Meso Scale Study of Rapid Penetration into Granular Media

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Meso scale study of rapid penetration in granular media

- Motivation and background
- Experimental methods
- Macro scale results
- Refractive index matching - transparent soils
- Digital image correlation
- Meso scale results
- Summary and Conclusions
• **Motivation**
  - Military applications (fortress design, underground targets, etc.)
  - Subsurface investigation
  - Planetary impact
  - Oil and gas industry
  - Physics of granular media

• **Some open questions:**
  - How does the penetrator energy dissipate as it penetrates soil
  - What is the role of the soil density, saturation, etc.?
  - What are the main soil-penetrator interaction mechanisms?
• Phenomenology of rapid penetration

Equation of motion: \( -m \frac{dv}{dt} = \alpha v^2 + \beta v + f(z) \)

- Inertial term:
- Viscous term: \( f(v) \)
- Frictional bearing resistance: Depth dependent? \( f(z) = ? \)

\( dm = \rho dv = \rho Av dt \rightarrow dp = dm v = \rho Av^2 dt \)

\[ F = -\frac{dp}{dt} = -\rho Av^2 \]
• **Approach:**
  • Subscale tests
  • Measure projectile penetration time history \( p(t) \)
  • Record projectile velocity
  • \[ a(t) = \frac{d^2 p(t)}{dt^2} \]

• **Two methods used:**
  • High-speed imaging
  • Photonic Doppler velocimetry
High speed imaging:
- Use long rod as projectile
- Track markers on projectile using high-speed camera
- Derive penetration time history

Four projectile shapes used:
- Conical, hemispherical, blunt rod, and sphere
• **Experimental setup**
  - Camera: 4 MPx @1.6 kHz
  - Imaging frequency: 50 kHz, 5 us exposure
  - 1.25 kW tungsten halogen light
  - Impact velocity ~ 80 m/s

Time lapse sample frames during penetration
• **Limitations:**
  - Higher velocities difficult to image with required resolution
  - Differentiation amplified noise

• **Photonic Doppler velocimetry (PDV):**
  - Directly obtain velocity (no differentiation)
  - Extremely high resolution for $v(t)$
  - Large depth of field
  - Much higher velocities possible – 300 m/s used in our research
**PDV measurement principle:**

- Coherent light source is reflected from a moving surface
- Reflected light wave has a Doppler shifted frequency, $f_D$, compared to original wave frequency, $f_0$
  \[ f_b = |f_D - f_0| \]
- Frequency shift relates to velocity of moving object, $v(t)$
  \[ f_b(t) = 2 \left( \frac{v(t)}{c} \right) f_0 = 2 \left( \frac{v(t)}{\lambda_0} \right) \]
  \[ v(t) = \frac{1}{2} \lambda_0 f_b(t) \]
  (c and $\lambda_0$ are speed and length of coherent light wave)
Rapid Penetration in Granular Media

- **PDV experimental setup:**

  Schematics of PDV setup

  Experimental setup used for penetration in soils

2/27/15
• Typical PDV measurements:
**Test matrix:**
- 80 tests performed
- Four soil types
- Dry and saturated
- Four projectile shapes
- Loose and dense packing
- Velocities of 80-300 m/s

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<tr>
<th>Soil Type</th>
<th>Relative Packing</th>
<th>Projectile</th>
<th>Saturation</th>
<th>Test ID</th>
<th>Impact Velocity (m/s)</th>
<th>Target Dry Density (g/cm³)</th>
<th>Packing Fraction</th>
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OS: Ottawa sand
CC: Crushed coral
FQ: Crushed fused quartz
CA: Aragonite
• **Test results:**
  - Transitions in velocity time history observed, particularly in dense sand
  - Acceleration: Initial impact deceleration, followed by steady state penetration, and final increase in deceleration
  - Oscillations in acceleration due to force chain formation and breakdown
• **Effect of nose shape:**
  - Significant in Ottawa sand
  - More important in dense sand
  - Conical nose penetrates farthest
  - Hemisphere and blunt are comparable
  - Nose not significant in crushable sand

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**Fig 12:** Effect of nose shape on penetration into dense Ottawa sand: (a) Penetration time history, (b) velocity vs. penetration, and (c) velocity vs. time (dashed lines represent raw data).

**Fig 13:** Effect of nose shape on penetration into dense Aragonite sand: (a) Penetration time history, (b) velocity vs. penetration, and (c) velocity vs. time (dashed lines represent raw data).
• **Effect of nose shape:**
  - Crushed soil forms false nose, thereby reducing role of nose shape

![SEM image of false nose](image_url)

*SEM image of false nose*

*Projectile recovered after test in aragonite*
Effect of saturation:

- Ottawa sand: not significant for loose sand – eliminates transition in dense sand
Effect of saturation:

- Crushed coral: crushing reduces role of saturation
• Supersonic penetration:
  • Another transition observed at approximately 80 m/s
• **High velocity transition:**
  
  • Trail of comminuted sand observed along projectile trajectory
  
  • Crushing diminishes below approximately 80 m/s
• **Low velocity transition:**
  - Frictional resistance taking over inertial resistance as velocity decays
  - Quasi static penetration tests confirm role of frictional resistance (depth dependent)
• **General emerging picture:**
  
  • Two distinct transitions found
  
  • First transition: crushing/non crushing
  
  • Second transition: inertial/frictional
  
  • **Ongoing:** analytical description according to modified phenomenology

![Diagram showing velocity regime during projectile penetration in granular media.](image)
• We measured forces and deceleration

What about soil deformation and soil-projectile interactions?

Can we look inside the soil??
• We measured forces and deceleration

What about soil deformation and soil-projectile interactions?

Can we look inside the soil??

YES WE CAN!!!
Refractive index matching - transparent soils

- Transparent soil = transparent granular material + index matching pore fluid

- Granular materials:
  - Silica gel (beads/crushed)
  - Amorphous silica powder
  - Crushed fused quartz
  - Glass beads

- Pore fluids:
  - Mineral oil blends
  - Water based solutions (NaI, Sucrose, etc.)
Diagnostic techniques

- Transparent soil - laser illumination

Experimental setup

Typical speckle pattern
Diagnostic techniques

- Transparent soil - embedded plane technique
- **Experimental setup**
  - High speed camera
  - Electro-pneumatic accelerator
  - Pressurized gas source
  - Lighting
  - Transparent soil model
  - Mobile workstation
• **Time lapse of penetration event**
  
  • $V_0=14$ m/s, Loose sample
  
  • Image acquisition rate: 6 kHz
  
  • Playback: 15 fps
  
  • Oil buffer prevents isolates air blast effect

• **How to analyze images??**
Digital image correlation

Step 1 - Acquire images; discretize into subsets

Step 2 - Calculate ZNSSD for each interrogation window (Eq. 2)

Step 3 - Locate correlation peak for each subset

Step 4 - Obtain displacement of each subset

ZNSSD(m,n) = \left[ \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} [f(i,j) - \bar{f}]^2}{\sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} f(i,j) - \bar{f}}^2} \right] - \left[ \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} [g(i+m,j+n) - \bar{g}]^2}{\sqrt{\sum_{i=1}^{M} \sum_{j=1}^{N} g(i+m,j+n) - \bar{g}}^2} \right]
Results: velocity field
Results: examples of shear and volumetric strain field
Results: examples of shear and volumetric strain field
Results: comparison of quasi static and dynamic penetration

Fig 18: Comparison of shear strain increments for quasi static and dynamic penetration of blunt nose projectile, shown at 2D, 4D, 6D, and 8D penetration depths.
Summary of findings:

- Transition zones in velocity time history related to changes in penetration mechanism
- High velocity transition: role of particle crushing
- Low velocity transition: role of frictional resistance
- Effect of density, saturation, and nose shape identified
- Velocity field obtained, and zone of influence determined
- Kinematics of penetration described in terms of shear and volumetric strains
Questions?