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Oblique impact cratering experiments in brittle targets: Implications for elliptical craters on the Moon

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ABSTRACT

Most impact craters observed on planetary bodies are the results of oblique impacts of meteoroids. To date, however, there have only been very few laboratory oblique impact experiments for analogue targets relevant to the surfaces of extraterrestrial bodies. In particular, there is a lack of laboratory oblique impact experiments into brittle targets with a material strength on the order of 1 MPa, with the exception of ice. A strength on the order of 1 MPa is considered to be the corresponding material strength for the formation of craters in the 100 m size range on the Moon. Impact craters are elliptical if the meteoroid's trajectory is below a certain threshold angle of incidence, and it is known that the threshold angle depends largely on the material strength. Therefore, we examined the threshold angle required to produce elliptical craters in laboratory impact experiments into brittle targets. This work aims to constrain current interpretations of lunar elliptical craters and pit craters with sizes below a hundred meters. We produced mortar targets with compressive strength of 3.2 MPa. A spherical nylon projectile (diameter 7.14 mm) was shot into the target surface at a nominal velocity of 2.3 km/s, with an impact angle of 5°-90° from horizontal. The threshold angle of this experiment ranges from 15° to 20°. We confirmed that our experimental data agree with previous empirical equations in terms of the cratering efficiency and the threshold impact angle. In addition, in order to simulate the relatively large lunar pit craters related to underground cavities, we conducted a second series of experiments under similar impact conditions using targets with an underground rectangular cavity. Size and outline of craters that created a hole are similar to those of craters without a hole. Moreover, when observed from an oblique angle, a crater with a hole has a topography that resembles the lunar pit craters. The relation between the impact velocity of meteoroids on the Moon and the probability of elliptical crater formation was investigated based on our experimental results and an existing empirical equation. The results suggest a distinct possibility that most craters in the 100 m size range on the Moon, given their elliptical shape, originated as secondary craters.

1. Introduction

Impact craters are the dominant features on solid-surface planetary bodies in the solar system. Most impacts on solid-surface planetary bodies occur at an oblique angle of incidence, and it has long been known that the most likely angle of incidence is 45° (e.g., Shoemaker, 1962). Impacts at a very shallow angle to the surfaces produce elliptical craters: if an impactor strikes the planetary surface at an angle less than a certain threshold angle, the resulting crater shape is not a circular and becomes elongated in the direction of impact. Only roughly 5% of all craters (greater than 1 km in diameter) observed on Mars, Venus, and the Moon have elliptical shapes with an ellipticity of 1.1 or greater, where the crater's ellipticity is defined as the ratio of its maximum and minimum rim-to-rim diameters (Bottke et al., 2000). Although elliptical impact craters may be rare on solid-surface planetary bodies, a better understanding of the formation of elliptical craters would contribute to our overall understanding of impact cratering. For instance, it is well-known that crater size depends on impact angle (e.g., Elbeshausen et al., 2009).

Recently, more and more craters in the 100 m size range have been observed on Mars and the Moon by the telescopic camera on board Mars Reconnaissance Orbiter and the Lunar Reconnaissance Orbiter

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Camera (LROC), respectively. These data reveal the variety of crater shapes on Mars and the Moon. Among some smaller craters observed on Mars and the Moon, deep pit craters are occasionally seen (e.g., Cushing, 2012; Robinson et al., 2012). These craters, characterized by their steep walls, are generally considered to be the results of roof collapses into subsurface cavities. On the Moon, deep pit craters with a diameter of more than 50 m were discovered in SELenological and Engineering Explorer (SELENE) Terrain Camera (TC) images (Haruyama et al., 2009, 2012) and were investigated in detail by LROC (Robinson et al., 2012). These deep pit craters are generally called Marius Hill Pit, Mare Tranquillitatis Pit and Mare Ingenii Pit. There are often called 'deep pit craters, 'deep pits', or 'holes'. In this study, we will simply refer to them as 'pit craters'. One possibility for their formation was the collapse of the roof of an underground cavity such as a lava tube, brought about by a random meteoroid impact (Haruyama et al., 2009, 2012: Martellato et al., 2013: Michikami et al., 2014). These maximum and minimum pit diameters are 57 and 48 m for Marius Hill Pit, 99 and 84 m for Mare Tranquillitatis Pit, and 103 and 66 m for Mare Ingenii Pit; the shapes of these pit craters are elliptical. In order to investigate the formation of Martian pit craters, Michikami et al. (2014) carried out impact experiments into brittle targets with a cavity at an impact angle of 90° from the horizontal, resulting in circular craters. However, the elliptical shapes of lunar pit craters cannot be explained by the data of Michikami et al. (2014). Therefore, it is necessary to carry out oblique impact experiments into brittle targets with a cavity.

Laboratory oblique impact cratering experiments into targets with a strength relevant to the surface of extraterrestrial bodies are still sparse, although there have been a number of studies of oblique cratering, both in experiments and modelling. Among the oblique impact experiments conducted, those of Gault (1973) and Gault and Wedekind (1978) are most widely known. They reported on impacts into granite and sand. Crater formation is generally divided into two regimes, the strength and the gravity regime, depending on which of the two effects dominates during cratering. The impacts into granite simulated impacts in the strength regime; those into sand were done to investigate impacts in the gravity regime. They found that the ellipticity of the crater increases with decreasing impact angle from the horizontal of the target surface. For instance, projectiles fired at an angle of 4.75° from the horizontal or less into sand targets produce an elliptical crater with an ellipticity greater than 1.1. Unfortunately, on rock targets, no data were given for impacts at angles less than 15° from the horizontal. In order to investigate the effect of impact angle on crater ellipticity in rock, Burchell and Whitehorn (2003) (From now on, we will abbreviate this to "BW03") carried out the oblique impact experiments in granite targets. They found that crater depth and excavated mass start to decrease immediately when non-normal incidence occurs. Their results suggest that projectiles shot at angle 10° from the horizontal or less into granite targets produce elliptical craters with ellipticities greater than 1.1.

As mentioned above, although several laboratory experiments have been conducted to simulate oblique impacts under conditions relevant to planetary surfaces, experimental data are insufficient as analogues for craters in the 100 m size range. Impact craters larger than a kilometer on the Moon would occur in the gravity regime (e.g., Holsapple and Schmidt, 1979; Collins et al., 2011). On the other hand, impact craters smaller than a hundred meters on the Moon would occur in the strength regime (e.g., Stöffler et al., 2006; Daubar et al., 2014). In the past experiments, for an example, the strength (a general compressive strength ~ a few hundred MPa) of granite targets adopted by BW03 would be larger than that of a planetary surface, which is admittedly not very well characterized, but is thought to be on the order of 1 MPa (e.g., Melosh, 1989; Collins et al., 2011; Daubar et al., 2014). Besides, both laboratory experiments (Gault and Wedekind, 1978; Christiansen et al., 1993; Burchell and Mackay, 1998; Burchell and Whitehorn, 2003) and numerical simulations (Collins et al., 2011) revealed that the angle below which elliptical craters form, the so-called threshold angle, depends on the properties of the target material. Therefore, it is important to simulate oblique impacts under conditions relevant craters in the 100 m size range by using brittle target with a strength on the order of 1 MPa.

The purpose of this study is twofold: our first aim is to examine the threshold impact angle for producing elliptical craters in the 100 m size range on the Moon. For this purpose, we carried out oblique impact experiments into mortar targets with a strength on the order of 1 MPa (Section 3.1). In Section 4.1, we compare our experimental results with previous studies for various target materials, e.g. the data of Grey et al. (2002), who report on laboratory oblique impact experiments into ice targets with a similar strength. We consider the influence of both target material and impact velocity because, according to previous studies (e.g., Collins et al., 2011; Elbeshausen et al., 2013), the threshold impact angles are strongly affected by not only the target material but also by the impact velocity. In Section 4.2, we then apply our experimental results to elliptical craters on the Moon, by investigating the effect of impact angle on elliptical crater formation at various impact velocities.

Our second aim is to explore the formation of lunar pit craters with elliptical shapes. For this purpose, we carried out oblique impact experiments for mortar targets with a cavity (Section 3.2). The craters in targets with and without cavity are compared in Section 3.3. We take a look at the relation between the craters in targets with a cavity and three pit craters on the Moon in Section 4.3. Finally, we present conclusions in Section 5.

2. Experimental procedures

2.1. Target production method and target properties

The targets were produced using same methods as described by Michikami et al. (2014). They were fabricated using a mixture of cement, water and Toyoura sand (an engineering standard-sand in Japan) in the ratio of 1:1:10, by weight. The particle size of the sand is about 0.2 mm. The mixture was then put in a mold and was compacted. In order to simulate the formation of elliptical craters and elliptical pit craters on the Moon, we produced targets without and with a rectangular cavity using two molds. Rectangular parallelepiped target with a length 20 cm, width 20 cm and height 6 cm, without a cavity, were produced to simulate elliptical craters. In order to simulate elliptical pit craters, rectangular parallelepiped target with a length 35 cm, width 25 cm and height 4 cm were produced, and a rectangular cavity was set into the target underground to yield a cuboid as shown in Fig. 1 (the roof thickness is 1 cm). After a few days, the mold was taken off and the targets were left to air-dry for about one week. In the end, both types of target had a bulk density of 1550 kg/m^3, a porosity of ~40%, a compressive strength of 3.2 MPa, and a tensile strength of 0.83 MPa (for more detail, refer to Michikami et al., 2014).

2.2. Impact experiments

The impacts were carried out using a two-stage light-gas gun at the Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS, JAXA). Seven oblique impact experiments for the targets without a cavity were performed at impact angles from 5° (glancing shot) to 90° (vertical shot) from the horizontal were performed and seven oblique impact experiments for the targets with a cavity were carried out at impact angles from 2° to 90° from the horizontal (Tables 1, 2). Spherical nylon projectiles 7.14 mm in diameter (mass 0.217 g and density 1140 kg/m^3) were fired into the target surface at a nominal impact velocity of 2.3 km/s. The impact velocities in the experiments with impact angle of 90° from the horizontal were exceptional in that they were slightly faster (2.44 km/s for s1941 and 2.62 km/s for s806) than those in the other