CODE WARS: A COMPARISON OF CODES AND MODELS FOR IMPACT CALCULATIONS.

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We agree with a recent statement in the literature [1]: "On top of this, we observed that the current exponential increase in computer power is already leading to grave difficulties in assessing the content of simulations of complex phenomena, as well as comparing them with high quality experimental data. Among other challenges, this situation leads to the erroneous possibility of thinking that because output is complex, we must be successfully modeling complex phenomena."

Increasingly, researchers in Planetary Sciences are turning to code calculations for the study of impacts between bodies of the solar system, an extremely complex phenomena indeed. The methods often use what are termed "hydrocodes", using finite difference, finite element, or smooth particle hydrodynamics methods; or n-body approaches with a large number of bodies. The hydrocode methods break a body into many small cells, and then integrate in time the equations of balance of mass, momentum and energy, augmented by equations for material behavior.

The LPSC conference of last year included over 30 abstracts describing results of such code calculations. The reasons for the increasing popularity are varied, but may include that 1) actual physical experiments often cannot be performed using the sizes and velocities of interest; 2) computing power is indeed growing by leaps and bounds; 3) computers are available to almost all of us, 4) much detail can be studied, 5) codes are well suited for graduate student efforts. Papers in the literature based on such calculations typically include a paragraph or two describing the code and its models, and many pages of detailed results and implications.

Some [4] have stated a different about the growth of computer power: "Recent exponential increases in computational power have enabled numerical simulations to become the method of choice to investigate these issues [impacts] in greater detail." Another statement [6] compares the theoretical scaling methods based on similarity analysis and dimensional analysis to code calculation approaches: "Scaling laws do allow interpolation and limited extrapolation of experimental results. Longer extrapolation is possible but runs the risk of missing a change in the dominant physics." We believe that this first declaration is premature, and the second, while true, applies equally to both codes and theoretical scaling methods. The purpose of this contribution is to document limitations and possible failures (or surprising results?) of recent code studies.

To be specific, we will compare models and calculations using the CTH code and its material models to examples in the literature using the SALE code and an SPH code, both of the latter using the Grady-Kipp fracture model based on crack size distributions. The CTH code has been developed over the last 20 years at Sandia for the weapons community. The other two codes have recently been augmented with the fracture model and used for, among others, calculations of fragmentation of asteroids [2], disruption scaling [3, 4], the Stickney crater on Phobos [5], cratering on a Gaspra-sized body [6], and cratering on Ida [7].

The material models in many codes require properties that are not always available for many materials of interest. That is commonly taken as sufficient justification to "dial-in" properties that match specific experiments. In other cases, when the use of the published data does not yield good code results, the conclusion is that the published data must be anomalous. In [2-7] results have been matched to specific small-scale disruption experiments by adjusting the number density of cracks (which directly sets the strength at a given strain rate). The number density and strength chosen are significantly different from some published values in the literature (see figure 1 and figure 2 below). (The figure 1 also illustrates that code methods rely on extrapolations from small-scale calibrations to large scale applications, just as do the theoretical scaling methods.) Then the codes have been exercised for the interesting cases in the Solar system mentioned above. While the results obtained for catastrophic disruption are not vastly different from other methods (a consequence of the fact that they were dialed-in to match the small-scale results, and all methods are based on similar and uncertain extrapolation), the results for cratering are up to a factor of 100 larger than existing data from large terrestrial weapons tests (see Figure 3 below from [8]).

These discrepancies will be presented and discusssed. The chief difficulty is that mathematical models that describe the material behavior of geological materials over the vast ranges of the physical parameter space encountered in impacts are not well developed. The nature of such models will be presented. Simple models that work for one

problem cannot be expected to work at vastly different size scales, or for phenomena governed by different properties. Different types of problems exercise different aspects of "strength" (figure 4). The fracture model used may work for phenomena dominated by tensile fracture, but results in complete fluid behavior in much of the region of interest: an unsuitable model for fractured rock under compression.

Comparisons of the results from [2-7] to results from the CTH code will be made for similar calculations; both for material models of the same type and for more general models. Possible reasons for differences will be discussed. Generally, it is shown that large uncertainties exist for code calculations of impacts, and extreme caution in accepting the results and implications is warranted.

References: [1] Trucano, T. G., Sandia Report SAND98-2776 (1998). [2] Ryan E. V. and Melosh H. J., *Icarus 133*, 1-24 (1998). [3] Melosh H. J. and Ryan E. V., *Icarus 129*, 562 (1997). [4] Benz W. and Asphaug E., *Icarus 142*, 5-20 (1999). [5] Asphaug E. and Melosh H. J., *Icarus 101,* 144-164 (1993). [6] Nolan M. C., Asphaug E., Melosh H. J. and Greenberg R., *Icarus 124,* 359-371 (1996). [7] Asphaug E., Moore J. M., Morrison D., Benz W., Nolan M. C. and Sullivan R. J., *Icarus 120,* 158-184 (1996). [8] Holsapple, K. A., Giblin, I., Housen K., Nakamura A., to appear in *Asteroids III*, (2002). [9] Grady, D.E. , Lipkin, *J., Geo Phys Lttrs* 7, N.4, 255-258 (1980). [10] Housen, K., Holsapple K., *LPSC XXXI* (1999). [11] Schmidt R., Housen K., Holsapple, K., DNA Report DNA-TR-86-182 (1986).

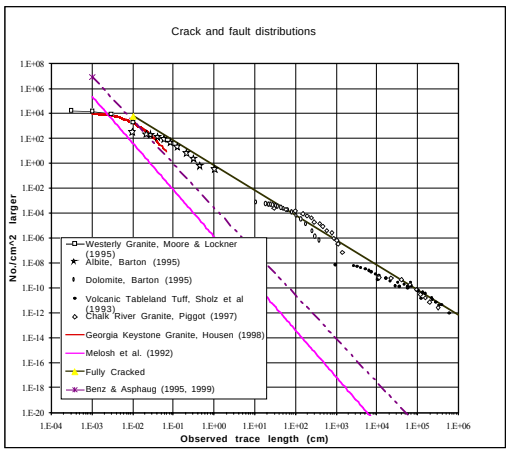

Figure 1. Crack number distributions, measured and modeled. (Originally from [10])

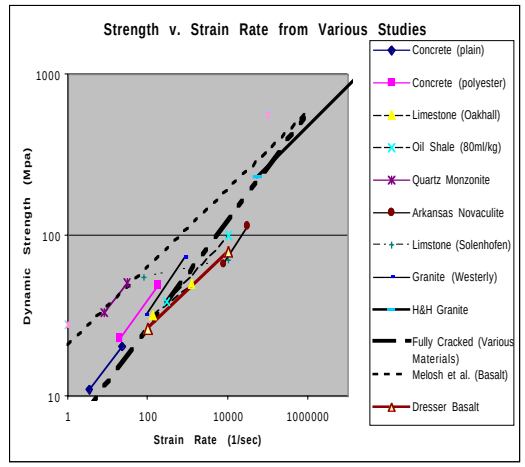

Figure 2. Strength v. strain rate, measured and modeled. (Originally from [9])

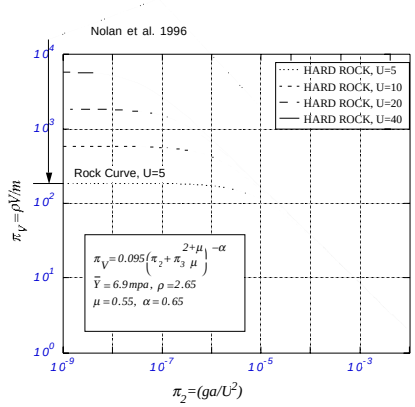

Figure 3. Code cratering results v. Scaling Predictions from [11].

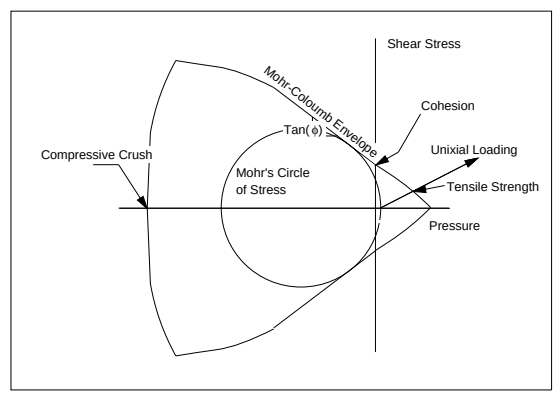

Figure 4. Different regions of strength modeling.