Hypervelocity Penetration of Near Earth Objects

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Introduction

• Purpose
  – Apply a basic understanding of penetration mechanics to the penetration capability of Near Earth Objects
  – Examine effects of penetration and the ability to mitigate threatening Near Earth Objects

• Objectives
  – Derive mathematical penetration model to simulate projectile impact
  – Apply models to a range of scenarios
Background

• Alekseevskii-Tate Model
  
  – Jet penetration requirement
  
  \[
  \frac{\rho_p v^2}{\sigma_i} \gg 1
  \]
  
  – Pressure of impact is significantly larger than internal resistance forces, hypervelocity
  
  – Modified Bernoulli equation applies
  
  \[
  \frac{1}{2} \rho_p (v - u)^2 + Y_p = \frac{1}{2} \rho_i u^2 + R_t
  \]
Governing Equations

- **Alekseevskii-Tate Penetration Equations**
  - Eroded length
    \[
    \frac{d\eta}{d\tau} = \xi(1 - A) + \frac{B}{\xi}
    \]
  - Penetration depth
    \[
    \frac{d\Theta}{d\tau} = \xi A - \frac{B}{\xi}
    \]
  - Tail velocity
    \[
    \frac{d\xi}{d\tau} = -\frac{C}{1 - \eta}
    \]
  - Cavity diameter
    \[
    \varsigma = \left(\frac{\left(\xi^2 - 2C\right)\left[\xi^2(1 - A) + B\right]}{C_0\left(\xi^2 A - B\right)}\right)^{1/2}
    \]

\[
A = \frac{1}{1 + \sqrt{\rho_t / \rho_p}}
\]

\[
B = \frac{R_t - Y_p}{\nu_0^2 \sqrt{\rho_t \rho_p}}
\]

\[
C = \frac{Y_p}{\rho_p \nu_0^2}
\]

\[
C_0 = \frac{2a}{\rho_p \nu_0^2}
\]
2004 VD17 Impact
6 m by 0.65 m Tungsten Alloy at 10 km/s
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Apophis Impact
7 m by 1 m Titanium Alloy at 10 km/s
Apophis Impact
7 m by 1 m Titanium Alloy at 10 km/s
Apophis Impact
7 m by 1 m Titanium Alloy at 10 km/s
1999 JU3 Impact
5.5 m by 0.7 m Tungsten Alloy at 15 km/s
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### Impact Velocity Composition

- **7 m by 0.75 m cylindrical Titanium Alloy projectile**
- **1.0 g/cm³ asteroid**

<table>
<thead>
<tr>
<th>Impact Velocity (km/s)</th>
<th>Penetration Depth (m)</th>
<th>Cavity Diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>13.7</td>
<td>9.8</td>
</tr>
<tr>
<td>15.0</td>
<td>13.9</td>
<td>15.8</td>
</tr>
<tr>
<td>20.0</td>
<td>14.2</td>
<td>21.4</td>
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<tr>
<td>25.0</td>
<td>14.1</td>
<td>26.9</td>
</tr>
<tr>
<td>30.0</td>
<td>13.9</td>
<td>32.5</td>
</tr>
</tbody>
</table>
Impact Velocity Comparison

Impact at 10 km/s

Impact at 20 km/s

7 m by 0.75 m cylindrical Titanium projectile impacting a 1.0 g/cm³ carbonaceous asteroid
Projectile Size Comparison

• Cylindrical Tungsten Alloy projectile
• 1.0 g/cm³ asteroid
• 10 km/s impact velocity

<table>
<thead>
<tr>
<th>Projectile Length (m)</th>
<th>Projectile Diameter (m)</th>
<th>Penetration Depth (m)</th>
<th>Cavity Diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>1.0</td>
<td>18.4</td>
<td>19.6</td>
</tr>
<tr>
<td>5.0</td>
<td>2.0</td>
<td>15.1</td>
<td>39.1</td>
</tr>
<tr>
<td>7.5</td>
<td>1.0</td>
<td>29.2</td>
<td>19.6</td>
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<td>10.0</td>
<td>1.0</td>
<td>40.0</td>
<td>19.6</td>
</tr>
<tr>
<td>10.0</td>
<td>2.0</td>
<td>36.7</td>
<td>39.1</td>
</tr>
</tbody>
</table>
Projectile Diameter Comparison

5 m by 1 m Cylinder

5 m by 2 m Cylinder

Cylindrical Tungsten projectile impacting a 1.0 g/cm³ carbonaceous asteroid at 10 km/s
Cylindrical Tungsten projectile impacting a 1.0 g/cm³ carbonaceous asteroid at 10 km/s
• 7 m by 0.75 m cylindrical projectile

• 10 km/s impact velocity

• Results obey hydrostatic limit

<table>
<thead>
<tr>
<th>Projectile Composition</th>
<th>Asteroid Composition</th>
<th>Penetration Depth (m)</th>
<th>Cavity Diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten Alloy</td>
<td>Carbonaceous</td>
<td>25.8</td>
<td>14.7</td>
</tr>
<tr>
<td>Tungsten Alloy</td>
<td>Silicaceous</td>
<td>17.6</td>
<td>18.6</td>
</tr>
<tr>
<td>Tungsten Alloy</td>
<td>Metallic</td>
<td>15.6</td>
<td>19.8</td>
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<tr>
<td>Titanium Alloy</td>
<td>Carbonaceous</td>
<td>14.3</td>
<td>9.8</td>
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<tr>
<td>Titanium Alloy</td>
<td>Silicaceous</td>
<td>9.1</td>
<td>12.7</td>
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<tr>
<td>Titanium Alloy</td>
<td>Metallic</td>
<td>8.1</td>
<td>13.6</td>
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</tbody>
</table>
Titanium Alloy

Tungsten Alloy

7 m by 0.75 m cylindrical projectile impacting a 2.0 g/cm³ carbonaceous asteroid at 10 km/s
Results

- Penetration obeys hydrostatic limit
  - Penetration depth requires massive projectiles
  - Long and narrow advantageous within limits
  - Density versus launch capability tradeoff

- Cavity diameter sensitive to projectile diameter and impact velocity

- Penetration restricted by
  - Significantly higher impact velocities
  - Larger projectile diameters
Future Research

• Examine high fidelity hydrocode capabilities for computing results of rigid body motion of asteroid impacts

• Detailed asteroid material compositions
  – Inclusions, cavities, voids, ice
  – Asteroid chemical composition information useful

• Penetration impact on asteroid mass distribution
Summary and Conclusions

• Alekseevskii-Tate
  – Well suited for preliminary analysis
  – Hydrocode model required for deformable body mechanics and detailed simulations

• Penetration profile necessary for explosive predictions, momentum change ability

• Velocity profile necessary for design specifications