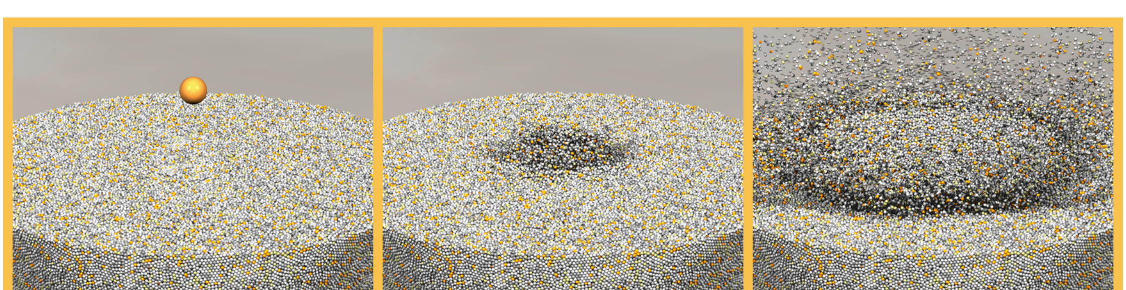

**Fig. 1.** Cratering simulation using a target comprising 1,137,576 particles. A 9-cm-radius projectile impacts perpendicular to the surface at a speed of 100 m $s^{-1}$ into a 155-cm-radius half-shell filled with 1cm-radius grains of collisional restitution coefficient 0.2. From left to right: 5 ms prior to impact; 15 ms after impact; and 375 ms after impact.