The effects of target density, porosity, and friction on impact crater morphometry: Exploratory experimentation using various granular materials

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Abstract—The dimensions of relatively small-scale impact craters are undoubtedly sensitive to the physical properties of the target. Studying gravity-controlled crater formation at the laboratory scale often relies on cohesionless, granular materials, which, by their nature, make it difficult to separate the individual contributions to this process from all of the relevant target properties. Here, we conduct a suite of impact experiments to isolate and evaluate the effects of density, porosity, and internal friction on impact crater morphology. Each made from one of four different granular materials, targets were impacted vertically with 4.76 mm aluminum projectiles at an average speed of ~1.55 km s\(^{-1}\). Two different methods were used to load these materials into the target bucket (pouring and sieving), resulting in targets that varied in bulk density and internal friction. The experimental results indicate that depth–diameter ratios of the craters are largely influenced by the loading method of the target material and are sensitive to the friction and porosity of the targets. Sieved targets (relatively higher density, lower porosity, and higher friction angle) produce craters that are markedly shallower, have notably smaller volumes, and exhibit a flat-floored morphology, with some possessing small central mounds. Flat-floored craters are typically attributed to a strength-layered target; in these experiments, however, they were produced in cohesionless targets. This study demonstrates that a flat floor is not necessarily diagnostic of strength layering in a target and, in some instances, might be the consequence of greater shear strengths in granular materials with high coefficients of static friction.

INTRODUCTION

The latest generation of orbital cameras returning high-resolution images of a variety of planetary surfaces has made it possible to conduct photogeologic examinations of impact craters down to the scale of only a few meters (e.g., Daly et al., 2020; Noguchi et al., 2020; Robinson et al., 2010; Stopar et al., 2017; Walsh et al., 2019). Previous works have demonstrated that the morphologies and morphometries of craters at this scale are sensitive to the physical properties of the target (e.g., Housen & Holsapple, 2003; Quaide & Oberbeck, 1968; Schmidt, 1980; Schmidt & Housen, 1987). These relatively small and very abundant craters, therefore, offer a new opportunity to probe the surficial and near-surficial properties of the planetary bodies that host them. This type of interpretation is, however, invariably fraught because it relies on previously established empirical relationships that relate crater morphology and morphometry to impact conditions. Inferences of target properties are therefore dependent on the completeness of those experimentally derived relationships.

Some recent efforts in impact cratering studies have focused on understanding the cratering process in highly porous media. Extremely high-porosity targets, such as the surfaces of some asteroids and comets, act as momentum traps for projectiles (Housen & Holsapple, 2003). Such targets yield craters with
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The stress term in experiments of this work were cohesionless (e.g., Hirata et al., 2009; Housen & Holsapple, 2003; Noguchi et al., 2020), phenomena that have been duplicated experimentally by Housen and Holsapple (2012) and Housen et al. (2018). Such high values of porosity (much higher than the 40% average porosity of dry sand and gravel piles in terrestrial settings) lead to a different regime in crater growth referred to as compaction cratering by Housen and Holsapple (2003), in which a change in failure mechanism from shear to permanent crushing of grains is thought to occur.

The bulk density and porosity of granular targets are intimately related, complicating empirical attempts to isolate their separate effects on the outcomes of impact events. The few cratering studies designed to investigate porosity have either focused on impacts into cohesive aggregates (e.g., Love et al., 1993) or probed porosity regimes that are typically so high as to be observed only on comets and asteroids, where compaction cratering appears to dominate (e.g., Housen et al., 2018; Housen & Holsapple, 2003; Schultz et al., 2005). More specifically for the purposes of this effort, the high levels of porosity in the latter studies were achieved with mixtures of quartz sand and grains of expanded perlite or pumice, which contain their own intragranular porosity. The inclusion of those materials frustrates any attempt to derive the effects of intergranular porosity from the data.

The friction angle of a target material also plays a role in determining the size of a crater formed in both the classical “gravity” and “strength” regimes of cratering (Holsapple, 1993). (These two “regimes” can be considered as endmembers of a continuum. A crater whose growth is ultimately arrested by the cohesion of the target material [e.g., small impacts into rock] is said to form in the “strength regime,” while one whose growth is stopped by the effects of gravitational acceleration [e.g., very large craters or those forming in cohesionless materials] has formed in the “gravity regime.”) In both cases, shear is thought to be the actual failure mode of the material being displaced or ejected from the growing cavity in low to moderately porous targets (Housen et al., 2018).

The Mohr–Coulomb criterion can be used to describe the shear strength (τ) of a sand-like material and is expressed as \( \tau = \sigma \tan \phi_s + c \), where \( \sigma \) is the normal stress, \( \phi_s \) is the angle of internal friction, and \( c \) is the cohesion. Because the sands used in these experiments of this work were cohesionless (\( c = 0 \)), the angle of internal friction can be approximated by the angle of repose (\( \alpha \)). For applications relating to the study of impact craters formed in the gravity regime, the stress term \( \sigma \) can be substituted for the overburden pressure, which is the product of density, local gravity, and depth (e.g., \( \rho g z \)). This means that the granular material will have an effective strength that is both dependent on the overburden pressure and sensitive to the internal friction of that specific material. Even though the differences in effective strength can be small under static conditions at the laboratory scale, they can produce noticeable effects on a growing crater when the transient stress from the impact is combined with the overburden pressure (Barnouin-Jha et al., 2007; Prieur et al., 2017).

Computational studies are free from the difficulty of separating specific codependent target properties and are able to conduct simulations where variables such as porosity, bulk density, target strength, and internal friction can be modified at will (Elbeshauen et al., 2009; Wünneumann et al., 2006). Some of the computational results to this end indicate that increasing the friction angle of a granular target while holding other properties and impact conditions fixed will result in a decreased crater diameter (Prieur et al., 2017; Wünneumann et al., 2011). There is some experimental evidence that increasing a target’s internal friction will decrease cratering efficiency and crater depth (Housen et al., 2018; Schmidt, 1980), but these observations were not comprehensive. Instead, general trends were suggested on the basis of experiments where multiple properties were allowed to vary (e.g., grain sizes, grain shapes, or both).

Understanding the interplay among porosity, bulk density, and friction in regulating crater growth is still in its nascent stages. Despite the contributions provided by computational techniques in untangling the mélange of target properties responsible for defining the morphometries of impact craters, these results ultimately must be benchmarked through experimental observations. In this study, we explore the influences of bulk density, friction, and porosity by conducting a suite of impact experiments using cohesionless targets that allow each of these properties to be decoupled from the others. We then compare the resulting crater morphometries with those of other experimental, photogeologic, modeling, and scaling studies.

**EXPERIMENTAL METHODOLOGY**

**Target Materials and Preparation**

The suite of experiments presented in this study was designed to allow the bulk density of the targets to be changed while the porosity could be held constant. Modifying the bulk-target density was achieved by using four different sands that had similar grain size distributions. These included one material that was unusually small depth–diameter ratios and a conspicuous lack of ejecta (i.e., Hirata et al., 2009; Housen & Holsapple, 2003; Noguchi et al., 2020), phenomena that have been duplicated experimentally by Housen and Holsapple (2012) and Housen et al. (2018).
predominately quartz (>90% and will be referred to as “quartz” from here on), and the other three being monomineralic alumina, garnet, and olivine (Fig. 1; Table 1). Since the bulk porosity of a granular material is largely determined by the grain size distribution (among other parameters like grain shape), this provided an opportunity to set the porosity of each target by using specific packing techniques.

Targets were fabricated using two different packing techniques for each of the four sands. First, a set was constructed by pouring the sand into the cylindrical PVC target bucket (26.2 cm diameter and 12.2 cm depth). This material was allowed to heap at the angle of repose until the container was completely filled. Excess sand was then scraped off the top of the bucket with a metal straightedge to form a flat surface. This process yields relatively high porosity targets for each material, since the sand is packed at its loosest state. A second set of targets was constructed using a pluviation technique, in which the sand was poured through a 1 mm sieve held above the target bucket. The sieve did not modify the grain size distribution of the materials, but produced more densely packed, lower porosity targets. Similarly, the excess sand was then scraped off the top of the bucket before the shot. The target densities obtained through this pluviation process were similar to the values for these materials at their maximum packing fraction. In comparison to the other materials, the quartz sand packed to a higher density for a given fabrication technique due to it having a rounder grain shape (see Figs. S1–S4 in the supporting information), while the other three materials yielded similar porosities. The poured quartz target had an identical porosity to the sieved targets of the other three materials. Therefore, three total porosities were achieved with the eight targets tested, 0.36 ± 0.01, 0.45 ± 0.01, and 0.53 ± 0.01 (Table 1).

### Defining the Angle of Repose/Maximum Coefficient of Static Friction

Porosity and bulk density are not the only physical properties of the target that are dependent on the packing method; the angle of repose is also directly affected. Many protocols exist to determine the static and dynamic angles of repose for a granular material, but there currently is no accepted standardized procedure (for a review, see Al-Hashemi & Al-Amoudi, 2018). The most commonly used technique is the “fixed funnel” method, in which the granular material is allowed to flow through a funnel and pour onto a horizontal surface to form an unconfined heap. The angle of repose is then taken as the angle formed between the horizontal and the slope of the heap. A good approximation for the maximum static coefficient of friction (μs) can then be obtained by taking the tangent of this angle. The fixed-funnel method has been used to define both α and μs for the poured targets, but another procedure must be used for the targets that have been constructed using the pluviation method.

Experimental fault reactivation studies using cohesionless sands have demonstrated that the coefficient of friction is sensitive to the process of handling these materials, and that higher values will be observed for greater packing densities (Carson & Pittenger, 1998; Krantz, 1991; Montanari et al., 2017). It is therefore critical to recognize that the angle of repose (α) and, by consequence, μs for the pluviated sand will not be the same as that of the poured sand.
We used the circular heap method, briefly described in Carson and Pittenger (1998), to measure $\alpha$ of the sands at their maximum packing fraction. This technique uses an elevated, circular platform placed inside a larger, tall, thin-walled cylindrical container that can be filled with sand and then drained from the bottom at a controllable rate (Fig. 2a). It is important to note that this method was not originally designed to measure the angle of repose at elevated packing fraction. We modified the technique to get the maximum density of the sand by tapping the outside of the PVC cylinder 100 times with a 3-lb rubber mallet before removing the drain plug. The heap remaining on the cylindrical stand after the sand was drained was then imaged with a 3-D scanner and the angle of repose determined from the average of four slopes acquired at 90° intervals. As predicted, $\alpha$ and thus $\mu_s$ determined for the sands used in this study were found to be demonstrably larger at maximum packing fraction than for those that were poured. The sand heaps formed at higher density consistently displayed taller, sharper peaks and the ability to support local ridges along the wall slope (Figs. 2b, 2c and 3).

For a comparison with the fixed funnel method, sand at pour density was also tested using the circular heap method. The results indicate that the calculated $\alpha$ values for the poured sands tested using this method are consistently ~3° higher than those determined with the fixed-funnel method at the same packing fraction. This error is small in comparison to the range of $\alpha$ values that can be observed when using some of the other published measurement techniques for the angle of repose. The differences between using internal (draining sand forming a “V”) and external slopes (heaping sand forming an inverted “V”), for example, can return values of $\alpha$ that vary by as much as 10° for the same granular material (Al-Hashemi & Al-Amoudi, 2018). In the poured sand, the small difference between the measured values of $\alpha$ determined using both techniques helped inform the decision to use the more commonly accepted fixed-funnel method as the measure of $\alpha$ for poured sand targets. This choice also allows for a closer comparison of our results to those of previous studies.

**Impact Experiments**

Impact experiments were conducted using the vertical gun in the Experimental Impact Laboratory of the Astromaterials Research and Exploration Science Division at NASA Johnson Space Center. Spherical aluminum projectiles, with diameters of 4.76 mm (3/16”) and masses of 0.156 g, were launched at speeds of 1.55 ± 0.03 km s⁻¹ normal to the surface of each horizontally mounted granular target (Fig. 4). Each shot was conducted at room temperature (~298 K) and a chamber pressure of 1.000 ± 0.002 torr. Undesired effects from the propellant gases were mitigated with three types of blast deflection: a hinged flapper valve located a few inches from the muzzle, a screened debris filter that also acts to disrupt gas flow, and a thin Mylar diaphragm placed at the entrance to the impact chamber. The diaphragm was perforated by the projectile as it entered the impact chamber and was thin enough as to leave the projectile itself unaffected (e.g., Hörz et al., 1994, 1995).

Immediately before and after each experiment, a high-resolution NextEngine 3-D scanner was affixed to the exterior of the impact chamber and used to capture morphometric data at a submillimeter scale. These scans

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Fig. 2. a) Schematic of the circular heap method for determining the angle of repose. The panel on the right shows renderings from 3-D scans that show heaps of garnet sand produced by either the (b) circular heap or (c) the fixed-funnel method. Both scans use the same height scale, which is shown in the upper right corner. (Color figure can be viewed at wileyonlinelibrary.com.)
were then processed using the open-source software package CloudCompare. A variety of crater measurements, cross sections, and topographic maps were produced from the scans using the tools that are integral to the software. It is important to note that we determined and present measurements that are made relative to both the crater rim crest and the original preimpact surface (e.g., the displaced volume). Values of “apparent” diameter, depth, and volume calculated with respect to the preimpact surface (Barnouin et al., 2019; Holsapple & Schmidt, 1979; Housen & Holsapple, 2011; Pike, 1977a) are labeled with the subscript $a$. Otherwise, variables with the subscript $r$ indicate measurements made relative to the rim crest of the crater. A schematic of these definitions is provided in Fig. 5; definitions of all relevant variables can be found in Table 2.

**RESULTS**

**Crater Morphology and Morphometry**

The appearance of the impact craters formed in the poured sand targets was macroscopically distinct from those in the targets produced by pluviation/sieving (Fig. 6). The poured sand craters were all conical in shape; the deformed aluminum projectile and a quantity of pulverized target material were typically found buried ~1 cm below the bottom of the crater. All of the sieved...
targets, in contrast, produced craters that were markedly more bowl-shaped and contained higher albedo detritus on the crater floor. This debris was comminuted target material, much of which appeared to have been sintered into weakly agglomerated chunks. In all four cases, the projectile was found either on top of the sieved targets (e.g., Shot 6811 in Fig. 6) or on the floor of the impact chamber (implying that it rebounded off the target). In an extreme case (shot 6828 in sieved olivine sand), the projectile was found to be resting on a relatively tall (~5 mm) and slender pillar of sintered olivine directly below the impact point. (The pillar is still intact in the photograph in Fig. 6 and the profile shown in Fig. 7.)

In contrast to those in the sieved targets, craters formed in the lower density, higher porosity, and poured sands were consistently larger and deeper, with shorter rim crests and less voluminous rims (Fig. 7; Table 3). The wall slopes of all craters, regardless of the target fabrication technique, were less than the measured static angle of repose by as little as ~4° for the garnet targets and as much as 10° for the quartz and olivine. The walls of the craters formed in the poured targets were all smooth and straight, while those of the craters in the denser, sieved targets were more complex. The slopes near the intersection of the wall with the floor in the sieved targets were typically similar to those of the craters formed in the poured targets, but the slopes increased from ~0.5δr up to the rim, leading to a convex-upward shape as the rim crest was approached.

The stark difference in morphology between the craters is reflected in a d_r–D_t plot for all eight shots (Fig. 8). Ignoring the quartz targets for a moment, it is clear that the craters in the targets with the highest porosity (Φ) of 0.53 were the deepest, with consistent values of d_int/D_t near 0.24. Decreasing Φ to 0.45, however, led to substantially depressed depth–diameter ratios, with nearly identical values for the alumina and olivine (~0.17), but an even lower value for the garnet (0.15). The quartz target yielded craters that were distinct outliers in their d_r–D_t ratios, with both being shallower than expected when using the other three materials as predictors. The more porous target, however, still produced the deepest crater. Some of these differences are addressed below.

### DISCUSSION

#### Crater Morphology

The d_r–D_t ratios of craters formed in targets with constant porosity can provide a macroscopic view of the influence of porosity (Φ) and static friction (μ_s) on crater shape. While no trend is observed in Fig. 8 between d_int/D_t and target density, the four targets at a porosity of 0.45 importantly represent both target fabrication methods. When the d_r–D_t ratios of all targets are separated by the packing technique (poured or sieved), less variability in d_int/D_t is observed, suggesting that changes in internal friction (resulting from the different packing techniques) have a larger influence on d_r–D_t ratios than does ρ or Φ.

Taking all calculated d_r–D_t ratios as a function of ρ alone yields no significant correlation (r^2 = 0.28), which could be expected from Fig. 8. Considering d_r–D_t ratios as a function of Φ, however, provides a fit with r^2 = 0.68; this general trend of increasing d_r/D_t with increasing porosity is in agreement with modeling efforts by Wünemann et al. (2011), Prieur et al. (2017), and Raducan et al. (2019) where porosity was interrogated independent of target friction. With the observation of a notable influence of friction on d_r–D_t ratios, this fit was further improved through the

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**Table 2. Variables used in this study.**

| Projectile Variable | Crater Variable | Materials and Misc. | π-groups |
|---------------------|----------------|---------------------|----------|
| δ, density          | d_r, depth from rim crest | τ, shear strength | π_1D = D_a/L |
| U, impact speed     | d_a, depth from preimpact surface | α, normal stress | π_0 = ρV/m |
| m, mass             | D_r, rim crest diameter | φ_a, friction angle | π_3 = 3.22gρ/τ^2 |
| p, radius           | D_a, diameter at preimpact surface | c, cohesion | π_0 = R/p = π_D |
| L, diameter         | D_t, diameter of transient cavity | ρ, bulk density | π_4 = d_a/p |
|                     | D_f, floor diameter | Φ, porosity | π_4 = ρ/δ |
|                     | V_r, volume from rim crest | g, gravity | π_4 |
|                     | V_a, volume from impact surface | z, depth | π_4 |
|                     | R_a, radius at impact surface | α, angle of repose | π_4 |
|                     | R_r, rim crest radius | μ_s, coefficient of static friction | π_4 |
|                     | F, floor diameter | i, thickness of overlying layer k, D_a/D_f | π_4 |

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*The subscripts a and r refer to measurements made relative to the preimpact surface and the crater’s rim crest, respectively.

All nondimensional variables use apparent crater measurements.

*Most previous scaling work uses a for the radius of the projectile. In the discussions below, however, that usage would cause undue confusion.*
incorporation of the factor $1/\mu_s$ ($r^2 = 0.91$; Fig. 9). While the physical meaning of this correlation between $d_r/D_r$ and $\Phi/\mu_s$ will require further investigation, it is possibly hinting that another physical parameter or parameters, such as grain shape (roundness and/or angularity), could be important but not captured in this analysis.

When the depth and diameter are examined separately, it becomes evident that each follows a different functional relationship with the target properties. Figure 10 plots the scaled crater diameter ($\pi_D$) and scaled depth ($\pi_d$) as functions of $\pi_\delta$ (density ratio), $\mu_s$, and the respective products of these parameters (see Table 2 for definitions of the $\pi$ variables). The scaled crater diameter correlates better with $\pi_\delta$ ($r^2 = 0.80$) than with $\mu_s$ ($r^2 = 0.62$), mainly due to both quartz experiments being outliers. The scaled crater depth, however, correlates more satisfactorily with $\mu_s$ ($r^2 = 0.94$) than with $\pi_\delta$ ($r^2 = 0.64$). A decrease in crater depth as a function of increasing $\mu_s$ was also observed by Schmidt (1980) and is discussed in more detail below. The product $\pi_\delta\mu_s$ provides a nominally better value of $r^2$ for $\pi_D$, but does not improve that for $\pi_d$.

Comparing crater measurements made relative to the preimpact surface and rim crest also suggests that
the ratio between these two types of values may not be constant. Some authors, in the absence of direct measurements of $d_a$ and $D_a$, use previously established morphometric relationships between apparent and rim crest measurements to infer crater dimensions (Pike, 1977b). It is common, for example, to see conversions of crater radius, such as, $R_a = R_r/1.3$ used in experimental (Housen & Holsapple, 2011; Tsujido et al., 2015) and photogeologic studies (Dundas et al., 2010). However, our 3-D scans allowed direct measurements of the depths and diameters of the craters in this study relative to both their rim crests and the

Table 3. Target densities, impact conditions, and crater morphometries.

| Shot number | Target material | $\rho$ (g cm$^{-3}$) | $U$ (km s$^{-1}$) | $d_r$ (cm) | $d_a$ (cm) | $D_r$ (cm) | $D_a$ (cm) | $V_r$ (cm$^3$) | $V_a$ (cm$^3$) |
|-------------|-----------------|----------------------|------------------|------------|------------|------------|------------|--------------|--------------|
| Poured      |                 |                      |                  |            |            |            |            |              |              |
| 6730        | Quartz          | 1.47                 | 1.57             | 3.60       | 3.21       | 17.41      | 15.02      | 285.80       | 189.67       |
| 6827        | Alumine         | 1.59                 | 1.57             | 3.55       | 3.17       | 14.97      | 12.88      | 208.37       | 137.74       |
| 6812        | Garnet          | 1.78                 | 1.54             | 3.40       | 2.97       | 14.42      | 12.18      | 185.17       | 115.40       |
| 6793        | Alumina         | 1.85                 | 1.54             | 3.48       | 3.03       | 14.65      | 12.62      | 195.62       | 126.39       |
| Sieved      |                 |                      |                  |            |            |            |            |              |              |
| 6753        | Quartz          | 1.68                 | 1.52             | 2.63       | 2.25       | 16.07      | 13.35      | 177.89       | 105.03       |
| 6828        | Alumine         | 1.87                 | 1.55             | 2.37       | 2.06       | 13.72      | 10.82      | 116.85       | 63.17        |
| 6811        | Garnet          | 2.12                 | 1.53             | 1.99       | 1.63       | 13.25      | 10.13      | 91.51        | 43.81        |
| 6791        | Alumina         | 2.19                 | 1.54             | 2.35       | 1.90       | 13.74      | 10.92      | 116.20       | 59.34        |
Fig. 8. Depth ($d_\text{r}$) plotted versus diameter ($D_\text{r}$), measured at the rim crests, for all shots in this study. Four measurements of depth and diameter were made for each crater at 90° intervals; the error bars represent 2σ. Closed symbols represent poured targets and open symbols represent sieved targets. (Color figure can be viewed at wileyonlinelibrary.com.)

Fig. 9. Semi-log plot of depth–diameter ratio as a function of $\Phi/\mu_s$. (Color figure can be viewed at wileyonlinelibrary.com.)

preimpact surface. These results do not follow this widely used relation; in contrast, the ratios of $R_r - R_D$ and $d_r - d_a$ vary and appear to be influenced by the target properties. Specifically, a possible relationship emerged between these ratios and the product of bulk density and the coefficient of friction (Fig. 11). It is for this reason that we are being explicit throughout this work as to the specific measurement being used in each analysis.

Comparison with Previous Studies

Scaling relations can be used to compare many of the parameters of a given impact and the respective crater dimensions to other “similar” events (which implies that, although individual parameters might differ between the events, the relevant dimensionless groups [Table 4] will remain constant, e.g., Holsapple & Schmidt, 1980). A plot of cratering efficiency as a function of $\pi_2$ (Fig. 12) shows good agreement between the poured quartz targets and other studies using poured quartz sand, along with the “dry-sand scaling” relation of Schmidt and Housen (1987). All of the targets constructed of sieved materials tested here, however, have suppressed cratering efficiencies relative to the other quartz sands in Fig. 12. This is explained for the other poured targets with the increase in intrinsic grain density, but regardless of the specific granular material, the craters in each sieved target have distinctly lower values of $\pi_V$ compared to those of their poured counterparts. Schmidt (1980) and Housen et al. (2018) found the same behavior and attributed this depression of $\pi_V$ to the higher shear strength of the target due to an increased friction angle or to materials with higher values of $\alpha$. With all of the data in this study collected at a nearly constant value of $\pi_2$, we can now explore the origin of the depressed values of $\pi_V$.

Schmidt (1980) reported that reduction in cratering efficiency (or $\pi_V$) with increased friction angle was largely due to a decrease in the depth of the crater rather than the diameter. We made similar observations, shown in Fig. 10, that $\mu_s$ disproportionately affected $\pi_D$ and that combining $\mu_s$ with $\pi_D$ produced an improved fit. Plotting cratering efficiency as a function of $\mu_s$ does yield a fair correlation ($r^2 = 0.80$), but it can be improved slightly by also including the $\pi_4$ term ($r^2 = 0.85$; Fig. 13). This supports the suggestions of Schmidt (1980) and Housen et al. (2018) that friction is the dominant factor controlling cratering efficiency in the context of these experiments and manifests itself largely in the depths of craters in otherwise similar experiments.

The targets in Fig. 13 were well characterized, but it is still difficult to separate the effects of porosity and friction with confidence, given that only three different porosities could be produced with the materials and packing techniques used here. The modeling study of Prieur et al. (2017) reported on the effects of porosity and friction by independently varying each parameter in a series of simulated impacts. Their results can be compared to those of this study (Fig. 14), but in doing so, it is important to note that the $\pi_D$ values of Prieur et al. (2017) are cast in another commonly used form given as $\pi_D = D_1(\rho/m)^{1/3}$, where $D_1$ is the transient crater diameter. It was not possible to measure the diameter of the transient cavity in the present experiments, so the apparent diameter is used. In addition, the current study was designed to compare craters formed at constant $\pi_2$, so a detailed comparison with the model results of Prieur et al. (2017), as would be preferred, is precluded. Nevertheless, the experimental data and modeling results agree in terms of the relative ordering of different combinations of
porosity and friction values. In essence, the models capture the general dominance of friction in controlling the crater’s diameter at this location in porosity-friction space. Since their models typically truncate the cratering process near when the maximum transient cavity is obtained, however, it is unclear if their models would...

Fig. 10. Scaled crater diameter plotted as a function of density ratio (a), coefficient of static friction (b), and the product of these two parameters (c). Panels (d)–(f) have the same abscissas as (a)–(c), but are plotted against scaled crater depth. All experiments were conducted at nearly constant $\pi_2$. Closed symbols represent poured targets and open symbols represent sieved targets. (Color figure can be viewed at wileyonlinelibrary.com.)
The ratio of rim crest (a) radius and (b) depth to their respective apparent values plotted as a function of the product of the target’s measured bulk density and coefficient of static friction, plotted on a log scale. (Color figure can be viewed at wileyonlinelibrary.com.)

Fig. 11. The ratio of rim crest (a) radius and (b) depth to their respective apparent values plotted as a function of the product of the target’s measured bulk density and coefficient of static friction, plotted on a log scale. (Color figure can be viewed at wileyonlinelibrary.com.)
Table 4. \( \pi \)-groups for each experiment in this study.

| Shot number | Target material | \( \pi_V \) | \( \pi_2 \) | \( \pi_4 \) | \( \pi_R \) |
|-------------|-----------------|----------|----------|----------|----------|
| Poured      |                 |          |          |          |          |
| 6730        | Quartz          | 1945     | 3.056 \times 10^{-8} | 0.543    | 36.56    |
| 6827        | Olivine         | 1515     | 3.067 \times 10^{-8} | 0.588    | 31.43    |
| 6812        | Garnet          | 1348     | 3.163 \times 10^{-8} | 0.657    | 30.28    |
| 6793        | Alumina         | 1387     | 3.177 \times 10^{-8} | 0.683    | 30.76    |
| Sieved      |                 |          |          |          |          |
| 6753        | Quartz          | 1408     | 3.273 \times 10^{-8} | 0.623    | 33.74    |
| 6828        | Olivine         | 1043     | 3.147 \times 10^{-8} | 0.693    | 28.81    |
| 6791        | Alumina         | 1144     | 3.176 \times 10^{-8} | 0.809    | 28.85    |
| 6811        | Garnet          | 859      | 3.222 \times 10^{-8} | 0.784    | 27.82    |

\( \pi \)-groups are defined in Table 2 and use measurements of the apparent crater for comparison with previously published work. The mass and density of the projectile were constant at 1.56 g and 2.76 g cm\(^{-3} \), respectively.

Considerations for the Lunar Cratering Record

As shown in Figs. 6 and 7, the two target fabrication techniques produced different crater morphologies. The targets made by pouring sand yielded conical craters typical of laboratory impacts into sand, but the sieved targets generated structures that were essentially flat floored and, in the cases of the quartz, alumina, and olivine, even possessed incipient central mounds. The reliefs of these mounds were small, only on the scale of two to three grain diameters in height; unfortunately, the relatively coarse grain size of the materials used here was not conducive to precise measurement of the mound heights. Further discussion on the morphometry of possible central mounds in sieved targets will be deferred until experiments can be conducted on finer grained materials.

Regardless of the presence of a central mound, the creation of flat-floored craters was unexpected. This is especially important since such features typically have been viewed as being indicative of the presence of a cohesive or competent horizon beneath a fragmental regolith. The experimental work of Oberbeck and Quaide (1967, 1968) and Quaide and Oberbeck (1968) (the latter being referred to as “Q&O” in the remainder of this paper) examined the changes in crater morphology as a function of “regolith” depth over a competent unit by burying epoxy-bonded aggregates under cohesionless quartz sand. These works defined the classic progression of morphology from simple craters, through central mound and flat-floored structures, and ultimately ending with concentric craters as the regolith thickness decreased. This same sequence of continual morphologic change has also been documented in experimental work by Anderson et al. (2020, 2021). To
put the flat floors of the current study into context, Fig. 18 shows a cross section of the crater in the sieved quartz target (shot 6753) and one of an unpublished crater from a target containing a competent substrate buried under 2.4 cm of poured sand (shot 6741, graciously provided by J.L.B. Anderson). The similarity between the two profiles is notable. Shot 6741 used the same quartz sand as that of shot 6753, but it was poured onto the cohesive substrate, leading to different values of static angle of repose (for the regolith component) between these two targets. Otherwise, the actual impact events used identical projectiles (4.76 mm spherical aluminum) and had comparable impact speeds of 1.516 (6753) and 1.535 km s\(^{-1}\) (6741).

The experimental data of Q&O also provided quantitative information on the ratio of the diameter of the flat floor to the crater diameter and how that ratio changed as a function of the regolith thickness. Q&O derived a functional relationship between the two as follows (see Table 2 for definitions of variables):

\[
D_F/D_T = k - \frac{2\ell\cot\alpha}{D_T}
\]

\[
\pi_2 \times (\rho/m)^{1/3} = \pi_4 \text{ constant within each experimental series}
\]

Bart et al. (2011) and Bart (2014) rearranged this equation as

\[
t = \frac{1}{2} \left( k - \frac{D_F}{D_T} \right) \tan\alpha
\]
equation can, in a similar way, also be used to estimate the regolith thickness that would be inferred from the observed morphometry of shot 6753 (sieved quartz), notwithstanding the fact that it contained no actual competent layer. Doing so yields an estimated “regolith” thickness of 4.2 cm, quite different from the known depth of 2.4 cm for shot 6741.

Since shear is the primary mode of material failure during crater formation (Barnouin-Jha et al., 2007; Holsapple, 1993; Housen et al., 2018; Housen & Holsapple, 2012), some estimates of the effective strength of this target can be gleaned from the analysis in the preceding section. Using the target density of 1.68 g cm\(^{-3}\) and a burial depth of 2.4 cm, the calculated effective shear strength \(\tau\) of target 6753 was \(-350\) Pa. The unconfined compressive strength of the cohesive substrate used in shot 6741 was measured at \(-2\) MPa, while the tensile strength, derived by the “Brazilian” technique (Jaeger & Cook, 1969), was 0.46 MPa. Approximating \(\tau\) with the tensile strength (Holsapple & Housen, 2007), the densely packed quartz sand (shot 6753) at depth had a lower value of \(\tau\) than the cohesive substrate (shot 6741) by about three orders of magnitude.

At least two possibilities exist that might account for the similarity in morphology between these two craters in the face of the discrepancy in effective \(\tau\) and the estimated burial depth of the competent layer. The first is that the contribution from the stress wave was not included in the calculation of effective \(\tau\) for the dense quartz sand. The peak shock stresses and their rates of decay for the shots presented in this study are not known, so the calculated effective \(\tau\) of the sieved quartz sand at depth (~350 Pa) can be considered only as an extreme lower bound. Nevertheless, the dynamic contribution to \(\tau\) from the passing stress wave could be significant. It has been demonstrated, for example, that crater growth times and \(d-D\) ratios of transient cavities are sensitive to impact speed, implying a role for greater effective \(\tau\) as a consequence of higher peak stresses (Barnouin-Jha et al., 2007).

The second possibility could relate to use of the angle of repose in Equations 3 and 4. Q&O demonstrated that the ratio of \(D_F/D_r\) was “pronouncedly sensitive” to the value of \(\alpha\) for the material that composed the loose regolith. To this end, they experimented with overlying regolith of differing \(\alpha\), using 24 mesh (~0.7 mm) quartz sand (31°) and 6–8 mesh (~2.4–3.4 mm) crushed quartz (40°). They compared the \(D_F/D_r\) values from experiments using those materials to values predicted by Equation 3 and noted that there was a good agreement between the two when it came to the quartz sand, but the match between predicted and observed \(D_F/D_r\) for the crushed quartz presented difficulties. A better agreement for the crushed quartz was achieved by substituting the slope of the crater wall for the static angle of repose in Equation 3. Those wall slopes were likely controlled by the dynamic angle of repose, not the commonly measured static version. The dynamic angle of repose is different from the static angle in that it describes the angle created by frictional “freezing” of individual grains moving down a slope (similar to the process occurring in an avalanche). In this case, the dynamic angle is established in the modification stage during collapse of the over-steepened cavity walls. Typically, this value is ~3–10° lower than its static counterpart (Al-Hashemi & Al-Amoudi, 2018; Barnouin-Jha et al., 2007; Kokelaar et al., 2017) and can be observed in practice when comparing the measured static angle of repose and resultant crater wall slopes in Fig. 7. It is important to note that the two different sands used by Q&O had different values of static angle of repose. Since the dynamic angles of repose were also almost certainly different, different wall slopes resulted after cavity modification.

Despite the differences in the static angle of repose for both quartz sand targets in this study (6730 and 6753) and the unpublished experiment of J.L.B. Anderson (6741), they all produced almost identical...
crater wall slopes. This can be expected since the same sand was used in all three shots, and it is the dynamic angle of repose that will determine this angle (which is a direct function of the grain shape). Use of the wall slope from shot 6753 (24°) as the angle of repose in Equation 4 provides a new, estimated depth of the competent layer of 2.2 cm, much closer to that of the 2.4 cm depth to the cohesive substrate in shot 6741. Combined with the observations of Q&O, the data presented here for the quartz sand suggest that, when using Equation 4 to estimate a regolith thickness, the wall slope or dynamic angle of repose might be a more appropriate value for α in the relation provided in Q&O.

It is evident that the regolith thickness estimated by Equation 4 is sensitive to the chosen value of α. Derived from Lunar Orbiter 1 images of crater wall slopes, the value of α for the lunar regolith used by Q&O and subsequently by Bart et al. (2011) was 31°. Static friction angles determined from Apollo samples (Carrier III et al., 1991), however, suggest even higher values that range between 30° and 50°. With this wide range of possible α, it becomes important to understand the range of its influence on Equation 4. Figure 19 addresses this by plotting the theoretical regolith thickness as calculated with Equation 4 for a target of fixed $D_r/D_f$ (0.23, from shot 6753) as a function of α. The calculated regolith thickness is indeed heavily dependent on α, with a change from 25° to 40° (at constant $k$) causing the calculated value of t to decrease by 57%.

The calculated regolith thickness is also directly dependent on $k$ ($D_m/D_f$), which was shown in Fig. 11 not to be constant across the targets tested here, but instead dependent on the density and friction angle of the target. The different values of $k$ used in Fig. 19 represent those from the original Q&O study (0.86), the value determined from the sieved quartz crater (0.83), and the maximum (0.89) and minimum (0.76) determined from the craters of this study. At a constant α of 31°, for example, changes in the estimated regolith thickness of 22% are found as $k$ varies between the minimum and maximum values for the craters produced in this study alone.

The previous analysis, along with Fig. 18, demonstrates that using morphometric data from craters to estimate the depth of a regolith overlying a more competent layer should be done cautiously. The unconstrained assumption of relevant physical properties of the impacted surface, such as the angle of repose, can lead to substantial errors in the calculated burial depth of a competent layer, should one even exist. These results also suggest that the presence of flat-floored craters might not exclusively indicate the existence of a more competent buried horizon, as the combination of high friction angles and impact stress might provide sufficient $\tau$ for the material at depth to feign the presence of such a layer. This is not intended to imply that small flat-floored craters on the lunar maria are not due to regolith overlying competent basalt. Instead, it is to recommend caution in using such craters as infallible indicators of layers in other terranes, such as the lunar highlands or asteroidal surfaces.

**d–D Ratios: The Lunar Case**

Photogeologic studies by Stopar et al. (2017) show that relatively fresh lunar craters smaller than a few hundred meters in diameter are noticeably shallower than current scaling relationships would suggest. Craters with diameters between 100 and 400 m, for example, tend to have $d$–$D$ ratios of ~0.15–0.17, whereas those on the scale of 400–1000 m in diameter and larger display larger $d$–$D$ values of ~0.2, typical of larger, fresh, simple craters (Pike, 1974). Importantly, the smaller craters exhibit a further dependence of $d$–$D$ ratio on crater size,
CONCLUSIONS

We presented data from impact experiments that were designed to investigate the individual roles of bulk density, porosity, and friction on the crater formation process. These different material properties were found to modify crater morphology and morphometry in dissimilar ways. Crater diameters were most dependent on bulk density, with the densest targets having the smallest diameters. Crater depths, however, displayed a greater relative change overall, with the target’s friction coefficient being the dominant controlling factor. The consequence of this asymmetrical influence of friction was a wide range of depth–diameter ratios and crater volumes (and consequentially $\pi_V$) for experiments conducted at constant $\pi_2$. When not taken into account, such dependencies could, for example, complicate the interpretation of ages derived from crater size–frequency distributions (e.g., Williams et al., 2018) and the construction of scaling relationships.

The targets with the highest internal friction resulted in crater morphologies that would be classified as flat-floored, with some targets even displaying nascent central mounds. Both of these morphologic features are typically used as indicators of a stronger horizon below the impact site. Even though no such layer was present in any of the targets used here, we applied the commonly invoked relation developed by Quaide and Oberbeck (1968) to calculate the depth to this hypothetical cohesive layer. That exercise demonstrated a strong sensitivity of the predicted “regolith” thickness to the material properties of the target, especially the angle of repose. Our analysis also demonstrates that the dynamic, rather than the static, angle of repose is the more appropriate measure to use with this relation when estimating the thickness of a fragmental regolith overlying a stronger substrate. In such applications, the dynamic angle of repose can be approximated by the wall slope of the crater. Finally, caution must be exercised when using only the existence

with the smallest possessing the lowest ratios. Stopar et al. (2017) inferred that the gradual change in $d/D$ ratio between diameters of 200–400 m could be indicative of the transition region between the strength-controlled and gravity-controlled regimes of crater formation.

The similarity between the data of Stopar et al. (2017) and those in Fig. 8, which shows a separation of $d/D$ ratios by the method used to make the target, is notable. The sieved targets yielded $d/D$ values between 0.15 and 0.17, whereas those from the poured targets were considerably higher at 0.21–0.24, largely influenced by the target’s specific coefficient of static friction, $\mu_s$. This does not necessarily imply that the observed differences in $d/D$ ratios as a function of fabrication method are indicative of a transition between the strength and gravity regimes, but they do allude to a possible contribution of increased friction/lower porosity to the range of $d/D$ ratios observed on different lunar terranes (e.g., highland, mare, ejecta blankets, etc.). The upper few tens of meters of the lunar surface are structurally complicated and highly variable by location, generally taking the form of a relatively fine-grained, fragmental regolith overlying basalt flows in the maria and numerous, potentially block-laden, ejecta deposits in the highlands (Carrier et al., 1991; Cooper et al., 1974; Li et al., 2020; Zhang et al., 2020). As a direct consequence of this chaotic stratigraphy, the structure of this upper column presents many different combinations of locally changing physical properties such as friction, porosity, density, grain size, and effective strength, all of which can affect the cratering process. This then implies that predictions of crater morphology and morphometry on the basis of generalized terrane properties should be made with caution.

Fig. 19. Calculated regolith thickness as a function of angle of repose using Equation 4. The ratio of $D_F/D_r$ is fixed at 0.23, and varying values of $k$ are shown by different colored curves. Example thickness estimates (dashed lines) use $k = 0.86$; they represent the wall slope from shot 6753 and the angles of repose for the poured and sieved quartz sand. The burial depth of the substrate from shot 6741 is shown by the red arrow on the $y$-axis; the blue-shaded region encompasses the range of $\alpha$ for the near-surface lunar regolith as reported by Carrier et al. (1991). (Color figure can be viewed at wileyonlinelibrary.com.)
of flat floors and central mounds to infer the presence of cohesion at depth. Results of the experiments presented here definitively show that such features could also be produced as a consequence of the effective strength provided to a target through increased friction caused by the passing stress wave and existing overburden.

The inference of a target’s subsurface properties on the basis of crater morphology is a process that requires a certain level of a priori assumption. The near-surface lunar structure, for example, has heterogeneous physical properties on both regional and local scales, precluding any robust presupposition of the idealized “continuums” that impact experiments and models often employ. To complicate this further, the interplay among porosity, grain size distribution, density, friction, and effective strength is convoluted and can make experimental interpretations of craters in even simple, single-material targets difficult to untangle. These exploratory experiments have begun the process of probing some of the relevant variables in order to sort out the relative contributions of naturally codependent target properties. Future studies that extend this type of analysis to greater ranges of density, friction, and effective strength is convoluted and can make experimental interpretations of craters in even simple, single-material targets difficult to untangle. These exploratory experiments have begun the process of probing some of the relevant variables in order to sort out the relative contributions of naturally codependent target properties. Future studies that extend this type of analysis to greater ranges of density, friction, and effective strength should continue to advance our understanding of the crater formation process, particularly at lunar scales near and below a few hundred meters.

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Data Availability Statement—All relevant data necessary to duplicate the findings of this study are available within the data tables contained herein.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Fig. S1. Photomicrograph of quartz sand. Scale bar is 1 mm.

Fig. S2. Photomicrograph of alumina sand. Scale bar is 1 mm.

Fig. S3. Photomicrograph of garnet sand. Scale bar is 1 mm.

Fig. S4. Photomicrograph of olivine sand. Scale bar is 1 mm.