THE EFFECT OF POROSITY AND FRICTION ON EJECTION PROCESSES: INSIGHT FROM NUMERICAL MODELING

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Introduction: The growth of an impact crater is the result of three processes: compaction of pore space, plastic deformation of the target surrounding the crater, and ejection of material from the crater on ballistic trajectories. Quantifying the relative importance of these three processes during crater formation, and how they are affected by target properties, is crucial for understanding the numerous implications of impacts in the solar system. In particular, the amount of material ejected, and the velocity and angle at which this material is expelled, has many ramifications in planetary science. 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 interplanetary transfer of surface material [1]. Moreover, one of the few practical means of shifting the orbit of an asteroid on collision course with Earth is to impact on its surface. The material thrown off the asteroid exerts a thrust in the opposite direction, amplifying the impulse of the impactor itself and helping to change the course of the asteroid [2]. Whether this process can supply sufficient momentum to avoid a catastrophe on Earth depends critically on how efficiently impacts can excavate the material on the surface of asteroids and comets--how much material is ejected and at what speed and angle?

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 [3], or directly, by making stroboscopic photographs of grains in ballistic flight [4, 5]. However, the difficulty of measuring the motion of ejecta in such brief, rapid, small-scale events has precluded thorough quantification of the ejection process. In particular, the effects on ejection velocity of target properties, such as porosity and strength, are not well understood due to the practical difficulties of not only measuring ejection velocity, but also constructing targets with a range of porosities and strengths.

Numerical modeling using the Discrete Element Method shows great promise in simulating crater excavation in granular targets [6], 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 [7]. iSALE is a multi-material, multi-rheology extension to the continuum hydrocode SALE [8].

Results: In addition to several model validation simulations, which gave good agreement with experimental data [5, 6, 9], we performed over fifty impact simulations spanning a range in target porosity from 0-88% and target friction coefficient from 0-0.75. Our results show that ejection velocity is lower at all launch positions for targets with higher friction (Figure 1). This is because more of the target's kinetic energy is expended as plastic work during excavation in a target with higher friction.

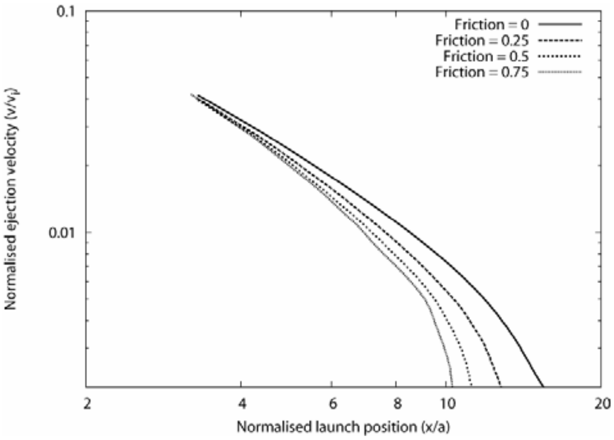

Figure 1: *Normalized ejection velocity as a function of normalized launch position for targets with different friction coefficients (v_i is impact velocity, a is projectile radius).*

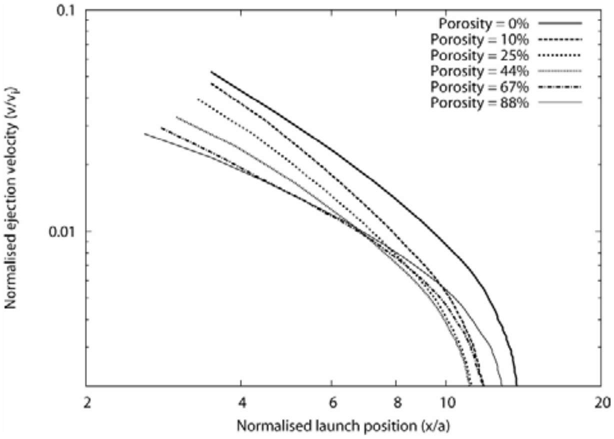

Figure 2: *Normalized ejection velocity as a function of normalized launch position for targets with different porosities.*

The effect of porosity is more complex. As target porosity is increased the target density is reduced, but the attenuation of the shock wave is increased. The effect of increased shock attenuation is to reduce ejection velocity; the effect of reduced density is to increase ejection velocity. In general, shock absorption is the dominant effect and ejection velocity is lower in targets with higher porosity; however, for very high porosity (>50%) the extremely low density of the target becomes important during the late stages of crater growth, and ejection velocities near the crater rim can increase with increasing porosity (Figure 2).

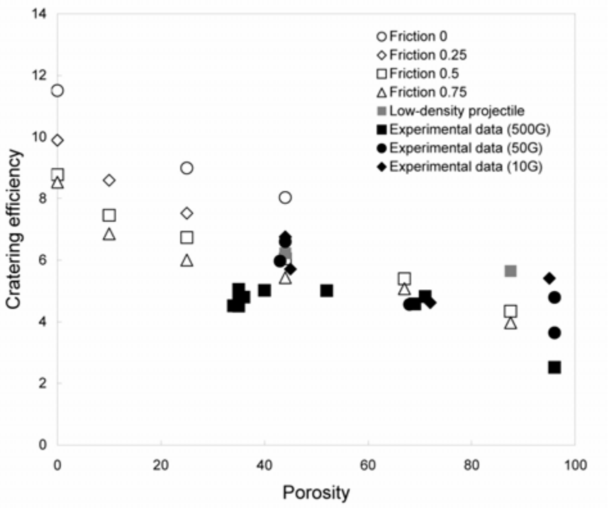

Figure 3: *Cratering efficiency (π_R) versus porosity and friction derived from model results.*

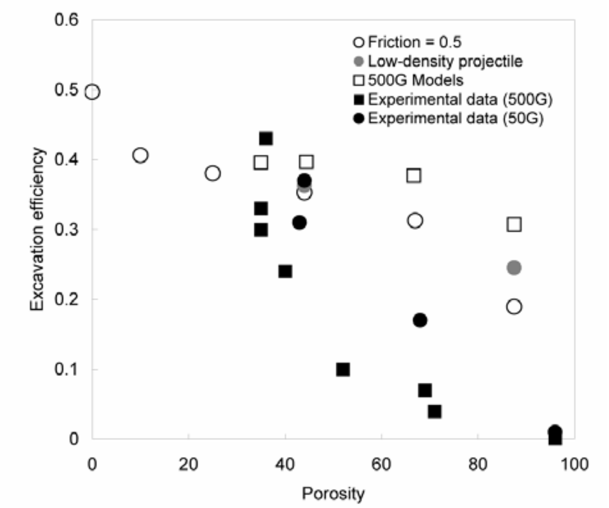

Figure 4: *Excavation efficiency versus porosity*

The competing effects of increased shock attenuation on one hand, and increased compaction and lower density on the other hand, also control the relationship between target porosity and crater size. For low target porosity the effect of shock attenuation dominates; for high porosity the effects of increased compaction and dominate. Consequently, as target porosity increases from 0-25% crater diameter and volume decrease, but for porosities above ~25% crater diameter and volume increase with increasing porosity. Despite this increase in crater size with increasing porosity, cratering efficiency—the mass of material displaced to form the crater relative to the projectile mass—decreases monotonically with increasing porosity, in excellent agreement with experiment (Fig. 3). Excavation efficiency—the volume of material excavated relative to the total volume of the crater—also decreases monotonically with increasing porosity (Fig. 4), although in this case our model results show some disagreement with experiment at very high porosity [9].

Ejecta scaling: The dependence of ejection velocity v (normalized by $\sqrt{gR}$, where g is gravitational acceleration and R is transient crater radius) on normalized launch position (x/R) is qualitatively the same for all porosities and friction coefficients, with trends similar to those shown in Figs. 1 & 2. For $0.3 < x/R < 1.0$ normalized ejection velocity decreases with increasing launch position according to:

$$\frac{v}{\sqrt{gR}} = k\sqrt{\left(\frac{x}{R}\right)^{-2e_x} - \frac{x}{R}}$$

Point-source 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 [10]. These theoretical values are supported by some experimental data [e.g. 3, 5] and DEM models [6], but do not agree with other experimental data [4] 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 numerical modeling, is required to resolve this apparent discrepancy.

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