

LIMITATIONS OF POINTS-SOURCE ANALOGY FOR METEORITE IMPACT AND IMPLICATIONS TO CRATER-SCALING K. Wünnemann¹, G. S. Collins², D. Elbeshausen¹ ¹Humboldt-Universität zu Berlin, Museum für Naturkunde, D-10099 Berlin, Germany ²Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK (Contact: kai.wuennemann@museum.hu-berlin.de).

Introduction: The dimensions of meteorite impact craters provide an important measure of the energy that was released by an impact event. To evaluate the consequences accompanying the strike of a meteorite, therefore, it is of particular importance to find a relationship between crater size and impact energy. Deducing the original size of the impactor from a given crater size is impossible because velocity, impact angle and material properties are usually unknown. The inverse question, however, of how large a crater will be produced by an impact of given size, mass, velocity, and angle of incidence has been investigated in many experimental [1,2] and numerical modeling studies [3], which have resulted in the development of so-called scaling laws.

A fundamental assumption underlying cratering scaling laws is that an impact event may be approximated as a stationary point source of energy and momentum buried at a certain depth in the target, analogous to the detonation center of an explosive source [4,5,6,7]. If this assumption holds true for any hypervelocity impact, the kinetic energy (and momentum) of the impactor that is effectively available as an energy (and momentum) point source is defined, according to the theory, by the so-called coupling parameter. It is assumed that the coupling parameter combines the properties of the impactor (velocity U , diameter L , density δ) into one scalar parameter: $C = LU^\mu \delta^\nu$ [6]. In two theoretical end-member cases, the coupling parameter is exactly proportional to the kinetic energy (where $\nu=1/3$, $\mu=2/3$) or the momentum ($\nu=1/3$, $\mu=1/3$) of the impactor, respectively. However, experimental evidence suggests that the coupling parameter is somewhere between these limits; in other words, it is proportional to some combination of kinetic energy and momentum ($\nu=1/3$; $1/3 < \mu < 2/3$) [6]. The exact form of the coupling parameter appears to depend on target properties. In addition, impact angle plays an important role [8] and has not yet been successfully incorporated into scaling laws.

We conducted numerous numerical impact experiments (hydrocode models) of crater formation to investigate crater dimensions as a function of projectile properties (impact velocity, size, density, angle of incidence) and target characteristics (density, coefficient of friction, cohesion, porosity, gravity). Here we present the available data base in comparison to experimental data and discuss the implications of our results for impact crater scaling.

Pi-group scaling: The primary purpose of scaling laws is to meaningfully extrapolate the results of small scale laboratory impact experiments so that they may be applied to large scale natural craters. To achieve this, dimensionless ratios are used to estimate the relative importance of different

physical processes during crater formation. Dimensionless measures of the properties of impactor and target can be related to scaled crater dimensions implying that the relative crater size is independent of the real size of an impact event.

The most successful approach in dimensional analysis of impact crater scaling is the so-called Pi-group scaling [4]. Instead of defining for instance the crater volume V as function of six (or more) target and projectile properties (e.g., $V = F(U, \rho, \delta, Y, g, m)$, where U is impact velocity ρ is target density, δ is projectile density, Y is strength, g is gravity, and m is projectile mass) the use of dimensionless ratios reduces the number of independent variables to three: $\pi_V = F(\pi_2, \pi_3, \pi_4)$, where the so-called crater efficiency $\pi_V = \rho V/m$, the gravity-scaled size of an impact event $\pi_2 = 1.61 g L/U^2$, and the strength-scaled size $\pi_3 = Y/(\delta U^2)$, and the density ratio $\pi_4 = \rho/\delta$. Note that the angle of impact θ is yet not considered in this concept (compare [9]).

The assumption that an impact can be represented as a stationary point-source has been shown to imply that many impact-related phenomena are related to the dimensionless ratios π_2 , π_3 and π_4 by power laws. For instance, if gravity is the dominant influence on crater growth, crater efficiency π_V can be expressed as a power-law of π_2 and π_4 : $\pi_V = C_V \pi_4^\alpha \pi_2^\beta$, where the exponents α , β are related to the exponent in the coupling parameter: $\beta = -3\mu/(2+\mu)$, and $\alpha = (2+\mu-6\nu)/(2+\mu)$ [4]. A large number of impact experiments in sand and water [1,2] have demonstrated the utility of this, and other power law relationships, over the parameter range that can be realized in impact experiments (Fig.1). Note, that the dashed lines were fitted to data from cratering experiments for $\pi_2 < 10^{-5}$ [1].

Comparison between experimental and modeling data: We conducted a series of numerical experiments of crater formation with the well-known hydrocode iSALE [10,11]. First, we kept the impact velocity constant at $U=6.5$ km/s, comparable to velocities in laboratory experiments, and varied projectile size and gravity to investigate how crater efficiency changes with π_2 . In general, we found a good agreement between numerical models and experimental data for purely hydrodynamic targets (water) and dry sand (Fig. 1). For the latter, appropriate values for the coefficient of friction and porosity were required to match the experimental data.

For an oblique angle of incidence the models show that crater efficiency decreases with decreasing angle of incidence (Fig. 2) [8]. The data can still be approximated by a power-law for low impact velocities ($U=6.5$ kms), a density ratio between projectile and target $\pi_4=1$, and impact angles

$\theta > 30^\circ$. All available data (for vertical and oblique impacts and same friction coefficient) plot approximately on the same line if the velocity U is replaced by the vertical velocity component $u_v = \sin\theta U$ in the definition of the gravity-scaled size of an event π_2 : $\pi_V = C_V \pi_2^\alpha \pi_2^\beta \sin^{-2\beta} \theta$ [8,9].

Limitations of point-source: The fact that cratering efficiency (and a number of other measures of an impact) is related to π_2 by a power-law is indirect support for the validity of the point-source approximation. However, the finite size of the impactor implies that close to the impact site the point source approximation must break down. In other words, the point source approximation can only be strictly valid at sufficient distances from the impact (and, accordingly, a certain time after impact). Thus, we can define the “coupling zone” to be the near-field region within which the point-source approximation does not hold. Processes that occur in the coupling zone may still follow a power-law behavior but in such cases the power-law exponent may not be proportional to the velocity exponent μ , which it should be if the point-source approximation applies.

Experiments that imaged the evolution of crater growth in both vertical and oblique impacts [12] provide compelling evidence that the stationary point source concept may not hold for oblique impacts, or strong contrasts in density between projectile and target for instance due to porosity (dissipative targets, compare [4,5]). However, little numerical work has been done to constrain the dimensions of the coupling zone (and how this is affected by impactor and target properties), or to examine whether the size of the coupling zone is different for the various impact related phenomena for which scaling laws exist (e.g. ejection velocities, crater growth rate, shock pressure decay). Our goal here is to quantify the size of the coupling zone as a function of impactor and target properties and, thus, to put constraints on the applicability of the point source solution and Pi-group scaling for processes related to crater formation such as crater dimensions, ejection of material, and shock wave propagation.

Impact crater scaling laws might be expected to break down when the volume of the coupling zone is comparable to or larger than the crater volume. [6] suggested that the coupling zone might have a radius of ~ 2 impactor radii; in this case, the point-source approximation would be invalid for cratering efficiencies π_V less than ~ 8 . For typical impact scenarios on Earth (coefficient of friction=0.7, $g=9.81$, $U=18$ km/s), cratering efficiencies of 10 or lower equate to an impactor size of $L > 100$ km ($\pi_2 > 5 \times 10^{-3}$) for a vertical impact and $L > 20$ km ($\pi_2 > 1 \times 10^{-3}$) for oblique (30°). This would suggest that impact cratering scaling laws are applicable over almost the entire range of interest in planetary cratering. However, preliminary results of our numerical models indicate that the coupling zone is larger than two projectile radii, particularly in oblique impacts and impacts with large projectile-to-target density or porosity ratios.

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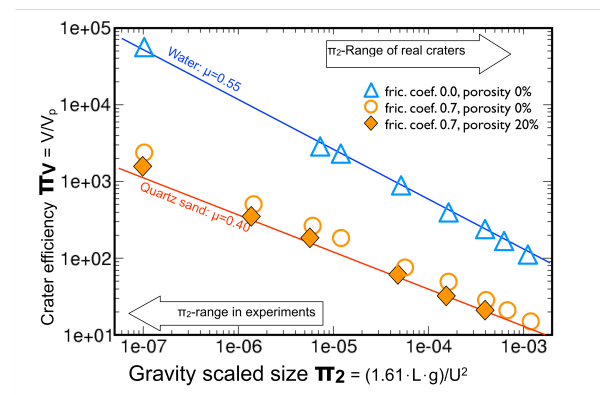


Fig. 1: Gravity-scaled size π_2 versus crater efficiency π_V for vertical impacts. Triangles, diamonds and circles represent numerical modeling results. The impact velocity was 6.5 km/s in all models. Solid lines are based on impact crater experiments [Schmidt87].

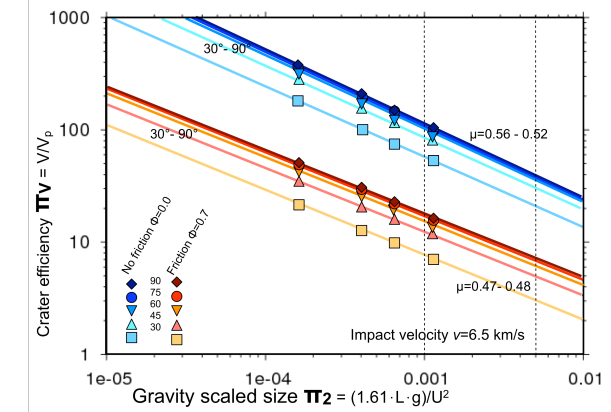


Fig. 2: Gravity-scaled size π_2 versus crater efficiency π_V for oblique impacts ($\theta=30^\circ-90^\circ$) and different friction coefficients ϕ . Blue lines correspond to a $\phi=0.0$, yellow-red lines correspond to $\phi=0.7$. The impact velocity was 6.5 km/s in all models.