Centrifuge Impact Cratering Experiments: Scaling Laws for Non-Porous Targets

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This work is a continuation of an ongoing program whose objective is to perform experiments and to develop scaling relationships for large-body impacts onto planetary surfaces. The development of the centrifuge technique has been pioneered by the present investigator and is used to provide experimental data for actual target materials of interest. With both powder and gas guns mounted on the rotor arm, it is possible to match various dimensionless similarity parameters, which have been shown to govern the behavior of large-scale impacts. Current work (Schmidt and Housen, 1986: Schmidt et al. 1985,1986) is directed toward the determination of scaling estimates for non-porous targets. The results are presented here in summary form.

The table below lists our scaling estimates in two forms. The upper part of the table gives the results in the nondimensional form shown in the accompanying figures. Note that the equation for time of formation, expressed in terms of crater volume and gravity, is independent of material type. As can be shown with the coupling parameter theory given by Holsapple and Schmidt (1986), the crater volume "accounts" for variations in target and impactor properties. The lower part of the table shows the same scaling laws in a dimensional form (with cgs units) in terms of the impactor energy and velocity, and gravity. In constructing these scaling laws, the density ratio was assumed to be constant, because in most cases there were insufficient data to determine the dependence on density. The lower part of the table was calculated with the target density appropriate for each material and a nominal impactor density (δ) of 3 gm/cm^3. Crater dimensions in all cases refer to the apparent crater.

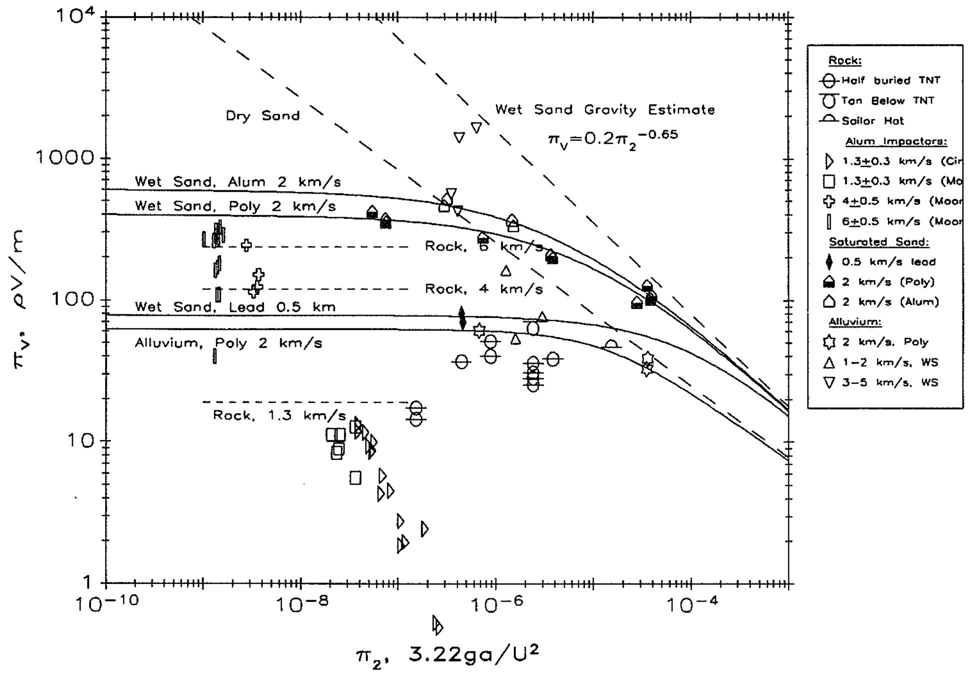
V=crater volume
R=crater radius
T=crater formation time
ρ=target density
Y=target strength
g=gravity
a=impactor radius
U=impactor velocity
E=impactor energy
t=time

	Dry Sand	Wet Sand	Water
Crater Volume	$\Pi_V = 0.24\,\Pi_2^{-0.51}$	$\Pi_V = 0.2\,\Pi_2^{-0.65}$	$\Pi_V = 2.1\,\Pi_2^{-0.65}$
Crater Radius	$\Pi_R = 0.84\,\Pi_2^{-0.17}$	$\Pi_R = 0.8\,\Pi_2^{-0.22}$	$\Pi_R = 0.94\,\Pi_2^{-0.22}$
Volume vs Time	$\Pi_V = 0.16\,\Pi_t^{0.86}$	$\Pi_V = 0.25\,\Pi_t^{1.07}$	$\Pi_V = 1.1\,\Pi_t^{1.07}$
Time of Formation	$\Pi_T = 1.9\,\Pi_2^{-0.58}$	$\Pi_T = 1.6\,\Pi_2^{-0.61}$	$\Pi_T = 2.3\,\Pi_2^{-0.61}$
	$T = 0.8\,V^{1/6}\,g^{1/2}$		

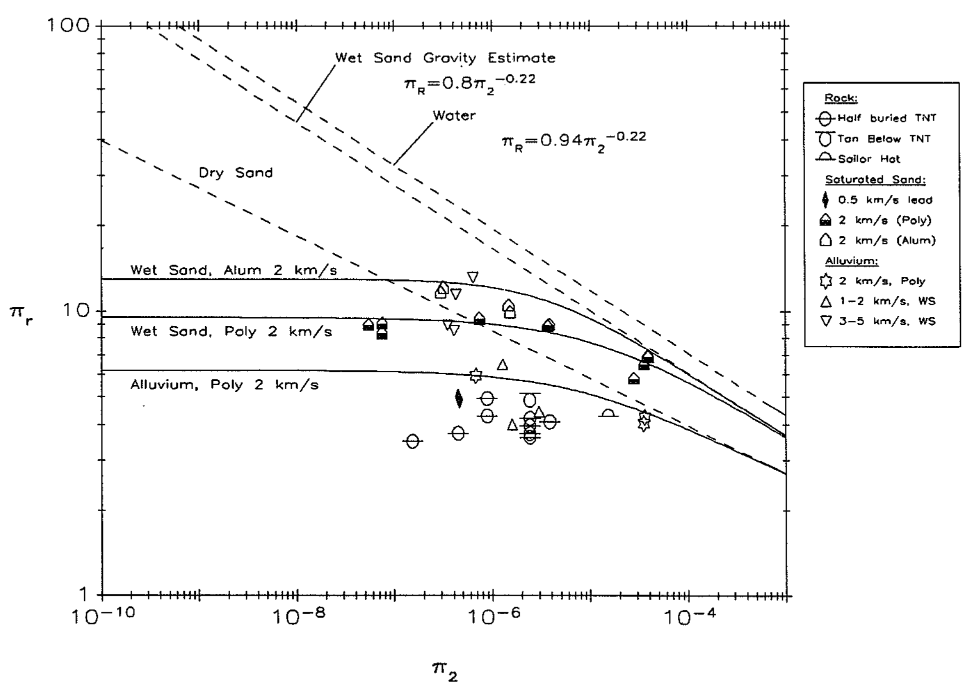
$\Pi_V = \rho V/m$
$\Pi_R = R\,(\rho/m)^{1/3}$
$\Pi_2 = 3.22ga/U^2$
$\Pi_t = Ut/a$
$\Pi_T = UT/a$

	Dry Sand	Wet Sand	Water
Volume	$V=0.20E^{0.83}U^{-0.64}g^{-0.51}$	$V=0.13E^{0.78}U^{-0.27}g^{-0.65}$	$V=2.9E^{0.78}U^{-0.27}g^{-0.65}$
Radius	$R=0.77E^{0.28}U^{-0.21}g^{-0.17}$	$R=0.70E^{0.26}U^{-0.09}g^{-0.22}$	$R=1.1E^{0.26}U^{-0.09}g^{-0.22}$
Vol vs t	$V=0.29E^{0.71}U^{-0.57}t^{0.86}$	$V=0.21E^{0.64}U^{-0.22}t^{1.07}$	$V=1.9E^{0.64}U^{-0.22}t^{1.07}$
Form. Time	$T=0.74E^{0.14}U^{-0.12}g^{-0.58}$	$T=0.62E^{0.13}U^{-0.04}g^{-0.61}$	$T=0.89E^{0.13}U^{-0.04}g^{-0.61}$

The slopes of the lines in the two figures below are based on a value of μ=0.4 for dry sand and μ=0.55 for water and wet sand. Also note that the effective size scale for the wet sand shots was not large enough to put them fully in the gravity regime. Thus, the proposed scaling estimate was constructed as an asymptote to the data, with a slope calculated from a value of μ=0.55. The estimate is significantly above the dry sand line because of better coupling in the (nonporous) wet sand, but below the line for water targets. The wet sand line is regarded as a current best-estimate for rocky materials, and differs from our earlier estimate (Schmidt and Holsapple, 1982) where the slope was calculated based on a value of μ more appropriate to porous materials.



Cratering efficiency for impacts and explosions in dry sand, alluvium, wet sand, and rock. The dashed line (labeled Wet Sand Gravity Estimate) is proposed as a current best estimate for large-scale cratering in rock.



Scaled crater radius results for impacts and explosions in various materials.
The dashed line (labeled Wet Sand Gravity Estimate) is proposed as a current best estimate for large-scale cratering in rock.

Scaling estimates for large-scale cratering in rock proposed previously by others have assumed that the crater radius is proportional to powers of the impactor energy and gravity, with no additional dependence on impact velocity. The energy exponent is typically reported to be 0.28 to 0.29 while estimates of the gravity exponent range from 0.11 to 0.17. The size scaling laws proposed here differ from earlier ones in three respects. First, a distinct dependence of impact velocity is recognized, even for constant impactor energy. The effects of velocity are smallest for nonporous targets, which approach (but do not reach) the asymptotic case of pure energy scaling. The porosity of materials like dry sand result in velocity-dependent energy losses. Hence, the velocity dependence is greatest for these materials. Second, the present energy exponent for low-porosity targets, like competent rock, is lower than earlier estimates. Although the difference might appear to be small (the present estimate is 0.26 versus the values of 0.28-0.29 mentioned above), the effect of this difference can be significant when extrapolating many orders of magnitude in energy up to kilometer-sized craters. Third, the gravity exponent is recognized here as being related to both the energy and the velocity exponents. As shown in the table below, these exponents are all determined by the single scaling exponent, μ, as defined by a coupling parameter of the form $C = aU^{\mu}\delta^{\nu}$

	Strength Regime	Gravity Regime
Crater Volume	$\frac{\rho V}{m} \propto (\frac{\rho}{\delta})^{1-3\nu} (\frac{Y}{\rho U^2})^{\frac{-3\mu}{2}}$	$\frac{\rho V}{m} \propto (\frac{\rho}{\delta})^{\frac{2+\mu-6\nu}{2+\mu}} (\frac{ga}{U^2})^{\frac{-3\mu}{2+\mu}}$
Formation Time	$\frac{UT}{a} \propto (\frac{\rho}{\delta})^{-\nu} (\frac{Y}{\rho U^2})^{\frac{-(1+\mu)}{2}}$	$\frac{UT}{a} \propto (\frac{\rho}{\delta})^{\frac{-\nu}{2+\mu}} (\frac{ga}{U^2})^{\frac{-(1+\mu)}{2+\mu}}$
Growth of the Transient Crater	$\frac{\rho V}{m} (\frac{\rho}{\delta})^{3\nu-1} (\frac{Y}{\rho U^2})^{\frac{-3\mu}{2}} = F\left[\frac{Ut}{a} (\frac{\rho}{\delta})^{\nu} (\frac{Y}{\rho U^2})^{\frac{1+\mu}{2}}\right]$	$\frac{\rho V}{m} (\frac{\rho}{\delta})^{\frac{6\nu-\mu-2}{2+\mu}} (\frac{ga}{U^2})^{\frac{3\mu}{2+\mu}} = F\left[\frac{Ut}{a} (\frac{\rho}{\delta})^{\frac{\nu}{2+\mu}} (\frac{ga}{U^2})^{\frac{1+\mu}{2+\mu}}\right]$
	Prior to the onset of strength or gravity effects	
	$\frac{\rho V}{m} \propto (\frac{\rho}{\delta})^{\frac{1+\mu-3\nu}{1+\mu}} (\frac{Ut}{a})^{\frac{3\mu}{1+\mu}}$	

As mentioned above, the wet-sand result is assumed to be a current best-estimate for large-scale cratering in rock. We stress however that this approximation is tentative until a better understanding is achieved of the dominant material properties which govern cratering in the gravity regime (e.g. density and friction angle). Once the role of density and friction angle are understood, reasonable analogues of rock might be constructed for which laboratory experiments can be performed in the gravity regime.

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