WHAT DO WE NEED TO KNOW TO MODEL IMPACT PROCESSES?

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Introduction. The computer modeling of hypervelocity impacts into planetary bodies is one of the most challenging computer tasks we attempt. The physical states encountered in impact events can begin with pressures measured in gigabars and temperatures measured in hundreds of electron-volts, and then proceed all the way down to the ordinary partial bars of pressure and few degrees of temperature as in our common experience in terrestrial soils and rocks. The interest in planetary science applications spans not only those common terrestrial soils and rocks, but also gases, ices at extreme low temperatures, and very loose, rubble-pile materials that could not even withstand the pressures of the Earth's gravity without crumbling.

The extreme range of physical conditions and materials makes the job of a modeler extremely difficult, especially for descriptions of the models for the material behavior. While, in principle, current computer power would seem to allow the detailed calculation of any specific impact event of interest by integrating the known physical laws, that view is specious. The cold, cruel facts are that, first, we do not yet know how to mathematically model the extreme range of conditions of importance, and second, even if we develop meaningful models, we do not have sufficient physical tests to measure the material properties needed for those models.

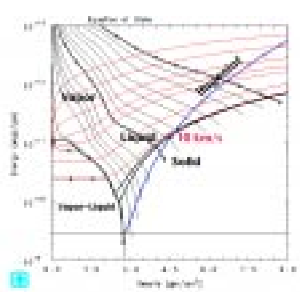
This state of affairs means that the community must be aware of the shortcomings, and must spend much more time and effort on the development of models of material behavior, on the laboratory and field measurements to calibrate those models, on calculations to determine the sensitivity of the results on the models, on actual physical experiments of impacts, and, finally, on calculations of those physical laboratory results and large scale field events with known impact conditions. The computer tools must prove their reliability and robustness for calculations when both the initial and final conditions are well known before they can be used with any meaning to determine unknown impact conditions.

This presentation is to review what we know and what we do not know; what needs to be known, and what remains to be discovered about material modeling for impacts.

The EOS. The evolution of the pressure and temperature states from extremely large to very small leads to a parallel separation of the required material models into two distinct but intertwined parts. First are the models for the high-pressure behavior in the early stages of the process. Those pressures are commonly much larger that the material stress scales: the compressibility modulus and various material strengths, so the stress deviators can be ignored. The state is then measured by five state variables: the pressure p, mass density ρ, internal energy e temperature T and entropy η. Any pair can be chosen as independent, and the other three are then given in terms of those two by the "equations of state" which are material property functions. However, insofar as the solution for the motion is concerned, it is only the relation between e, p and ρ that matters.

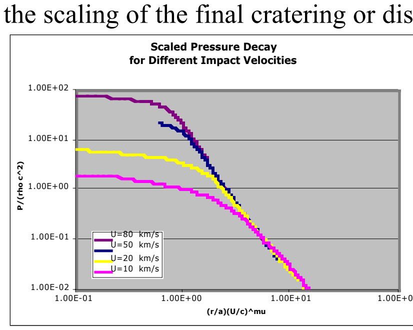
Since impact problems encounter the same extreme conditions as nuclear events, it is not surprising that we borrow the knowledge and tools of the national weapons laboratories for those equations of state, which they have been studying for over half a century.

There are a variety of EOS models: simple algebraic models that relate pressure and density with no dependence on temperature (e.g. linear elasticity or Murnaghan); simple analytical models for single solid phases (Mie-Gruneisen and Tillotson); complex analytical models including phase changes such as melt and vapor (ANEOS); and complete tabular databases such as the SESAME and SESLAN libraries from the DOE laboratories. Those latter two are often developed from complex solid-state physics theories using the PANDA computer code [1]. The EOS equations govern the early-time response and determine a number of significant aspects of the energy coupling, including the initial pressure and velocity, and the decay of the pressure and velocity as a shock propagates through the target.



A typical EOS is as shown at the left. The important elements include the Hugoniot, which relates the conditions at the shock, and the "release adiabat" the path followed during the unloading behind the shock.

These paths determine a measure of an equivalent point source input, which in term determines most of the scaling of the final cratering or disruption results.



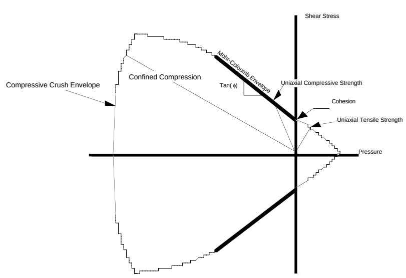
The left figure illustrates the commonality of different impact problems arising from the simplicity of the point-source measure. (See [2] and many prior references of the author and his colleagues.)

These EOS descriptions are quite well developed and understood, a consequence of the fact that they are needed for calculations and development of nuclear weapons. For impact calculations, it is necessary to choose the model and its constants. However, for any particular geological material, that can often be a difficult task, so that the resulting model is usually quite uncertain.

Strength. When the shocks decay into the kilobar pressure range, material strength dominates the target response and subsequent cratering or disruption. Here we borrow from the civil engineering soil-mechanics and rock-mechanics communities.

Strength models include none (hydrodynamic), constant strength in tensile or compression, constant strength in shear (Tresca), maximum deviator invariant J_2 (VonMises), pressure-dependent shear strength (Mohr-Coloumb), pressure-dependent J_2 (Drucker-Prager), rate-dependent tensile (e.g. Grady-Kipp), and complex damage models (e.g. Johnson-Cook). This description of the fracture, flow or yielding (generically called "failure") is the most difficult part of impact calculations into geological materials.

A common starting point is to describe how the initial failure depends on the stress or strain tensors, which have six independent components; or, equally well, three invariants and three directions. Assuming isotropy, directions are of no consequence and the stress tensor can be measured by the three invariants. It is common to further suppose that only two are necessary, taken as the pressure or mean stress (essentially the first invariant), and what is commonly denoted by J_2 , the second invariant of the deviator stress. Then the ranges of stress for which flow or fracture does not occur are described by defining an enveloping curve in pressure-J_2 space. (Changes to this envelope such as hardening or softening are described below).



The figure at the left indicates the general nature of an initial failure envelope for a geological material, as a plot of the maximum shear stress versus the confining pressure. Various different measures of "strength" exist and are indicated on this envelope. There is a curve of limit shear stress that depends on pressure, commonly modeled as a Mohr-Coloumb (shear strength versus pressure) or a Drucker-Prager envelope (J_2 versus pressure). Often those curves are assumed to be linear, but that assumption is not essential. Then since failure can also occur at sufficiently high pure compressive pressure, a "cap" is constructed to model that compressive pressure crushing; that is the termination of the envelope at the left of this figure.

For uniaxial tension loading, the loading path as shown intercepts the failure envelope at a uniaxial stress limit known as the tensile strength. In pure uniaxial compression, the path as indicated intercepts the shear envelope at a higher stress, called the compressive strength. In pure shear, the maximum is at the intersection of the shear envelope with the vertical axis, the shear strength or "cohesion". Biaxial or triaxial loading can proceed along different paths until they intersect these limit curves, those define biaxial and triaxial strengths. A confined compression curve is shown sloped to the left and intersecting the compression cap.

The next part of the modeling concerns the question of the change of this envelope as failure proceeds. These questions involve the features of ductility (plastic flow) versus brittle (fracture or flaw growth). Commonly, brittle failure occurs at low values of confining pressure, especially tensile states; while ductile failure occurs at high values of confining pressure in compressive states. Ductile failure is modeled by describing how the material develops plastic strain (the "flow rule") and by how that flow affects the failure envelope (hardening or softening). Common metal-plasticity models include those effects. Brittle failure is commonly modeled using a "damage" parameter, which measures the internal damage of the material in a macroscopic way. It typically ranges from zero at no damage, to unity at complete damage. An equation describing its evolution as a function of the current stress or strain state is required to track its values at material points. The Grady-Kipp model is an example of a damage model for brittle tensile failure. All of these aspects can also depend on the temperature.

When failure occurs, a granular material also has a tendency to "bulk": an increase in volume and decrease in density at constant pressure. That can be suppressed by the pressure state, but then adds a component of pressure. Equally well, bulking is included if an associated flow rule is used with a pressure-dependent shear strength, since that flow rule has a component of dilation. The relative amounts of deviator and dilation can be adjusted by using a non-associated flow rule.

I will review various material property data and different models used in the community, and relate their features and failures to this overview picture.

References:

[1] Kerley G. I., "Users Manual for PANDA II: A Computer Code for Calculating Equations of State", Sandia Report SAND88-2291, 1991.

[2]Holsapple, K. A., "The Scaling of Impact Processes in Planetary Sciences", *Annual Reviews of Earth and Planetary Sciences* **21** pp333-373, 1993.