Craters from Impacts and Explosions

Keith A. Holsapple
University of Washington, Seattle, WA 98195, holsapple@aa.washington.edu

Kevin R. Housen
Applied Physics, MS 2T-50, P.O. Box 3999, Seattle WA 98124, kevin.r.housen@boeing.com

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1. Introduction

During the last 50 years, it is become well-known that impacts are a major contributor to the geology of solar system objects. They are the source of the multitude of craters found on the surfaces of both the large and small objects. An impact sometimes breaks up an objects.

And there have been major effects on Earth. Most believe that a major impact led to the demise of the dinosaurs. A giant impact may have created our moon.

On Earth, craters can also be formed by explosives, both for military or excavation applications. The physics of that cratering process is very much the same as for a high-speed impact, so it is prudent to study both fields. In either case, the energy and momentum of the "source" is transferred via shockwave into a "target". And in both planetary studies and in military studies a common question is about the size and other important characteristics of the crater formed from the source. And the reverse question is the one most often asked for planetary studies: what was the source that created an observed crater? Such questions are very important in studies of solar system evolution and history, deflections of threatening asteroids, effectiveness of a military system, and so forth.

Over the last several decades such questions have been mostly answered, at least for many of the important applications. Using modern scaling theories, we can predict the outcome of a hypervelocity impact of a given projectile onto a given object in the solar system. Those theories tell us how the outcome depends upon impactor size, impactor velocity and material, target properties, and target gravity field, etc. Similarly, for explosive cratering we can predict how the resulting crater and its characteristics depend upon the type of explosive, it's shape, and his placement relative to the surface. We can predict how

big the crater will be, it geometry, the magnitude of the shock wave in the target, and the distribution of the ejecta from the event. In fact, we have such predictions both for conventional "high explosives" and for nuclear explosives.

While these scaling theories are quite highly developed, they are not always easily accessible to a researcher. Results are often couched in "dimensionless groups", with so-called "pi-groups" that are sometimes difficult to unravel. And, as is true for any study in engineering, it is easy to get the units wrong. In addition, the actual data that provides the quantitative backbone to the scaling theories is scattered throughout the literature; and in addition much of the data for explosives is in the so-called "grey literature" of military and company reports that is not always easily accessible to a general researcher.

The authors of this paper had been involved in studies of cratering of both explosives and impacts for almost 40 years. During that time they accumulated, with the help of colleagues, considerable data. In addition they have been authors or co-authors of a large number of journal papers that develop the underlying scaling theory.

The purpose of this contribution is to make that data and theory easily accessible to any person with a scientific background. Here we present a web-based application that allows the user to define conditions of interest and obtain all of the primary characteristics of a resulting crater, either for impacts or explosives. In some cases, the result is quite definite, but in others it might be little more than a best guess. But at least it is a guess based on an extensive study of the problem.

The discussion here attempts to describe the basis and fidelity of the data and scaling forming the basis for the predictions.

The web-based application is available at[1]

http://keith.aa.washington.edu/craterdata/scaling/index.htm

2. User Information

The use of this web tool should be rather transparent to the user. However, it does provide links with further information about its use and the underlying theory, similar to

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[1] A refresh or reload of a web browser will assure that a user is using the latest version.

that given here. The applet calculates the characteristics of the craters that are created from a hypervelocity impact ("Impacts" button) or from an explosion ("Explosions" button). Both simple bowl-shaped (smaller) craters and complex craters (large lunar craters) are considered. A variety of important target soil or rock types are included, as well as different gravity levels (i.e. for small Solar System bodies).

As stated, it is based on the physically-based scaling methods developed over the last 20 years, primarily by Keith Holsapple, Robert Schmidt and Kevin Housen, as indicated in the reference list below. It does not use older and now obsolete methods such as "Energy Scaling" or "Yield Scaling" or strictly semi-empirical dimensional forms. Instead it is based on the non-dimensional forms required by any valid physical theory. But it also uses additional important simplifications (primarily the point-source approximations) that have been validated by 20 or more years of application, by experiments, field data, and numerical simulations.

The scaling theory supplies the necessary functional forms for all of the dependences on the problem inputs, but not the necessary scaling coefficients. For those, one needs a body of data. For explosions, there is a database of over 1500 events that has been studied extensively. And there are a fair number of lab impact tests. Then, in addition, there are known guidelines (Holsapple, 1980) to compare explosive and impact cratering, so that same database gives importance guidance to the laboratory tests and numerical simulations of impacts, and it can be used to fill in the holes in the data. While an extensive study of the explosion data was presented in the Schmidt et al. 1986 DNA report cited below, that reference is limited in distribution. However, all of the raw data for both conventional and nuclear explosions in included in the database that can be accessed here: Impact and Exposion Cratering Data Base. The nature of that data is discussed below.

Here I present only the final numerical forms, first for explosives, and then for impacts.

3. General Considerations, Impact and Explosive Cratering

For impacts the "source" is the impactor, while for explosions, the "source" is the explosive charge. We assume that the source is much smaller than a "target" body. The

simplest and best known scaling is for "high explosives" in which the explosive typically has on the order of 5 10^{10} ergs/g specific energy; and for hypervelocity impacts, where the impact velocity is greater than the target sound speed: from a few to many km/s. The effective specific energy of an impactor with a velocity of 3 km/s is about the same as a standard HE explosive. In that range, the source shape is of little consequence, as long as it is relatively compact. The results do not apply to long rod or penetrator designs, nor m/s impact velocities. The results do account for different impact angles, but not shallow, glancing impacts, and for the explosive placement relative to the surface.

The cratering outcomes for a given source are determined by, primarily, the target strength and the surface gravity, and often only one of these. The smaller craters are determined by the target strength, while the larger craters are determined by the surface gravity. That defines two regimes of cratering: the "strength regime" and the "gravity regime"[2], with in-between transition cases.

3.1. Dimensionless Forms

As the primary example, the volume V of a crater formed by a given impact can be expected to depend on the impactor radius a, velocity U, and mass density δ. Note that those 3 variables also defined the kinetic energy, momentum, and mass of the impactor, so equally those could be used, as well as any other choice of three independent variables containing the three independent units of mass, time and length.

The target has some strength measure Y, a mass density ρ, and a porosity ϕ. Below it will actually be assumed that the strength depends on the event size, but for now it is treated as a constant. We can ignore the additional properties for a fixed choice of target types, and we consider only one target type at a time. The surface gravity is denoted as g. Then the crater volume depends on those variables by some functional relationship:

$$V = F[\{\rho, Y\}, \{a, U, \delta), \{g\}]$$

(1)

As is the case for any physical results, the results can always be stated in terms of

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[2] For very small target bodies such as asteroids, one should be very careful in assuming the strength level, because even almost negligible cohesion values can dominate the equally negligible gravity.

dimensionless forms. That is a simply the condition that the results must be independent of the choice of units. So we begin with a simple dimensional analysis. In addition, it will be assumed that the impactor measure can be considered as a "point source", since the region of influence is much larger than the impactor dimensions. Definite power-law forms are the outcome of that assumption. The presentation here follows the (Holsapple, 1993) review paper on impact cratering as well as Holsapple and Schmidt, 1980, 1982 and 1987. I will not reproduce those presentations here, but will just present the final forms.

The general form for a scaled volume is given in the Eq. 18 of (Holsapple, 1993) is

$$\pi_V = K_1 \left\{ \pi_2 \left(\frac{\rho}{\delta} \right)^{\frac{6\nu-2-\mu}{3\mu}} + \left[K_2 \pi_3 \left(\frac{\rho}{\delta} \right)^{\frac{6\nu-2}{3\mu}} \right]^{\frac{2+\mu}{2}} \right\}^{\frac{-3\mu}{2+\mu}}$$

$$\text{with } \pi_V = \frac{\rho V}{m}, \quad \pi_2 = \frac{ga}{U^2}, \quad \pi_3 = \frac{Y}{\rho U^2}$$

(2)

having the two scaling exponents μ and ν, and two coefficients K_1 and K_2. Those must be determined from actual data. (The last exponent $-3\mu/(2+\mu)$ is often denoted as α.) The first term with π_2 dominates for large events, and that defines the gravity regime. That dimensionless π_2 group is sometimes called the "gravity-scaled size parameter". The second π_3 term with the target strength dominates for small events, it defines the strength regime.

Explosive cratering is much like impact cratering, but with an additional independent variable: the depth of burial d of the explosive. That is commonly measured as a ratio to the explosive radius[3] a as $dob=d/a$. For now, we consider only the "half buried" case where the charge center is at the surface level.

For the analysis of explosions, the specific energy of an impactor, $U^2/2$, is replaced by the specific energy Q of the explosive material[4]. Also, it is more common to use the explosive weight W rather than its radius to define its size[5]. Using those, the gravity-scaled size parameter π_2 and the strength parameter π_3 for explosions are traditionally defined a

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[3] For non-spherical but compact explosive shapes, a weight-equivalent radius can be used.
[4] The specific energy of TNT is the same as that of an impactor at the velocity of 2.9 km/s.
[5] Even nuclear explosives are measured by the equivalent TNT weight for the same energy. Therefore, the equivalent TNT weight and the actual weight for nuclear devices differ by many orders of magnitude. Both are shown in the application.

little differently than those above for impacts, but using the same gravity-strength composite scaling form

$$\pi_V = \bar{K}_1 \left\{ \bar{\pi}_2 \left(\frac{\rho}{\delta} \right)^{\frac{6\nu-2-\mu}{3\mu}} + \left[\bar{K}_2 \bar{\pi}_3 \left(\frac{\rho}{\delta} \right)^{\frac{6\nu-2}{3\mu}} \right]^{\frac{2+\mu}{2}} \right\}^{\frac{-3\mu}{2+\mu}}$$

(3)

but now with $\pi_V = \dfrac{\rho V}{m}$, $\bar{\pi}_2 = \dfrac{g}{Q} \left(\dfrac{W}{\delta} \right)^{1/3}$, $\bar{\pi}_3 = \dfrac{Y}{\rho Q}$

When compared to the dimensionless groups used for impacts, since for impacts $Q=U^2/2$, we have the relations

$$\bar{\pi}_2 = 3.22\pi_2, \quad \bar{\pi}_3 = 2\pi_3$$

(4)

The K_1 constants determine the magnitude of the crater in both the gravity and strength regimes, they are determined by the "early-time" coupling of the source energy and momentum into the target. The K_2 constants determine the event size for the transition between strength scaling and gravity scaling. They depend upon the target density and porosity, but here I make no attempt to characterize those dependences. Also, this equation has no specific inclusion of the angle of repose of the target. So, while the webpage shows values for the density, porosity and angle of repose for different materials, those values are not directly used. Instead the constants K_1 and K_2 are individually chosen for each material type from the data.

It is well established over the last several decades (e.g. (Holsapple, 1993)) that for relatively dissipative materials such as "dry" soils and sands the exponent μ is about 0.4, and for wet and rocky targets it is about 0.55. (An source couples more kinetic energy into the less porous materials.) The exponent ν is 1/3 if some combination of the mass and specific energy (defining also the energy and momentum) of the source determines its measure, but experiments give uncertain values, ranging from about 0.2 to 0.4. Here the value of 1/3 is adopted, primarily because of its simplicity. That value is not of much consequence for the ranges of the density ratio ρ/δ of interest.

Note that there is the combined product K_2*Y in the above equations that defines the transition between the gravity and strength regimes, where Y is the "strength". But a target material has a tensile strength, compressive strength, shear strength, cohesion (shear

strength at zero confining pressure), crush strength, disruption strength and other strength measures applicable to various conditions. Some combination of those may determine the cratering outcome. But which one?

It is that strength that determines the transition between the strength and gravity regimes. And it only for explosions that we have data on both gravity and strength regimes for many materials. Thus, the explosion data can be used to determine values for the product K_2*Y. If we arbitrarily choose $K_2=1$, then the values indicated from the data for the strength Y are consistent with both the tensile strength and the cohesion, which typically have about the same values. That is the choice made here.

So for explosions the value of K_2 is unity. However, the scaling forms used for impacts are slightly different from those used for explosions. Since in these two cases the same target material should use the same strength measure, we can derive that[6] $\bar{K}_2 \doteq 0.8$.

And there is one final complexity. It is now generally accepted that the strength of rocky bodies (but not soils and sands) depends on the size scale of the event (e.g. Housen and Holsapple, 1999). The explosion data in the strength regime for rocks clearly shows that affect. The strength one measures on the lab for a 10 cm pristine sample of say, basalt, is not the strength that governs a 100 m crater in basalt. That size dependence of strength is a consequence of the fact that natural geological materials are permeated by cracks and flaws of all sizes, and it is those flaws that limit the strength.

While it is not appropriate to delve into that issue in detail here, the web application includes a size-dependent strength, assuming the strength decreases as the negative 1/n power of the crater diameter. Specifically, it uses the input of a lab-sized cohesive strength Y_0, and then it iterates the strength Y according to the size of the resulting crater using the formula $Y=Y_0(10cm/D_{cm})^{-1/n}$. Thus the reference "lab" strength Y_0 is what is measured for a 10 cm specimen. The degraded value found is indicated by the application.

Those flaws have a much greater effect on tensile failures than on shearing failures. While that feature is not yet well researched, here the size-dependence on the crater sizes, which for normal craters are dominated by the shear strength, use n=4. Spall craters are formed primarily by tensile failures, and in that case this program uses n=2, which is the

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[6] The analysis of the relations between the scaling coefficients for impacts and explosions is given in the Appendix A.

smallest expected value for *n* and which occurs for "fully cracked" materials. The interest reader can consult Housen and Holsapple, 1999.

4. Explosive Cratering Data

Since there is more useful data for explosions compared to impacts, the explosive crater data are discussed first. The reference cratering database lists values for a large number of experiments in the lab and for larger field tests using from a few grams to 100 ktons of explosives (for nuclear tests, equivalent TNT weight). Much of the field data is from the "Nuclear Geoplosics Sourcebook" listed in the references, which is in the open literature. In the Schmidt et al. DNA 1988 report, curves were presented for the various target geology types, which aids in the data sorting and interpretation. Those curves are not directly given here, but instead the web page presents a link ("show me the data plot") to the actual data plots for the crater size as a function of either the strength of the gravity parameter for each case of interest.

4.1 Half-buried Explosives.

When a spherical explosive is just half-buried, then *dob*=0. That case is considered first. The values for the coefficients are again found by a study of the data, as was done in the Schmidt et al. 1988 report. That can be done in a systematic order. Although the explosive cratering data is somewhat sparse, and also has a lot of scatter, it does provide reasonable estimates of the transition size between strength and gravity. That transition occurs when the two terms in the scaling forms above are equal in magnitude. With ν=1/3 that becomes for explosions:

$$\bar{\pi}_2 \left(\delta / \rho \right)^{\frac{1}{3}} = \left(\bar{K}_2 \bar{\pi}_3 \right)^{\frac{2+\mu}{2}} \tag{5}$$

Using the (cgs) values Q=4.2 10^{10}, δ=1.64, g=981, and the choice for the transition charge weight W from the data, allows one to easily solve for the product $\bar{K}_2 Y$ at that transition size. From that, and the choice $\bar{K}_2 = 1$, it is not hard to find the lab-scale strength Y_0.

Once the value of $\bar{K}_2$ is determined, the value of $\bar{K}_1$ can be set, from the value of the indicated scaled crater size at the chosen transition point.

The net results are as given in the flowing table. Note again that the web application allows one to see the actual data plots upon which these choices are based.

Material	K_1	K_2	μ	ν	Y(dynes/cm^3)	ρ (g/cm^3)
Water	0.85	0	0.55	0.33	0	1
Dry Sand	0.12	0	0.4	0.33	0	1.7
Dry Soil	0.12	1	0.4	0.33	1.4E6	1.7
Wet Soil	0.09	1	0.55	0.33	3.5E6	2.1
Soft Dry Rock/Hard Soils	0.12	1	0.55	0.33	7.5E6	2.1
Hard Rocks	0.12	1	0.55	0.33	1.2E8	3.2
Lunar Regolith	0.12	1	0.4	0.33	1E5	1.5
Cold Ice	0.12	1	0.55	0.33	5e6	0.93

Table 4. Cratering Coefficients for Explosions.

Note that in the gravity regime for any given π_2, all of the non-porous materials have the same gravity regime π_V, so the resulting crater volumes for the same explosive mass vary as the reciprocal of their density.

While the value of K_1 is determined solely from the gravity regime results, the values for the strength coefficient K_2 were assumed equal to unity[7], and then the effective cratering strengths were chosen to match the strength regime data.

4.2 Fully Buried Explosives.

When an explosive is buried several radii, all of the transmission of its energy and momentum into the target material occurs before any stress wave reaches the surface, thus the presence of the surface has no affect in the transmission of energy and momentum into the target material. In that case, it is again valid to suppose that it can be approximated as a point source, using the coupling parameter form $aU^\mu\delta^\nu$ as its measure. But the final crater size depends on that burial depth, so that *dob* parameter *d/a* is an additional independent

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[7] Recall again that it is the factor of 2 difference in the scaled strength term that leads to the choice of *K$_2$*=0.5 for impacts.

dimensionless parameter, and the scaling must involve some function of d/a also. This was presented in some detail in the 1988 DNA report, but primarily for the case of dry sand where lab data was obtained. And, of course, for dry sand there is no strength regime.

Here it was assumed that for deep burials the dependence on d/a is the same in either the gravity or strength regime, so we can just include a multiplicative factor as

$$\pi_V = F\left(\frac{d}{a}\right)\bar{K}_1\left\{\left[\pi_2\left(\frac{\rho}{\delta}\right)^{\frac{6\nu-2-\mu}{3\mu}}+\left[\bar{K}_2\pi_3\left(\frac{\rho}{\delta}\right)^{\frac{6\nu-2}{3\mu}}\right]^{\frac{2+\mu}{2}}\right]^{\frac{-3\mu}{2+\mu}}\right\}$$

For sands, and for $d/a>1$ The DNA report gave a form equivalent to
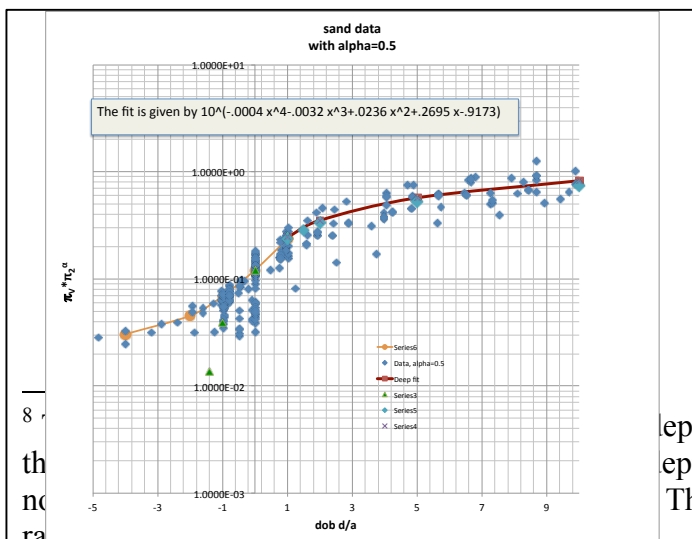
$$F(\frac{d}{a})\bar{K}_1 = 0.26\left(\frac{d}{a}\right)^{0.53}$$

for buried explosions, and it was shown to be valid for depths from $d/a>1$ to very deep burial depths[8] approaching the "optimum" burial depth.

4.2 Near Surface Explosions.

The most definitive data for near surface and height-of-burst explosives is the lab data as reported in the Schmidt et al. DNA report. That data for dry sand is reproduced here, in a plot of $\pi_V\left(\pi_2\right)^{3\mu/(2+\mu)}$ versus *dob*:

sand data
with alpha=0.5

The fit is given by 10^(-.0004 x^4-.0032 x^3+.0236 x^2+.2695 x-.9173)

The curve for the case of buried charges defined above for d/a>1 is shown. In addition, the data and a fit for the near surface and height of burst data is also shown, with a polynomial fit to its log. That is the programed dob fit for all materials.

epth. The "optimum" dob is defined as epths not much larger, the explosion does The optimum dob is on the order of 10+

5. Impact Results

5.1. Target Materials

In Holsapple 1993, results are given for impacts into each of five target types: dry sand, dry soils, wet soils, dry soft rocks, and hard rocks. That choice of material classifications mimics that for the extensive study of small and large explosions in the Schmidt et al, 1988 DNA report. Those explosive results defined the strength asymptote for small craters and, in most cases, the gravity regime for large ones. To those classifications I added three more: dry lunar regolith, cold ice, and water, both for impacts and for explosions.

While there are also considerable experimental data for impacts into various material types (mostly lab data), there are also significant holes in that data. Here I summarize the nature of impact data. What are needed are values for the two constants K_1 and K_2. Any gravity regime data can be used to obtain K_1. Then according to the argument above, using $K_2=1$, the value for the "cratering strength" Y is determined by the strength regime results.

5.1.1. Dry Sand

Dry sand targets are often used for laboratory experiments. Both 1G and gravity at up to 500G tests[9] have been made, for velocities from 1 to 5 km/s. Since there is no strength measure Y for dry sand[10], all results are in the gravity regime. The results conform to the power-law expectations almost exactly, and furnish irrefutable evidence of the accuracy of the point-source assumption. This data is primarily for Ottawa sand and is very robust, although one must be aware that different sands do have slightly different cratering results. Those results give guidance to other material's results that are not so well known.

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[9] The reason for testing at increased gravity is because it is a way to vary the π_2 parameter, in place of increasing the impactor size. See the references.

[10] Dry sand gets its strength when subjected to pressure via its angle of friction.

5.1.2. Wet Sand

The database includes about a dozen experiments in wet sand, at various gravity levels. Those results were presented in (Schmidt and Housen, 1987) and interpreted in terms of gravity and strength regimes. Since the data were mostly in the strength regime, those authors made estimates for a gravity regime based on the water and dry sand results. I use those estimates here.

5.1.3. Wet Soils

There are no impact experiments for general wet soils, and there may well be significant variation depending on the soil. However, there are some explosive results for wet soils. Here I assume generic results as the same as for the wet sand impacts, and check against the comparisons to the explosive results, which are described below.

5.1.4. Dry Soft Rocks, Hard Rocks, Ice

There are no definitive impact experiments for dry soft rocks, hard rocks or for ice. While there are some small-scale impact experiments, the outcomes are shallow surface spall craters, not excavation craters. It is known that craters in brittle materials at Earth's gravity will be spall craters as long as they are under a few meters in diameter (Holsapple and Housen, 2013) , so those small-scale results are not definitive for larger excavation craters. However, there are large explosive excavation data, but still all in the strength regime. For impacts in the strength regime, I will base the estimates on the explosive data, using the equivalences to impact presented below.

For the gravity regime, the strength is no longer of any consequence. For that reason, our best estimates are that all non-porous materials have the same gravity regime outcomes as wet sand.

5.1.5. Water Impacts

Several researchers have reported hypervelocity impacts into water targets. For such impacts, "crater size" is measured when the crater is at its maximum depth. Subsequently the crater collapses, with the radius moving in an outward wave, and the crater center rebounding upwards, creating a centered water-spout. As for dry sand, there is no strength

regime, only a gravity one. The scaling of these craters was given in Holsapple and Schmidt, 1982. That interpretation was directly used here.

5.2. The Impact Target Constants

The constants used for impacts in this web application are:

Material	K_1	K_2	μ	ν	Y (dynes/cm^3) At lab scale	ρ (g/cm^3)
Water	0.904	0	0.55	0.33	0	1
Dry Sand	0.14	0	0.4	0.33	0	1.7
Dry Soil	0.14	0.75	0.4	0.33	1.4E4	1.7
Wet Soil	0.094	0.75	0.55	0.33	1.2E6	2.1
Soft Dry Rock/Hard Soils	0.012	0.8	0.55	0.33	1.5e8	2.1
Hard Rocks	0.012	0.8	0.55	0.33	1.6e9	3.2
Lunar Regolith	0.14	0.75	0.4	0.33	1.4e4	1.5
Cold Ice	0.012	0.8	0.55	0.33	1.5e8	0.93

Table 1. Scaling Constant for Impacts

5.3. The Impactor and Gravity Properties

For hypervelocity impacts of compact projectiles, the mass density is needed, but not other properties. Here are the values used:

Impactor type	Mass density, (g/cm^3)
Aluminum	2.7
Plastic	0.95
Steel	7.8
C-Type	1.8
S-Type	3.0
Comet	0.8

Table 2. Assumed Impactor Properties

A user may pick other values in the app are made by choosing "Other" in the pull-down menu for the impactor type.

Gravity is pre-set for Terrestrial, Lunar and two asteroid cases, or the input can be adjusted by the user if "Other" is selected. The velocity can be set to any value, but a warning ensues for any values below 1 km/sec, where the data is sketchy and the point source assumption becomes iffy. For non-vertical impacts, the vertical component $U \cos(\theta)$ is used.

5.4. Simple Crater Shapes

In each material type, the craters except for the very largest are assumed to have the same fixed "bowl" shape. The shapes of simple craters are calculated from $R=K_r V^{1/3}$ and the depth from $D=depth=K_d V^{1/3}$. The values indicated by the data and programmed are as follows:

Material	K_r	K_d
Water	0.8	0.75
Dry Sand	1.4	0.35
Dry Soils w/ cohesion	1.1	0.6
Soft Rock	1.1	0.6
Hard Rock	1.1	0.6
Cold Ice	1.1	0.6

Table 3. Crater Shape Parameters.

In all cases, the rim diameter is assumed to be 1.3 times the excavation diameter and the lip height 0.36 times the rim diameter, consistent with the data and measured terrestrial and lunar simple craters. The ejecta volume is assumed to be 80% of the excavation volume. The crater formation time is from Schmidt and Housen 1987, and the Figure 12 in (Holsapple, 1993) as

$$T = 0.8\sqrt{\frac{V^{1/3}}{g}} \tag{6}$$

5.5. Melt and Vapor Volumes

Melt and vaporization of target material occurs when the initial impact pressure is high enough. That is defined by the equation of state; it is where the Hugoniot curve crosses the melt boundary. For melt, I assume that the velocity threshold is $U = \sqrt{10E_{melt}}$ in terms of the specific energy of melt for the material. I take a generic value for the melt energy for silicates as $5 \cdot 10^{10}$ ergs/g. I use the "less than energy scaling" from Holsapple, 2003 matched to some of the results from (Pierazzo et al., 1997) and get

$$V_{melt} = 0.5 V_{impactor} \left[\frac{U^2}{5E10} - 10 \right]^{0.9} \tag{7}$$

Vapor production is in a volume much closer to the impactor, so I use strict energy scaling with a generic vapor energy of 1.5E11:

$$V_{vapor} = 0.4 V_{impactor} \left[\frac{U^2}{1.5E11} - 10 \right]^{1.0} \tag{8}$$

I have not yet added the melt and vapor for impacts into ice, there are significant questions about its many phases at cold temperatures.

5.6. Complex Craters

For craters with a simple transient radius greater than some value R^*, the simple excavation crater with the radius R_e undergoes a late-time readjustment into a much broader and shallower "complex crater". The data for lunar craters by Pike 1977 gives a transition to complex shapes beginning at D^*=10.6 km rim diameter. The transition in rim heights begins at a larger size, D^*_{rh}=22.8 km diameter. The onset of flat floors is gradual, but is fully developed at D^*_{fl}=20 km diameter.

I assume that any transition diameter such as D^* depends on the strength and gravity as $D^* \propto Y/(\rho g)$. Thus, assuming (in cgs units) a lunar strength Y=2E6, density ρ=1.7, and gravity g=162 , the transition diameter for other bodies is given as

$$D^* = 10.6 \left(\frac{162}{g} \right) \left(\frac{1.7}{\rho} \right) \left(\frac{Y}{6 \times 10^6} \right) km \tag{9}$$

Let D_r^f denote the final rim diameter, and D_r^t the transient (simple) rim diameter. The analysis of the relation between simple and complex craters is based on an incompressible readjustment from the simple crater shapes measured in laboratory experiments and those observed for lunar craters, using primarily the data of Pike 1977. The approach is outlined in Holsapple, 1993. The primary result is an expression for the ratio of the final to transient rim radius:

$$\frac{D_r^f}{D_r^t} = 1.02 \left(\frac{D_r^f}{D^*} \right)^{0.079} \tag{10}$$

which gives, using the ratio 1.3 for the transient rim to excavation rim diamters,

$$D_r^f = 1.33 \left(D_e\right)^{1.086} \left(D^*\right)^{-0.086} \tag{11}$$

The Pike data for lunar craters gives for the depth of complex craters larger than D^*=10.6 km as $d=1.044(D_r^f)^{0.301}$ in km units. This matches the simple crater result, $d = 0.2D_r^f$ at the transition onset using the dimensionally consistent form

$$d = 0.2D^* \left(\frac{D_r^f}{D^*}\right)^{0.301} \tag{12}$$

For the rim height, Pike gives $h= 0.236\ (D_r^f)^{0.399}$ for complex craters and $h = 0.036D$ for simple craters. With the transition of rime heights at D^*_{rh} =22.8 km diameter, that gives the equation

$$h = 0.036D^* \left(\frac{D_r^f}{D^*_{rh}}\right)^{0.399} \tag{13}$$

The flat floor diameter is given for lunar complex craters as $D_f=0.187(D_r^f)^{1.249}$ for diameters greater than D^*_{fl}=20 km. Assuming this dimension is zero at the 10.6 km onset of complex craters, the fit used was

$$D_f = 0.292 \left(D^*_{fl}\right)^{-0.249} \left(D_r^f - D^*\right)^{1.249} \tag{14}$$

Finally, the volume below the rim uses a profile with a flat floor, and a uniform slope from the floor diameter to the rim diameter and the rim height. The outcome is given as
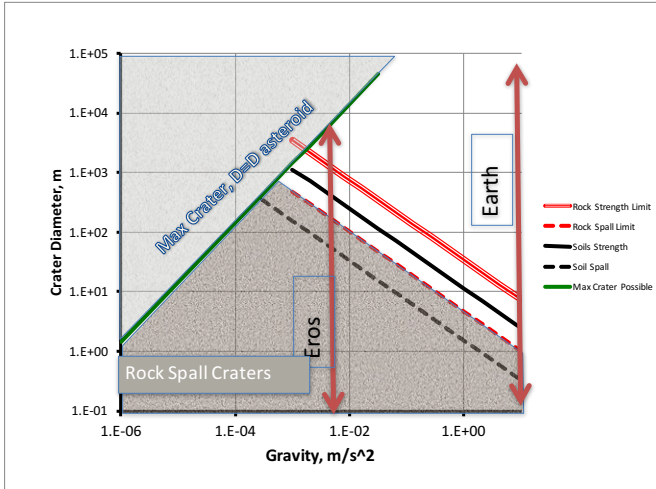
$$vol = \frac{\pi d}{4}\left[D_f^{\,2} + \frac{1}{3}(D_r^f - D_f)(D_r^f + 2D_f)\right] \tag{15}$$

Note that in the app, the display section for complex craters only appears when the crater sizes are larger than the transition diameter.

5.7. Ejecta Scaling

The definitive references on the amounts and properties of the ejecta from impact cratering are (Housen et al., 1983) and (Housen and Holsapple, 2011)

6. Small Spall Dominated Craters

Spall occurs when

$$D < 0.1\left(\frac{Y(D_{exc})}{\rho g}\right)$$ in terms of the

excavation crater D_{exc} (Holsapple, LPSC). With a size-dependent

strength $Y = Y_0\left(\frac{D_o}{D}\right)^{1/n}$ this can be

manipulated to

Spall Crater Regime, Size depend strength

$$\frac{D}{D_0} < \left[0.1\frac{Y_0}{\rho g D_0}\right]^{\frac{n}{n+1}}$$

(16)

which is always a subset of the strength regime. Here for spall it is assumed that n=2. In this spall cases, the spall diameter can be as much as a factor of 4 than the excavation crater diameter D_{esc}:

$$D_{spall} = f(D_{exc})D_{exc} \tag{17}$$

with

$$f(D_{exc}) = Max(1, Min(3, 5(1 - 0.8D_{exc} / D_{exc\lim}))) \tag{18}$$

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