CRATER SCALING FOR OBLIQUE IMPACTS IN FRICTIONAL TARGETS: INSIGHT FROM 3D HYDROCODE MODELLING

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Introduction: One of the most fundamental questions in the study of meteorite impacts is how the size of the resulting crater depends on the properties of the impacting body and the impacted target. Various scaling-laws have been proposed [1,2,3,4] to calculate the volume, depth and diameter of a crater from the properties of the projectile (density ρ_p, velocity v_i, diameter L) and the target (density ρ_t, strength Y, gravity g). The assumption that an impact can be approximated as a point source of energy and momentum [HOLS] implies (amongst other relationships) that a power-law function relates the scaled crater volume π_V (cratering efficiency) with the gravity scaled source size π_2:

$$\pi_V = \frac{V}{V_p} \cdot \frac{\rho_t}{\rho_p} = C_V \left[\frac{g}{v_i^2} \left(\frac{m}{\rho_p} \right)^{1/3} \right]^{-\gamma} = C_V \pi_2^{-\gamma},$$

where γ and C_V are scaling parameters that have to be determined empirically and depend on the properties of the target material (e.g. friction, porosity) [1,2,3].

However, most scaling-laws were developed for vertical impact which is the most unlikely scenario for meteorite impacts in nature [5]. Moreover, laboratory-scale oblique impact experiments suggest that it is not appropriate to approximate oblique impacts by a stationary point-source [6]. In this study we use three-dimensional (3D) numerical modeling of oblique hypervelocity impacts to investigate the effect of the angle of impact on the volume of the transient crater for "gravity-dominated" craters. Cratering is defined to be gravity dominated when crater growth is retarded by gravity rather than the cohesive strength of the material; this is the case for most impact craters on planetary surfaces and for all craters in granular materials like sand. The study of late-stage crater formation processes for oblique impacts is computationally very expensive and experimentally very difficult to realize, particularly when the target material has no cohesion – few experimental studies have investigated crater scaling in oblique impacts [7,8,9,10], and most of these addressed the formation of strength-dominated craters. We have developed a highly efficient 3D hydrocode iSALE-3D [11] (based on [12,13]) that is specifically designed to perform simulations of the entire crater formation process at relatively low computational costs. We used this code to carry out an extensive parameter study that comprises more than 100 3D-simulations. Our main goal is to quantify the influence of impact angle on crater size for gravity-dominated craters in hydrodynamic and frictional target materials.

Model Setup: To investigate the effect of impact-angle on crater size, we assumed Earth-like conditions with a gravity of g = 9.81m/s^2 and granite as both target and projectile material. We used the Tillotson equation of state [14] to compute the thermo-dynamical state of the material. To adequately resolve the projectile in our simulations and remove the complication of material vaporisation we fixed the impact velocity at v_i*=6.5 km/s*, which is substantially lower than typical terrestrial impacts but within the range of impact velocity achievable in the laboratory. We varied the projectile diameter L between 250 m and 3 km to cover a range in gravity scaled source size π_2 of 1.e-3 to 1.e-4, which spans the range of impact craters on Earth > 20 km diameter. The impact angle was varied between 30° and 90°. We modelled impacts into an idealised uniform granite target with no cohesive strength. In the first instance, we assumed a strengthless target (hydrodynamic) to separate the effect of impact angle from strength effects. In addition, we assumed a Mohr-Coulomb strength model (where shear strength is proportional to pressure, $Y = f \cdot P$) and varied the friction coefficient f between 0.2 and 0.9.

The influence of impact angle on crater size: In agreement with [7,8] we found that crater volume decreases with impact angle in a sinusoidal manner. The effect of impact angle is almost independent of impactor size (of different π_2-scenarios, see Fig. 1).

By plotting π_2 versus crater efficiency π_V we found a scaling exponent of γ=0.65 (Fig. 2) which is the same as the empirically determined value for wet sand and water [2]. This parameter is close to the energy scaling limit of γ=0.75 and does not change significantly with impact angle (Fig. 2). Thus, if friction is neglected, the crater efficiency for impact angles >30° is controlled by the projectile's kinetic energy. If crater efficiency was instead controlled by momentum γ would be 0.43.

The effect of friction in oblique impacts: With increasing friction coefficient f crater volume decreases (Fig. 2). Fig. 1 shows that the effect of the impact angle is greater for a larger friction coefficient. For f=0.7 the crater volume decreases with the impact angle as $V(\alpha) = V(90°) \cdot \sin(\alpha)^{2\gamma} \approx V(90°) \cdot \sin(\alpha)$ in agreement with experimental studies in quartz sand by [7,8]. The scaling exponent γ=0.57 is lower than in the hydrodynamic case and closer to the momentum scaling limit (γ=0.43) and the experimentally determined value for vertical impacts into sand (0.5; [2]). Thus, impactor momentum becomes more important for crater formation if the effect of target friction is considered.

Conclusions and further studies: Our models confirm the experimental observation that crater efficiency decreases with decreasing impact angle in a sinusoidal manner. The power-law scaling of the crater volume holds for impact angles as low as 30°. Friction further reduces crater efficiency, and increases the importance of the projectile's momentum. Crater scaling gradually changes from almost pure energy scaling in case of vertical impacts into hydrodynamic material towards momentum-controlled crater growth for increasing friction coefficients (and decreasing angle of impact). In the future we plan to carry out models of smaller π_2-scenarios, and study the effects of a broader range of friction coefficients and other important target properties such as cohesion and porosity. Preliminary results indicate that the effect of friction coefficient on crater scaling is the same for all impact angles (above 30°).

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References: [1] Holsapple, K. A. (1993) *Annu. Rev. Earth Planet. Sci. 21*, 233-273. [2] Schmidt, R. M. and Housen, K. R. (1987) *IJIE, 5,* 543-560. [3] Holsapple K. A. and Schmidt R. M. (1987), *J. Geophys. Res.* **92**, 6350-6376. [4] Housen, K. R. and Holsapple, K. A. (1999) *Icarus 142*, 21-33. [5] Shoemaker, E. M. (1962) *Physics and Astronomy of the Moon,* 283-359. [6] Anderson, J. L. B. and Schultz, P. H. (2006) *IJIE 33*, 35–44. [7] Gault, D. E. and Wedekind, J. A. (1978), *Proc. LPSC IX,* 3843-3875. [8] Chapman, C. R. and McKinnon, W. B. (1986), *Satellites, Univ. of Arizona Press,* 492-580. [9] Burchell, M. J. and MacKay, N. G. (1996), J. Geophys. Res. 103(E10): 22761-22774. [10] Wallis D. et al. (2005) *Mon. Not. R. Astron. Soc. 359*, 1137-1149. [11] Elbeshausen, D. et al (2007) *LPSC XXXVIII, #1952.* [12] Amsden, A. A. and Ruppel, H. M. (1981) *NUREG/CR-2185 (LA-8905).* [13] Wünnemann K. et al. (2006) *Icarus 180*, 514-527. [14] Tillotson, J. H. (1962) *Gen. At. GA-3216,* 140ff.

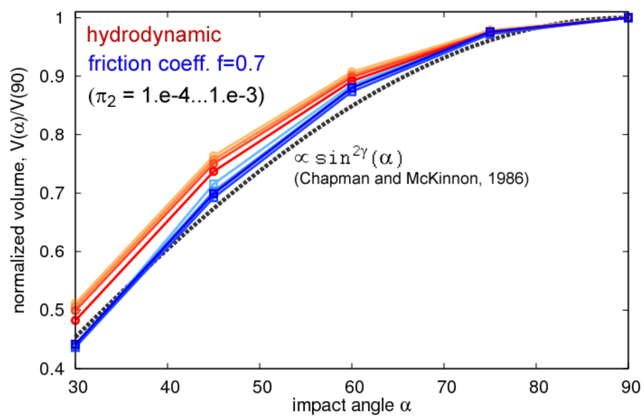

Fig. 1 Transient crater volume normalized with the maximum of the corresponding vertical impact for different angles.

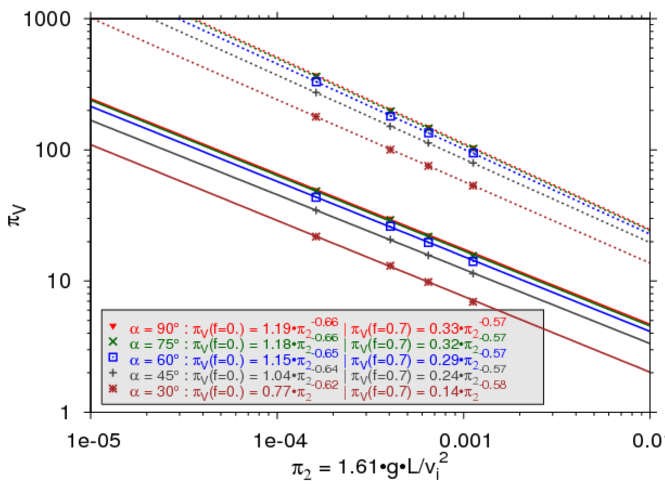

Fig. 2 Scaled transient crater volume vs. π_2-scenario for different impact angles and the resulting scaling laws. (Dashed lines: hydrodynamic, solid lines: f=0.7)