EXPERIMENTAL SIMULATION OF LARGE-SCALE IMPACTS ON POROUS ASTEROIDS.

K. R. Housen and W. J. Sweet, Applied Physics, The Boeing Co, MS 2T-50, PO Box 3707, Seattle WA 98124, kevin.r.housen@boeing.com, william.j.sweet@boeing.com

Introduction: Spacecraft observations [1-3] and laboratory experiments [4] indicate that the mechanics of impact crater and ejecta blanket formation depend substantially on the porosity of the target material. In particular, when target porosity is high, impact craters form mainly by permanent compaction of void spaces rather than by shearing and excavation of material. As a result, impacts on porous asteroids and satellites are expected to produce craters with only minimal ejecta deposits [5]. This abstract summarizes our recent experiments to better understand crater formation on porous bodies.

Cratering in cohesive soils: For all but the simplest geological materials (e.g. water or dry sand), large-scale impacts cannot be directly simulated by small experiments conducted at 1G gravity. The reason is that many aspects of cratering are *scale dependent*. For example, consider a cohesive soil target with only moderate porosity (~30%). A small impact crater formed in such a material is determined by the cohesive strength of the material. On the other hand, for large craters, the lithostatic overpressure, i.e. gravity, determines the shear strength (through the soil friction angle) and the crater size.

This trade-off between cohesive strength and gravity results in the behavior shown in Fig. 1, a standard plot of cratering efficiency, π_V, versus the gravity-scaled size of the event, π_2. For small impacts, i.e. small π_2, the cratering efficiency is determined by the cohesion, independent of event size. Above the strength-gravity transition, the cratering efficiency goes down because of the higher gravity-induced shear strength at large scales, which dominates the cohesive strength. This behavior has been observed in laboratory impact and field explosion cratering experiments.

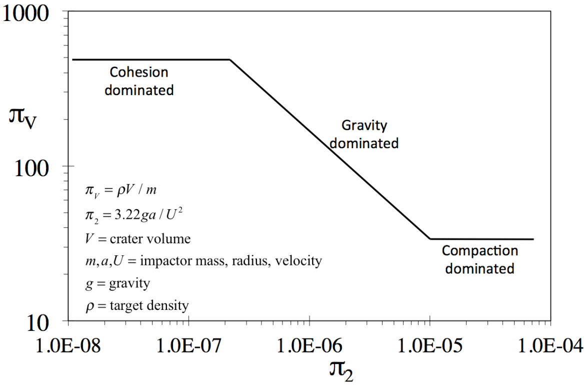

Fig. 1. Cratering efficiency for a cohesive soil.

Cratering in porous soils: Note that *any* dominant measure of material strength will result in a horizontal trend in Fig. 1. For highly porous materials, where much of the crater volume is created by compaction of voids, the crater size may be determined by the crushing strength of the target material. In contrast to cohesion, the crush strength is expected to be important mainly at large scales. Although the cratering efficiency decreases with increasing π_2 in the gravity regime, the crater volume cannot be smaller than the volume created by crushing. Therefore, the cratering efficiency is expected to approach a horizontal asymptote at large π_2. The experiments reported here show, for the first time, evidence of this compaction dominated regime.

Centrifuge experiments: Because of the scale dependent behavior shown in Fig. 1, a small impact experiment conducted at 1G gravity cannot correctly simulate the formation of a large crater on an asteroid, where π_2 is much bigger. However, these large scale events can be simulated by performing experiments at elevated gravity, so that the experiment matches the value of π_2 in the asteroid cratering event [5, 6]. These experiments reproduce the lithostatic overburden stress, as well as the ejecta ballistics, of a much larger impact on an asteroid. The "scale factor" for a centrifuge experiment is the ratio of the acceleration in the experiment to the gravity in the asteroid impact. Using the Boeing 500-G centrifuge, we can directly simulate the formation of asteroid ($g \sim 10^{-3}$G) craters several tens of km in diameter.

Our previous centrifuge experiments [4] used porous targets made from sand, fly ash and perlite. The bulk porosity of the target was varied by controlling the ratio of the sand to the highly porous perlite. Fly ash, a binding agent, was added to keep the sand and perlite from separating during target preparation. As a result, the targets used in the earlier study had noticeable cohesion. The measured crater volumes showed a basically flat trend on a π_V-π_2 plot with a slight downward trend at the largest π_2. The cohesion of the target material prevented study of a possible compaction dominated regime at large π_2.

The new experiments reported here use two target materials that are essentially cohesionless. The first consists of mixtures of sand and perlite, this time without the fly ash binder, which was found to be unnecessary. The porosity of this material can be varied from ~35% (pure sand) to ~95% (pure perlite). The two component remain well-mixed during target preparation by adding a small amount of water, which is later removed by drying the target in an oven. The second material is dry cohesionless granular pumice, sieved to a size range of 2 to 4 mm. The porosity of this material is 84±0.3%. The experiments reported here use targets made from granular pumice and from a perlite-sand mixture that also has the same porosity and density (380 kg/m^3) as the pumice.

The crushing strength of the materials was measured by placing samples of the materials in a 50.8 mm diameter x 25.4 mm deep cylindrical pocket of a steel fixture. The sample was then compressed in a servo hydraulic load frame while measuring the applied load and displacement of the load head. Figure 2 shows the resulting compaction curves for the two target materials and for dry quartz sand. The crush strength is defined here as the stress required to produce a 20% change in the specimen volume (circular symbols). As shown in the figure, the crush strength of the pumice is a factor of 100 smaller than sand. The perlite-sand mixture is even weaker, with a crush strength ~10x smaller than the pumice.

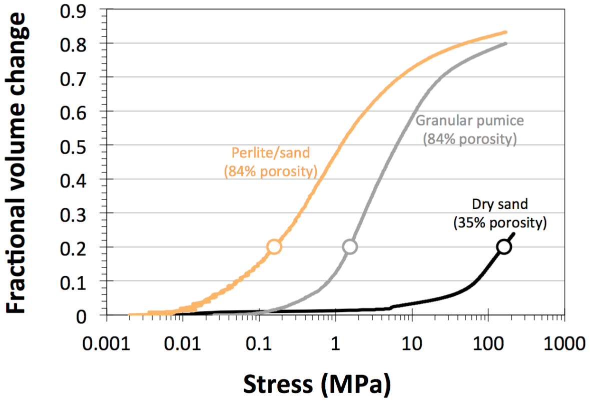

Fig. 2. Compaction curves for three target materials.

A series of impact experiments was performed for each target material. The acceleration was varied from 10G up to 500G (a 1G experiment was also performed for the granular pumice). In all cases, the projectile was a 12.2mm x 12.2 mm polyethylene cylinder (1.33 gm) that impacted the target ~10-deg from the surface normal. After an experiment, the target was removed from the centrifuge and the resulting crater profile was measured along two perpendicular diameters using a laser profilometer method. The experiments were conducted under ambient atmospheric pressure. The impact speed was held constant at 1.8 km/s.

Results: Figure 3 shows the cratering efficiency for the two target materials, as well as a line representing previous results for dry quartz sand. The results show a definite dependence on gravity indicated by the pronounced decrease of π_V with increasing π_2. There is no horizontal asymptote at small π_2 because of the negligible cohesion of the materials. Even though the perlite sand and the granular pumice had the same density and porosity, the cratering efficiency of the pumice was about a factor of two lower, presumably because of its higher crushing strength. This suggests that the craters were never entirely gravity-dominated, i.e. the effect of crush strength was significant.

Interestingly the results for the perlite-sand follow the trend shown in Figure 1 for a compaction dominated regime. That is, the cratering efficiency flattens out to an asymptote at large π_2. As noted, this is due to the fact that the crater volume cannot be smaller than the volume created by shock compaction of the void spaces. The lack of such an asymptote for the pumice is probably due to its much higher crush strength.

We are currently investigating other materials for a compaction dominated regime, and studying how this relates to the observed lack of ejecta blankets in porous materials. As a part of this study we will conduct quarter-space experiments on the centrifuge in which the dynamics of crater and ejecta formation can be viewed in cross section, providing further insights into the mechanics of crater formation on porous bodies. The results of the quarter-space tests will be presented at the meeting, along with the data summarized here.

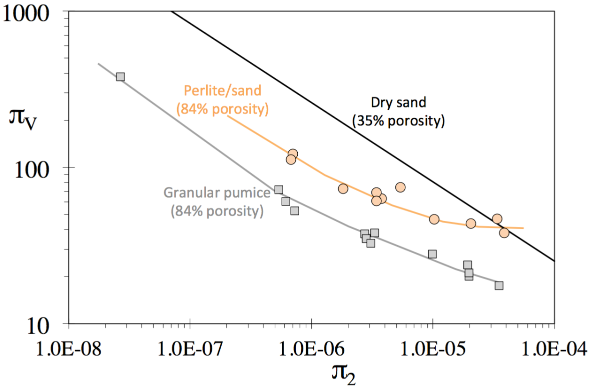

Fig. 3. Cratering efficiency from centrifuge experiments.

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