Impact Cratering: Shock physics on a planetary scale

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Impact cratering is an important geologic process
Impacts shaped the solar system and the evolution of life

- Mass extinction & evolution of life
- Formation of the moon, planetary accretion
- Properties / age of planetary surfaces
- Future hazard
- Ore / hydrocarbon deposits
Key questions in impact cratering:

- How do impacts affect the local and global environment?
- What hazard do asteroids and comets pose to humanity?
- How might we deflect an incoming object?
- What can Earth’s impact craters tell us about the surface of other planets?
- **How does crater size and shape depend on impactor and target properties?**
Craters show a size-morphology progression

Images courtesy of NASA
Crater formation divided into 3 stages

- **Contact and compression**
  - shock physics

- **Excavation**
  - fluid dynamics

- **Modification**
  - rock mechanics
  - rheology, gravity
Different physics important in different zones

- Shock physics
- Hydrodynamics
- Rock mechanics
Large impacts can only be simulated by modelling

- iSALE: Eulerian finite-difference "hydrocode"
- 2D geometry (axial symmetry); vertical impacts
- Multi-material, multi-rheology, compressible flow
- Tillotson/ANEOS equations-of-state
- Custom constitutive model (relating stress to strain/strain rate) for impacts into geologic media
- Efficient porous compaction model
Rock Failure is Complicated!

Cohesion

Brittle
(Intact Rock
(Lundborg, 1968)

Ductile
(Damaged Rock
(Stesky et al., 1974)

von Mises Yield Limit

Pressure, MPa

Shear Strength, MPa
Rock strength decreases with increasing temperature

Thermal Softening of Dunite and Granite

- Dunite (Stesky et al., 1974): $\tanh(0.6*(T/Tm-1)$
- Granite (Stesky et al., 1974): $\tanh(1.2*(T/Tm-1)$
- Peridotite (Stesky et al., 1974): $\tanh(0.85*(T/Tm-1)$
Simple crater formation

Damage, time = .000 s
Complex crater formation
Models tested against geological and geophysical data
Case study: How big was the Chicxulub impact?
Best-fit model suggests impactor was ~10-km diam.
Broad agreement between numerical and geophysical models
Summary so far...

- Impact cratering is an important geologic process, controlled by shock physics

- Large crater formation is also controlled by gravity and complicated target strength

- Complex material models for rocks are needed for useful numerical simulations of impacts

- Modelling is a powerful way to estimate impact energy from complex crater size and shape
How is cratering affected by target properties?

- Cratering in nonporous, crystalline rock now quite well understood

- Porosity is important in many contexts:
  - Asteroids
  - Comets
  - Icy satellites
  - Regoliths
  - Sedimentary rocks
  - Early planetesimals

- Cratering in porous targets is poorly understood:
  - Crater size?
  - Melt and vapour production?
  - Momentum transfer?
Asteroids show a large range in porosity

Porosity increases shock attenuation and shock heating.
Effect of porosity difficult to study in lab-scale impacts

Cintala et al. (1999)

Housen and Holsapple (2003)

44% Porosity

70% Porosity

Johnson and Burchell (2004)
ε-alpha model for porous compaction

(Wünnemann, Collins and Melosh, 2006)

Compaction of pore space separated from compression of solid matrix:

\[
P = f(E, \rho, \alpha) = \frac{1}{\alpha} P_s(\alpha \rho, E) = \frac{1}{\alpha} P_s(\rho_s, E).
\]

Thus, equation of state for the solid material can be used for porous material

Just need to define the distension (porosity) as a function of volume change:

\[
\alpha = f(\varepsilon_V) = \begin{cases} 
\alpha_0 & |\varepsilon_V > \varepsilon_e \\
\alpha_0 e^{\kappa (\varepsilon_V - \varepsilon_e)} & |\varepsilon_V < \varepsilon_e
\end{cases},
\]
ε-alpha model for porous compaction

(Wünnemann, Collins and Melosh, 2006)

Diagram showing different regimes of compaction:
- (i) elastic regime
- (ii) plastic compaction of pores
- (iii) compression of matrix

Graphs illustrate the relationship between compression pressure/volumetric strain and porosity, with sections for initial distension and fully compacted states.
Model validated against Hugoniot data from experiments

Difference due to thermally induced phase transition??
Model validated against experiments
Porous material absorbs shock wave more efficiently
Porosity reduces crater diameter and cratered mass

Nonporous

Porous
Porosity and friction decrease cratering efficiency

Increasing shock attenuation
Decreasing target density
Porous targets absorb shock energy
This means lower ejection velocity and smaller craters
Porosity greatly reduces velocity and total mass of ejecta.
Application: Asteroid deflection by direct impact

Momentum before impact

\[ m_i \circ \quad v = 0 \]

Momentum after impact, including effect of cratering

\[ m_a + m_i - m_e \]

\[ \delta v \approx \frac{(m_i v + L)}{m_a} \]
10 yr lead: <~400-m wide asteroids could be deflected
With 1 yr lead, this drops to $\sim 150$-m asteroids.
Conclusions

- Porosity has an important effect on impact cratering

- Porous materials absorb shock wave energy, leading to lower cratering efficiency
  - Less mass excavated and displaced
  - Lower ejection velocities and shock pressures
  - Less efficient momentum transfer
  - Efficacy of deflection by impact reduced if asteroid porous

- The absorbed energy leads to greater melting of porous materials
  - More melt expected in sedimentary target craters
  - Impact melt production in early, low velocity collisions of planetesimals?