NUMERICAL MODELING OF IMPACT EJECTION PROCESSES IN POROUS TARGETS.

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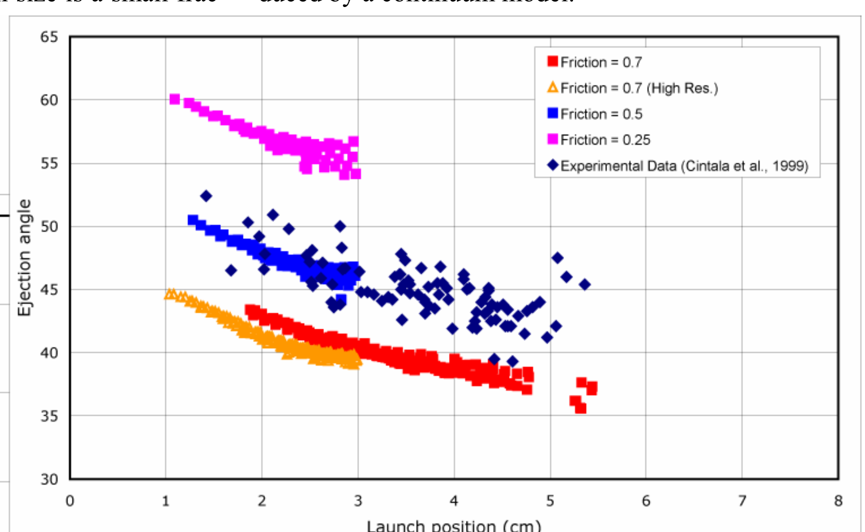
Introduction: Quantifying excavation and ejection processes that occur during an impact event is important for understanding many solar system processes. Much of the final crater's volume and the majority of the deposit around the crater results from the excavation and ejection of target material. Material ejected at sufficiently high velocity may escape the gravitational field of the target body, which has important consequences for early planetary growth, the collisional evolution of asteroids and the origin of Lunar and Martian meteorites [1].

Previous Work: Quantitative experimental studies of ejection dynamics have provided much insight into the relationship between ejection velocity and launch position either indirectly, by tagging target material and locating its post-impact position [2], or directly, by making stroboscopic photographs of grains in ballistic flight [3]. However, the difficulty of measuring the motion of ejecta in such brief, rapid, small-scale events has precluded thorough quantification of the ejection process. Numerical modeling using the Discrete Element Method shows great promise in simulating crater excavation in granular targets [4], particularly in cases where the particles are similar in size to the projectile. However, there has been little continuum modeling of ejection processes, which is more appropriate for hypervelocity impacts into targets where the grain size is a small fraction of the projectile size, primarily because the effects of porous compaction were not properly quantified. In this paper we examine the effect of porosity and friction on crater excavation using the iSALE hydrocode with the epsilon-alpha porous compaction model [5]. iSALE is a multi-material, multi-rheology extension to the continuum hydrocode SALE [6].

Measuring ejection processes and model validation: To validate the use of iSALE for studying the ejection process we performed simulations that mimicked the experimental conditions of [3]. The most robust method found for measuring ejection velocity and angle as a function of launch position was to track the motion of massless Lagrangian tracer particles that formed part of the ejecta curtain. For each tracer we fit a parabola to the ballistic section of its locus; the ejection angle and velocity can be derived from the coefficients of the parabola [3]. Our model results show excellent qualitative agreement with the experimental data; however, the exact experimental trends of ejection angle and ejection velocity as a function of launch position could not be matched simultaneously with a single friction coefficient (Fig. 1). This may be due to the low resolution of our model (5-10 cppr), or because the behavior of the coarse sand grains used in the experiments (~1/5—1/2 projectile diameter) is not correctly reproduced by a continuum model.



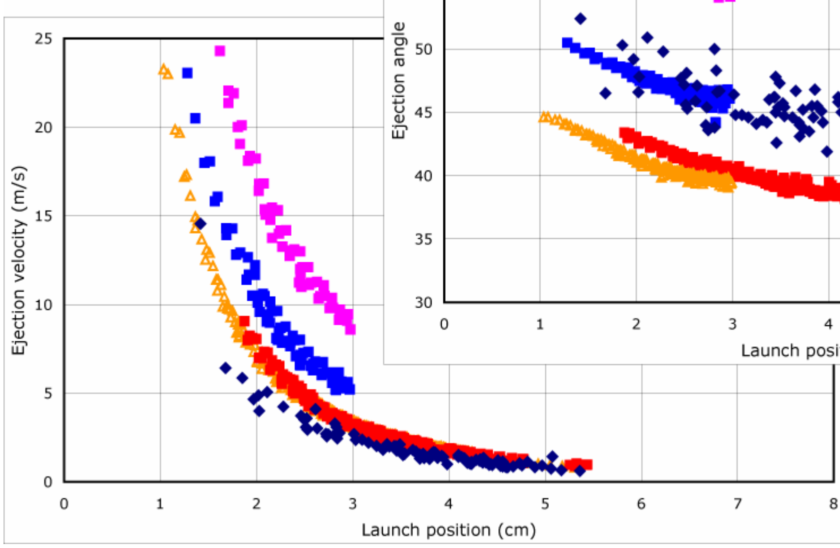


Figure 1: *iSALE model results of ejection velocity and angle versus launch position for a cohesionless target with 44% porosity and various coefficients of friction, in comparison to coarse sand experiments of* [3].

The effect of porosity and friction on crater excavation: In addition to model validation simulations, we also performed over fifty impact simulations to investigate the effect of porosity and friction on crater excavation and ejection processes. We modeled basalt-basalt impacts, using a 1-km diameter impactor at 15 km/s and a gravitational acceleration of 1 m/s, and varied the target porosity and friction coefficient. Our results show that increasing friction coefficient and porosity reduce ejection velocity, leading to a monotonic decrease in cratering efficiency—the mass of material displaced to form the crater relative to the projectile mass (Fig. 2).

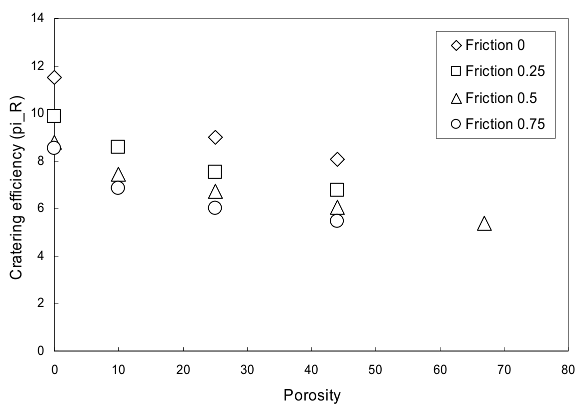


Figure 2: *Cratering efficiency (π_R) versus porosity and friction derived from model results.*

Excavation efficiency—the volume of material excavated relative to the total volume of the crater—also decreases monotonically with increasing porosity (Fig. 3), in qualitative agreement with experiment [7].

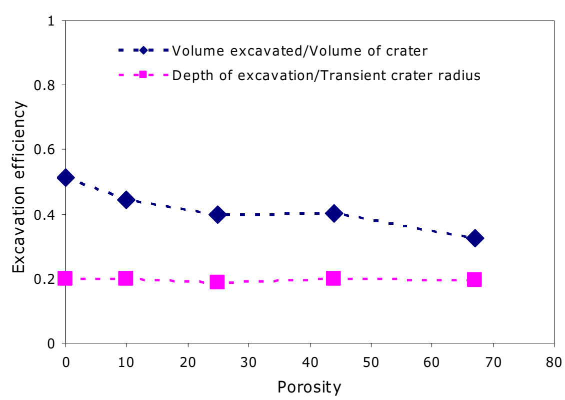


Figure 3: *Excavation efficiency versus porosity*

However, as crater volume is in part the result of excavation, and part in part the result of compaction, the transient crater volume (and diameter) reaches a minimum at around 25% porosity before increasing with increasing porosity, as compaction dominates excavation (Fig. 4).

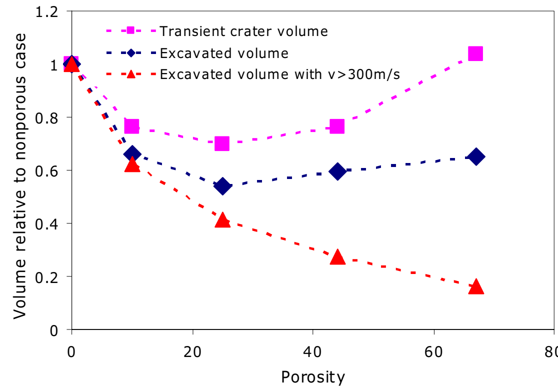


Figure 4: *Transient crater and excavated crater volume versus porosity.*

The dependence of ejection velocity and ejection angle on normalized launch position (*x/R*, where *R* is transient crater radius) is qualitatively the same for all porosities and friction coefficients, with trends similar to those shown in the model validation simulations (Fig. 1). Ejection angle decreases by 5-10 degrees between $x/R = 0.2$ and $x/R = 0.8$; the maximum ejection angle decreases with increasing friction coefficient. Ejection velocity *v* (normalized by $\sqrt{gR}$, where *g* is gravitational acceleration) falls off approximately as an inverse power of normalized launch position:

$$\frac{v}{\sqrt{gR}} = k\left(\frac{x}{R}\right)^{-e_x}$$

This functional form is that predicted by dimensional analysis combined with a point-source approximation of impact cratering [8]. Theory suggests that the exponent e_x can range between 1.5 and 3, and should be ~2.5 for sand, and ~1.8 for water [8]. These theoretical values are supported by some experimental data [e.g. 2] and DEM models [4], but do not agree with other experimental data [3] and our model results. In general, we find that e_x *decreases* with increasing porosity, from ~1.8 at 10% porosity to ~1.2 at 67% porosity. More work, both experimental and modeling, is required to resolve this apparent discrepancy.

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