VERIFICATION AND VALIDATION OF THE FLAG HYDROCODE FOR IMPACT CRATERING SIMULATIONS.

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Introduction: Impact cratering is the dominant geologic process in the solar system [1]. Crater size and geometry depend on many factors, among them the size and velocity of the impactor, the materials of the impactor and target, local gravity, and impact angle [2]. The strength of the target material can affect geomorphology of impact craters. Strength models incorporate stress, strain, and fracture, in addition to other material properties. In order to effectively model crater formation, these properties must be considered for some impacts.

Early stages of crater formation are driven by thermodynamic properties, while later stages are governed by additional factors such as internal friction and local gravity [3]. The role of material strength depends on the mass and velocity of the impactor. Once the impactor meets or exceeds a threshold velocity of about 12 km/s, the target material is subjected to melting. Once a material has melted, its strength is no longer a factor [1].

Hydrocode simulations have been used to model the impact cratering process, but these methods are often unable to capture the solid mechanics necessary in understanding crater formation. The FLAG hydrocode [4], developed at Los Alamos National Laboratory, allows for the incorporation of various strength models which can be applied to solid materials. FLAG also allows for solids to be treated as strengthless when running simulations.

Verification: Here we show verification of the FLAG hydrocode when implemented with solid material strength models. We simulate an aluminum projectile impacting an aluminum target at impact velocities of 5 km/s and 20 km/s, and we compare the results to those found using other hydrocodes. We also compare these results to the analytical impedance matching solutions for each impact velocity.

We treat aluminum as strengthless using a tabular equation of state from the LANL database SESAME in order to recreate the conditions set forth in the hydrocode verification by Pierazzo, et al. [5]. For the 5 km/s impact velocity, the hydrocodes tested by Pierazzo, et al. produced results with a mean maximum pressure of 40.4 GPa, with a mean relative error of 33.3% [5]. Using the FLAG hydrocode, our simulation resulted in a maximum pressure of 56.3 GPa, with a relative error of 4.2%. For the 20 km/s impact velocity, Pierazzo, et al. obtained a mean maximum pressure of 379.0 GPa, with a relative error of 27.5% [5]. Using the FLAG hydrocode, our simulation resulted in a maximum pressure of 407.8 GPa, with a relative error of 19.46%.

Figure 1: Visualization of FLAG output for a 5 km/s aluminum-on-aluminum impact.

Mesh Resolution Using the aluminum-on-aluminum impact verificaiton problem, we conduct a mesh resolution study on FLAG. We vary the resolution from 5 cells-per-projectile-radius (cppr) to 45 cppr. Our mesh resolutions include 5 cppr, 10 cppr, 20 cppr, 40 cppr, and 45 cppr. We compare these results with the resolution results from Pierazzo, et al. to show convergence of FLAG with a sufficiently refined mesh by examining the shock pressure decay 10 km into the target [5].

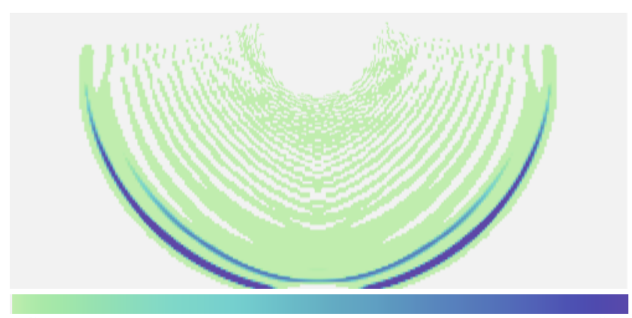

Figure 2: Pressure wave propagating 10 km into the target in the 5 km/s aluminum verification problem.

For an impact velocity of 5 km/s, FLAG appears to converge at a resolution of only 10 cppr, compared to 20 cppr for many of the hydrocodes tested by Pierazzo, et al. [5]. For an impact velocity of 20 km/s, FLAG appears to converge at a resolution of 20 cppr, consistent with the hydrocodes tested by Pierazzo, et al. [5]. The lower resolution required in FLAG results in a much lower computation time.

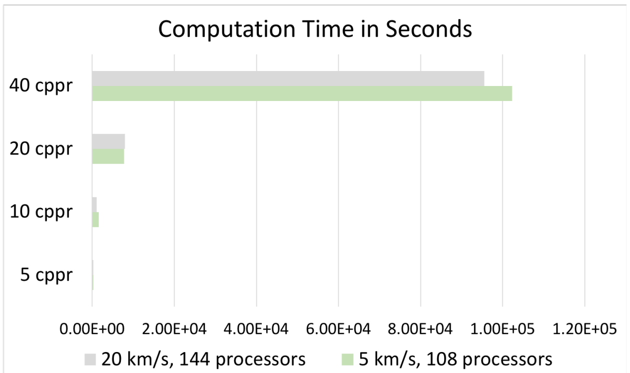

Figure 3: Computation time for FLAG aluminum impact verifcation problem at varying mesh resolutions.

Validation: We demonstrate validation of the FLAG hydrocode by simulating a laboratory impact of a glass sphere impacting a water target. We compare the resulting crater radius and depth to experimental results. This simulation requires no strength model, although gravity does play a role and must be included.

Time (ms)	Experimental Radius (cm)	FLAG Radius (cm)	Relative Error
0.191	1.608	1.67545	4.20%
0.382	2.297	2.17945	-5.12%
0.764	2.963	2.83958	-4.17$
1.146	3.423	3.2807	-4.16%
1.91	4.112	3.89451	-5.29%

Table 1: FLAG simulation results of crater radius evolution for glass-on-water impact validation problem.

Time (ms)	Experimental Depth (cm)	FLAG Depth (cm)	Relative Error
0.191	2.35	2.17491	-7.45%
0.382	2.6	2.7026	3.95%
0.764	3.32	3.56664	7.43%
1.146	3.85	4.04701	5.12%
1.91	4.61	4.65711	1.02%

Table 2: FLAG simulation results of crater depth evolution for glass-on-water impact validation problem.

Due to the relative size of the impactor (2 mm in diameter) to the target (width of 76 cm, height of 23 cm), we use a varying mesh resolution. Zone sizes near the point of impact are 0.02 cm, and zone sizes far from the point of impact are 0.5 cm. Even with this coarse resolution (5 cppr at its finest), FLAG results match well with experimental data, with errors having magnitude less than 5% in most cases. We also compare the depth-to-radius ratio in both the laboratory experiment and our FLAG simulation, with good agreement.

Figure 4: FLAG simulation of the crater resulting from a glass spere impacting a water target at 4.64 km/s 1.146 ms after impact.

References

[1] H Jay Melosh. *Planetary surface processes*, volume 13. Cambridge University Press, 2011.

[2] KA Holsapple and RM Schmidt. On the scaling of crater dimensions: 2. impact processes. *Journal of Geophysical Research: Solid Earth*, 87(B3):1849–1870, 1982.

[3] Gareth S Collins. An introduction to hydrocode modeling. *Applied Modelling and Computation Group, Imperial College London*, pages 2–11, 2002.

[4] James L. Hill. Flag user's manual. Technical report, Los Alamos National Laboratory, January 2017. LA-CP-17-20057.

[5] E Pierazzo, N Artemieva, E Asphaug, EC Baldwin, J Cazamias, R Coker, GS Collins, DA Crawford, T Davison, D Elbeshausen, et al. Validation of numerical codes for impact and explosion cratering: Impacts on strengthless and metal targets. *Meteoritics & Planetary Science*, 43(12): 1917–1938.

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