

Momentum Enhancement during Kinetic Impacts: Benchmarking and Validation of Shock Physics Codes in the Context of AIDA. R. Luther¹ (robert.luther@mf.n.berlin), S.D. Raducan², C. Burger³, K. Wünnemann^{1,4}, M. Jutzi², C. M. Schäfer³, D. Koschny^{5,6}, T. M. Davison⁷, G. S. Collins⁷, Y. Zhang^{8,9}, P. Michel⁸, ¹Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science, Germany; ²Space Research and Planetary Sciences, University of Bern, Switzerland; ³Eberhard Karls Universität Tübingen, Germany; ⁴Freie Universität Berlin, Germany; ⁵European Space Agency, ESTEC, the Netherlands; ⁶Chair of Astronautics, TUM, Germany; ⁷Impacts and Astromaterials Research Centre, Imperial College London, UK; ⁸Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France; ⁹Department of Aerospace Engineering, University of Maryland, College Park, USA.

Introduction: The AIDA international collaboration, which includes the DART (NASA) and Hera (ESA) missions [1,2], aims to test the technology of asteroid deflection by a kinetic impactor and to enhance our understanding of small bodies in general. The DART spacecraft was successfully launched on the 24th of November 2021 and will impact asteroid Dimorphos on the 26th of September 2022. The momentum imparted by the spacecraft and the momentum carried away by the material ejected from the crater (which amplifies the imparted momentum) will change the orbital period of Dimorphos around its primary, Didymos. Hera, will arrive at the system about four years after the impact to characterise the system and the impact consequences.

The objective of this study, which is conducted in the context of the NEO-MAPP project and the Hera Impact Working Group, is to: i) validate three shock physics codes (iSALE, Bern SPH and miluphcuda) against laboratory experiments, and ii) benchmark the three codes against each other when applied to a DART-like scenario. Although all codes solve similar forms of the governing conservation equations and use similar constitutive models, they employ different numerical schemes: iSALE uses an Eulerian grid-based approach, while miluphcuda and Bern-SPH use a Lagrangian, grid-free smooth particle approach.

Numerical methods: iSALE-2D [3] is a grid-based arbitrary Eulerian/Lagrangian (ALE) code and is suitable to study crater formation and the propagation of shock waves from a high velocity impact into targets with a variety of properties. The two Smoothed Particle Hydrodynamics codes (SPH), Bern SPH [4,5] and miluphcuda [6,7] are appropriate to study the crater formation, and also processes where the entire target body is involved. All three codes include sub-resolution material models that describe the compaction of porous materials (iSALE: ϵ - α compaction model; SPH: P- α compaction model) and different strength models. To describe the strength of the material, we employ the Lundborg rheology parameterisation [8]. The ejection behaviour is analysed as described in [9,10] and used to determine the momentum enhancement factor $\beta = (\text{ejecta} + \text{impactor momentum}) / \text{impactor momentum}$. This approach was used previously for systematic

parameter studies [11] and benchmarking studies [12,13].

In a first step, we compare results from the shock physics codes against observations from a recent laboratory study [14], where PVC projectiles with a mass of ~25 mg were accelerated to velocities of up to 2.5 km/s. The granular targets were composed of glass beads, sand and regolith simulant. Here, we focus on the regolith simulant experiments. In a second step, we continue the benchmarking work done by the Hera impact working group [13] to explain and reconcile differences between the results from the three numerical codes, iSALE, miluphcuda and Bern's SPH.

Validation: We modelled impacts into regolith simulant at velocities between 1.4 and 2.5 km/s. The coefficient of friction for the regolith simulant was set to $f = 0.77$ and the initial porosity to 42%.

We first analysed the resulting crater and momentum enhancement for all three shock physics codes applied in this study and compared the results to the experiments (Fig. 1). The simulation results from all three codes are in good agreement with the experimental results. The scatter between numerical results does not exceed the scatter within the experimental results.

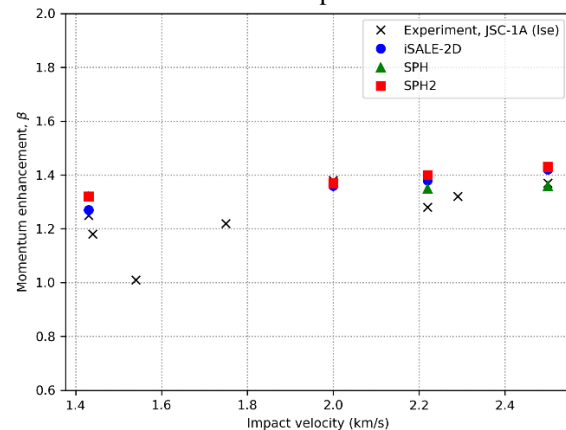


Figure 1: Experimentally (crosses) and numerically derived momentum enhancement factors, β , from impact into regolith simulant from iSALE-2D (blue), Bern-SPH (green) and miluphcuda (red) simulations.

Benchmark: In this benchmark study, we focus on the influence of target cohesion and target porosity on the

momentum enhancement factor, β . We model DART-like kinetic impacts (i.e., 600 kg projectiles, impacting at 6 km/s at an impact angle of 90°). The targets have various porosities, between 10 and 50%, and cohesions from 1 to 100 kPa. In a previous study [12], we found a generally good agreement between the results derived with iSALE and SPH (Fig. 2). However, for certain porosities the differences between the results were larger (e.g., 20% porosity and 1 kPa or 100 kPa cohesion).

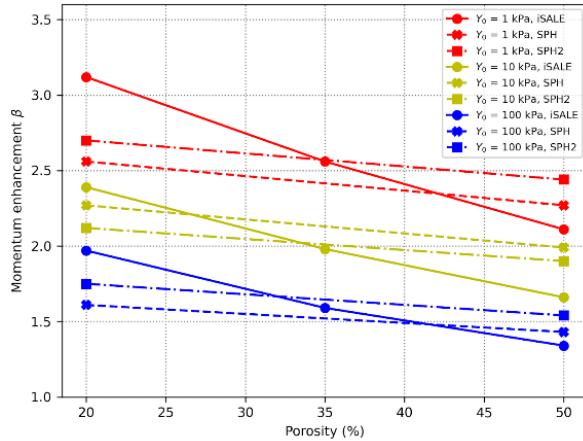


Figure 2: Momentum transfer efficiency β from iSALE-2D (solid lines), Bern-SPH (dashed lines) and miluphcuda (dotted-dashed lines) simulations of vertical impacts into targets with various cohesion and porosity configurations.

To reduce the differences between the results derived by the different shock physics codes, we conducted new model runs with more consistent crush curves, which align the parameterisations from the ϵ - α (iSALE) and the P- α porosity (SPH) compaction model (Fig. 3). This procedure improved the agreement of our results to 10% (Fig. 4).

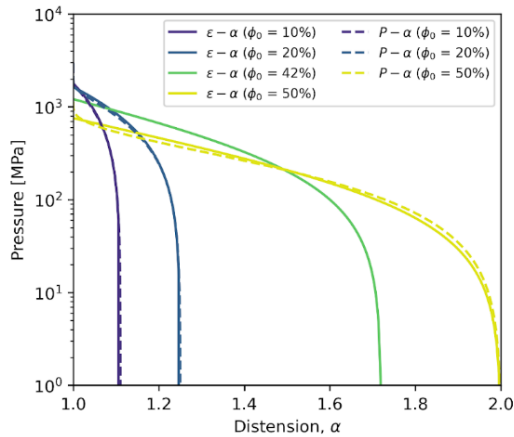


Figure 3: Porosity compaction curves for materials with different porosities used in the simulations done with iSALE, Bern-SPH & miluphcuda.

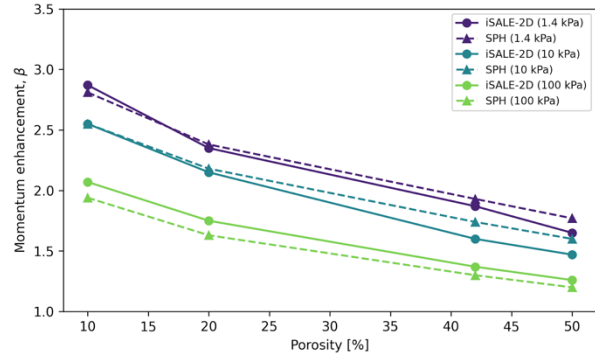


Figure 4: Momentum transfer efficiency β from iSALE-2D and Bern-SPH simulations of vertical impacts into targets with various cohesion and porosity configurations, using the improved crush curve fit.

Summary: Our joint modelling and experimental approach to study the efficiency of impact momentum transfer shows that there is generally a good agreement between different numerical approaches (grid-based iSALE-2D and meshless Bern SPH and miluphcuda) and experimental work. Our preliminary benchmark results further show that differences in β can be up to 25%, however, aligning the crush curves reduces the deviations between the different numerical approaches. Note that further differences between the results can also relate to user defined parameters that have no direct correlation between codes.

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References: [1] Cheng, A. F. et al. (2018) Planet. Space Sci, 157:104–115. [2] Michel, P. et al. (2018) AdvSpace Res. 62:2261–2272. [3] Wünnemann, K. et al. (2006) Icarus, 180:514–527. [4] Jutzi, M. et al. (2008) Icarus, 198:242–255. [5] Jutzi, M. (2015) Planet. Space Sci, 107:3–9. [6] Schäfer, C. et al. (2016) A&A 590, A19. [7] Schäfer, C. et al. (2020) Astr.&Comp. 33, 100410. [8] Collins, G.S. et al. (2004) M&PS 39 (2), 217–231. [9] Jutzi, M. & Michel, P. (2014) Icarus, 229:247–253. [10] Luther, R. et al. (2018) M&PS 53 (8), 1705–1732. [11] Raducan, S. D. et al. (2019) Icarus, 329:282–295. [12] A. Stickley et al. (2020), Icarus 338 113446. [13] R. Luther et al. (2019) EPSC-DPS2019-1776. [14] Chourey, S. et al. (2020) PSS, 194.