THE ROLE OF ASTEROID STRENGTH AND POROSITY IN IMPACT MOMENTUM TRANSFER.
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Introduction: Near-Earth Asteroids represent a low-probability, high-consequence natural hazard to Earth. Momentum transfer from a kinetic impactor, such as a large spacecraft, is one of the most straightforward methods of deflecting a small asteroid from an impacting trajectory, if the body is detected well in advance [1]. The NASA Double Asteroid Redirection Test (DART) would be the first mission to test a controlled deflection of a near-Earth asteroid, by impacting the moon of Didymos [2].

Previous studies have shown that the deflection of an asteroid is strongly dependent on the target asteroid’s properties and composition [3, 4]. Depending on how the asteroid formed, properties such as porosity, internal structure and cohesive strength of the surface material can vary significantly from one object to another and, without a close approach, cannot be accurately determined [5].

Numerical studies using a range of initial conditions provide a method to determine the reaction of different types of asteroids to a possible impact, and subsequently to determine the momentum transferred from the impactor for deflection. The momentum transferred (Δp) can be quantified using the mass-velocity distribution of crater ejecta that exceeds the escape velocity, and is often expressed by the multiplication factor β [6]:

Δp = βmv

where m is the impactor mass and v is the impactor velocity.

Here we present the results of numerical simulations of DART-scale impacts onto asteroids of different strengths and porosities, to quantify the sensitivity of the expected outcome to uncertainties in asteroid properties. The mass-velocity distribution of ejecta produced during the impact was recorded and used to determine the β factor. We also investigate the role of cohesive strength, coefficient of internal friction and porosity of the target material on crater size and shape.

Numerical Methods: Two-dimensional impact simulations were performed using the iSALE multi-material, multi-rheology shock physics code [7, 8]. We considered a ≈ 300 kg aluminium spherical projectile with a density of 1000 kg/m3, which represents the structure of a possible spacecraft, impacting vertically onto an asteroid surface at 7 km/s. The projectile material was modelled using the Tillotson equation of state and the Johnson-Cook strength model for aluminium. The target material was modelled using the Tillotson equation of state for basalt and we compared two strength models, which we refer to here using the abbreviations LUND and ROCK. The LUND model is a simple pressure-dependent strength model typical of rock materials [9], which asymptotes to a certain strength at high pressure and is not dependent on strain or damage. The ROCK model is a more complex model, in which strength is reduced with strain as damage accumulates. The strength of the intact material was varied in magnitude from 10 kPa to 1 MPa, while the strength of the damaged material was varied from 10 Pa to 10 kPa, based on estimates of asteroid regolith cohesion [10]. We modelled porosity using the ε−α model [8]; initial target porosity was varied between 10% and 50%. The surface gravity was kept constant and consistent with an escape velocity of 9 cm/s.

To capture the high velocity ejecta, high spatial resolution was required at early times, but owing to the low strength of the target, the long crater formation timescale precluded simulations with a high spatial resolution throughout the calculation. Consequently, we used iSALE’s regridding option, which allowed us to coarsen the domain by a factor of two after a predetermined amount of time, starting with a resolution of 40 cells per projectile radius (cppr) and ending with a resolution of 5 cppr. Resolution tests showed that using the regridding method was as accurate as using a 20 cppr resolution throughout the simulations, but took 10% of the equivalent calculation time.

Results and Discussion: Simulated crater dimensions were most sensitive to the cohesive strength of the (damaged) material (Yd0). The LUND and ROCK strength models produced similar crater dimensions when the damaged material in the ROCK model had the same cohesive strength as used in the LUND model (Fig. 1). For a porosity of 20%, which is the current best estimate for the Didymos system, crater radii ranged from 6 m (Yd0 = 10 kPa) to 15 m (Yd0 = 0.1 kPa). While these are somewhat larger than previous estimates of crater size for the DART impact that assumed higher target strengths [2], they lie between scaling law extrapolations of experimental data for weakly cemented basalt (WCB) [11] and for sand & fly ash (SFA) [12], which appear to be the most appropriate analogs for porous rocky asteroid surfaces.
Figure 1: Scaled crater diameter as a function of strength-scaled impact size for two strength models, compared with the experimental results for WCB [11] and SFA [12].

For a given impact scenario, the mass-velocity distribution of ejecta predicted by the two strength models was also similar when the damaged material in the ROCK model had the same cohesive strength as used in the LUND model. Figure 2 shows mass ejected at speed $v > v$ as a function of ejection speed $v$ for simulations using the ROCK model for various values of $Y_d$. Ejection speeds, launch positions and mass were recorded by Lagrangian tracer particles. At intermediate ejection speeds, the cumulative ejected mass is well fit by a power law, consistent with point-source theory. According to this theory, $M(>v)/m \propto (v/U)^{-3\mu}$, where $U$ is the impact speed and $\mu$ is the velocity exponent of the coupling parameter [11]. From our results, we infer $\mu = 0.47$, consistent with the empirically determined value for WCB [11]. At low velocities, the ejecta mass-velocity distribution asymptotes to the total ejected mass, which at these low target strengths is $> 1000$ impactor masses. As the cohesive strength of the target material is decreased, more material is ejected at low velocities and the total ejected mass is greater.

Ejected mass-velocity distributions were integrated to determine the cumulative, vertically ejected momentum $p_{ej}/mU = (\beta - 1)$ as a function of both launch position $x$ and ejection speed $v$ (Fig. 3). Most of the ejecta momentum resides in the slowest ejecta, which is last to leave the crater. The total ejected momentum depends strongly on the total ejected mass (and crater size) and, hence, $Y_d$. Compared to previous DART simulations, the low target cohesions assumed in this work lead to $\beta$ values greater than 2.

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Figure 2: Ejecta mass-velocity distribution for different asteroid strengths. $m$ and $U$ are the mass and speed of the projectile.

Figure 3: Total ejected momentum (vertical) as a function of ejection velocity normalised by impactor momentum $mU$. The value at the left end of each curve is equal to $\beta - 1$. 