THE INFLUENCE OF TARGET MATERIAL STRENGTH ON THE SCALING OF CRATERING AND EJECTA DATA. Fred M. Sauer, Physics International Company, San Leandro, CA 94577

Much of what is inferred about the dynamics of formation of lunar and planetary impact craters and their ejecta deposits is derived from observations on very small scale hypervelocity impact cratering experiments in laboratory materials and larger high explosive experiments in terrestrial geologies. Even the larger nuclear explosion craters, e.g., the Sedan crater, are several orders of magnitude smaller than the larger lunar impact craters and laboratory size craters are another three orders of magnitude smaller than their lunar prototypes. Thus questions arise as to the influence of scale on the dynamics of crater formation: do small craters exhibit similar particle flow fields and consequently similar ejecta velocities and particle initial locations when compared with large craters, and what is the influence of gravitational forces and strength of the target material on the dynamic similarity between large and small craters?

A qualitative answer to these questions for explosion-produced craters may be derived from an approximate theoretical treatment of the cratering dynamics (1), (2), which considering the work of Oberbeck (3), may also be applicable to impact craters. The basic assumptions in this analysis are that the "cratering flow field," defined as the particle flow field in the region of the transient crater but behind the initial outgoing shock front, approximates incompressible flow and can be described by a simple power law

\[ \dot{R} = \alpha R^{-Z} \]  

(1)

where \( \dot{R} \) is the radial velocity, \( R \) is the radial distance from the explosive source, \( \alpha \) is related to the energy of the cratering source (E), and \( Z \) characterizes the shape of the flow field. To a good first approximation \( \alpha \) and \( Z \) are constants and for surface and shallow-buried explosions \( Z = 3 \) seems to be a good approximation (4). The crater radius (\( R_C \)) is determined by equating the kinetic energy in the flow field of Eq. (1) to the work done against material strength* and gravity. The time at which this energy balance occurs, the time of crater formation (\( T_C \)), is also uniquely determined. \( R_C \) and \( T_C \) are functions of E and the ratio of work done against gravity per unit crater volume to the work done against material strength per unit crater volume (\( \rho g R_C^2 \)) where \( \rho \) is the density of the target material, \( g \) is the acceleration of gravity and \( S \) is the material "strength."

* Actually against the Von Mises limit of a Mohr-Coulomb material failure model but as will be seen later it is desirable to define strength more loosely.
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To evaluate the influence of strength of the energy source on "scaling" parameters the results can be put in the form

\[ R_C \sim E^{1/n_d}, \quad T_C \sim E^{1/n_t}, \quad T_C \sim R_C^{1/m_t} \quad (2) \]

where the power law exponents are all functions of \( \rho g R_c/S \) (Figure 1a-c). The results are evaluated for \( Z = 2.707 \), the value of \( Z \) which exactly conserves momentum (2), \( Z = 3.0 \) and \( Z = 4.0 \), a value of \( Z \) typically observed near the free surface in numerical cratering calculations. The results are seen reasonably independent of \( Z \).

For small craters, low gravity and/or large material strength, where \( \rho g R_c/S < 1 \), \( R_C \sim E^{1/3}, \quad T_C \sim E^{1/3} \) and consequently particle velocities at locations "scaled" by \( R_c \) and times scaled by \( T_C \) (or \( R_c \)) are invariant with crater size, the usual Cauchy "scaling" rule. For large craters, high gravity and/or low material strength such that \( \rho g/R_c/S \gg 1 \), \( n_d \) approaches 3.5 (for \( Z = 3.0 \)), \( n_t \) approaches 7, \( m_t \) approaches 2 and the usual Froude scaling applies. This result implies that maximum ejecta velocities increase as \( E^{1/7} \) or \( R_c^{1/2} \). The result \( n_d = 3.5 \) for cratering in low strength materials agrees with the experimental results of (5) and (6) for cratering in dry sand and with (7) for large nuclear craters in alluvium so the \( Z = 3 \) approximation is again confirmed by data.

The remaining question is the influence of material strength. Competent rocks have strengths several orders of magnitude larger than the strength of dry sand or alluvium. If these strengths were assumed to apply throughout the cratering process, scaling factors intermediate between Cauchy and Froude scaling could apply for laboratory size impact cratering or even small high explosive size experiments. On the other hand shock degradation of the failure strength of competent rock could theoretically change the scaling exponents significantly from what would be expected on the basis of preshock strength since, as pointed out in (8), the major fraction of work done against material strength is at near zero pressure where the material cohesive strength applies. Clearly, correct characterization of target material strength during the cratering process is essential if the possibility of large errors in extrapolating laboratory data is to be avoided.

At present it appears that the question of the proper scaling rules for explosion and impact cratering in rock is unresolved since the proper scaling experiments have not been performed and the post-shock material strength characteristics of rocks have not been experimentally defined.
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Figure 1 Variation of Scaling Exponents with Crater Size.

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