BENCHMARK AND VALIDATION STUDIES WITH SPH AND ISALE, IN THE CONTEXT OF THE DART AND HERA MISSIONS.

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Introduction: NASA's Double Asteroid Redirection Test (DART) will impact the secondary of the 65803 Didymos system, Dimorphos, in October 2022 [1, 2]. The impact will cause a measurable change in the orbital period of the binary. The Hera mission will arrive at the system several years after the DART impact and will characterise the binary system in detail, particularly the small moon and the crater produced by DART on its surface.

Impact simulations using so-called shock physics codes have been widely used to predict the outcome of the impact of a kinetic impactor [e.g., 3, 4]. Such models, if rigorously validated against laboratory experiments, are able to accurately assess the full suite of consequences related to the collision of a spacecraft with an asteroid in order to redirect its trajectory. The problem in numerically modelling such events is that the impact related processes occur on very different spatiotemporal scales related to the micro-gravity regime, which are computationally very challenging to simulate.

The work presented here was generated in the context of the NEO-MAPP project, and it aims to develop new modelling strategies, by combining different numerical codes, to model the DART impact. The results generated will provide quantitative and reliable predictions regarding the outcome of the impact with respect to parameters that are measurable by spaceborne and in-situ instrumentation provided by the Hera mission. Here we present validation tests against laboratory experiments and a series of systematic benchmark studies purposely designed to detect, assess and remove deviations between two different numerical schemes, iSALE (in 2D and 3D) and Bern SPH.

Methods: iSALE-2D/-3D [5, 6] is a grid-based arbitrary Eulerian and/or Lagrangian (ALE) code and is best suited to study the crater formation and the propagation of shock wave from a high velocity impact. On the other hand, Bern's grid-free Smooth Particle Hydrodynamics (SPH) [7, 8] is most appropriate to study the ejection of material and processes where the entire target body is involved. Both codes include material models suitable to simulate the behaviour of geological materials, various equations of state and porosity compaction models (e.g, $\epsilon - \alpha$ model in iSALE and $P - \alpha$ model in SPH). Despite the fact that all codes in principle solve similar forms of conservation equations and use similar constitutive models, different numerical schemes tend to produce more or less varying results.

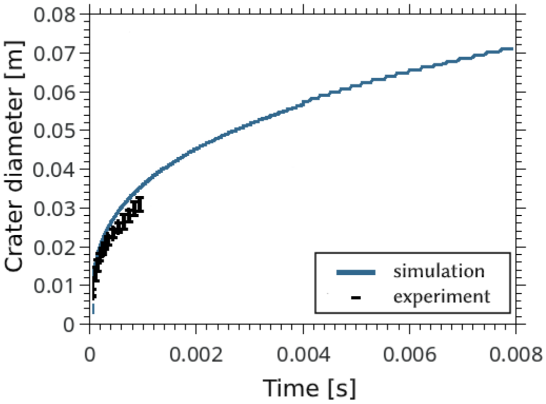

Figure 1: Evolution of the crater diameter from a 25 mg PVC projectile impacting a glass beads target at 2.41 km/s (shot #35). The simulation was performed in iSALE-2D.

Validation tests: In order to improve the reliability of results from numerical modelling, accurate validation tests against laboratory experiments are required. The ejecta dynamics (i.e. ejection velocities/angles and ejected mass) is crucial for predicting β and has been validated in previous studies for different sand types [4, 9]. Here, we present first results of a new validation study that extends the range of tested target materials to glass beads and regolith simulant (i.e. smaller or larger coefficient of friction, respectively, and larger Y_0 for regolith simulant), and compare against results from a recent laboratory study [10]. The target materials have been impacted by PVC projectiles of $\approx$25 mg at velocities of up to $\approx$2.5 km/s. Although this study does not provide ejection dynamics in terms of launch angles and velocity, it provides results of the momentum enhancement, crater diameters, and ejecta curtain angles. Here we have assessed the evolution of the crater diameter during the first ms of crater growth from high-speed images (Fig. 1). Both simulations set-ups (glass beads targets and regolith simulant targets) have been simulated using iSALE-2D. The glass beads targets had a coefficient of internal friction, f of 0.39 and

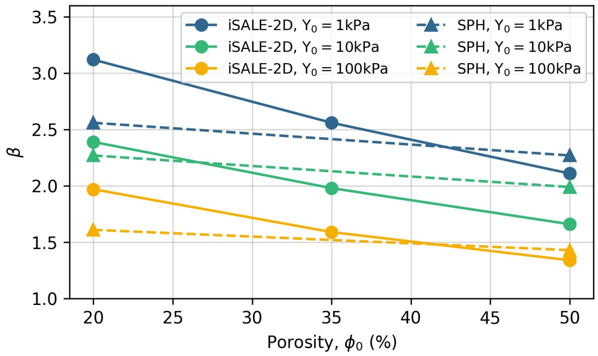

Figure 2: Momentum transfer efficiency, β, from iSALE-2D and SPH simulations of vertical impacts into targets with various cohesion, Y_0, and porosity, ϕ, configurations.

a porosity, ϕ_0 of 35%, while the regolith simulant had f = 0.64 and ϕ_0 = 42% (Fig. 1). We determined the momentum enhancement for both models, yielding β=3.8 for the glass beads target and β=1.5 for the regolith simulant target. These results are slightly larger than the β values measured in the experiments (2.75–3.25 and $\approx$ 1.3), but still within a reasonable range. These simulations will also be performed in SPH.

Benchmark studies:

Influence of target porosity For this benchmark study we consider a spherical aluminium projectile (m = 500 kg) at 6 km/s, impacting targets with varying cohesion (Y_0 = 1 kPa – 100 kPa) and varying initial porosity (ϕ_0 = 20–50%) and at vertical. 90°. Both the $\epsilon - \alpha$ (in iSALE) and the $P - \alpha$ (in SPH) porosity models used a crush curve broadly consistent with the quasi-static crush curves of lunar regolith. Fig. 2 shows the momentum transfer efficiency, β ($\beta = \Delta P/mU$, where mU is the impactor momentum), as a function of target initial porosity, ϕ_0 and different target cohesions (Y_0). Our preliminary study shows that there is generally a good agreement between the two numerical approaches, grid-based iSALE-2D and meshless SPH, when similar impact conditions are considered. However, in some scenarios (i.e., Y_0 = 1 kPa, ϕ_0 = 20% or Y_0 = 10 kPa, ϕ_0 = 50%) there can be an up to 25% difference in the β calculation. This difference in β can be attributed to user defined parameters that have no direct correlation between codes or to different users using the two codes.

Influence of the impact angle: In addition to surface material properties, another uncertainty is the DART impact angle. Fig. 3 shows β from numerical simulations of DART-like impacts into a Y_0 = 1 kPa, 20% porous target, at 7 km/s. The numerical simulations were performed in iSALE-3D and in SPH. In these scenarios, the two codes show a remarkably good agreement. Note that these simulations were performed by the same user.

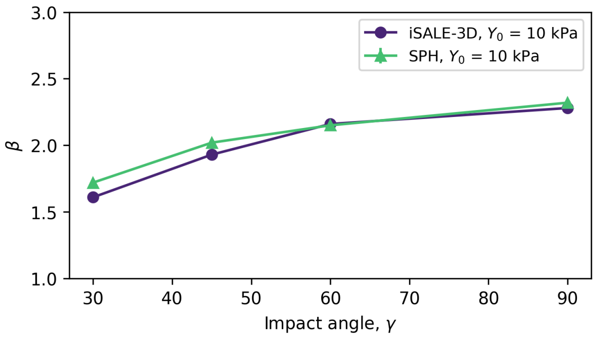

Figure 3: Momentum transfer efficiency, β, from iSALE-3D and SPH simulations of vertical and oblique DART-like impacts into a 10 kPa, 20% porous target. iSALE-3D and SPH show good agreement.

Conclusions and future work: Our joint modelling and experimental approach to study the efficiency of a kinetic impactor to deflect an asteroid shows that there is generally a good agreement between different numerical approaches and experimental work on estimating crater size and ejection parameters. Independent of the methodological approach all studies agree that a detailed knowledge of the asteroid surface properties and impact conditions (e.g., strength, porosity, impact angle) are essential to provide reliable estimates on the outcome of the DART deflection experiment. In a next step, we will investigate in depth small deviations between different modelling schemes and, in particular, effects of internal heterogeneities, and global consequences on the entire impacted asteroid. Furthermore, coupling the results of shock physics codes with the parallel N-body code pkdgrav will allow for a better quantification of the crater growth and late stage ejection of material, when material is displaced at low velocities.

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