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Experimental study on impact-induced seismic wave propagation through granular materials

Minami Yasui *, Eri Matsumoto, Masahiko Arakawa

Graduate School of Science, Kobe University, 1-1, Rokkkodai-cho, Nada-ku, Kobe, Hyogo 657-8501, Japan

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ABSTRACT

Impact-induced seismic waves are supposed to cause movements of regolith particles, resulting in modifications of asteroidal surfaces. The imparted seismic energy is thus a key parameter to determining the scale and magnitude of this seismic shaking process. It is important to study the propagation velocity, attenuation rate, and vibration period of the impact-induced seismic wave to estimate the seismic energy. Hence, we conducted impact cratering experiments at Kobe University using a 200-μm glass beads target to simulate a regolith layer, and measured the impact-induced seismic wave using three accelerometers set on the target surface at differences ranging from 3.2 to 12.7 cm. The target was impacted with three kinds of projectiles at ~100 m s^{-1} using a one-stage gas gun. The propagation velocity of the seismic wave in the beads target was 108.9 m s^{-1}, and the maximum acceleration, g_{max}, in the unit of m s^{-2}, measured by each accelerometer showed good correlation with the distance from the impact point normalized by the crater radius, x/R, irrespective of projectile type. They also were fitted by one power-law equation, $g_{max} = 10^{2.19} (x/R)^{-2.21}$. The half period of the first peak of the measured seismic waves was ~0.72 ms, and this duration was almost consistent with the penetration time of each projectile into the target. According to these measurements, we estimated the impact seismic efficiency factor, that is, the ratio of seismic energy to kinetic energy of the projectile, to be almost constant, 5.7×10^{-4} inside the crater rim, while it exponentially decreased with distance from the impact point outside the crater rim. At a distance quadruple of the crater radius, the efficiency factors were 4.4×10^{-5} for polycarbonate projectile and 9.5×10^{-5} for alumina and stainless steel projectiles.

1. Introduction

It is well known that high-velocity impacts on solid bodies form impact craters on the surface, and that seismic waves propagating through the subsurface could be simultaneously activated by the impact. One of the important effects caused by impact-induced seismic waves is a resurfacing process on asteroidal surfaces; for example, the surface features such as slumps and debris aprons on asteroid 433 Eros (e.g., Veverka et al., 2001). These features are supposed to be formed through the movement of regolith particles activated by seismic shaking. The seismic shaking may also have affected the crater size distribution on 433 Eros. It was observed that impact craters with diameters smaller than ~100 m were deficient, which was demonstrated by the finding that the crater number density at <100 m was smaller than that extrapolated from the number of large craters on the cumulative number distribution (Robinson et al., 2002). This may have been caused by a process that selectively erased small craters through the seismic shaking.

Several researchers have carried out numerical simulations to study the effects of an impact-induced seismic wave on the resurfacing of an asteroidal surface, and the surface particle velocity or surface acceleration induced by an impact has been calculated to evaluate the possibility of resurfacing on small bodies (Asphaug and Melosh, 1993; Nolan et al., 2001; Richardson et al., 2005). Asphaug and Melosh (1993) and Nolan et al. (2001) calculated global velocity distributions of surface regolith on asteroid-sized bodies, and found that the regolith particles could have a peak velocity higher than 1 m s^{-1} even far from the impact point due to impact jolting. Furthermore, they found that the jolting caused by the large impact event was effective in erasing impact craters. Recently, Richardson et al. (2005) calculated the gravity-driven flow of a regolith layer caused by global seismic shaking on an Eros-sized body, and found that impact craters with diameters smaller than 100 m were erased selectively due to impact-induced seismic activity. They also showed that the impact seismic efficiency factor, which is the ratio of the imparted seismic

* Corresponding author. Fax: +81 78 803 5741.
E-mail address: minami.yasui@pearl.kobe-u.ac.jp (M. Yasui).

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energy to the kinetic energy of the impactor, could control the global seismic intensity. That is, the seismic efficiency factor is a key parameter in estimating the resurfacing rate and scale on asteroids. However, the impact seismic efficiency factor has not been studied sufficiently, and those obtained by laboratory experiments, military experiments, and Apollo missions have ranged widely, from 10^{-2} to 10^{-6} (Gault and Heitowit, 1963; Titley, 1966; Latham et al., 1968, 1970; McGarr et al., 1969; Moore et al., 1970). In order to determine the impact seismic efficiency factor, the seismic energy induced by the impact should be investigated.

A few research studies have determined the impact seismic efficiency factor by measuring the seismic vibration in a laboratory. McGarr et al. (1969) conducted high-velocity impact experiments of loose sands and epoxy-bonded sands using a lexan projectile at an impact velocity of 0.8–7 km s^{-1} at NASA's Ames Research Center, and observed the impact-induced seismic wave using four accelerometers on the target surface. They obtained an efficiency factor of $\sim 7.6 \times 10^{-5}$ for the bonded sand. On the other hand, in the case of the loose sand, it is necessary to obtain an attenuation rate of the acceleration with distance due to dissipation. Additional characteristics of a seismic wave, such as propagation velocity and vibration period, are also necessary to estimate the seismic energy, but they did not obtain the attenuation rate from their experimental results, and so did not provide the impact seismic energy. It is necessary to determine the attenuation rate by measuring the seismic wave at different distances from the impact origin, and the propagation velocity and vibration period of the wave also should be measured simultaneously to obtain the impact seismic energy.

Incidentally, impact-induced seismic waves provide clues to the internal structure of solid bodies (e.g., Toksöz et al., 1974; Lü et al., 2011) and Walker (2003) and Teanby and Wookey (2011) surveyed the seismic waves using artificial impacts or meteoroid collisions to explore subsurface structures of solid bodies. It is thus very important to examine the relationship between the intensity of the impact-induced seismic wave and the size of the impact crater for the calibration of obtained exploration data in future missions. Various types of projectiles have been considered for use in the formation of artificial craters on these missions; moreover various types of impactors form natural craters on asteroids. Therefore, the effect of projectile materials on the intensity of impact-induced seismic waves should also be studied.

In this study, we carried out impact cratering experiments in a laboratory, and observed impact-induced seismic waves using accelerometers in order to study the impact seismic efficiency factor. In order to examine the effect of projectile material, the target material was fixed and the impact velocity was almost constant. Three types of projectile were used. We conducted the measurement of impact-induced seismic waves by setting the accelerometers on the target surface in a way similar to McGarr et al. (1969). The distance between the position of the accelerometers and the impact point was changed systematically to obtain the attenuation rate of the maximum acceleration of the seismic waves. Furthermore, the crater size was measured to scale the attenuation of the acceleration with the distance. Finally, we estimated the seismic energy and the impact seismic efficiency factor by assuming a simple sinusoidal wave for the impact-induced seismic wave, and also estimated the distance from the impact origin at which the seismic vibration could occur.

2. Experimental methods

We used spherical glass beads with a diameter of 180–250 μm (weighted average value of 200 μm) as a target to simulate the surface of asteroids covered with a regolith layer. The glass beads were put into a container 28-cm in diameter and 10-cm deep. The bulk density of the glass beads target was 1.51 g cm^{-3}, and the porosity was about 40%. The projectiles were a polycarbonate cylinder with a diameter of 10 mm and a height of 10 mm, and both alumina and stainless steel spheres with a diameter of 3 mm. These were used to examine the effects of the size and density of projectiles on the propagation of impact-induced seismic waves.

Impact experiments were conducted at Kobe University, using a vertical-type one-stage light-gas gun set. A schematic illustration of the experimental setup is shown in Fig. 1a. In the case of the alumina and stainless steel projectiles, a cylindrical sabot was used to accelerate them. The sabot (diameter 10 mm; length 35 mm) was composed of a polycarbonate part glued to a polystyrene part, as shown in Fig. 1b. The spherical projectiles were set in a notch cut crosswise with a depth of 5 mm at the head of the polystyrene part. A sabot stopper system was installed at the exit of the gun barrel to stop the sabot for launching the spherical projectiles at a direction perpendicular to the target surface. The impact velocity, V_i, ranged from 89.7 to 148.8 m s^{-1}, and the physical parameters of the impact-induced seismic wave did not change with impact velocity in this range. We had two reasons for selecting this velocity range. The first was that McGarr et al. (1969) conducted impact experiments at higher impact velocity, $\sim$km s^{-1}, so in order to study the elementary processes of impact-induced seismic waves, it was important to expand the velocity range, particularly to low-impact velocity. The second was that the projectile deformation and destruction, and the heating of target materials, etc., expected to occur at the high-impact velocity range ($\sim$km s^{-1}, the range of the main belt asteroids proposed by Bottke et al. (1994)) could not occur, so we would be able to observe the effect of projectile penetration without deformation and destruction on the seismic wave. The target chamber was evacuated below 10^3 Pa. The experimental results of Johnson et al. (1969) and Schultz (1992) using the π-scaling theory proposed by Housen and Holsapple (2003) showed the crater size and scaled crater size did not change with atmospheric pressure below 10^4 Pa. So we can assert that the difference of atmospheric pressure did not affect our results below 10^3 Pa. All shots in our experiments were carried out under Earth's gravity, 1G.

In order to measure the impact-induced seismic wave on the target, we used two types of piezoelectric accelerometers (SV1113 and SV1103, Nippon Avionics Co., LTD). These are one-axis accelerometer systems, so they could detect acceleration only in the direction normal to the contact surface of the accelerometer. According to the specifications of the accelerometer system, a compressive force on the accelerometer generated a positive signal in volts, and the sensitivity and response frequency of these accelerometers were 5.1 pC m^{-1} s^2 and $0.5\text{–}7 \times 10^3$ Hz for SV1113, and 0.061 pC m^{-1} s^2 and 0.5–10^4 Hz for SV1103. We used three accelerometers for each shot, and they were set at the sensitive direction normal to the target surface and buried at a depth of 1.0 and 2.5 cm from the surface. The accelerometers were systematically set at varying distances from the impact point, x, ranging from 3.2 to 12.7 cm, as shown in Fig. 1c (i.e., almost out of the crater diameter). In this study, the physical parameters of impact-induced seismic waves did not change with the buried depth of the accelerometer at the same x. Acceleration observed changing with time was recorded with a data logger with an A/D conversion rate of 100 kHz (mini LOGGER GL900-4, Graphtec Co.).

The projectile launched to the target surface was observed using a high-speed digital video camera (Memrecam fx-K3, NAC Image Tech., Inc.) to determine impact time on the target surface. Furthermore, in order to synchronize the high-speed video trigger with that for the data logger, an oscilloscope (DS-5514, IWATSU ELECTRIC Co., Ltd.) generated a trigger signal so that these devices worked simultaneously when a velocity measurement system detected a signal showing a projectile had passed through.