USING CONTROLLED IMPACT EXPERIMENTS TO UNDERSTAND THE EFFECTS OF COHESIVE BLOCKS ON THE CRATERING PROCESS.

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Introduction: When considering large-scale impact events that occur in the gravity-regime, small-scale target heterogeneities (on order of the projectile diameter) are anticipated to have a minimal effect on the cratering process and are therefore not considered in scaling relations [1-3]. Such heterogeneities and other details of the target's strength and structure, however, become increasingly influential as the magnitude of the impact decreases [4]. At the scale of craters forming mostly in regolith on the Moon (< a few meters), for example, target properties such as cohesive strength, density, porosity, and friction have more leverage than gravity to influence the resultant crater dimensions [5]. Further complications beyond just target properties can manifest in many forms, such as subsurface layers [6]; the presence of random, competent blocks [7]; buried lenses of impact melt; and/or pockets of regolith compacted or indurated to varying degrees by previous impacts. Summing the total effect of target properties and any additional heterogeneities for integration into scaling relations is not straightforward, as each individual parameter will have unequal, and so far, unquantified, effects on the final crater. Even when craters are produced under a best-case scenario of controlled laboratory conditions, understanding the entire relevant parameter space can be a formidable task, and deconvolution of all the contributing factors can be a complex undertaking.

To begin the process of quantifying such effects, we are conducting an extensive series of impact experiments to build a framework for the interpretation of craters observed on the characteristically complex surfaces throughout the solar system. Here we present the first, and simplest, configuration to be examined in this multi-year experimental campaign: one in which solitary, cohesive blocks are placed in the path of the projectile's trajectory at different burial depths in granular, sand targets. Among the variables to be investigated in this configuration are the influence of block size, compressive strength, and burial depth.

Methods: All experiments were conducted with the vertical gun in the Experimental Impact Laboratory at the NASA Johnson Space Center. The targets were made by filling cylindrical PVC buckets (26.2 cm diameter, 12.2 cm depth) with a predominantly quartz, fine-grained sand, and included one synthetic sandstone block per target. These cubic blocks, with edge lengths ranging from 5 to 33 mm, were fabricated in silicone molds, using the same fine-grained quartz sand, but made cohesive with the addition of an organic binder. Their compressive strengths were controlled by the amount of binder mixed into the sand, with three different strengths being used, 0.5, 4.2, and 7.4 MPa. In each experiment, a block was placed at one of five different vertical locations, directly at or below the impact point: (1) the base of the block resting on the surface of the sand (tangent above), (2) block half-buried, (3) the top face of the block aligned with the surface (tangent below), (4) with the top face of the block at $d_{ref}/2$, and (5) with the top face of the block at d_{ref}, where d_{ref} refers to the depth of a reference crater formed in the same sand without a block being present (Fig. 1). All impact experiments were conducted at an atmospheric pressure of 1 torr, with the target/block surface normal to the impact vector. The projectiles used were 4.76 mm (3/16") Al_2O_3 spheres that were accelerated to 1.53±0.02 km s^{-1}. The ejecta were photographed with the Ejection-Velocity Measurement System (EVMS) [8], and crater morphometry was recorded after completion of each experiment with a Peel 2 3D-scanner. At the time this was written, a total of 66 shots had been completed.

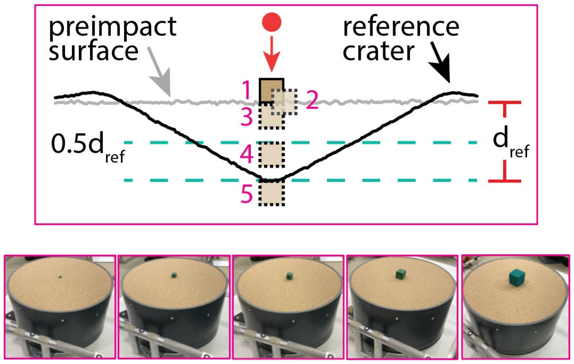

Figure 1. Upper frame: Schematic of the possible block locations with the burial depth of a block being defined by its uppermost face. The half-buried block is shifted to the right for clarity. Lower frames: Size comparison of the five block sizes in the "tangent above" configuration. The scale of the smallest block is similar to those of the spherical, ceramic projectiles used in the experiments.

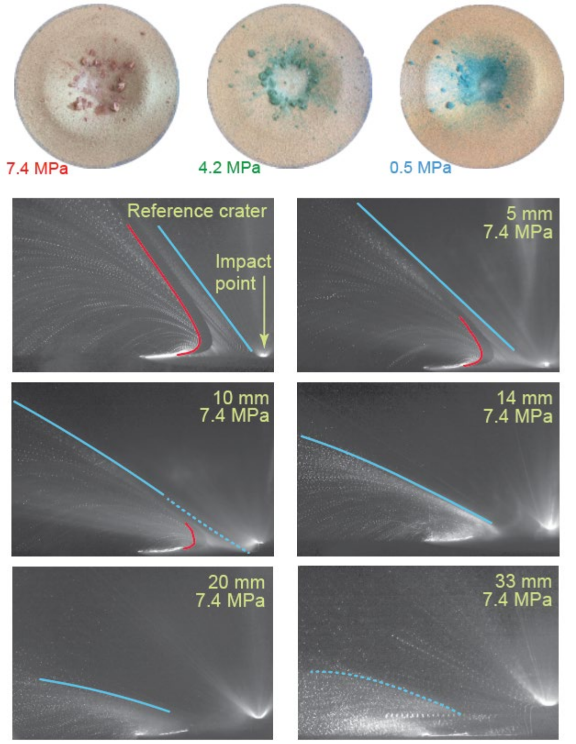

Figure 2. Top: Three craters formed with half-buried 33 mm blocks of varying strength (top). Below them are EVMS images collected from the reference target and five others, each with a block of different size but the same strength on its surface (tangent above). The red curve in each frame is the location of the ejecta curtain 12 ms after impact (where discernable), while the blue one is an approximation of the highest-angle trajectory visible from the sand target. Particles from the blocks were ignored here.

Results: *Morphometry/Morphology* – A reference crater was created using a block-free target and was used as a basis of comparison for all measurable dimensions. This crater exhibited the expected simple, conical morphology, with a rim-crest diameter of 18.32 cm, and a depth (measured from the rim crest) of 4.00 cm. The introduction of competent blocks into the targets did affect crater dimensions in most instances, but all craters would still be classified as conical in shape. Blocks placed in the tangent-above configuration had the most influence on crater dimensions, with both diameter and depth decreasing as the size of the block increased. Half-buried blocks, regardless of size, produced minimal changes to the measured diameter and depth, while most shots in the tangent below and $d_{ref}/2$ configurations display a trend of marginally increased crater dimensions with increasing block size. No block placed with its top surface at d_{ref} had an observable influence on the final crater's morphometry. For any given size and location of block, there appeared to be no trend observed between block strength and crater dimensions over the entire test matrix. Importantly, all observed morphometric changes across the entire experimental suite were relatively small in magnitude, but the distribution and survivability of disrupted block fragments varied significantly with block strength (Fig. 2, top).

Ejecta – Similar to the effects on crater morphometry, ejecta patterns appear to be more influenced by the size and location of the block than its strength. A qualitative trend, for example, was demonstrated for the tangent-above configuration, in which increasing block size depressed the maximum ejection angle of the cohesionless sand ejected (Fig. 2, bottom). The dependence of ejection angle on block size waned as burial depth increased and vanished when the block was tangent below or deeper. The maximum ejection angle appeared to be unaffected by any block once it was buried to $d_{ref}/2$.

Discussion: Despite the inability of even the largest tested block size to have a significant effect on the subsequent crater dimensions, the surface expression of fragment-laden craters as a function of block strength and burial depth may provide helpful clues into regolith evolution and gardening processes. Blocks placed on the surface (regardless of size or strength), for example, left no trace within roughly two crater radii of their original locations. This material was completely disrupted and ejected fast enough to hit the impact chamber walls (thus preventing determination of ballistic range), suggesting long-range transport of surficial block material. In contrast, blocks buried to the reference depth were usually fractured in place with no block material being ejected, providing an opportunity to make these now smaller, shocked pieces more prone to mobilization during subsequent but necessarily larger impact events.

A major objective of this study was to examine how projectile energy lost to disrupting competent material would effect cratering efficiency. In light of these findings, however, follow-up experimentation is now planned to analyze the mobility/survivability of blocks placed at different radial positions outside of the impact location.

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