EVALUATION OF PLANETARY IMPACTS USING NUMERICAL AND EXPERIMENTAL TECHNIQUES

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ABSTRACT

Numerical modelling is an important facet of impact cratering research, offering a means for examining various stages of the impact event that cannot be investigated by other methods, particularly for large planetary impacts. Experimental techniques, such as light gas gun impacts, are important to understand cratering processes at smaller scales. In this study the 2D AUTODYN hydrocode [1] is used to demonstrate the capabilities of simulations in replicating large planetary impact events. We highlight some common issues arising from modelling planetary impacts, and relate laboratory results attained from light gas gun impacts to our modelled output, in order to further our understanding of cratering processes at all scales.

1. USING CHICXULUB TO EVALUATE STRENGTH MODELS

Chicxulub crater is a complex crater with interpreted diameters ranging from ~150 [2] to 300km for a proposed multi-ringed basin [3]. Typical estimates for the transient cavity lie between 85km [4] and 100km [e.g. 2] for the diameter and 33km [2] for the depth. Our models were initialised with a three layer stratigraphy comprising 3km sediments (calcite), 27km granite (westerly granite) and mantle (dunite) [e.g. after 5]. The materials indicated in brackets are those selected from the AUTODYN library to represent each layer. We model the impact of a 10km diameter dunite projectile striking at 20km/s.

As part of a series of fundamental parameter tests into the sensitivity of output to material model input, initial models vary only the yield strength of the materials. This sensitivity study is further motivated by the observation that data available in the literature for any particular material can cover a wide range, sometimes over several orders of magnitude. We subsequently find that the output yielded by numerical simulations is extremely dependent on these input values (Table 1). When varying only the yield strength from 0.1MPa to a few hundred MPa the crater depth is found to vary from 5 – 33km and crater diameter from 144 – 72km respectively. Neglecting yield strength altogether intuitively results in a flat surface.

Yield strength values for the materials used in the Chicxulub impact event are quoted by [6] as 344MPa for the crust and 619MPa for dunite (which is chosen to model both the mantle and the projectile). This produces a crater of 72km by 33km, comparable to published data for the transient cavity [e.g. 2]. However, it is the lower yield strength values that yield the most favourable final crater dimensions, for the initial conditions stated. This implies that, as concurred by [e.g. 7], standard strength models used in hydrocodes are not successful for describing crater collapse. Indeed, when the rock is initialised with its static strength properties, we observe that the crater does not collapse significantly, if at all.

The dynamic behaviour of crater collapse and relaxation can be described by the acoustic fluidisation model [8], which allows for the ephemeral fluidisation of rock. It is based on the premise that acoustic vibrations within a granular material become violent enough to temporarily relieve the overburden pressure, and therefore reduce the internal friction resistance of the material. Consequently, the material will behave as a fluid. However, this fluidisation is short lived, or else the end result would be a flat surface.

Target Yield Stress	**Final Diameter, D (km)**	**Final depth, d (km)**	**Depth to Diameter Ratio (d/D)**
Crust: 344MPa **Mantle: 619MPa**	**72**	**33**	**0.46**
10MPa	**117**	**13**	**0.11**
0.1MPa	**144**	**5**	**0.03**

Table 1: Effect of target yield stress on final crater dimensions. For the first line of data, the crust (to a depth of 30km) and mantle are assigned different values [after 6], as indicated.

Crater collapse is evidently a very complicated, non-linear process that is not easily described by a numerical code. Indeed, acoustic fluidisation is not implicitly included in our models, although adjustment of the yield strength may prove a suitable approach to reproduce these effects. It is therefore with some caution that material models and parameters can be applied in hydrocodes if the desired output is to accommodate transient cavity collapse into a complex crater.

2. METEOR CRATER

Meteor Crater is an excellent example of a well-preserved simple crater, with a text-book bowl shaped morphology of diameter 1.2km and depth 180m below the pre-impact surface, that formed simply by the relatively straightforward collapse of the transient crater to the angle of repose. An additional 200m deep lens of brecciated material lies beneath the crater floor [9].

2.1 A numerical approach to investigate projectile size and angle of impact.

Preliminary efforts to model this impact event used a single layered target of sandstone defined with standard shock equation of state (EoS) data [10]. We are currently using the Drucker-Prager strength and P-min failure models [1]. Further work will implement the P-alpha [1] and eventually epsilon-alpha equation of states for sandstone, which enables a more realistic approach to modelling porous materials [e.g. 11].

Data books [e.g. 12] state that yield strength values for various sandstones range from 2-360MPa, with Coconino Sandstone (the predominant material at the Meteor Crater site) exhibiting a yield strength of approximately 70MPa. We also investigate experimentally the yield strength of sandstone, the outcome and implications of which are discussed in section 2.2.

As highlighted in the previous section, high target yield strengths have resulted in simulations producing typical transient sized cavities; this was also the case for a Meteor Crater sized event when quoted yield strengths were applied to the models. For subsequent simulations we therefore chose to reduce the yield strength, initially to 10MPa. We subsequently varied only the projectile diameter from 50m to 25m; all other parameters remained the same. Simulations running at the time of submission are investigating lower yield strengths, given the outcome of the Chicxulub style simulations described in the previous section.

Our preliminary best fit crater diameter of 1112m was achieved with a 35m projectile impacting at 12km/s, producing a depth of 462m for these initial conditions. This depth is obviously more comparable to the 'true' crater depth, which is measured to the base of the brecciated zone. Indeed, our models do not account for the brecciated lens below the crater floor, or even any significant fall-back of ejecta. However, it is not unusual for simulations to overestimate crater depth. For example, this phenomenon has also been observed by [13], whereby an overestimate of 300m is calculated using SALEB and SOVA codes for an observed crater depth of 550m. This apparent overestimate can obviously be in part attributed to the material strength values assigned to the materials within the simulation, as discussed previously.

An additional but no less important factor lies in the implicit assumption by 2D simulations of a vertical (90 degree) impact, whereas the most likely angle of impact will be 45 degrees [14]. Indeed, [15] show that, at laboratory scale, crater depth and excavated mass start to decrease immediately when non-normal incidence occurs. This effect is also illustrated through the Earth Impact Effects Program [16] whereby the crater depth decreases by ~100-200m with increasing obliquity for a Meteor Crater type event, using our preferred 35m diameter projectile (Fig. 1). It is therefore reasonable to assume that our 2D simulations are overestimating the depth of the crater by a similar amount, therefore putting our crater depth at a value closer to that observed. It is envisaged that oblique simulations using 3D AUTODYN will further support this dependence of impact angle on crater dimensions.

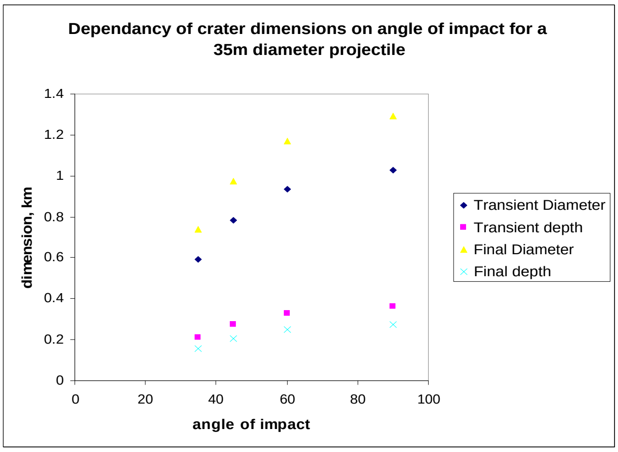

Fig. 1. The dependency of crater dimensions on impact angle, as demonstrated by the Earth Impact Effects Program [16] for a Meteor Crater type event.

2.2 An experimental approach to investigate the effect of local target conditions

The predominant material at the Meteor Crater impact site is the porous (~23%) Coconino Sandstone. In addition [17] suggest that this material may have in part been saturated, due to the influence of a local water table. Experiments [e.g. 11, 18] have shown that at a lab scale, it requires more energy to produce craters of the same size in porous targets than in non-porous targets, due to the additional energy required to collapse the pore spaces. In addition, studies have shown that the brittle strength of a rock is reduced in the presence of water [e.g. 19] and that water reduces the compressibility of porous materials [20]. Moreover, particularly at large scales, the target is mechanically disrupted by expanding steam after the passage of the shock wave, which increases the volume and enhances cavity growth in comparison to dry rocks [20].

In order to assess the influence of target saturation and porosity on crater dimensions we perform light gas gun impacts into wet and dry sandstone targets of differing porosity. Porosity was determined using standard laboratory techniques based on volume differences between wet and dry samples. In addition, the yield strengths of wet and dry core samples were also determined in the lab, using the Servo-Controlled 200KN universal load equipment at UCL. Our lab-characterised data is shown in Table 2. The wet core sample was determined to have approximately half the strength of the dry core sample.

Light gas gun impacts were carried out at the University of Kent. Impact conditions were set at 5km/s +/- 0.2km/s and used a 1mm diameter stainless steel projectile. While we are comparing two materials with only 6% difference in porosity, we still observe differences in crater dimensions. Initial results indicate that a higher porosity sandstone allows a crater with a larger diameter but smaller depth to form than in a lower porosity sandstone (Fig. 2). We find that the higher porosity wet target yields a wider and deeper crater than the lower porosity wet target (Fig. 3).

We also find that a wet target allows a greater volume of material to be excavated than in a dry target (Fig. 4), consistent with pilot studies by [20]. However, while we find that a wet target yields a deeper crater than a dry target, [20] observe a shallower depth in their wet target. This may largely be due to differences in experimental setup and target heterogeneities. It may be of interest to note that the experiments conducted by [20] use centimeter sized projectiles, whereas we use millimeter sized projectiles; perhaps the outcome of the two experiments is in part attributed to scale differences. The grain size of the materials may also be responsible for this observation; our Pilot Test Sandstone has a grain size of <0.4mm which is comparable to the difference in crater depth between the two sandstones (Figs. 2 & 3), and may also be analogous to large-scale ‘mega-block’ type failure.

3. SIMULATING LABORATORY RESULTS WITH AUTODYN

In order to represent porosity in our simulations, we first attempt to simulate our light gas gun impacts. Current models implement standard shock EoS data [10], which precludes explicit consideration of porosity. Our sandstone model therefore is representative of a non-porous sandstone. We use the yield strength attained in the lab for the dry pilot test sandstone (90MPa), defined within the Drucker-Prager strength model. Our output (Fig. 5) is consistent with the observation of [18] that more impact energy is required to produce a similar sized crater in a porous material than non-porous. Although the morphology of the craters are different, the profiles show that the dimensions are in fact very similar. This observation, along with the laboratory results, could be used to suggest that porosity effects morphology more than crater dimensions. Future efforts will focus on implementing, testing and applying both the P-alpha [1] and epsilon-alpha [11] equation of states, along with our own experimentally derived data [20, 21].

Sample	Grain size, mm	Dry Density, g cm^{-3}	Wet Density, g cm^{-3}	Porosity	Dry Yield Strength, MPa	Wet Yield Strength, MPa
Pilot Test	<0.40	2.20	2.35	17%	90	43
Coconino	<0.15	1.80	2.00	23%	tbd	tbd

Table 2. Parameters characterised in the laboratory for two sandstone samples.

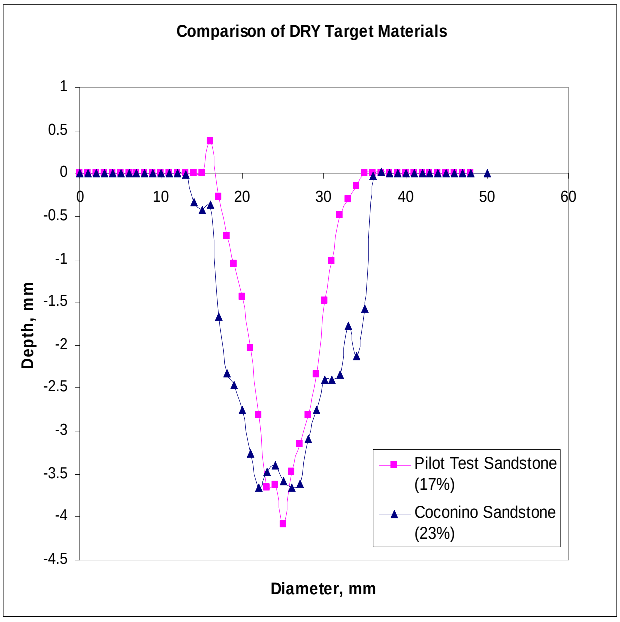

Fig. 2. Comparison of craters in dry target materials. Note the main difference is morphology; the depth of the two craters are essentially identically, especially when the grain size (<0.4mm) is taken into consideration.

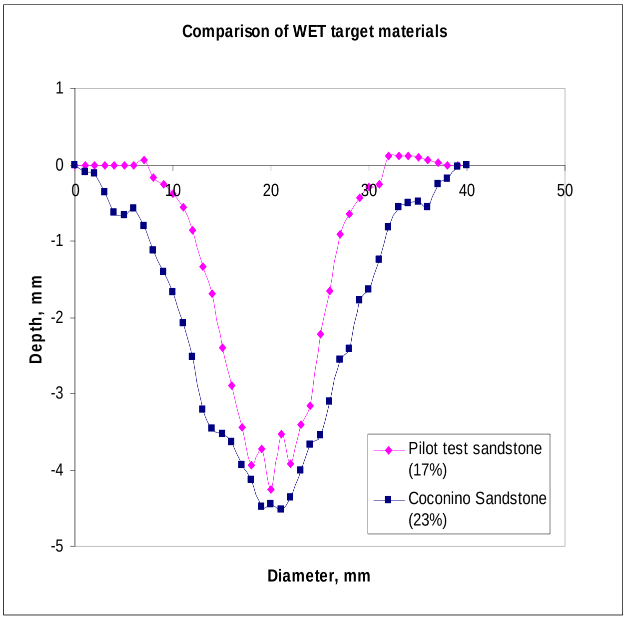

Fig. 3. Comparison of craters in wet target materials.

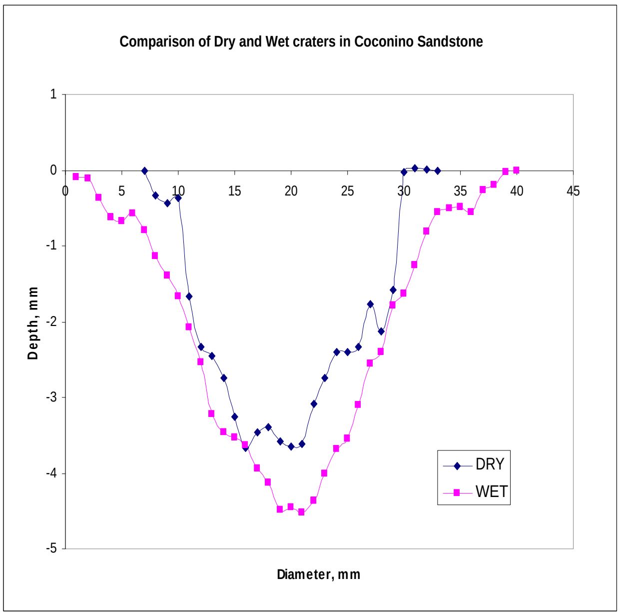

Fig. 4. Comparison of craters in dry and wet Coconino Sandstone

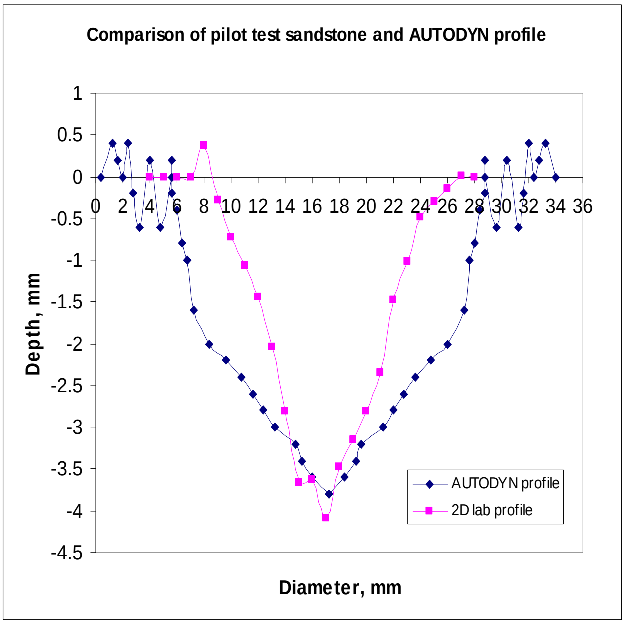

Fig. 5. Comparison of experimental crater with simulation output.

4. SUMMARY

We find that the output yielded by numerical simulations is only as effective as the material models that are applied. For a realistic model to be successful we require input data concerning equation of state parameters, strength and failure models (i.e. mechanical and elastic properties such as yield strength, shear modulus and ultimate tensile strength). It is also important to consider local conditions such as the influence of water or porosity.

Although it is imperative to choose strength models at a laboratory scale, it is the material weakening mechanism, along with crater collapse under gravity, which is important at large planetary scales. At this large scale we have shown that the material must behave as a strength-less material in order to reach the observed crater dimensions. This is obviously not the case for small-scale lab impacts, where the strength regime is the controlling factor, and in general, only the transient cavities of the crater are recorded.

Simulations of our normal incidence light gas gun hypervelocity impacts into sandstone illustrate the need for consideration of factors such as porosity and saturation when attempting to reconstruct laboratory impact events via modelling; therefore these factors are presumably also important for planetary scaled impacts. We are currently implementing into our models experimentally derived data, including revised equation of state data for geological materials that will include consideration of porosity for sandstone [21, 22].

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