Icarus 223 (2013) 222–233

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Impact and intrusion experiments on the deceleration of low-velocity impactors by small-body regolith

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ARTICLE INFO

Article history:
Received 19 March 2012
Revised 23 November 2012
Accepted 27 November 2012
Available online 10 December 2012

Keywords:
Regoliths
Impact processes
Asteroids

ABSTRACT

Previous laboratory impact experiments into sand and glass beads have enriched our understanding of the cratering process on granular media common on asteroids and planetary regolith. However, less attention has been paid to the fate of the projectile, such as its penetration depth in the granular medium, although this may be important for the regolith mixing process. We conducted laboratory experiments on the deceleration of projectiles with low impact velocities to understand the re-accumulation process of ejecta on small asteroids. Glass beads were used as a model of a granular target. Impact experiments using 6-mm plastic projectiles with velocities of $\sim$70 m s^{-1} were performed on the Earth's surface and under microgravity. Measurements of the resistance force of the glass beads against slow intrusion and penetration were also performed. In the impact experiments, the projectiles were decelerated mainly as a result of drag proportional to the square of the velocity. The drag coefficient was 0.9–1.5. Additionally, we found a possible term proportional to the projectile velocity corresponding to the viscous drag with a viscosity up to 2 Pa s. These forces are consistent with numerical simulations that we carried out. The slow intrusion and penetration measurements showed that the velocity-independent resistance force per unit area on a projectile is roughly 20 times larger than the lithostatic pressure. The penetration depth of re-accumulated ejecta was examined based on the drag parameters obtained in this study. A simple configuration was used to visualize the dependence of penetration depth on the drag parameters. The penetration depth was more sensitive to the drag parameters in the case of small particles impacting a relatively small model asteroid.

1. Introduction

Regolith particles and boulders are common on the surface of an asteroid (e.g., Veverka et al., 2001; Fujiwara et al., 2006). They are developed and evolved by impact from interplanetary space and the re-accumulation of ejecta (Housen et al., 1979; Hörz and Cintala, 1997). A visual example of re-accumulation of the ejecta on asteroids is seen on Asteroid 433 Eros, where most of the large ejecta blocks are attributed, based on their spatial distribution, to a relatively young large crater (Thomas et al., 2001). Given that the impact velocity of re-accumulation is limited by the escape velocity of the body, it is less than a few 100 m per second even for the largest main-belt asteroids of several 100 km in diameter. The low-velocity re-accumulation process includes the rebound of the impactors with a non-zero coefficient of restitution (Durda et al., 2011a), compaction (Fujii and Nakamura, 2009), or disruption of the impactors or the surface boulders (Durda et al., 2011b; Güttler et al., 2012), partial burial or penetration of the impactors, and secondary cratering on the surface. Regolith mixing and change in the size distribution proceed by high-speed primary impacts and also by such secondary impacts, i.e., re-accumulation of the ejecta blocks. The re-accumulation process might also affect the reshaping of a rubble-pile asteroid. However, it is not clear what fraction of the ejecta blocks could survive re-accumulation. The penetration depth of the impactors in the bed of regolith and the thickness of the regolith mixing zone are also unknown.

To understand the cratering process and to develop scaling relations for crater dimensions and ejecta, laboratory impact experiments onto non-cohesive and cohesive granular materials were performed at impact velocities up to several kilometers per second (Schmidt and Housen, 1987; Housen and Holsapple, 2011). In those studies, the fate of the impactor was largely ignored, because the impactor is severely broken under a high-velocity impact. On the

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http://dx.doi.org/10.1016/j.icarus.2012.11.038

other hand, studies of projectile-impacts in simulated regolith at velocities of less than 1 m s^{-1} were conducted under microgravity conditions to investigate collisions between planetary ring particles and those in proto-planetary disk environments (Colwell and Taylor, 1999; Colwell, 2003). The impactors in these cases were observed to embed themselves in the target material or to rebound with a very low coefficient of restitution.

In this study, we focused on the deceleration of the impactor by simulated regolith at velocities of tens of meters per second, velocities that are relevant for the process of re-accumulation onto small bodies. A better understanding of the deceleration process of impactors by a simulated small-body surface will also be useful for interpreting the results of active penetrometry experiments in space missions (Shiraishi et al., 2000; Kömle et al., 2001). The procedure used for impact experiments on the drag force for a projectile in a granular medium is presented in Section 2, as well as the procedure for measurements conducted to determine the velocity-independent resistance force for a projectile in the granular medium. In this study, we used a millimeter-sized plastic projectile as an impactor and tens or hundreds of micron glass beads as a target, representing regolith particles. The materials and the sizes of the projectile and target are very simplified and limited in comparison to real impactors and regolith surfaces. The purpose of the experiment was to determine the basics of how granular targets resist penetration by projectiles. The results of the experiments are described in Section 3. Section 4 presents a discussion of the experimental results and the relevant numerical simulations, and a demonstration of how the drag equation parameters could affect the re-accumulation process on an asteroid surface. A summary of the study is presented in Section 5.

2. Experiments

2.1. Impact experiments

Polydisperse soda lime glass beads of diameter $d \approx 50$ μm and particle density of 2.5 g cm^{-3}, used in previous experiments on porous sintered targets (Setoh et al., 2010), were used in this study. Fig. 1 shows a schematic of the target configuration. The glass

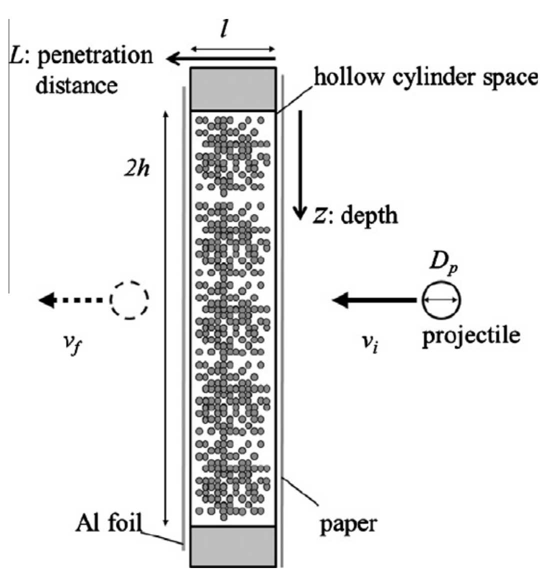

Fig. 1. A schematic view of the impact configuration. A cylindrical hollow space of diameter $2h$ = 5 cm was opened in acrylic plates of thickness l = 0.5, 1.0, and 1.5 cm. The hollow space was filled with glass beads. The muzzle side (right) of the bed of beads was covered by a sheet of paper 0.1 mm thick. The antipodal side (left) was covered by aluminum foil 0.012 mm thick to prevent the beads from spilling.

beads were packed into a circular hole in the center of an acrylic plate with a diameter $2h$ = 50 mm. We used three plates of thickness l = 5, 10, and 15 mm, respectively. The muzzle side of the hole was covered by a sheet of paper of thickness 0.1 mm. A projectile would penetrate the paper and impact the center (at the depth z (=h) = 25 mm) of the bead target. The downrange side of the hole was covered by aluminum foil of thickness 0.012 mm to prevent beads from spilling out from the hole. The bulk porosity of the packed bead beds in the plates was 41 ± 5%. This porosity of the glass-bead target was greater than the average macroporosity value estimated for S-class asteroids, but was similar to the average macroporosity value estimated for C-class asteroids based on the bulk densities of asteroids and ordinary and carbonaceous chondrites and on the assumption that respective chondrite classes are the building blocks of the corresponding asteroid classes (e.g., Britt et al., 2002). The macroporosity of the sub-kilometer S-class Asteroid 25143 Itokawa was estimated to be 41% (Fujiwara et al., 2006). The porosity of regolith can be much higher than the macroporosity of bulk asteroids and can be detected by reflectance measurements and modeling (Hapke, 2008; Shepard and Helfenstein, 2011). The near-surface bulk porosity (i.e., the sum of all porosities, including meteorite micro- and macroporosity) for radar-detected asteroid samples was estimated to be moderate, with a mean of 51 ± 14% (Magri et al., 2001).

We performed impact experiments using a commercial automatic electric airsoft gun under two different gravitational conditions: normal gravity and microgravity. The projectile was a plastic sphere of diameter D_p = 6.0 mm and mass m = 0.197 g. The microgravity experiment was conducted in an airplane (Gulfstream II, Diamond Air Service, Inc.). The airplane was initially pulled up to approximately 45° in attitude at about 10,000 m in altitude. Next, the pilots stopped the engine of the airplane and let the airplane fly in a parabolic trajectory. Each parabolic flight took approximately 1 min from start to end and enabled us to perform experiments under microgravity (acceleration due to gravity of less than 1 m s^{-2}) for 20 s. The parabolic flight was repeated eight times. The ambient pressure was 0.8 atm. The muzzle of the gun and the target of beads were contained in an acrylic box. We measured the velocity of the projectile after penetration using a high-speed camera (EX-F1) placed outside the acrylic box at 1200 fps. The projectile was illuminated by a lamp. In total seven successful shots were performed. The initial velocity v_i of the projectile was determined at atmospheric pressure on the ground using high-speed camera images for 19 shots and was 69.4 ± 1.2 m s^{-1}. We also conducted calibration shots in a reduced pressure room and found that the projectile velocity at 0.8 atm was on average only 1.0 m s^{-1} less than that under 1 atm conditions, i.e., the velocity difference was within the observed scatter of the initial velocity. Therefore, we considered the value determined in the laboratory under the 1-atm condition to be the initial velocity for shots without an initial velocity measurement. Similar experiments were performed on the ground using the same target system, the same gun, and the same camera for seven shots. We also conducted impact experiments using higher-speed cameras, either the Shimazu HPV-II or the Photron FASTCAM SA1.1, under conditions of backlight illumination. Experiments with target beads of d = ~420 μm were also conducted.

We conducted calibration shots into the paper and the aluminum foil to estimate the velocity decrease due to each covering. To cover a wider range of impact conditions for the calibration data of the aluminum foil, projectiles of diameter D_p = ~3 mm were also used. The projectiles were accelerated up to 320 m s^{-1} using a small gas gun installed at Kobe University (Setoh et al., 2010). The velocities of the projectiles before (v_i) and after (v_f) perforating the paper or the foil were determined from the high-speed images. We assumed that the deceleration of the projectile was due to the