Numerical study of the asteroid deflection efficiency of the kinetic impactor approach in the NEOShield project.

Martin Jutzi\textsuperscript{1}
Patrick Michel\textsuperscript{2}

\textsuperscript{1}Center for Space and Habitability, Physics Institute, University of Bern, Switzerland
\textsuperscript{2}Langrange Laboratory, University of Nice, Cote d’Azur Observatory, France
Kinetic impactor method
Kinetic impactor method
Kinetic impactor method

Momentum transfer:

\[ \vec{P}_{\text{target}} = \vec{P}_{\text{projectile}} + \vec{P}_{\text{ejecta}} > \vec{P}_{\text{projectile}} \]
Momentum transfer

- Normalized with projectile momentum
  \[ P_{\text{target}} = 1 + P_{\text{ejecta}} \equiv \beta \geq 1 \]

- Change of target velocity
  \[ \Delta V = \frac{P_{\text{projectile}}}{M_{\text{target}}} \times \beta \]
Momentum transfer

- Normalized with projectile momentum

\[ P_{target} = 1 + P_{ejecta} \equiv \beta \geq 1 \]

- Change of target velocity

\[ \Delta V = \frac{P_{projectile}}{M_{target}} \times \beta \]

- Target structure
- Material Properties
- Impact velocity
- Target size etc.
Numerical modeling of impacts

- Smooth Particle Hydrodynamics impact code

- To model impacts and collisions we include
  - Strength + friction (Drucker-Prager like yield criterion)
  - Porosity (based on P-alpha model)
  - (self-gravity)
  - Equation of State: Tillotson or ANEOS
Comparison with laboratory experiments

$T = 8.0\, \text{ms}$

Experiment (Kobe University)

Simulation

Jutzi et al., 2009
Comparison with laboratory experiments

Cumulative mass distribution

Jutzi et al., 2009

Comparison with laboratory experiments

Cumulative number of fragments

Experiment 060824-6
Simulation

Experiment 060418-4
Simulation

Experiment 070427
Simulation

Experiment 060825-4
Simulation

Mass fraction
Comparison with laboratory experiments

Impacts in Sand
1G or 464 G

Experiments by Kevin Housen
(IMPACT HYDROCODE BENCHMARK AND VALIDATION PROJECT)
Kinetic Impact Simulations

- **Initial conditions:**
  - **Target**
    - D = 300 m asteroid
    - Two different target types are investigated:
      - Micro-porous (pumice with 50% porosity)
      - Micro-porous + macroscopic cracks (inhomogeneity)
  - **Projectile**
    - 400 Kg
    - varying impact velocities (0.5 .. 15 km/s)
    - aluminium sphere ($\rho = 2.7 \text{ g/cm}^3$)
Impact simulations

Specific impact energy needed for disruption

![Graph showing specific impact energy needed for disruption in different materials. The graph plots $Q_D^*$ (erg/g) on the y-axis against radius (cm) on the x-axis. The graph compares non-porous (basalt) and porous (pumice) materials. The study results are highlighted with a blue dot.]
Impact simulations

Specific impact energy needed for disruption

![Graph showing specific impact energy needed for disruption](attachment:impact_energy_graph.png)

- $Q^*_D$ (erg/g)
- Radius (cm)

- non-porous (basalt)
- porous (pumice)

- this study

→ Cratering regime
Impact simulations

Simulated domain

300 m
Impact simulations (10 km/s impact)

micro - porous

10 m

micro+macro - porous
Beta computation

\[ \vec{v}_{eject} \]

\[ \vec{v}_{inf} \]

\[ \varphi_{inf} \]
Beta computation

From simulation

\[ \vec{v}_{\text{eject}} \]

\[ \vec{v}_{\text{inf}} \]

\[ \phi_{\text{inf}} \]
Beta computation

From simulation

\[ \vec{v}_{\text{eject}} \]

\[ \vec{v}_{\text{inf}} \]

Hyperbolic orbit:

\[ y^2 = (e^2 - 1)x^2 - 2epx + p^2 \]

e, p are determined by initial position and velocity of the ejecta and the mass and the radius of the target
Beta computation

From simulation

\[ \vec{v}_{eject} \]

\[ \vec{v}_{inf} \]

Hyperbolic orbit:

\[ y^2 = (e^2 - 1)x^2 - 2epx + p^2 \]

\[ e, p \text{ are determined by initial position and velocity of the ejecta and the mass and the radius of the target} \]

\[
\begin{align*}
v_{inf}^2 &= v_{eject}^2 - v_{esc}^2 \\
v_{zinf} &= \sin(\phi_{inf}) \times v_{inf}
\end{align*}
\]
Beta computation

From simulation

$\vec{v}_{\text{eject}}$

Hyperbolic orbit:

\[ y^2 = (e^2 - 1)x^2 - 2epx + p^2 \]

$e, p$ are determined by initial position and velocity of the ejecta and the mass and the radius of the target

\[ v_{\text{inf}}^2 = v_{\text{eject}}^2 - v_{\text{esc}}^2 \quad v_{\text{zinf}} = \sin(\phi_{\text{inf}}) \times v_{\text{inf}} \]

Momentum of ejecta using $v_z$ at infinity:

\[ p_{\text{ej}} = \sum_i m_i \times v_{z\text{inf},i} \quad \beta = 1 + p_{\text{ej}} / (M_p v_p) \]

Similar to Holsapple and Housen 2012
Effect of velocity correction ($v_{eject}$ vs. $v_{inf}$)

$\beta$

1 km/s impact
1 km target

Vertical velocity (m/s)
Momentum multiplication factor

Impact velocity (km/s)

- micro porous
- micro + macro porous
Momentum multiplication factor

The figure below shows the results for various materials, including:

- **Sand**
- **Basalt**
- **Pumice**
- **Olivine**
- **Compact snow**
- **Ice (low bnd)**
- **Comet analog (low bnd)**
- **Aerogel**
- **Aerogel (low bnd)**
- **River rock**
- **Scorified Olivine**
- **Scorified rock**

The y-axis represents the momentum multiplication factor, while the x-axis shows the impact velocity in km/s. The data points and lines illustrate the behavior of different materials under impact, with a focus on porous materials and their response to varying velocities.

From Housen & Holsapple, LPSC 2012
Scaling laws for idealized cases

Scaling laws are based on an idealized ejecta velocity distribution

Slope $\mu$: $1/3$ - $2/3$

$\sim 0.4$ for porous materials

$\sim 0.6$ for solid materials

$$P = K_{ps} \left[ mU \left( \frac{U}{\sqrt{Y/\rho}} \right)^{3\mu-1} \left( \frac{\rho}{\bar{\delta}} \right)^{1-3\nu} \right] F_{esc} \left[ \frac{v_{esc}}{v^*} \right]$$

$$\beta - 1 \sim U^{3\mu-1} \times F_{esc}$$

Holsapple & Housen 2012
Mass $M$ ejected with a velocity greater than $v$

$$M^* = \frac{M}{m_p} \left( \frac{U}{\sqrt{Y/\rho}} \right)^{-3\mu} \left( \frac{\rho}{\delta} \right)^{3\mu - 1}$$

$$\nu^* = \nu / \sqrt{Y/\rho}$$
Mass $M$ ejected with a velocity greater than $v$

$$\frac{M_e}{M} \left( \frac{U}{\sqrt{\gamma \rho}} \right)^{-3 \mu - 1}$$

$$M_e^* = \frac{M_e}{M} \left( \frac{U}{\sqrt{\gamma \rho}} \right)^{-3 \mu}$$

$\mu = 0.4$

$\nu^* = \frac{v}{\sqrt{\gamma \rho}}$
Point-source scaling limits

- Point-source scaling applies at some minimum distance from the impact.
- Power-law scaling holds from that point to the location where the ejection velocities are zero.
- Non-power-law scaling due to the influence of gravity or strength begins to arrest the cratering flow near the crater edge.

Plots of $M(x)$ versus position on logarithmic axes exhibit three behaviors:

1. For small values of $x$, there is no ejecta, or it does not follow the power-law form.
2. For intermediate values of $x$, the mass of fast ejecta is a tiny fraction of a gram.
3. For large values of $x$, the mass of the fast ejecta is usually quite small and is therefore hard to observe in high-speed films, or to trap in collector bins due to the large ballistic ranges involved.

- Failure to collect even a small amount of this high-speed material can cause significant underestimation of the mass of very high-speed material that can be ejected by the 'jetting' process here because it depends on details of the projectile shape.
- Jetting occurs when two surfaces collide at high speeds at a low angle. We ignore the jetting process (e.g. Yang and Ahrens, 1995) based on experimental data.
- The mass of ejecta goes to zero at high ejection speeds.
- The large distance that the power-law holds is proportional to the crater radius.
- As discussed below, this proportionality constant is close to 1.

Three additional important points should be made regarding the scaling:

1. The point-source scaling limits do not have sharply defined limits. That is, the effects of gravity or strength are eventually strong enough to stop the flow.
2. The scaling of the ejecta velocity distribution can be expected to break down at various points for various datasets depending on the specific impact conditions. This is true for all plots of the ejecta velocity distribution, a point that is discussed further below.
3. The power-law regime depends on impactor size and the other end depends on crater size for a given impact. In general then, one can write the left-hand point at which the power-law breaks down as $x = n_1 a$, so $x \sim n_1 a / R$, or $x = n_1 a / R$. There-
Velocity distribution

Mass $M$ ejected with a velocity greater than $v$

$M^*_e = \frac{M}{m_p} \left( \frac{U}{\sqrt{Y/\rho}} \right)^{-3\mu - 1}$

$\mu = 0.4$

Projectile is large compared to crater dimensions
$\Rightarrow$ No power law regime

$v^* = \frac{v}{\sqrt{Y/\rho}}$
$\beta$ - scaling with velocity

- $\beta - 1$

Impact velocity (km/s)

- micro porous
- $\mu = 0.55$
Effects of strength and porosity

Size scaling of tensile strength: $L = \text{??}$

\[ Y = Y_0 \left( \frac{L_0}{L} \right)^{1/m} \]

$m \sim 2-3$

Holsapple and Housen, 2012
Effects of strength and porosity

Impact velocity (km/s)

- 50% porosity
- 50% porosity, higher $Y_t$
- 50% porosity, lower $Y_c$
- 70% porosity
Effects of strength and porosity

- 50% porosity
- 50% porosity, higher $Y_t$
- 50% porosity, lower $Y_c$
- 70% porosity

Impact velocity (km/s) vs. $\beta - 1$
Summary

• Momentum multiplication factor is small for porous materials ($\beta < 2$ for $v < 15 \text{ km/s}$)

• Effects due to macroscopic inhomogeneities disappear at high impact velocities

• Strength (tensile and crushing) is important

• Comparison to scaling laws:
  ‣ Slope in velocity distribution is as predicted
  ‣ Slope of $\beta$ vs. impact velocity is slightly higher
Outlook

• Investigation of different material properties
  ‣ very low strength (tensile, crushing)
  ‣ very high porosities
• Higher impact velocities
  ‣ using more sophisticated ANEOS
• Surface and structural inhomogeneities
Questions?