NEOShield

A Global Approach to Near-Earth Object Impact Threat Mitigation

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Deutsches Zentrum für Luft - und Raumfahrt (DLR)	DLR, Project Coordinator	Germany
Observatoire de Paris	OBSPARIS	France
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18.05.15	1.0	Dr. P. Michel	Final version to NEOShield Coordinator with minor correction after project review

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1. Introduction

The work presented here is devoted to the kinetic impactor concept and in particular, to the characterization of the momentum transfer efficiency in asteroid impacts. This characterization is obtained by a deep investigation using state-of-the-art numerical simulations of asteroid impacts, adapted to this problem.

We recall that the momentum transfer is characterized by the so-called momentum multiplication factor β, which has been introduced to define the momentum imparted to an asteroid in terms of the momentum of the impactor:

$\beta = 1 + p_{ej}/(M_p\ v_p)$,

where p_{ej} is the component of the momentum of the ejecta in the direction opposite to the impact vector, and M_p and v_p are the mass and velocity of the impactor, respectively. In the limiting case of an impact which produces no ejecta, $\beta = 1$, and the momentum transferred corresponds to the momentum of the projectile (inelastic collision). However, in the case of an impact that produces a lot of material (ejected in the opposite direction) with velocities larger than the escape velocity, β can be much greater than 1 due to the contribution of p_{ej}. Therefore, it is important to determine the values of β for the different possible impact conditions of a kinetic impactor (e.g. impact velocity, projectile's density) and for the different possible internal structures of the target, as both have a great influence on the value of β.

In Deliverable D3.2, we described our first results of numerical simulations that we then published in the international journal *Icarus* (Jutzi and Michel 2014). We summarize in this introduction the main outcomes of this first study, as the current deliverable D3.3. is the natural following step of this investigation.

To perform the impact simulations, we use a Smooth Particle Hydrodynamics (SPH) impact code specially written to model geologic materials (e.g. Benz and Asphaug, 1995, Jutzi et al. 2008, 2013). We include the Tillotson equation of state and a tensile fracture model (Benz and Asphaug 1995), in which we replaced the von Mises yield criterion originally implemented in this model, which is independent on the confining pressure, with a standard Drucker-Prager yield criterion for rocky materials that allows shear strength to depend on the confining pressure.

In our first study (D3.2), we considered impact velocities going from 0.5 km/s to 15 km/s and focused on porous targets, using two different target structures:

- homogenous: microporous only

- heterogeneous: both micro- and macro-porous

For both structures, we assumed 50% porosity for the microporous material. For structure (b), in addition to the microporosity, macroscopic cracks with a size scale of ~0.3 m were randomly distributed in the target. The resulting total macroscopic void fraction was 10%. The microporosity was modeled using the approach by Jutzi et al. (2008, 2009). The following material parameters were also used: coefficient of internal friction (intact material) μ_i = 1.5, coefficient of friction (damaged material) μ_d = 0.55, cohesion Y_0 = 100 MPa, yield strength Y_m = 3.5 GPa.

The projectile was modeled as an aluminum sphere with a mass of m_p = 400 kg and a bulk density of 1 kg/m^3. The choice of this value for the bulk density already accounted for the fact that the projectile may correspond to an artificial spacecraft equipped with payloads and voids in between. Recently, NEOShield industrial partners indicated us that they actually consider even lower projectile's densities and in this deliverable, we will present how the β factor scales with projectile's density down to the low values used by our industrial partners.

For the first study published in Jutzi and Michel (2014), we considered head-on impacts only as this is the usually assumed geometry in mitigation studies. Oblique impact angles and the resulting components of the momentum transfer vector will be subject of a future study. Figure 1 shows the momentum carried by the ejecta in our simulations for the two considered structures of a 300 meter-diameter target. Figure 2 shows the same outcome for other strength and porosity values of the target, showing the influence of these target's properties on the momentum transfer efficiency.

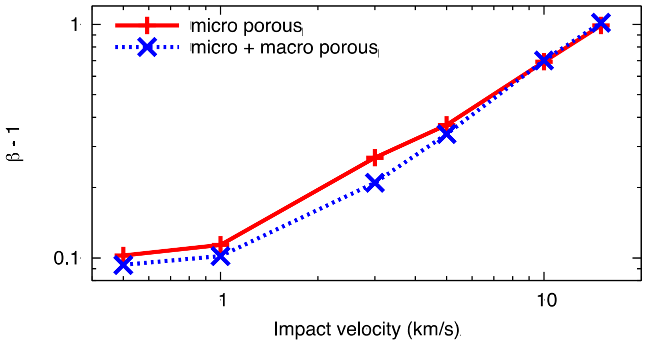

Figure 1: Momentum multiplication factor (β-1) as a function of impact velocity for the two considered structures (a: homogeneous microporous, and b: heterogeneous, micro- and macroporous). The nominal values for Y_t and P_e, P_s are used (see Deliverable 3.2; Jutzi and Michel 2014).

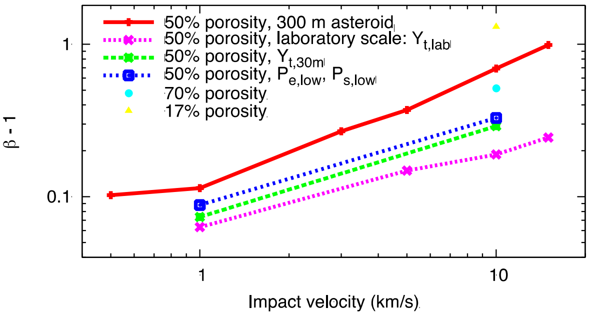

Figure 2: Momentum multiplication factor (β-1) as a function of impact velocity using target structure (a) and considering various strengths and porosities. Unless indicated in the labels, the nominal values for Y_t and P_e, P_s are used (see Deliverable 3.2; Jutzi and Michel 2014).

2. Comparison of simulations and experiments by EMI using non-porous targets

In Jutzi and Michel (2014), we compared our simulations with published experimental results and scaling laws on porous materials developed by our American colleagues (Housen and Holsapple 2012, Holsapple and Housen 2012). Since then, the EMI laboratory (partner of the NEOShield consortium) performed some impact experiments on targets with low porosity.

A first set of simulations, presented in D. 3.2, was performed using our 3D SPH hydrocode using the same conditions as the EMI experiments. We considered a non-porous target material with a density of 2.7 g/cc and a tensile strength of the same order of magnitude as the one measured for the real target material by EMI. However, for some technical reasons, we first considered a fully non-porous target in the simulations while the porosity of the targets used in the experiments was small (~3 %) but present.

For the two impacts with a projectile speed of 4.05 km/s and 5.57 km/s, our simulations on fully non-porous targets obtained a factor β about 2.7 and 5.0, respectively. These values are not exactly similar to the experimental ones of 3.10 and 4.35, although the deviation is not large given all other uncertainties (compare with the results of EMI hydrocode in D3.2, Table 2) and the fact that the porosity in the target was not identical. The main difference between the experimental and numerical results seemed to be the slope of the relation between β and the impact speed (i.e., the increase of β with the impact speed; see Fig. 3).

For this deliverable, other simulations have been performed, using the same small degree of porosity (3%) than the one used in the experiments. The compressive strength is set to 200 MPa, which is of the same order as the experimental one (189 +/- 18 MPa).

For the two impacts with a projectile speed of 4.05 km/s and 5.57 km/s, our simulations obtain a factor β about 3.4 and 4.9, respectively, to be compared with the experimental value of 3.1 and 4.3. The comparison is remarkably good, within the scattering of experiments, and more importantly, the slopes of the relation between β and the impact speed are almost similar (compare the blue and green curves on Fig. 3).

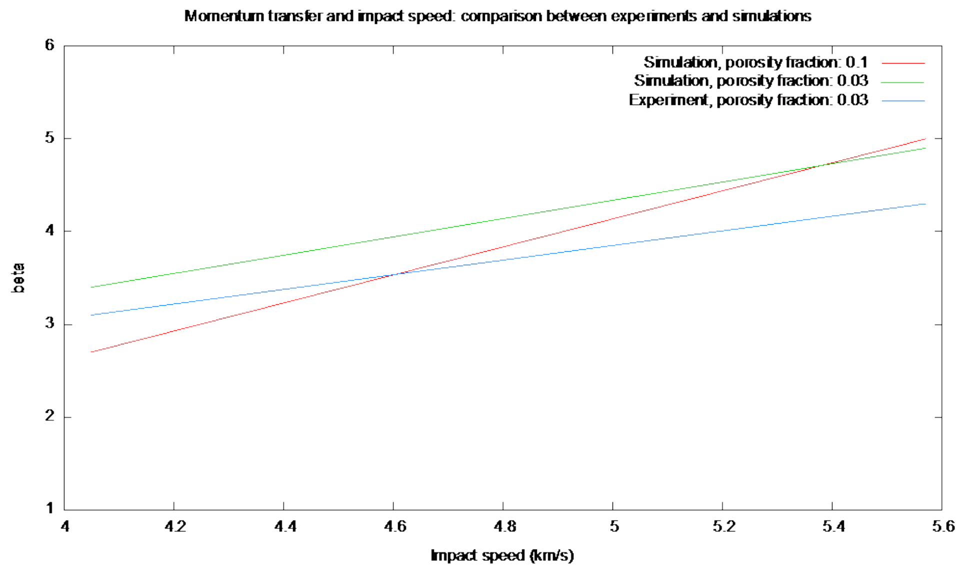

Figure 3: Momentum multiplication factor β as a function of impact velocity compared with impact experiments by EMI. When the same fraction of porosity is used (3%), the comparison is satisfying. When a non-porous target is used in the simulations (red curve, which has zero porosity and not 0.1 as the label indicates incorrectly), a difference can be seen, which is less pronounced for high impact speeds than for low impact speeds in simulation results. However, the slope of the curve (beta as a function of impact velocity) in the fully non-porous case is steeper than found for the experimental results and the simulations with 3% porosity. This is consistent with scaling theories (Holsapple and Housen 2012), which predict higher slopes for non-porous materials.

3. Application to the kinetic impactor concept studied by industrial partners

Our published results (Jutzi and Michel 2014) and the comparisons between our simulations and laboratory experiments (Sec. 2 above) allowed us to already have some results at asteroid scales for porous objects and to validate our numerical approach. We then started performing an application to one of the concepts defined by NEOShield industrial partners.

Some asteroids have already been identified as potential targets of a kinetic impactor mission test by our industrial partners. These are 2001 QC34, a Q-type asteroid, and 2000 FJ10, an asteroid belonging to the taxonomic S-complex. These classes are not understood to be composed of very porous objects (i.e. unlike C-type bodies). Therefore, in our simulations, we considered a target having 10% porosity, and a bulk density of 2.4 g/cc, as even non-porous small asteroids are assumed to have at least a small fraction of porosity due to the presence of faults (e.g. the S-type asteroid Eros), or because they may be rubble piles (e.g. the S-type asteroid Itokawa). For the material properties, we used the properties of pumice. In fact, basalt properties are often used when considering S-type asteroids. However, we cannot use basalt because for this material, which causes less dissipation than pumice during an impact, the shock wave dissipates at larger distance from the impact point, and the required numerical resolution to cover large distance is still beyond our limits. Nevertheless, since it is expected that for basalt material, β will be larger than for pumice, our simulations will give the lowest possible values. Our results can thus be considered as the worse case scenario. For the target diameter, because it is not well constrained, first we used both 300 and 150 meters-diameters. However, a few tests showed us that the results are essentially the same because the gravity is small enough, so we fixed the diameter to 300 m. Regarding the impact conditions of the projectile, we assumed a head on geometry and a speed of 10 km/s.

We then communicated with industrial partners, in particular Airbus Defence and Space (Germany) to have some information about their impactor design. They told us that they are actually considering artificial projectiles including a spacecraft and the upperstage (Fregat, 902kg dry mass) of the Soyuz launcher that will remain attached to the spacecraft in order to increase the impact mass (see Fig. 4). The resulting density is much lower, in the range 0.12-0.15 g/cc, than the assumed density in our previous studies (~1 g/cc). The main reason for these low spacecraft densities is the composition of the spacecraft, made of nearly "empty" boxes with huge spare room in between. Therefore, in contrast to an impact of a sphere or a plate of homogeneous density, at time of impact the spacecraft will experience a material compression (over a short timespan) before completely impacting. The question is then whether this "compression phase" has a relevant and unwanted (reduction) effect on the β factor / momentum transfer behavior. This is an important question since its answer might drive the whole mission concept when an optimization of the related parameters is required to achieve the mission objectives.

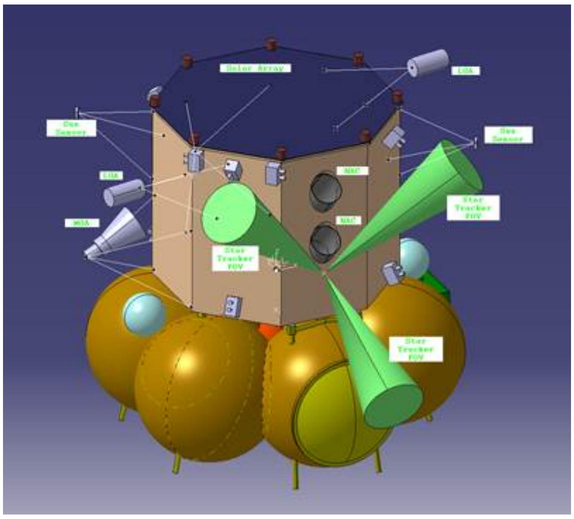

Figure 4: Kinetic impactor design (from Airbus Defense and Space). The yellow spheres are the propulsion tanks of the Fregat upper stage, which will remain attached to the spacecraft until impact to increase the impact mass. The green cones are the fields of view of the three star trackers used for attitude control.

Given the crucial aspect of this question for the industrial design, we took a first look at the influence of the projectile's density on the β factor.

3.1 Influence of a fixed projectile's density on the momentum transfer

Table 1 exposes the results of simulations for different projectile's densities (since β is usually normalized by the impactor mass, the mass does not come into play).

The impact conditions are the following:

- Impact speed: 10 km/s
- Target's diameter: 300 m (chosen to be a real possibility given the target choice by industries and diameter uncertainties).
- Target's material: pumice with crush-curve parameters scaled to 10% porosity and a density of 2.4 g/cc.
- Projectile's density: 0.1, 1. And 3 g/cc.

These simulations show that increasing by an order of magnitude the density (from 0.1 to 1 g/cc) does not even double β, and a factor 3 (for 1 to 3 g/cc) increases only slightly β. Therefore β does not seem to be "extremely" sensitive to the projectile's density. However, it should be note that for a deflection (demo-) mission using the spacecraft as projectile, the small sensitivity is still important. In effect, although the technical design degrees of freedom are constrained at early stages, the density optimization of the spacecraft could promise β improvements of about 10-20%, which should not be neglected. This holds also for real deflection missions, in which more budget would allow putting more projectile-mass with a higher density to the impactor and thus would improve β.

Projectile's density (g/cc)	β
0.1	1.5
1	2.5
3	2.8

Table 1: momentum transfer efficiency (β factor) as a function of projectile's density, everything else being equal (see text for details).

Scaling laws by Holsapple and Housen (2012) have been derived that link the projectile's density to the momentum (see, e.g. their Eq. (28)). Our results correspond to an exponent on the density of 0.3 in these scaling laws, which is slightly different than the value of 0.2 found by Holsapple and Housen (2012, see e.g. their Eq. (36)). In fact, in these scaling laws, the exponent on the density is equal to (1-3ν), where ν is a material parameter that, according to experiments, is generally equal to ~0.4 (our exponent of 0.3 results in a value of ν that is equal to 0.43, which is not very different from the experimental value). Therefore, we conclude that using an exponent of 0.2 (simulations) - 0.3 (scaling laws), industries can then easily estimate the possible range of β values for a given projectile's density, all other relevant parameters being fixed.

3.2 Influence of the projectile's porosity and shape

As explained above, the actual projectile designed by the industries has a density that is not homogeneously distributed and it is therefore expected that at the time of impact, it will experience a material compression (over a short timespan) before completely impacting. In order to estimate the influence of the porosity within the projectile on the β factor, we performed a simulation in which the projectile is characterized by a crush-curve, like a porous material.

We recall that the crush-curve is a material property that describes how the distention (ratio of the density of the solid component of the material and the bulk density of the material) evolves with pressure (see Fig. 5 for an example). This relation between pressure and density is used to modify appropriately the equation of state of the material accounting for its porosity (see Jutzi et al. 2008, 2009 for details).

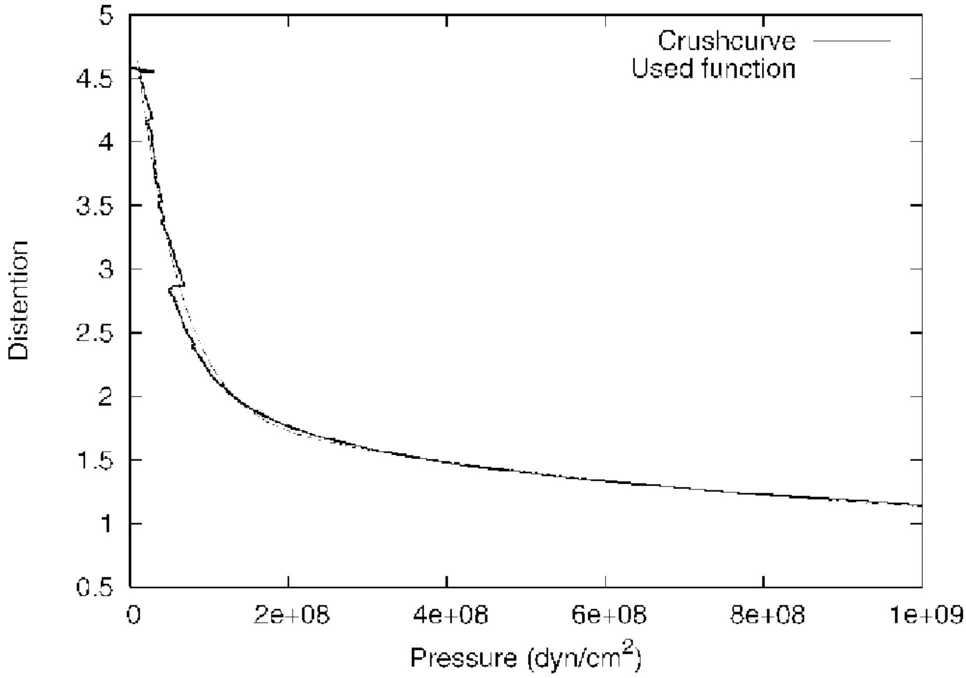

Figure 5: Crush-curve measurements of pumice targets (Kobe University, solid line). The Y-axis is the distension, while the X-axis is the pressure. The dashed line shows an example of a functional crush-curve used in simulations. From Jutzi et al. (2009).

In order to check how the presence of porosity in the projectile may influence the momentum transfer efficiency of the kinetic impactor, we assigned 95% porosity and an associated crush-curve to our projectile with a bulk density of 0.1 g/cc and performed an impact simulation with the same other initial conditions as described in the previous section. Although we chose an extreme case (95% porosity, low initial density), the result (Table 2) shows that there's a slight increase but not a big sensitivity of the β factor to the initial porosity of the projectile in this case.

We also investigated the influence of the shape of the projectile on the β factor. Instead of a spherical projectile, we used the extreme case of a round plate with a radius of 1.6 m and a thickness of 8 cm. We then performed an impact simulation using the same other initial conditions as in the previous section. Our results (Table 2) show a decrease of β when we use a "flat" projectile, compared to the value obtained when we use a spherical projectile.

Projectile's density (g/cc)	Shape	Initial porosity	β
0.1	Spherical	0%	1.5
0.1	Spherical	95%	1.8
1.0	Spherical	0%	2.5
1.0	Round plate	0%	2.0

These simulations are just two examples using extreme cases, suggesting that shape matters more than the presence of porosity for the investigated cases.

Perspectives

Obviously, more research is required to generalize our results and to cover the whole parameter space allowing us to have a database of outcomes of kinetic impacts as a function of initial target and projectile conditions. Further investigations will be performed in the framework of the NEOShield-2 project that contains a package devoted to a continuation of this research. In particular, our objectives are to continue to investigate the effects of various possible internal structures (shattered, rubble pile) and surface characteristics (such as the presence of regolith, of large boulders, of craters, different mineralogies) on an object's response to a kinetic impactor, as well as possibly the effect of the initial spin state. We will also consider a range of projectile characteristics (mass, speed) as well as those used in specific mission designs, such as those defined in the NEOShield-2 project as well as those defined for the AIDA space mission under study at ESA and NASA.

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