EFFECTS OF TARGET PROPERTIES ON THE CRATERING PROCESS. K.R Housen, Shock Physics, MS 2T-50, The Boeing Co., P.O. Box 3999, Seattle WA 98124. kevin.r.housen@boeing.com.

Impact events in the solar system occur in a variety of materials, ranging from the rocky surfaces of the terrestrial planets to the icy mantles of the satellites of the outer planets to the undoubtedly highly fractured and porous materials that make up many asteroids and comets. A major challenge to impact modelers has been to understand how the composition and mechanical properties of these varied target materials dictate the outcome of an impact event. Four sources of information have historically been used to study this problem.

Scaling theory provides guidelines as to when specific material properties may have a significant effect on the outcome of an impact event. The initial work in scaling separated cratering events into the strength and gravity regimes. In the former, crater size is determined by the mechanical strength properties of the target while, in the latter, strength is unimportant compared to the effects of the lithostatic overburden. The transition between the two regimes is determined by the condition $Y/\rho gh$ = constant, where Y is a measure of target strength, ρ is the density, g is gravity and h is crater depth. This simplistic picture has now been modified in two ways. First, Gaffney and Holsapple [1] noted that the strength of many geological materials depends on the rate at which they are loaded and that loading rates depend on the size scale of the event. As a result, mechanical strength of the target decreases with increasing event size, so the transition into the gravity-dominated regime occurs at smaller crater sizes than the simple constant-strength model would predict. Second, numerical simulations by Nolan *et al.* [2] indicate that passage of the shock ahead of the expanding crater bowl pre-fractures rocky target materials, which allows the crater to form in an essentially cohesionless (but not strengthless) material. In essence, an impact event can alter the mechanical properties of the material in which the crater forms.

Scaling considerations have also been applied to impacts in highly porous targets [3, 4], which may be representative of comets and many asteroids. In this case, craters are formed mostly by compaction of pore spaces. Crater size is therefore determined by the crushing strength of the target. Impacts in these materials may not experience a gravity regime because at large size scales (where gravity would be expected to dominate), the material crushes to a point where the lithostatic compressive stress is comparable to the crushing strength. Hence, a situation is never attained in which gravitational stresses are large compared to the important strength measure.

In addition to mechanical strength, scaling analysis has been used to identify conditions under which target viscosity is the most important property in determining crater size. Cratering in a viscosity-dominated regime has been applied to studies of Martian rampart craters [5] and craters on icy satellites [6].

Scaling theory is essential to identify the conditions under which various target material properties might be important in determining crater size and morphology. However, scaling laws by themselves cannot establish the relation between crater size and material properties. Instead, experiments and code calculations must be used to determine those dependences.

Field explosion experiments are a second source of information on the effects of material properties. Field tests are especially useful in that they can be conducted at size scales much larger than laboratory experiments. The largest conventional explosion test conducted in the U.S. involved 4.36×10^9 g of explosive and produced a crater 88.4 m in diameter [7]. While still small by planetary standards, these craters are more than 100 times larger than those that can be studied in the lab. Additionally, field tests have been performed in various geologic settings and can be used to illustrate the dramatic effects of material properties. For example, Figure 1 compares the crater profiles produced in two tests involving hemispheres of high explosives with a mass of 4.5×10^8 g, one in basalt and one in unconsolidated alluvium.

Laboratory experiments have of course been the main source of information for cratering studies. An advantage of laboratory experiments is that they can be conducted under controlled conditions, whereas field tests are at the mercy of the natural settings under which they are conducted. That is, it would be difficult to determine the influence of material properties from field tests alone because a multitude of important properties may vary from one test site to the next. As an example, Figure 2 uses the results of impact experiments to addresses the dependence of crater size on target density. Cratering efficiency (target density * crater volume/impactor mass) is shown for three cohesionless granular materials whose bulk densities vary by a factor of 2.6. The results show that cratering efficiency in nearly independent of target density for this particular type of target material

A limitation of laboratory studies is that they are, by definition, conducted at small size scales. Therefore, if any important material properties are scale dependent (e.g. the strength of rock), then the experimental results will not be directly applicable to larger events and must consider the scaling issues involved with extrapolation to larger sizes.

Numerical simulations have become a popular method for studying crater formation and offer the potential benefit of being able to study the separate effects of material properties on crater size and morphology. While this benefit is alluring, a considerable drawback to code calculations is that the results are only as good as the physical models that they incorporate. The constitutive models used in present codes such as CTH are reasonably accurate for some materials (e.g. metals), but are not well-developed for others, notably rock or highly porous soils. As a result, code results should be viewed with skepticism until validated extensively against laboratory and field tests [9]. Nevertheless, when such validations are accomplished, numerical simulations can provide tremendous insight into the effects of material properties.

Figure 3 presents an example. It was noted above that impact shock in rocky targets pre-fractures the material ahead of the expanding crater. This phenomenon has been used at times to assume that this pre-processing reduces the material strength to zero. While pre-fracturing should eliminate cohesion, the fractured rock will still have considerable strength in shear due to the effective friction angle associated with the interlocking of the rock fragments. The effect of friction angle is addressed in Figure 3, which shows the result of two CTH calculations of the Sailor Hat explosion event. Crater profiles are shown at an intermediate time during crater growth. The two simulations were identical except that the one on the left assumed a friction angle of 0° (equivalent to assuming a strengthless material), while that on the right shows a more realistic value of ~30°. These results show the significant effect that the material shear strength has on crater formation; an effect that is ignored in many calculations reported in the literature.

Additional calculations are underway. These results, along with those from scaling, field tests and laboratory experiments will be summarized to identify what is and is not known about the effects of material properties on crater formation.

References: [1] Gaffney E.S. and Holsapple K.A. (1983) Crater scaling relations for strain-rate dependent materials, (Unpublished report). [2] Nolan M.C. *et al.* (1996) *Icarus* 124, 359-371. [3] Housen K.R. *et al.* (1999) *Nature* 402, 155-157. [4] Housen K.R. and Holsapple K.A. (2002) Submitted to *Icarus*. [5] Gault D.E. and Greeley R. (1978) *Icarus* 34, 486-495. [6] Fink J. *et al.* (1984) *J. Geophys. Res.* 89, 417-423. [7] Lee C.K.B. and Mazzola T.A. *J. Geophys. Res.* 94, 17,595-17,605. [8] Holsapple K.A. and Housen K.R. (2002). *LPSC* Abstract.

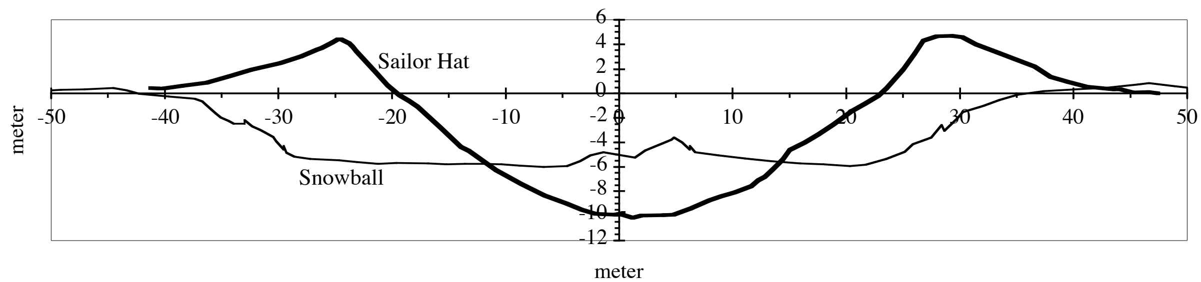

Figure 1. Comparison of crater profiles from two explosive field tests. Both tests used hemispherical charges of TNT (4.5×10^8 g) situated at the target surface. The Sailor Hat event was conducted in basalt, whereas Snowball was conducted in unconsolidated alluvium with the water table at a depth of approximately 7 m.

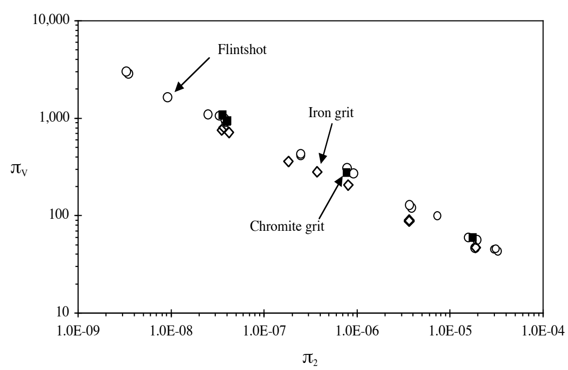

Figure 2. Cratering efficiency, π_V, vs π_2 for 1.8 km/s impacts into three granular cohesionless materials of density 1.8 (Flintshot sand), 3.1 (Chromite sand) and 4.6 gm/cm^3 (Iron sand). These data show that cratering efficiency is nearly independent of target density.

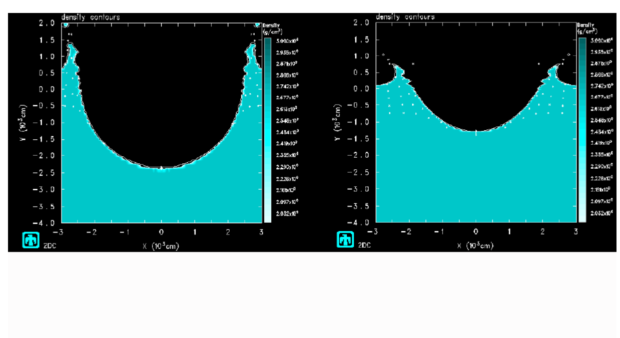

Figure 3. Comparison of two numerical simulations (CTH) of the formation of the Sailor hat explosion crater. The crater profiles are shown at an intermediate time of 0.18 s. Both models assume a Mohr-Coulomb behavior. The Profile on the left is for a case where the angle of internal friction is zero, while the case on the right is for approx. 30°. The formation time of the crater is ~0.5 s.