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USING MISSION IMAGES TO STUDY EVIDENCE OF BLOCK MOTION ON ASTEROIDS: DETERMINING PHOTOSEISMOLOGY MISSION REQUIREMENTS

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ABSTRACT

Asteroids preserve, in some form, the early geologic records of the Solar System, data that are important for understanding the processes and timescales for terrestrial planet formation. While it is relatively easy to examine the surface of an asteroid, little is known regarding their internal structure. A reliable, relatively inexpensive method for determining the internal structure of an asteroid using cameras and optical instruments would provide considerable benefits to the general knowledge of asteroids and to the processes of planetary formation and mechanisms of evolution; however, the imaging requirements for such an observation are not defined. Here we present the preliminary results of the first laboratory experiment designed to explore the imaging parameter space that could be used to estimate subsurface properties of asteroids based on changes on the surface. We constructed a small (60 cm square) box and filled it with sand and angular rocks and applied a physical jolt to the system. We compared images of the blocks taken beforehand to images taken afterwards and attempted to quantify the differences between the two sets. Preliminary results suggest that the optimal viewing angle for detecting motion is 90° and that a pixel size of cm/pixel is sufficient to detect block motion on an asteroid with gravity of 10^{-6} g. This research has direct implications on imaging requirements for missions such as the Asteroid Origins Satellite (AOSAT) and the Asteroid Impact and Deflection Assessment (AIDA).

INTRODUCTION

Asteroids, specifically Near-Earth Objects (NEOs), provide unique opportunities to study the physical characteristics, which are relics of the earliest stages of terrestrial planet formation. Conversely future asteroid impacts with the Earth are potentially hazardous, and a sound strategy for either deflecting or destroying an asteroid is not yet developed. Seismic data of an asteroid would significantly advance the study of NEOs and the development of planetary defense strategies. However, definitive understanding of asteroid internal structure will have to wait for seismological investigations, which has not been developed due to the perceived high complexity and cost. A reliable, relatively inexpensive method for determining the internal structure of an asteroid would provide considerable benefits to the general knowledge of asteroids, and to the processes of planetary formation and mechanisms of evolution.

Blocks are common on asteroids, but studies of blocks have generally been restricted to size frequency distributions on a body. These kinds of studies have been completed for Itokawa, Eros, Lutetia, and Vesta [1-8]. Block studies have also been conducted for Earth, but within the context of paleoseismology. Brune and Whitney [9] initially defined the characteristics of a precariously balanced rock (PBR), and subsequent studies have studied PBRs and their geographic distribution in further detail [10-13]. The number of studies that have focused on PBRs and the complex, non-linear partial differential equations that govern their motion [13-16] shows their effectiveness at estimating peak ground acceleration (PGA) on Earth caused by ancient earthquakes. We have previously proposed that the methodology applied to PBRs on Earth can be extended to ordinary blocks on asteroids and comets [17, 18].

A seismic event on a small body could range from an impact event to outgassing, so long as the event imparts some kind of energy to the small body's interior. Mass movement of material on an asteroid is expected to occur in the form of regional landslides, localized avalanches, nearby crater collapse, crater formation, and/or discrete block movements following a seismic event. Large blocks will be carried by the flow, and the largest discrete blocks will serve as tracers of the flow trajectory. We propose that these blocks can function as passive seismometers, similar to the way PBRs are used by seismologists on Earth as markers of peak seismicity [9, 13, 16]. In the ballistic approximation, a seismic impulse with peak particle velocity v_p encounters the surface and accelerates materials to distances of order $h = \frac{\;^{2}}{2}$, where g is the surface gravity. From close examination of images taken before and after the seismic event, it should be possible to work backwards to estimate peak particle velocities and, therefore, the energy transmitted at the boundary between the subsurface and surface of a small body.

Analytical and numerical models indicate that seismic motion on a small body is a powerful mechanism for stimulating regolith activity and boulder movement. The mechanics behind seismic shaking were investigated with computer models [19, 20] and attenuation scaling [21]. If distance and direction of reorientation or ballistic motion are known, it is possible to calculate the peak velocity of a particular block from simple kinematics. By comparing the displacements of blocks as a function of the initial distance of the blocks from the crater center and assuming that seismic energy is dissipated in a solid body as a function of its material strength, it is possible to constrain the properties of the internal structure of an asteroid. This idea of using blocks as a proxy for seismology provides a new tool to evaluate images from previous missions to asteroids.

In this report we present preliminary findings that will help refine imaging system requirements for future missions to asteroids. This is merely an exploration of the imaging parameter space, and is not meant as a substitute for more robust microgravity experiments. This research can be tested directly as a science objective in upcoming missions. Two possible test missions are the Asteroid Impact Deflection Assessment (AIDA) [22], a joint mission concept by NASA and ESA, and the AOSAT concept from ASU [23].

METHODS

We created a basic experiment designed to investigate the imaging parameter space in order to better define imaging requirements for future missions. We first built a 60 cm x 60 cm square “sandbox on a platform,” henceforth called “the sandbox,” and filled it with roughly 1 cm of playground sand and 180 angular rocks ranging in size from 0.8 cm to 6 cm. We provided a light source to simulate the lighting conditions on an asteroid at 1 AU from the sun. A plank of wood and a brick were used to create a basic lever and fulcrum, which allows for a seismic jolt to be applied to the bottom of the raised sandbox. A picture of the experimental set-up is shown in Figure 1.

Figure 1: A photograph of the experimental set-up. Notice that the sandbox is raised so that a basic lever (the plank and the brick) can be used to apply a seismic jolt to the bottom of the sandbox. Two cameras on tripods and the lighting source (attached to the meter stick taped to the recycling bin) are also visible.

The cameras were the only elements that moved throughout the experiment, aside from the rocks within the sandbox that moved as a result of the seismic impulse. Images were obtained from both cameras at 90°, 60°, and 30° at the positions shown in Figure 1 (orthogonal camera orientation), at 180° to each other, and at stereoscopic camera orientation.

Figure 1 shows our experimental setup. Using a doubled amount of rocks resulted in dramatic changes between the images for which it was too difficult to accurately determine which rocks moved to the new locations as they could not be correlated. On the other hand, an experimental set-up with too few blocks in the sandbox, resulted on only a few rocks moving yielding robust measurements. Our ideal set-up consisted of a distinctly higher density of rocks in one half of the sandbox.

After images had been obtained for all combinations of angles and camera positions, a single seismic jolt was applied to the system using the lever. The same combinations of angles and camera positions were then repeated. Images were imported into the software ImageJ, scaled, and converted into 32-bit grayscale images. ImageJ is an open source tool developed at the National Institute of Health for microscopy work [24,25]. Using the point tool within ImageJ we recorded the x coordinate and y coordinate positions of the centers of individual rocks in the before and after images. To calculate the displacement of the rock we used the basic geometric distance formula as a first order approximation. We did not take into account any rotation in the rock, only the motion of the approximate center of the rock. After the distances were calculated for 121 rocks, we recorded the original distance that each rock was from the seismic epicenter. We then graphed and analyzed the results.

RESULTS

Figures 2-5 show four images from the sandbox preliminary tests. Figures 2 and 4 are both before images, and figures 3 and 5 are after images. Figures 2 and 3 show the "Camera A" (180° from the seismic jolt location) perspective and figures 4 and 5 show the "Camera B" (90° from the seismic jolt location) perspective.

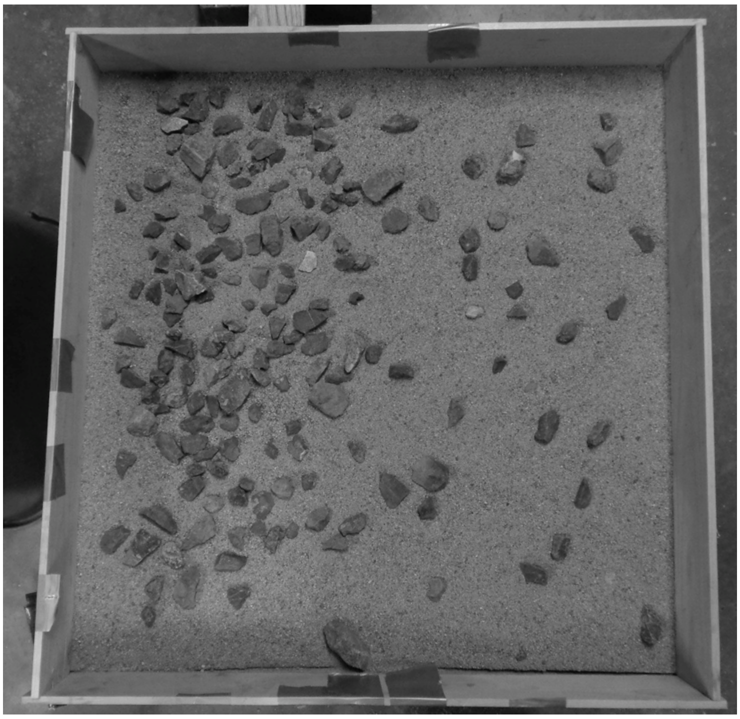

Figure 2: Before seismic jolt image from Camera A (180° from the seismic jolt location) perspective at inclination angle of 90°.

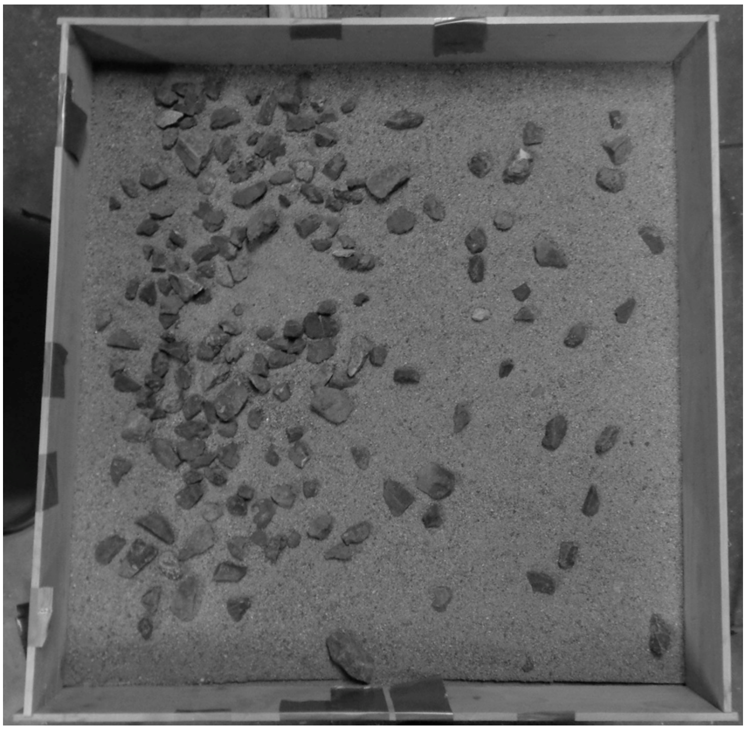

Figure 3: After seismic jolt image from Camera A (180° from the seismic jolt location) perspective at inclination angle of 90°.

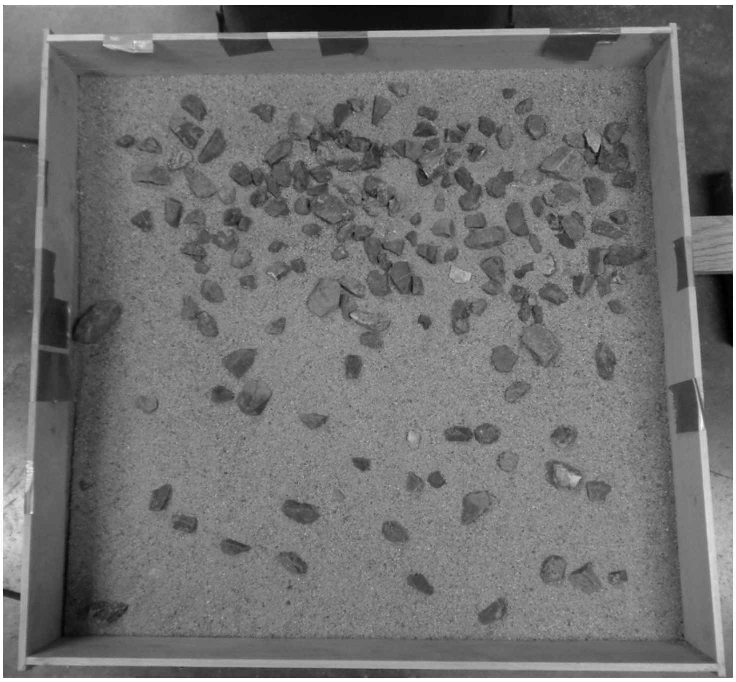

Figure 4: Before seismic jolt image from Camera B (90° from the seismic jolt location) perspective at inclination angle of 90°.

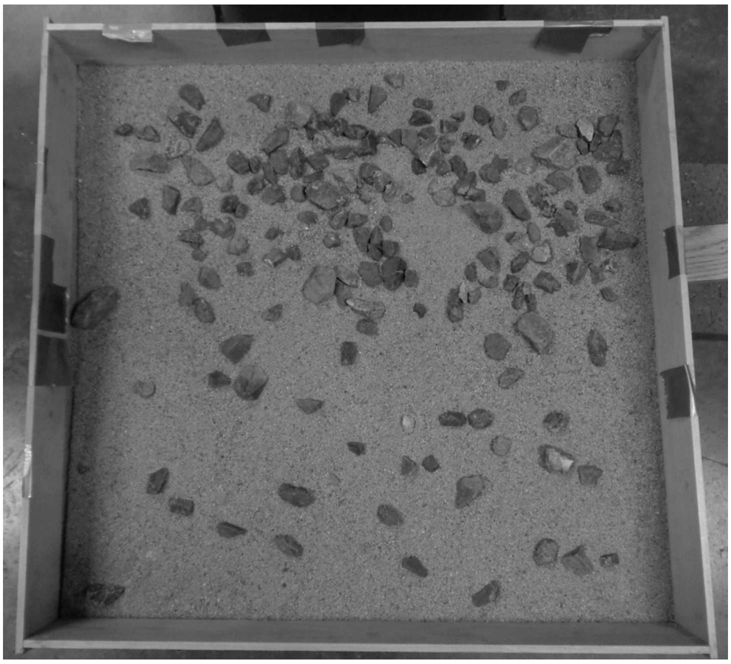

Figure 5: After seismic jolt image from Camera B (90° from the seismic jolt location) perspective at inclination angle of 90°.

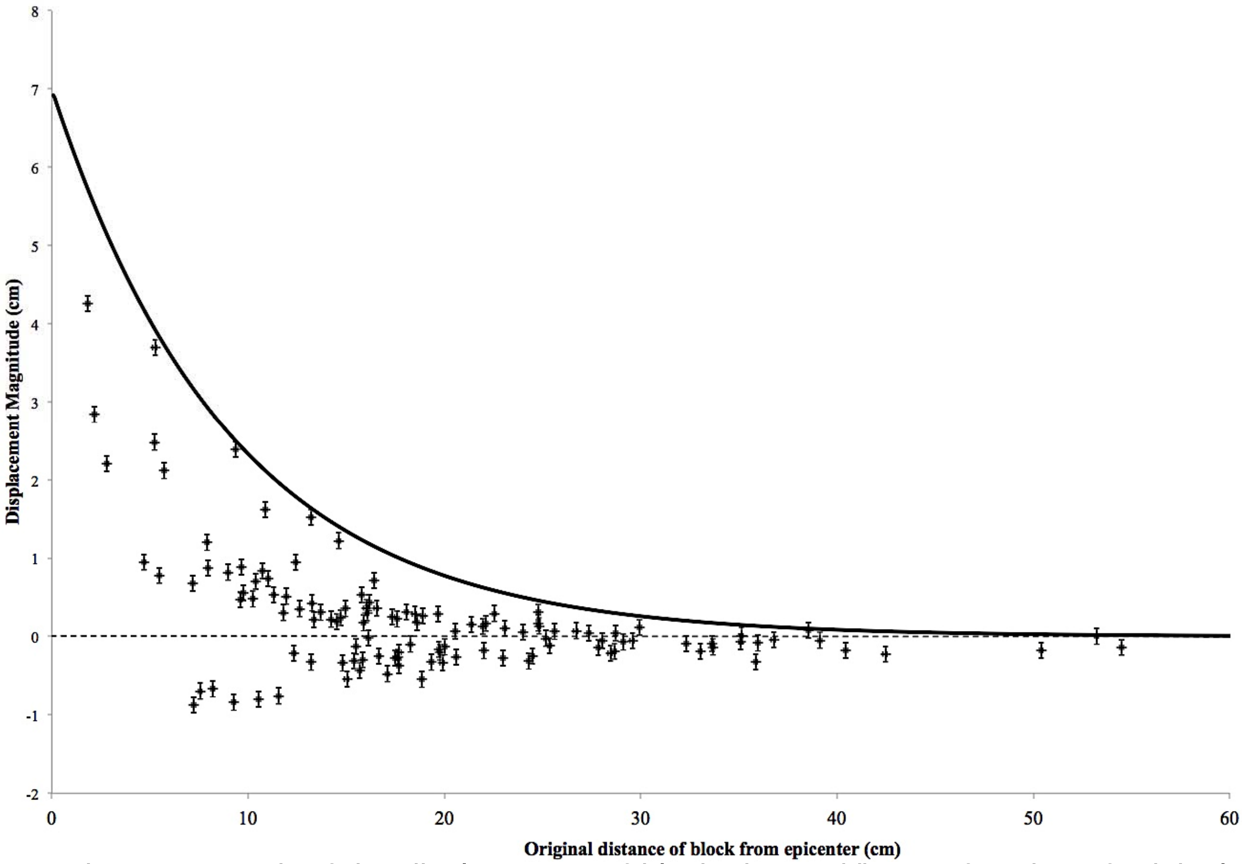

Figure 6: Graph of the displacement of blocks in cm (d) as a function of original distance of the block from the seismic epicenter in cm (D). The error bars are 1 mm on each side on both the x and y axes. The line fitting the envelope is a qualitatively fit generic exponential equation of the form . The negative values at low values of D could be the result of imperfect image calibration, an inclination angle less than 90° (easily visible by comparing the lengths of the sides of the sandbox on the bottom and top of the image), the movement and/or rotation of the entire sandbox system, and the off-center seismic epicenter, among other details not yet considered. The negative values at large D are probably due to a resolution limit on the camera for detecting slight motion.

Figure 6 is a graph of the data with displacement (distance that the rock moved) as a function of original distance of the rock from the epicenter. The envelope line was fit qualitatively, but is a general exponential function of the form $= 7 \quad {}^{-}\overline{10}$, where d is the displacement and D is the original distance from epicenter. The error bars for both the x and y axis are 1 mm on either side and represents ten times the resolution accuracy on ImageJ.

DISCUSSION AND EXPECTED SIGNIFICANCE

By comparing before and after images from both camera perspectives, it is clear that a “crater” is formed on the surface due to the seismic impulse from the bottom of the sandbox. As expected, the blocks closer to the seismic epicenter moved the farthest, but the block motion was still detectable at 10 cm away from the epicenter, despite the fact that the base is only a thin sheet of plywood. Also, the envelope appears to taper off exponentially and approach zero at large distances (in this case, 20 cm) from the epicenter.

Figure 6 shows some negative values at low D values, which could be due to a number of factors including: imperfect image calibration, an inclination angle less than 90° (easily visible by comparing the lengths of the sides of the sandbox on the bottom and top of the image), the movement and/or rotation of the entire sandbox system, and the off-center seismic epicenter, among other details not yet considered. The images presented here will continue to be refined and studied, as well as the images from other camera angles and orientations.

Qualitatively, the optimal viewing angle for detecting block motion is 90°. The probability for false positives increases as the viewing angle becomes more oblique because it is harder to accurately determine motion for blocks that are farther from the camera.

Future research includes: 1. Completing the measurements of block motion for all imaging combinations. 2. Using the Smoothed-particle hydrodynamics (SPH) code Spheral [26] to study surface velocity attenuation in an asteroid and its effects on surface characteristics 3. Building a sturdier sandbox for laboratory experimentation and 4. Refining the image correction factors for use in future experiments and missions.

The results from this research will have significant implications for providing mission requirements for future missions such as the Asteroid Origins Satellite (AOSAT) [22] and the Asteroid Impact and Deflection Assessment (AIDA) [23]. Further analysis of these results will yield better constraints on where future missions could focus their attention to study block motion and peak velocity on the surface of an asteroid post-seismic event. This will also constrain mission details such as altitude, number of passes over a certain area, required size of seismic blast, and data rate, as well as other observations that could be conducted on the same mission.

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