Strain Effects on Impact Dynamics

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Introduction
Granular impacts have been studied for many years in the scientific community. Force laws have been characterized, including universal scaling relations (Katsuragi and Durian, *Nature Physics* 2007). Despite this, little is known regarding the microscopic origin of these observations. In other words: we know what the projectile is doing, but what are the grains doing?

Further, scaling relations have only been extensively studied for the same initial conditions: a stirred-up, loose packing. We expect that modifying the initial force network within a granular material will change its subsequent failure on impact.

We can vary the energy of the impact and we apply different (small) strains to the system by translating a wall prior to impact. We can characterize how linear strain affects the bulk impact dynamics of a spherical intruder into granular material. We can also look for corresponding signatures at the microscale, focusing on nonaffine plastic rearrangements.

Objective
• How does preparation of the pile affect bulk impact dynamics?
• What microscopic signatures make up the bulk response?

Experimental Setup

<table>
<thead>
<tr>
<th>Adjustable Wall ~100,000 Borosilicate Beads</th>
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<tbody>
<tr>
<td>Carbon Steel Impactor</td>
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<tr>
<td>Electromagnet</td>
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<tr>
<td>Light Sensitive High Speed Camera</td>
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<tr>
<td>Index-Matched* Fluid</td>
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<td>*Dimethyl Sulfoxide + water, fluorescent dye</td>
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To translate a wall, a magnet is used to move the impacting wall either a small amount.

Depth vs. Total Drop Height (Kerstin Nordstrom).

Beads immersed in low-viscosity fluid behave similarly to dry ensemble, as shown in blue.

**Nonaffine Motion**


**Nonaffine Motion:**
- Nonlinear transformation
- Plastic deformation

**Affine Motion:**
- Linear (matrix) transformation
- Includes local strain, dilation/compaction, rotation

\[
D_{\text{aff}} = \min \left\{ \sum_{j} \left[ \Delta d_j \left( t \right) - E \cdot \Delta d_j \left( t \right) \right] \right\}
\]

\( j = \text{particle in some neighborhood of } t \) (about 10-15 particles total)
\( d = \text{starting distance between } i \text{ and } j \)
\( \Delta d = \text{relative displacement between } i \text{ and } j \)

\( \Rightarrow D_{\text{nonaff}} = \text{strength of nonaffine motion} \)

Bulk Measurements

**Depth vs. Time**
Small amounts of strain cause significant decrease in final penetration depth.

**Particle Tracking**

Particle trajectories, created from particle tracking algorithms, show decreasing range of particle movement as strain increases.

**Velocity Flow Fields**

At the same penetration depth for a set drop height, velocity profiles show slower particle motion with increasing strain.

**Conclusions**

- Able to study 3D high speed impacts using index-matched imaging
- \( D_{\text{nonaff}} \) measure of nonaffine motion suggests creating force chains within the material creates more affine rearrangement
- Irreversible nature of plastic rearrangements, and the direction of gravity, suggests that where more plastic rearrangements occur, the impact should be deeper.