OBLIQUE IMPACTS IN FRICTIONAL TARGETS – IMPLICATIONS FOR CRATER SIZE AND SCALING.

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Introduction: Almost every meteorite impact occurs at an oblique angle of incidence. However, the effect of the impact angle on the crater size or the formation mechanism is only poorly understood and not yet considered in current scaling laws. Here we present the results of a comprehensive, systematic numerical modeling study containing more than 200 three-dimensional hydrocode-simulations covering a broad range of projectile-sizes, impact angles and friction coefficients.

Scaling of crater size: Scaling laws describe the functional relation between the properties of the impacting body (density δ, velocity U, diameter L), the target (density ρ, strength Y, gravity g) and the size of the crater (here: volume V). Pi-group scaling [e.g. 1-3] allows to reduce the number of independent variables by using dimensionless ratios. If the effect of gravity is much larger than cohesive strength and both projectile and target are composed of the same material, a simple power law can be used to describe e.g. the crater volume: $\pi_V = C_V \bullet \pi_2^{-\gamma}$ (with $\pi_V = V \bullet \rho / m$, $\pi_2 = 1.61 gL/U^2$, m denotes projectile mass). C_V and γ are material-dependent parameters.

Model and setup: For this study we used iSALE-3D (see e.g. [4,5]), a three-dimensional, multi-material and multi-rheology hydrocode. For simplicity we assume the same granitic composition for both target and projectile. The material strength is described by a cohesionless Drucker-Prager model where shear strength Y is a linear function of pressure P, $Y = fP$, where f is the coefficient of friction. The thermodynamic state is calculated with Tillotson's Equation of State [6]. To avoid the complication of material vaporization we kept the impact velocity constant at a relatively low value of U=6.5 km/s in all simulations, which is substantially lower than the mean terrestrial impact velocity of 18 km/s but within the range of impact velocities achievable in the laboratory. We conducted numerical impact experiments for different π_2-values by varying the projectile diameter L between 0.325 and 3 km corresponding to a π_2-range over two orders of magnitude (10^{-3} to 10^{-4}). We assumed Earth-like gravity conditions (g = 9.81 m/s^2) and varied the angle of incidence between 30° and 90°. To explore the effect of internal friction on our model results, we first performed hydrodynamic simulations (where strength and internal friction are neglected) and then varied the coefficient of internal friction (f) between 0.2 and 0.7, where 0.7 corresponds to a typical value for sand.

Results: In agreement with observed crater populations on planetary surfaces and laboratory impact experiments oblique impacts at angles greater than 30° to the target surface produce circular craters. However, with increasing friction coefficient and decreasing angle of impact deviations from circular symmetry occur.

Both the impact angle and friction coefficient in the target significantly reduce crater efficiency (Fig. 1). This effect is independent on the gravity-scaled size (π_2) of an event (Fig. 2).

The coupling between the impactors energy/momentum depends on friction coefficient (Fig. 3) and can be considered by empirical determination of the scaling parameters C_V and γ (for scaling of crater efficiency) by numerical or laboratory vertical impact experiments in different materials with different friction coefficients. Note that other properties such as porosity also affects crater efficiency [7] but are not yet considered in this study.

For oblique impacts in targets with f=0.7 we found a sinusoidal decrease in crater efficiency (Fig. 2). This result is in agreement with experiments in sand [8] with a comparable friction coefficient. It suggests a modification of the scaling law for crater efficiency by only considering the vertical component of the impact velocity: $V(\alpha)=V(90°)\bullet\sin^{2\gamma}(\alpha)$ or $\pi_V(\pi_2,\alpha)=C_V\bullet\pi_2^{-\gamma}\bullet\sin^{2\gamma}(\alpha)$ [9]. However, this assumption does not hold for impacts into hydrodynamic targets and presumably also not for targets with coefficients of friction significantly different from 0.7.

Our results show that for increasing friction coefficient the scaling exponent γ for crater efficiency decreases, possibly approaching the momentum scaling limit for f>>0.7 (Fig. 3 and 4).

Conclusions: In general, we conclude from our numerical experiments that the point source concept and π-group scaling with the extension by Chapman and McKinnon [9] is applicable for oblique impacts (α=30°-90°) into natural materials with properties similar to those of sand with a coefficient of friction f=0.7 and no or very little cohesion. However, the simple extension to the scaling theory probably does not hold for materials with properties significantly different to sand. Other properties such as porosity or cohesive strength have not yet been incorporated into scaling laws or have only be taken into account for vertical impacts (cohesive strength; [10]). Experimental studies [8,11] indicate that strength dominated craters do not follow a simple scaling law where crater efficiency is scaled by the vertical component of the impact velocity. Moreover, the density ratio between the projectile and target seems to have a significant effect on the scaling of crater dimensions in case of oblique impacts [11]. It is questionable whether the assumption of a stationary point source is applicable for more complex impact scenarios such as oblique impacts into a frictional targets with a strong density contrast between projectile and target or whether it has to be replaced, for instance, by the concept of a superposition of point sources [12] or a moving point source. The depth and lateral position of burial of the virtual point source will then become a function of time that significantly complicates the derivation of theoretical scaling laws to describe the cratering process.

Further laboratory and numerical experiments will have to test the conditions where classical π-group scaling including the extension for oblique impacts is applicable.

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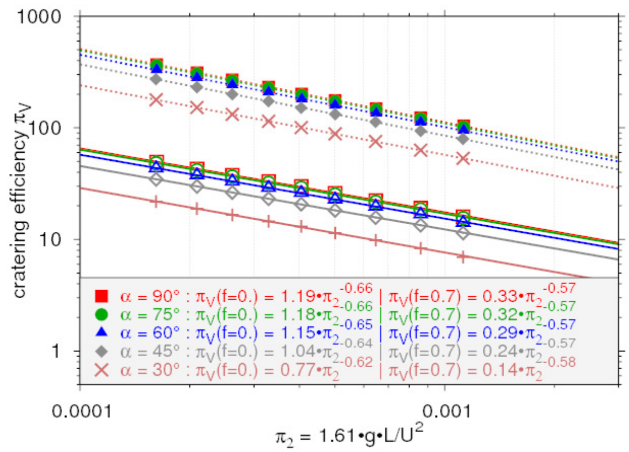

Fig. 1 *Cratering efficiency as a function of π_2 for different impact angles. Dashed lines/solid symbols represent hydrodynamic results, solid lines/open symbols show results for a frictional target (f=0.7).*

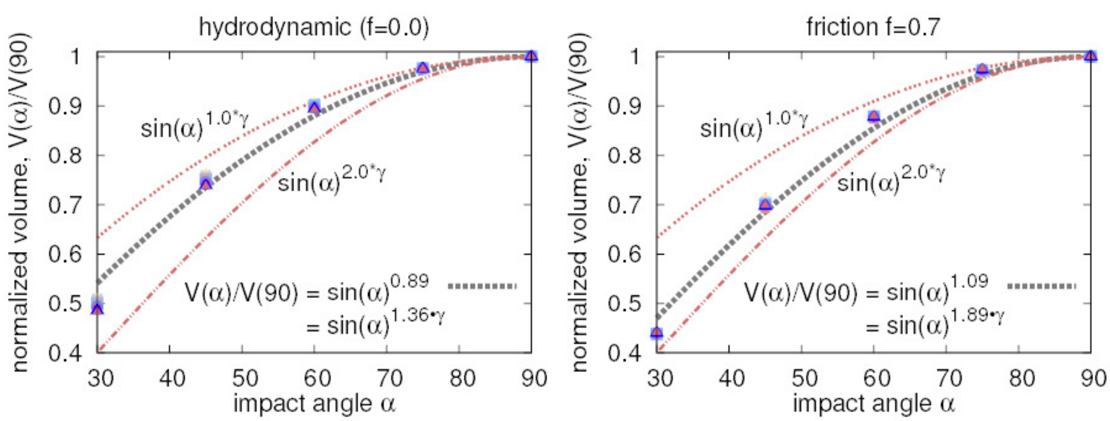

Fig. 2 *Effect of the impact angle on crater volume for hydrodynamic (left) and frictional target (right).*

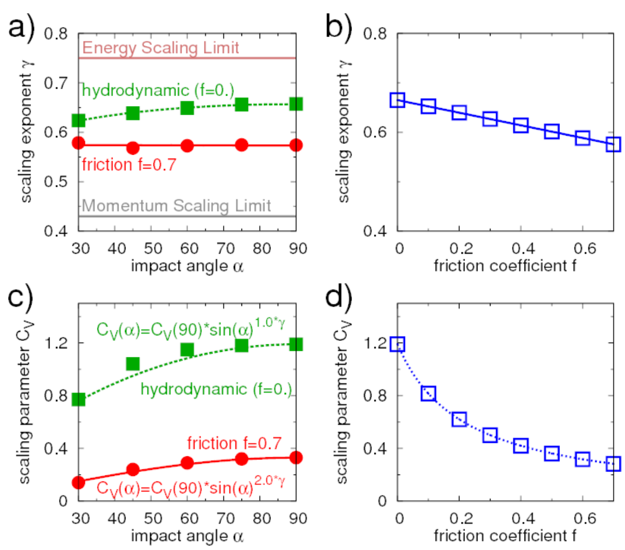

Fig. 3 *Scaling parameters as functions of the impact angle (left) and internal friction (right).*

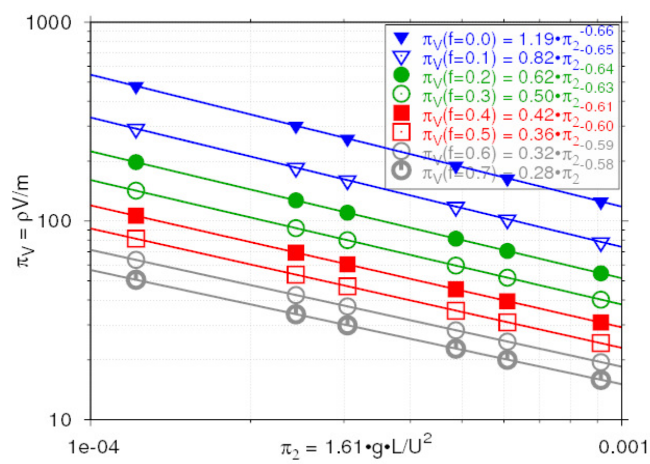

Fig. 4 *Scaled crater volume as a function of gravity scaled size for different friction coefficients (vertical impacts).*