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Dynamic Behavior of Fine Sand

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TCG-XI Review
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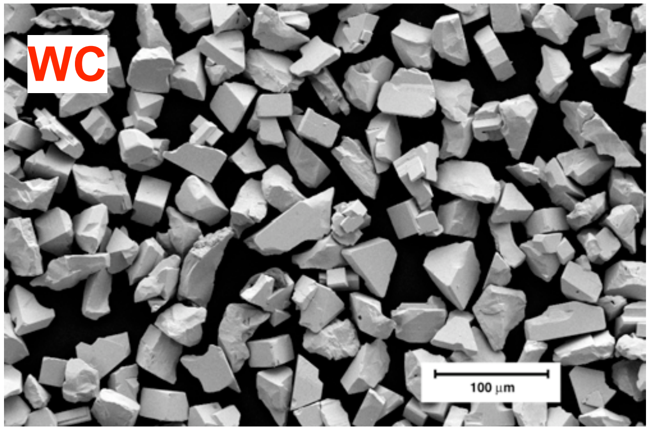
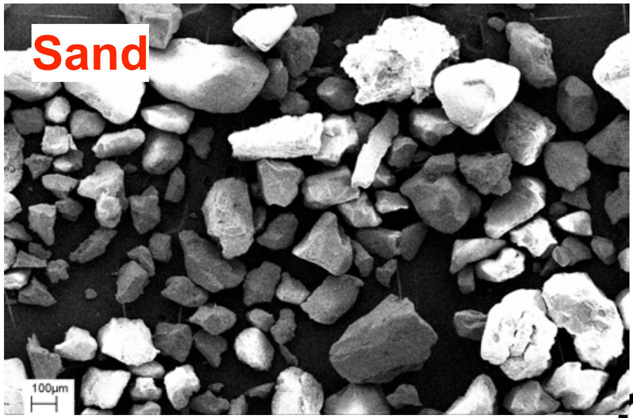
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

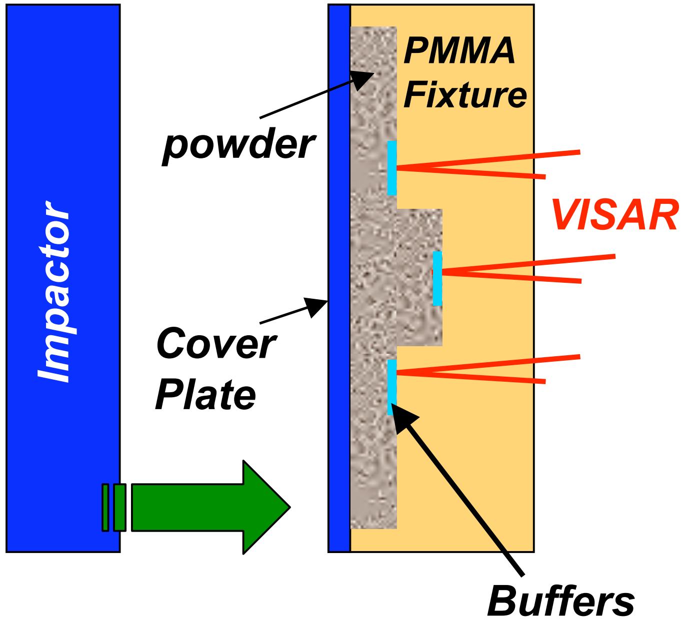
Background

- investigate dynamic compaction behavior of sand leveraging DOE program on granular ceramics
- develop insight into physics of dynamic behavior of these materials and the parameters that influence it
- explore a variety of techniques (quasi-static experiments, mesoscale simulations, etc.) to predict dynamic results
- determine suitability of current models within Sandia codes for simulating dynamic behavior of powders





Planar Impact Experiments on Granular Materials



multiple sample thicknesses on the same experiment for accurate shock velocity and uniform powder density; VISAR allows check for uniformity and steadiness

Vogler, T.J., Lee, M.Y., Grady, D.E., 2007. "Static and dynamic compaction of ceramic powders." *International Journal of Solids and Structures* **44**, 636-658.

Brown, J.L., Thornhill, T.F., Reinhart, W.D., Chhabildas,L.C., Vogler, T.J., 2007. "Shock response of dry sand." in Shock Compression of Condensed Matter – 2007, American Institue of Physics, 1363-1366.

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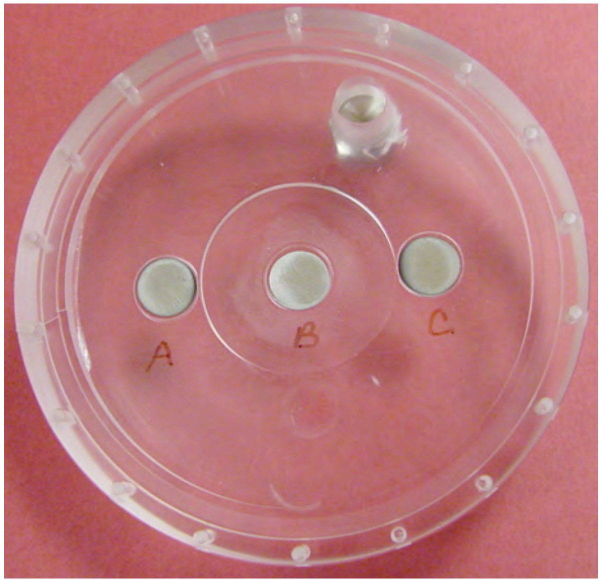
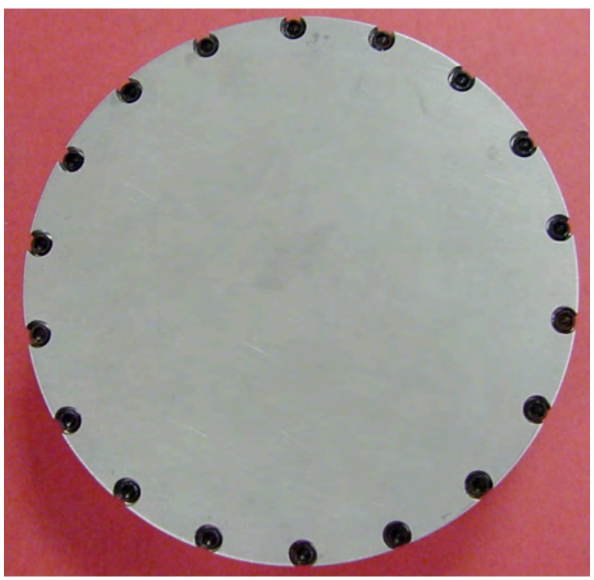
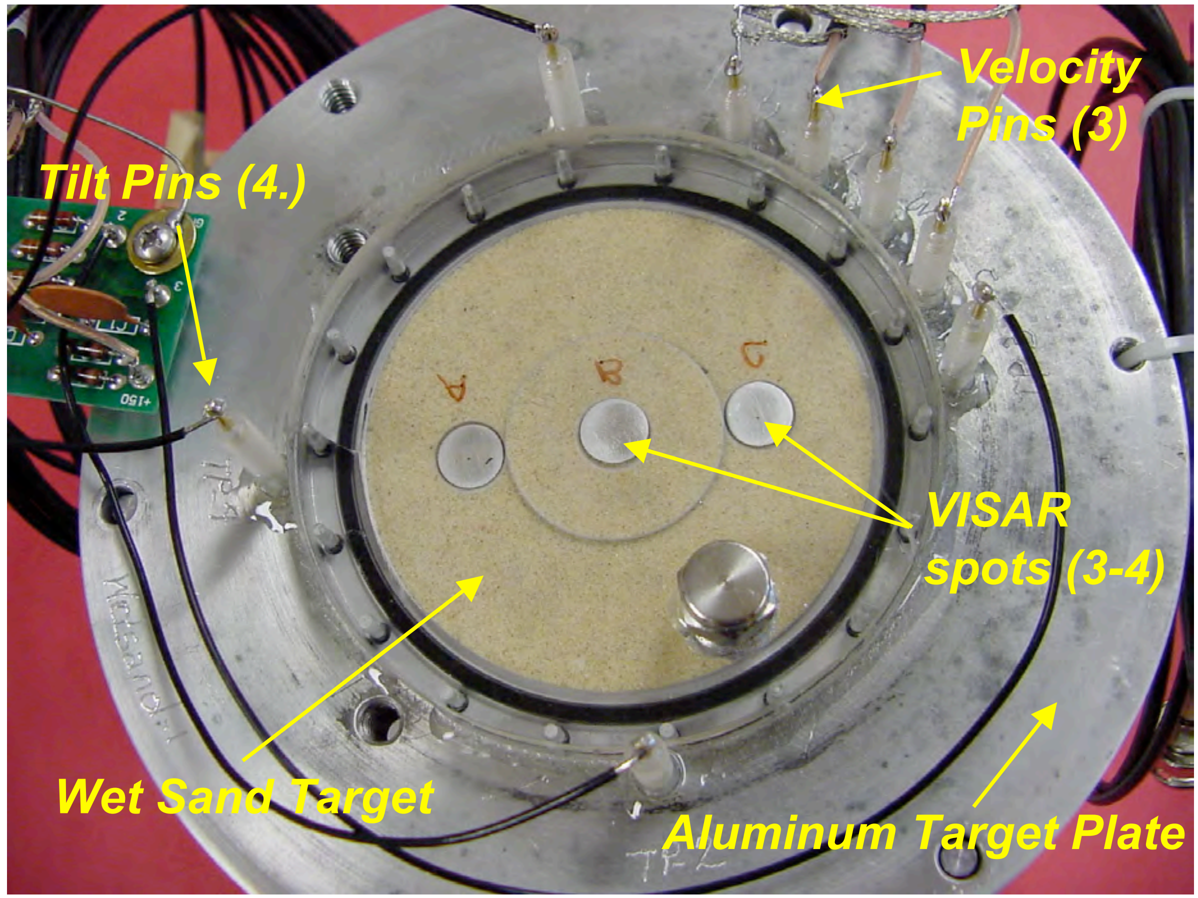
Wet Sand Targets







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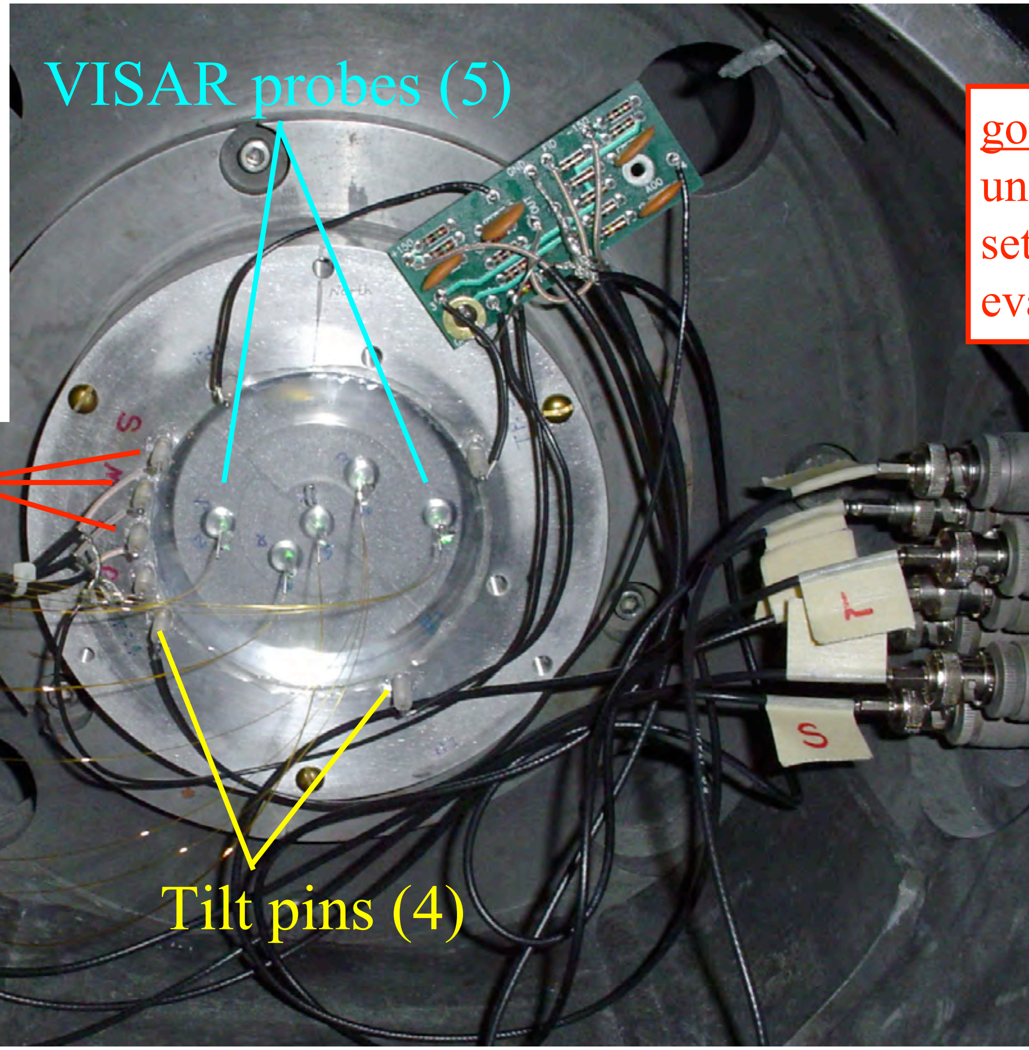
Target Mounted in Gas Gun

Single Stage Gun 100mm



<u>gotcha's:</u>
uniformity
settling
evacuation

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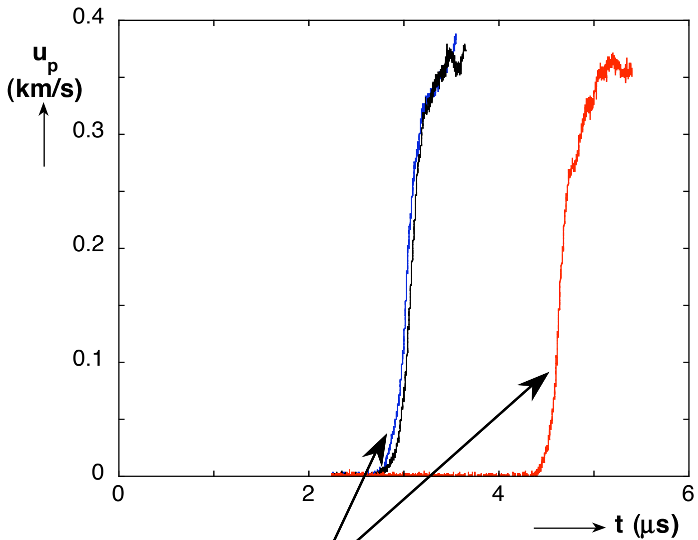
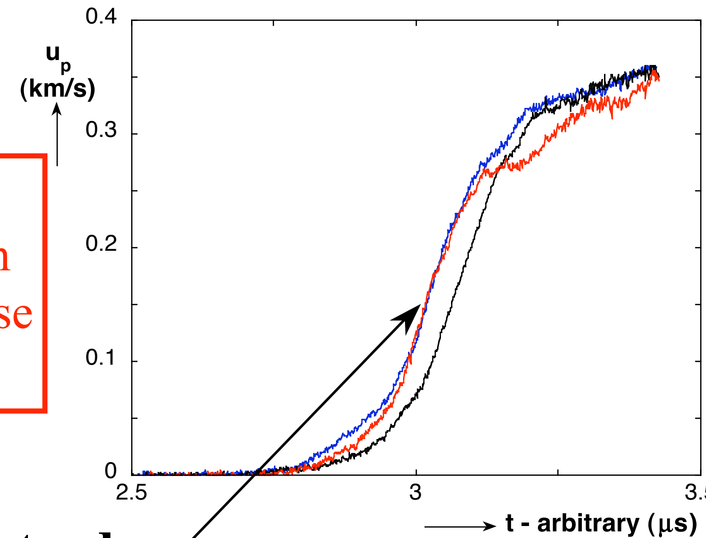
Measured Steady Waves



gotcha's:
attenuation
edge release
steadiness



shock velocity calculated based on powder thicknesses and arrival times

steady, structured waves

- since waves are steady, Rankine-Hugoniot jump conditions can be used even though waves have finite rise times

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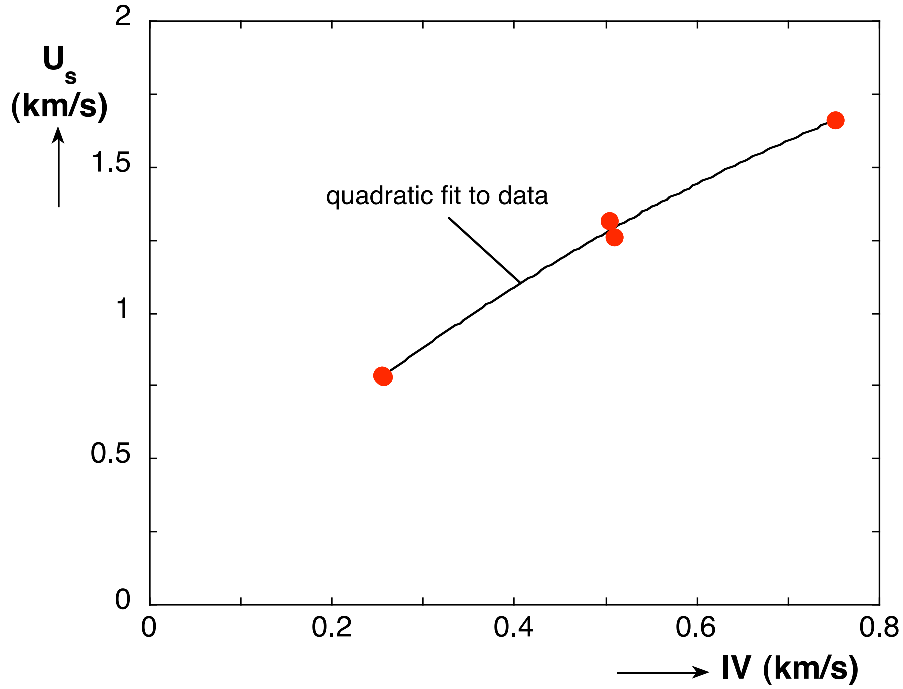
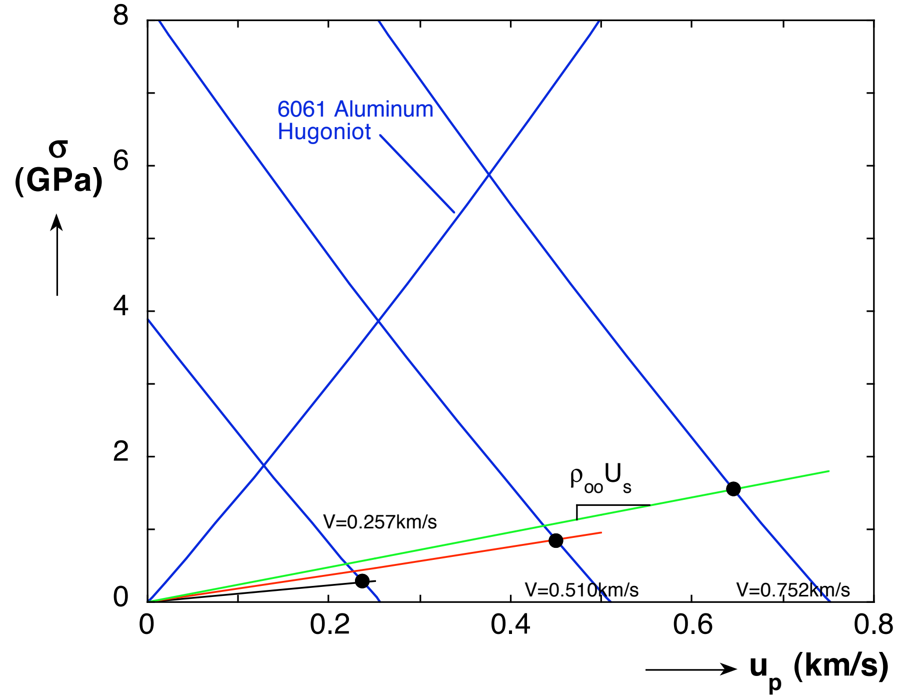
Shock Velocities and Hugoniot States

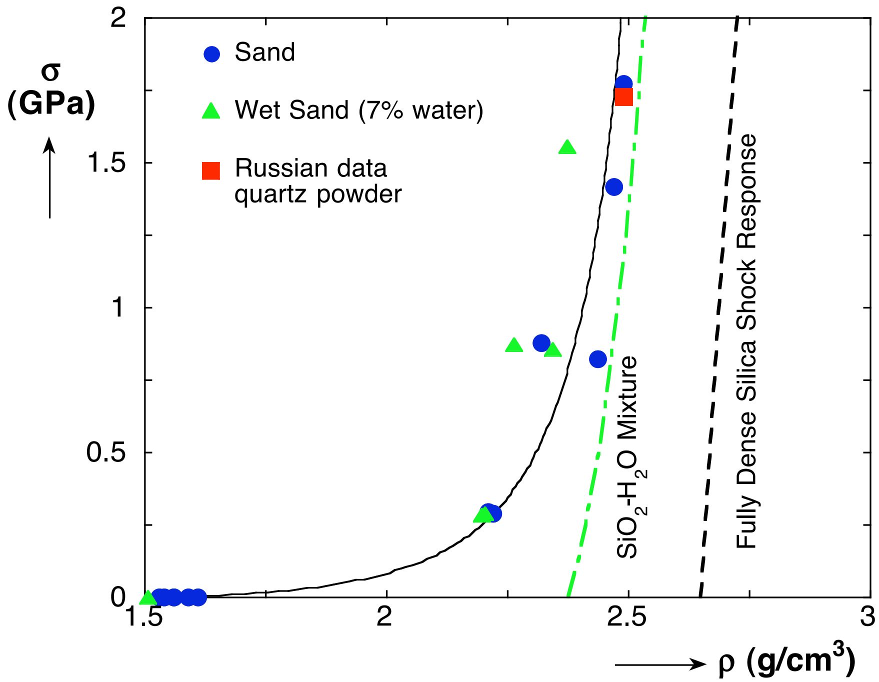


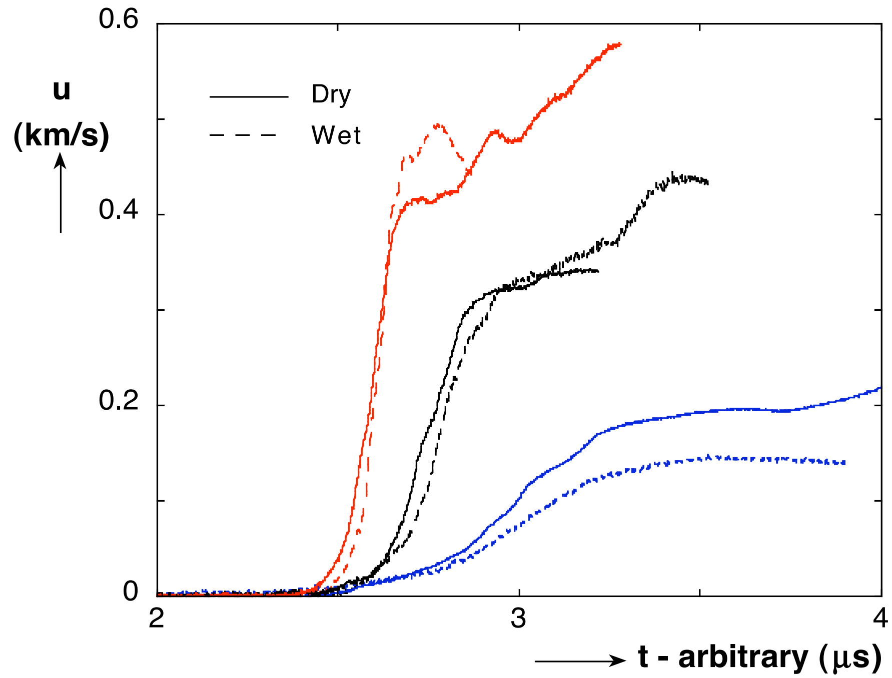


- impedance matching to aluminum impactor used to determine Hugoniot stress and particle velocity ($\sigma = \rho_o U_s u_p$)
- density then calculated from $\rho = \rho_o U_s/(U_s - u_p)$

Experimental Results

shock data for wet and dry sand





small differences in wave profiles between wet and dry sand

14% moisture will be shot soon

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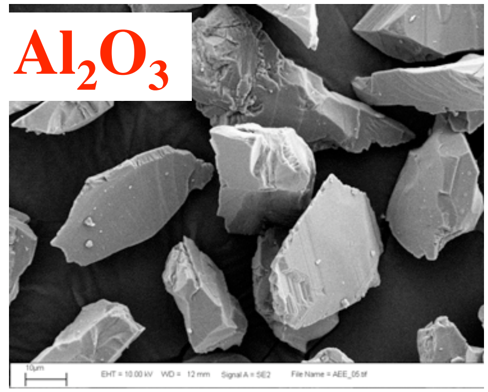
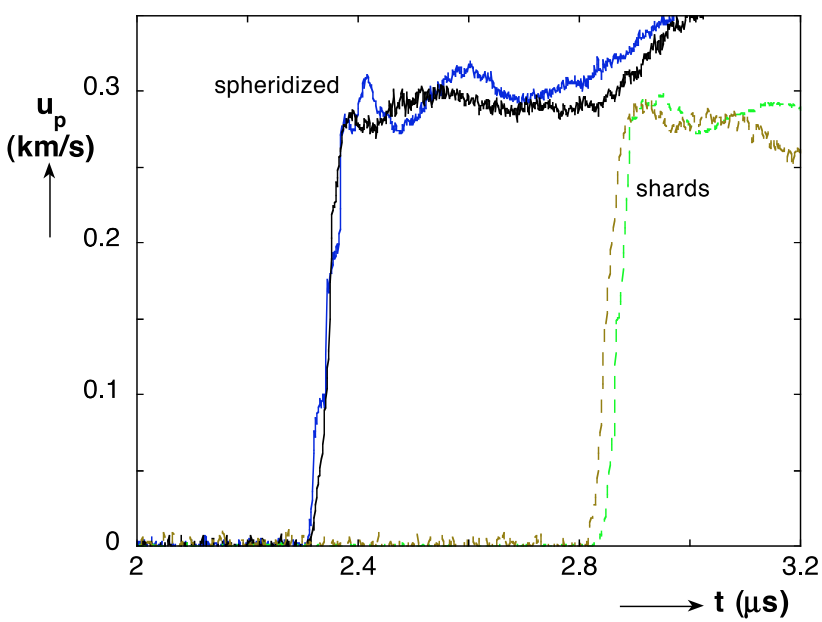
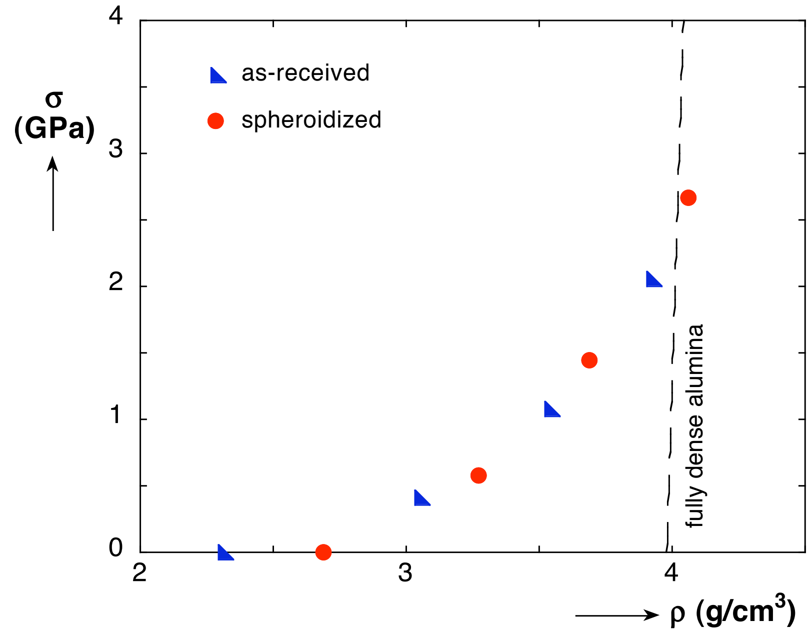
Effect of Particle Morphology

plasma processing used to create spheres, changing particle morphology



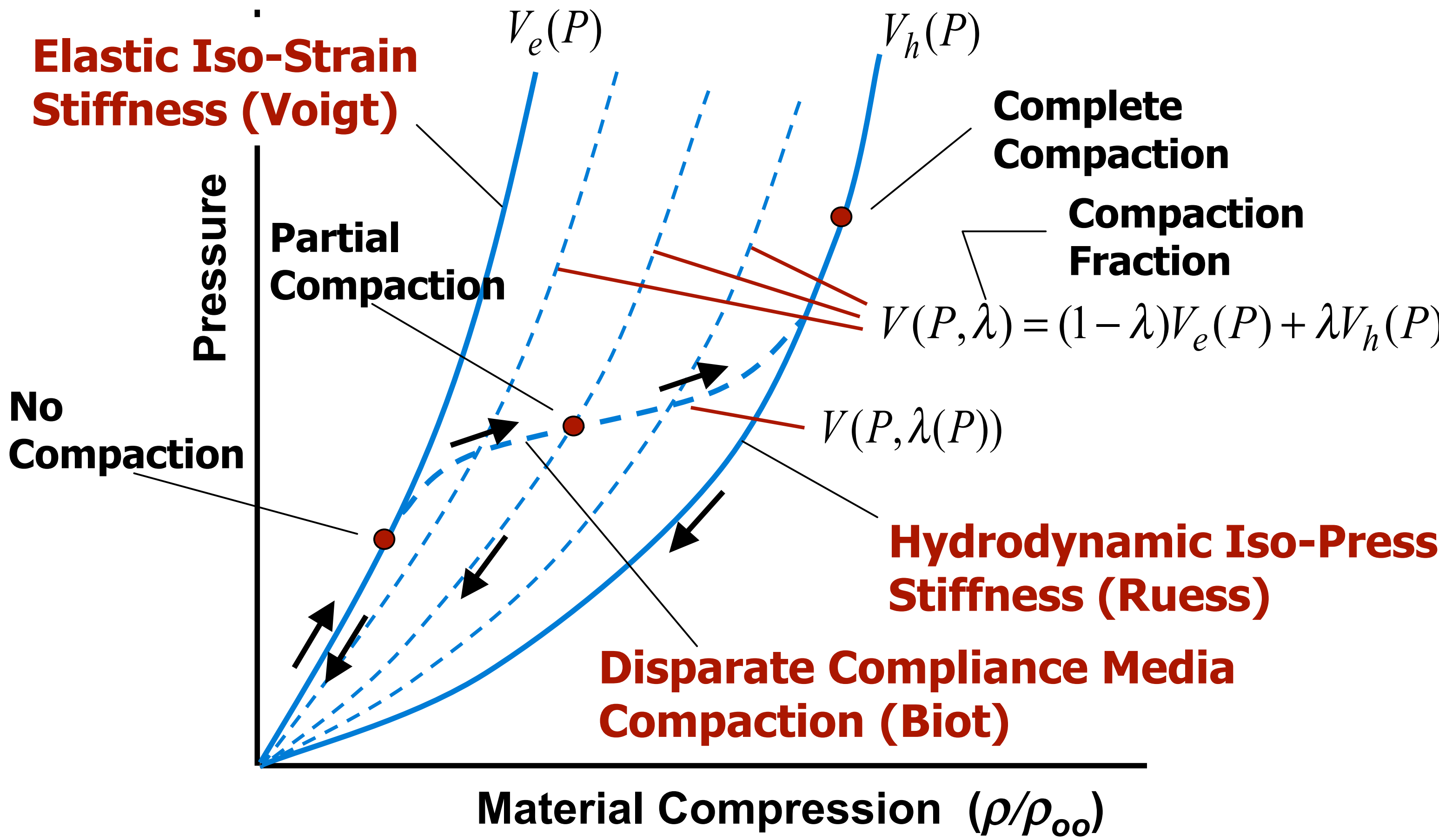




results are insensitive to particle morphology and grain size distribution

Continuum P-λ Model

more flexible variation on P-α developed by Grady *et al.*; allows multiple materials but maintains simplicity of P-α model



Grady, D.E., 2007. "Shock wave compression of ceramics with microstructures." *International Journal of Plasticity* (in press).

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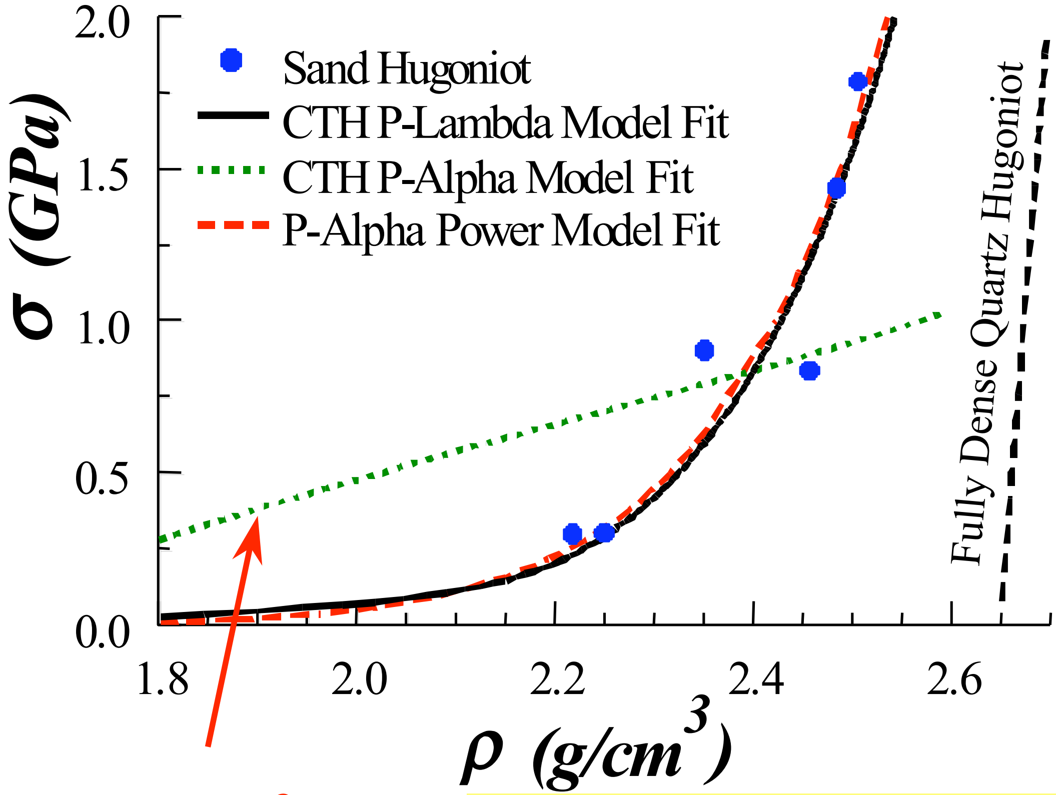
Continuum Model (P-α and P-λ) Calibration for Sand



current P-α form in CTH incorrect

P-λ model

$$\alpha = \rho_M / \rho$$

CTH form

$$\alpha(p) = 1 + (\alpha_0 - 1)\left(\frac{p_s - p}{p_s - p_e}\right)^n$$

alternate form

$$p(\alpha) = p_s \alpha^{-\eta}$$

P-λ model

$$v_m(p) = \lambda v_R(p) + (1-\lambda) v_V(p)$$

$$\lambda = 1 - e^{-\left(p/p_c\right)^n}$$

modification of P-a to correct fuctional form underway

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Mesoscale Modeling of Granular Materials

- follow approach of Benson et al. for 2-D simulations
- particles idealized as circles (rods) for initial work
- constant velocity boundary condition applied
- run in CTH (explicit Eulerian finite difference code)
- Mie-Gruneisen EOS, elastic-perfectly plastic strength for powder

Borg, J.P., Vogler, T.J., (2008). "Mesoscale calculations of the dynamic behavior of a granular ceramic." *International Journal of Solids and Structures* **45**, 1676-1976.

Borg, J.P., and Vogler, T.J. (2008). "Mesoscale simulations of a dart penetrating sand," *Int. J. Impact Eng*. (in press).

Borg, J.P., and Vogler, T.J. (2007). "Mesoscale calculations of shock loaded granular ceramics," in Shock Compression of Condensed Matter – 2007, American Institue of Physics, 227-230.

get at underlying physics of granular materials

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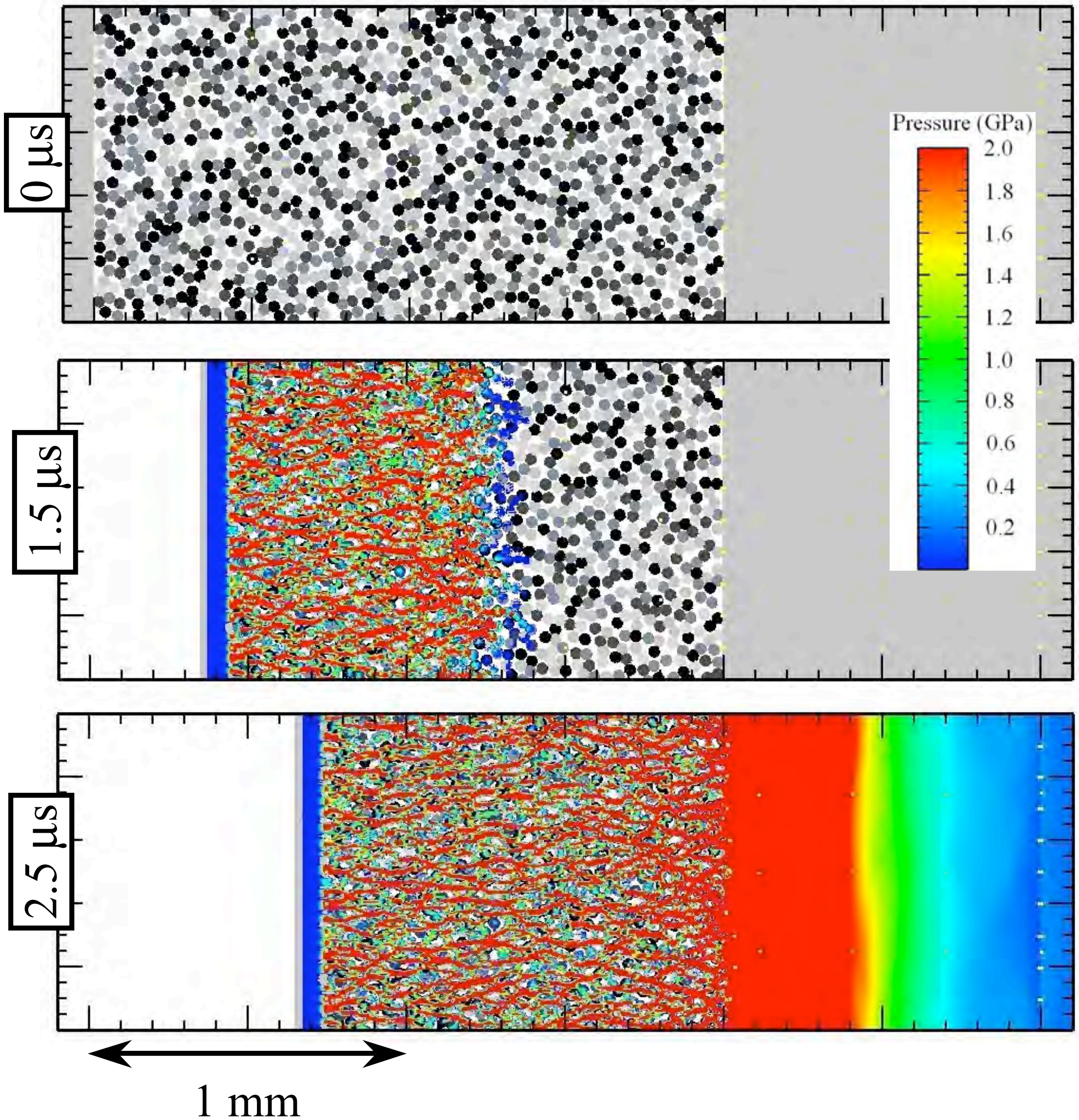
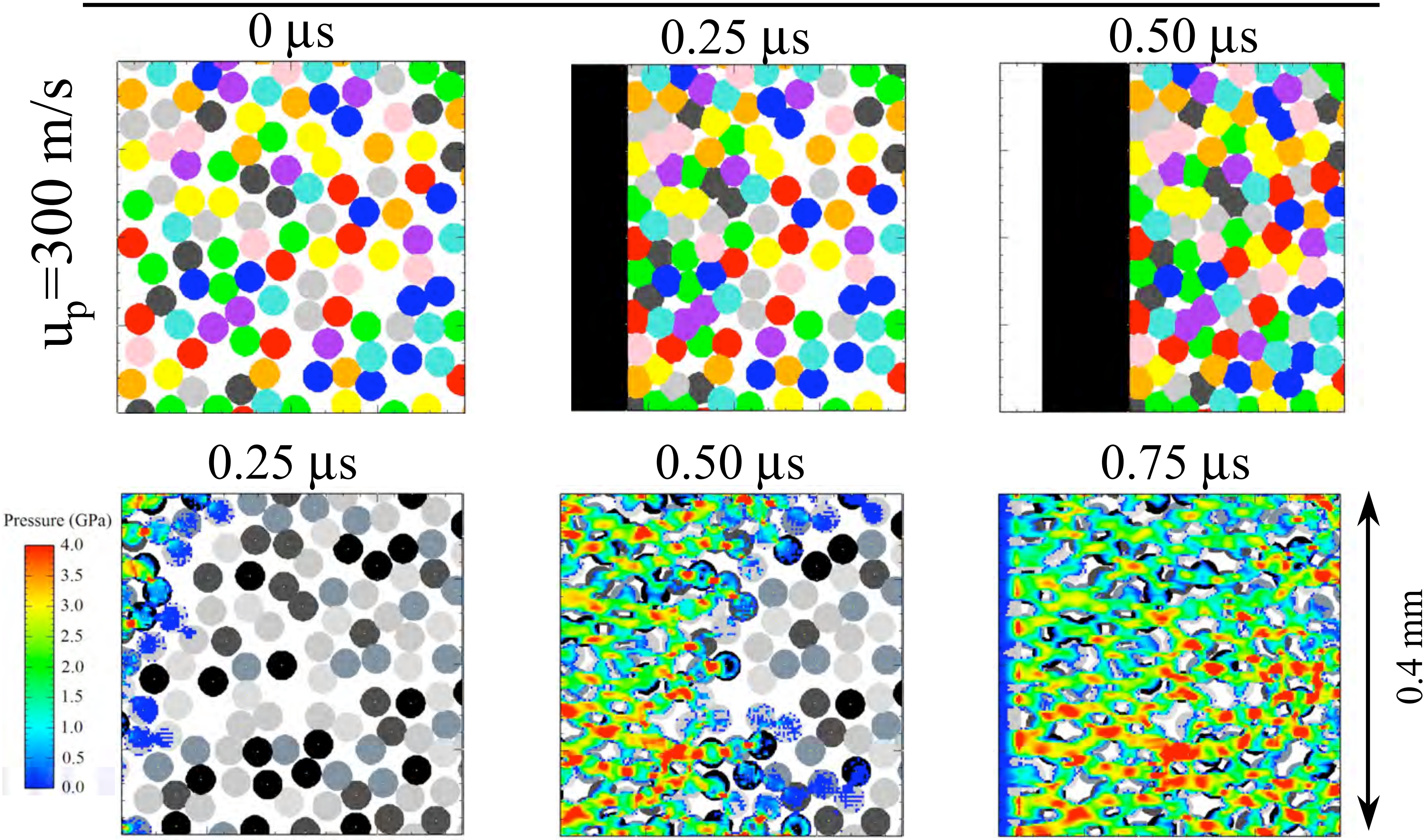
Computational Dynamic Compaction



- driver plate velocity u_p=300 m/s
- shock thickness on the order of ~2-5 particles
- strong force chains observed
- wave smooths in buffer

Close-Up of Compaction Process



no jetting or vortices so deformation is "*quasi-static*"
(Benson et al., 1997)

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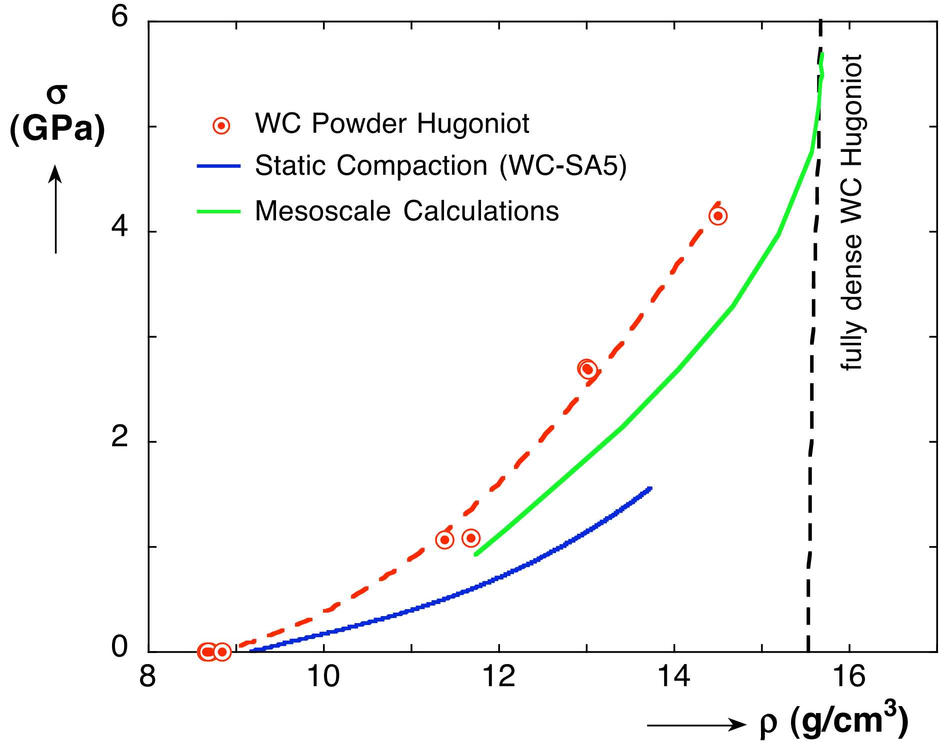
Calculated Hugoniot from Literature Parameters



$$\sigma = \rho_o U_s u_p$$

$$\rho = \rho_o \frac{U_s}{U_s - u_p}$$

- simulations provide reasonable estimate for Hugoniot
- shortcomings of model:
  - missing physics of granular contact and fracture
  - wrong connectivity in 2-D
  - spherical particles unrealistic
  - inaccurate strength for small particles

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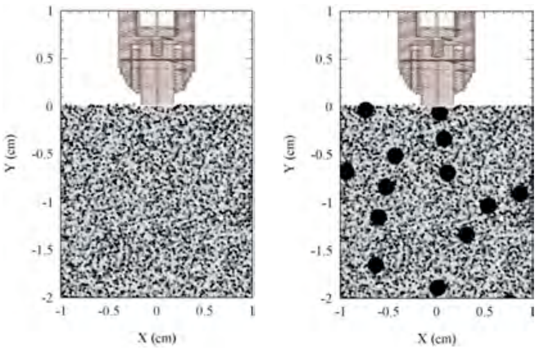
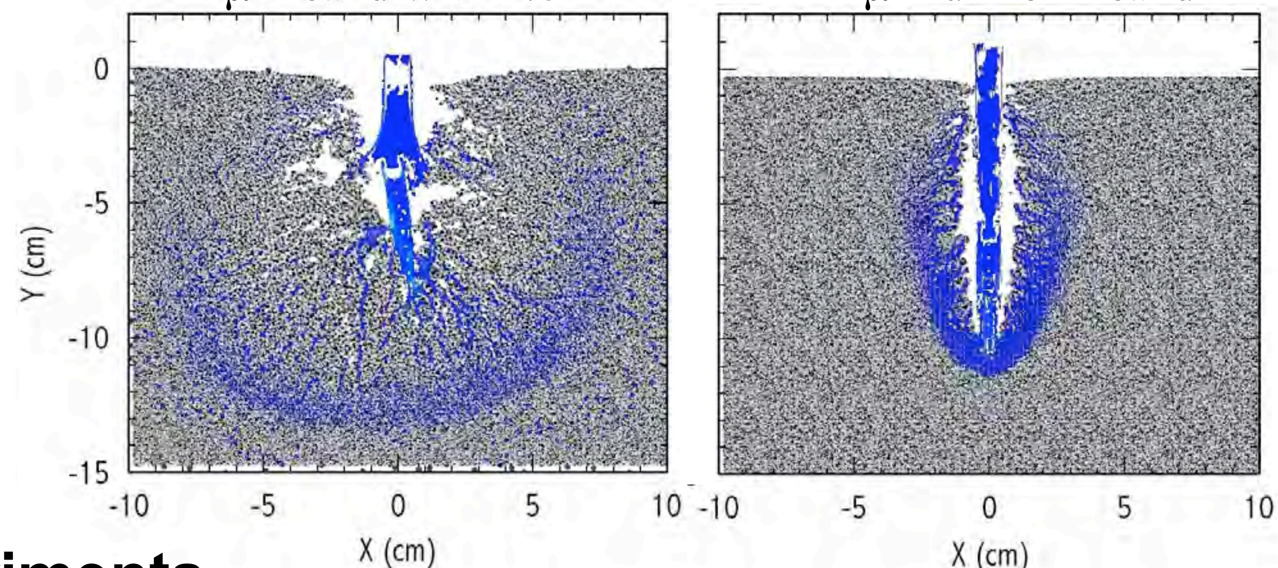
“System Level” Work
providing insight into nonuniform targets

Borg and Vogler, Int. J. Impact Engineering (in press)

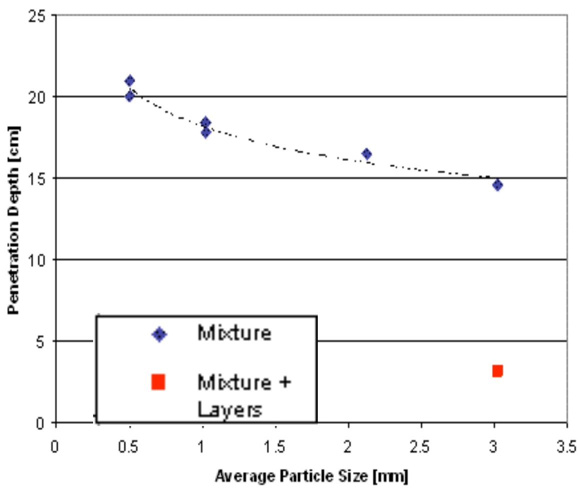


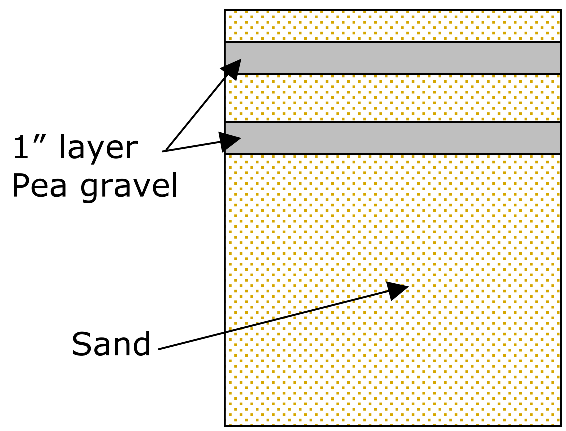
224 µm sand with 1.6 mm

224 µm uniform sand



small-scale experiments





mesoscale simulations in progress to understand deflection mechanism

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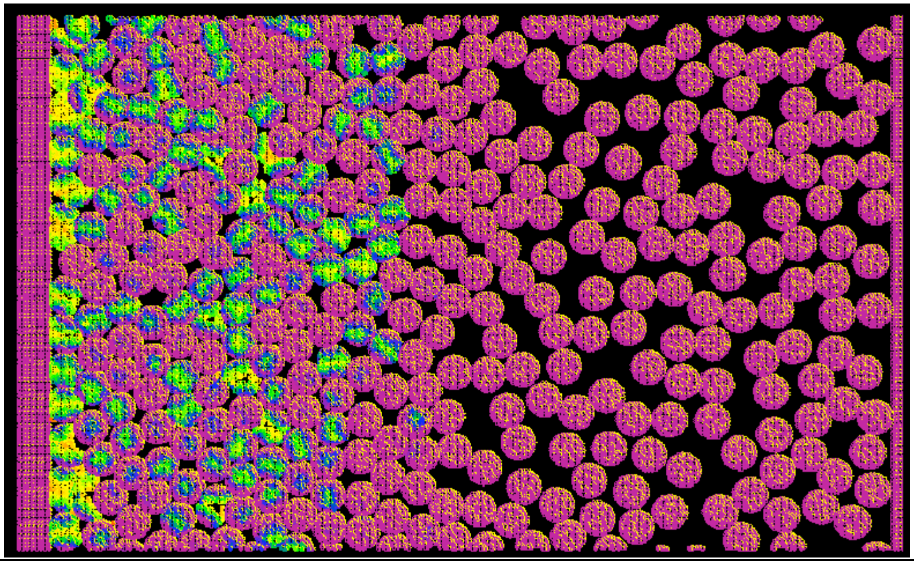
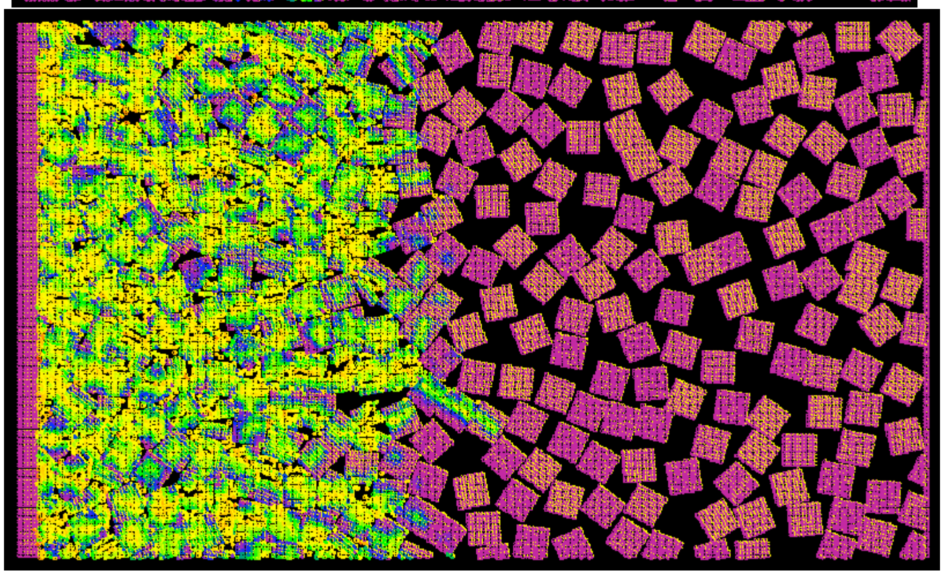
Initial Mesoscale Calculations with Peridynamics





- non-local method based on reformulation of governing equations in integral form (Silling, 2000)
- includes fracture and contact missing from CTH
- behavior somewhat different than for CTH
- response insensitive to particle shape despite large differences in particle fracture

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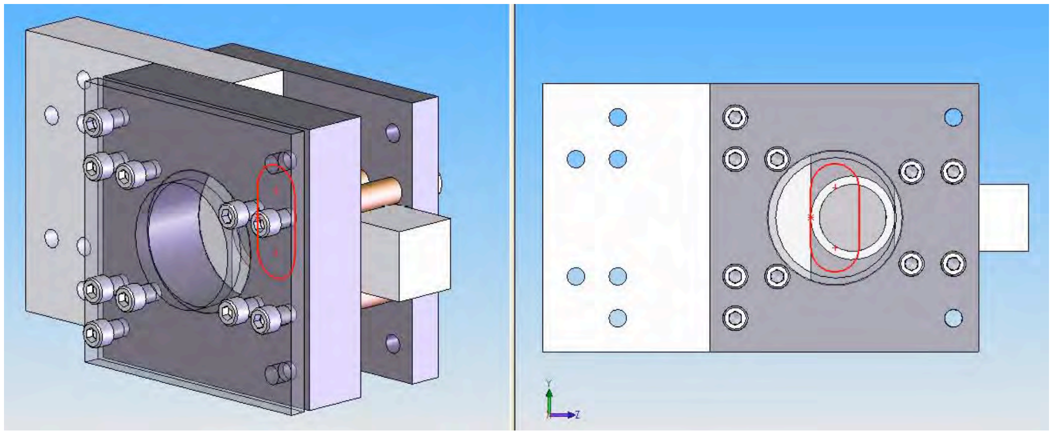
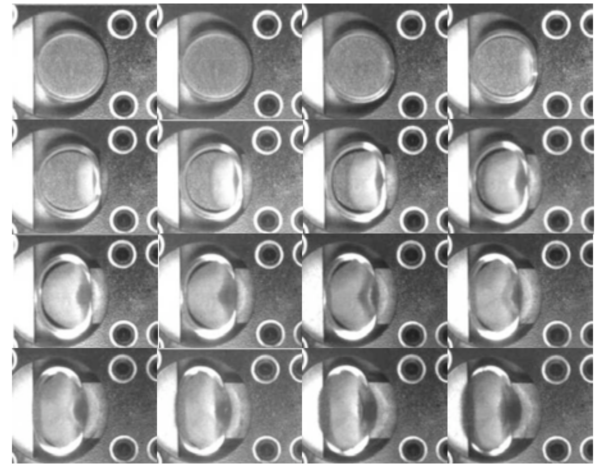
Dynamic Validation Experiments:
necessary to build confidence in models

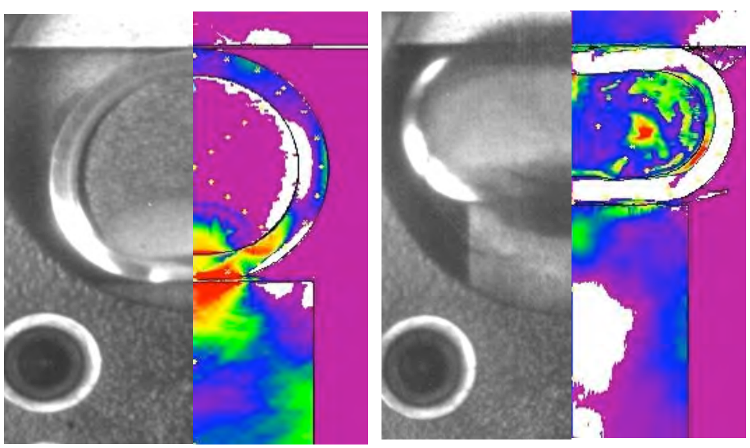
ring compaction experiments provide data for non-planar deformation

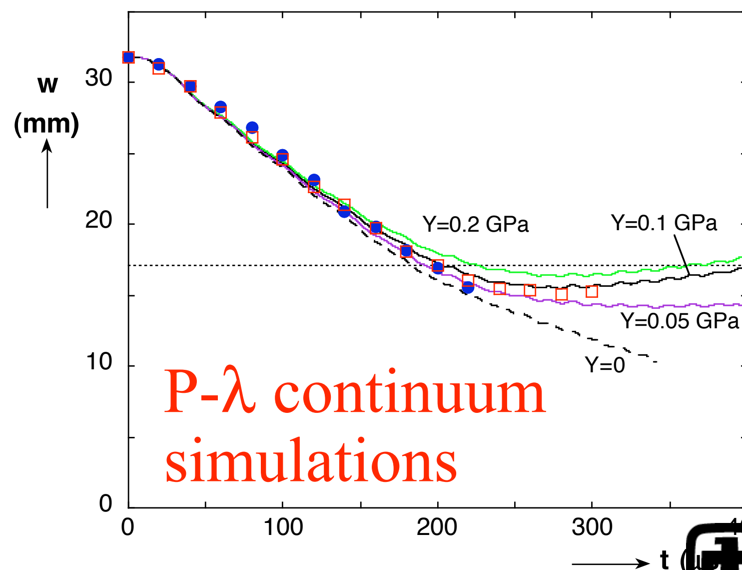




10 µs interframe time

2-D CTH continuum calculation





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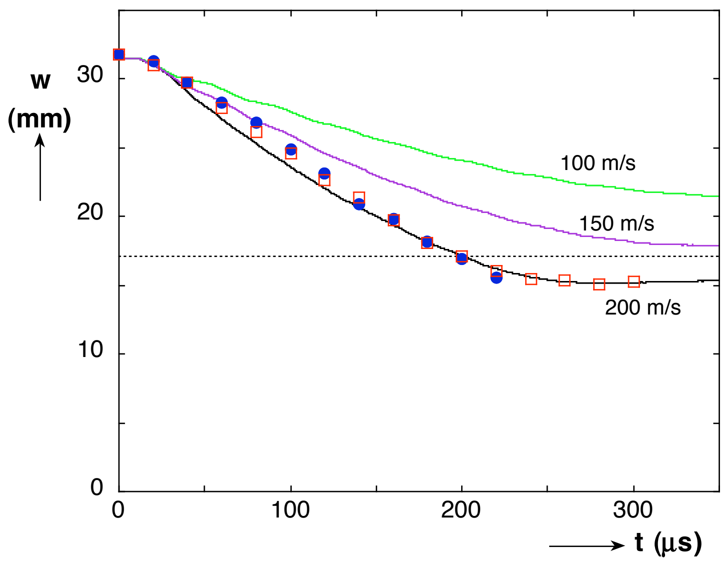
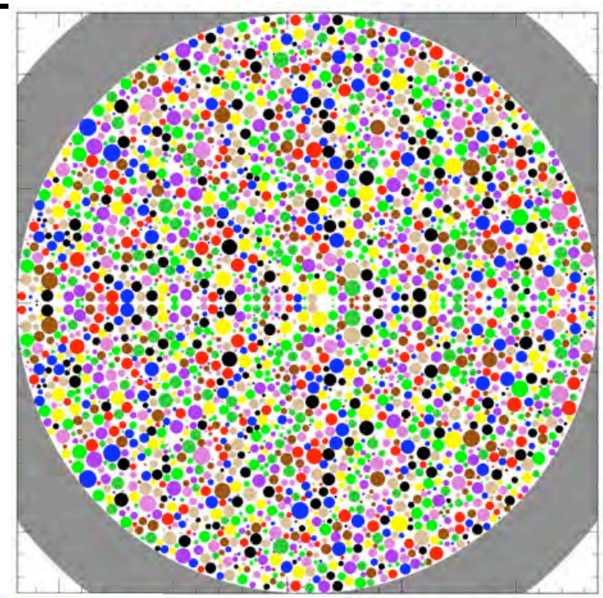
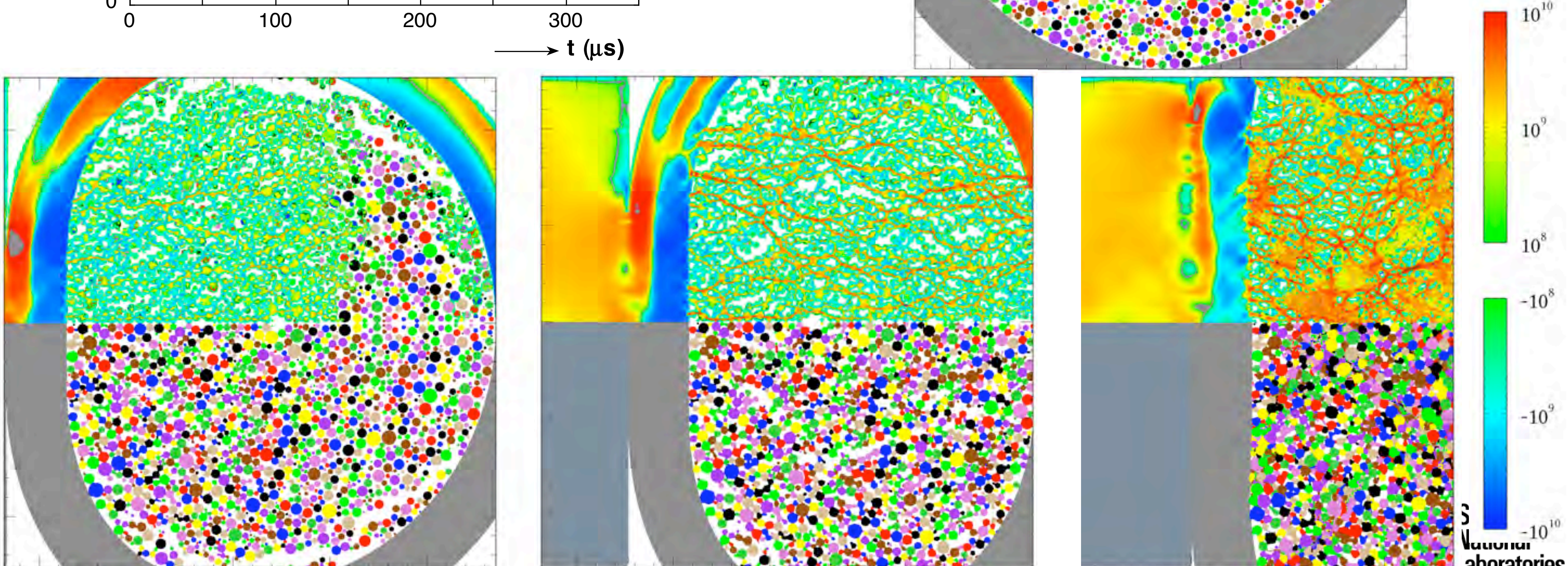
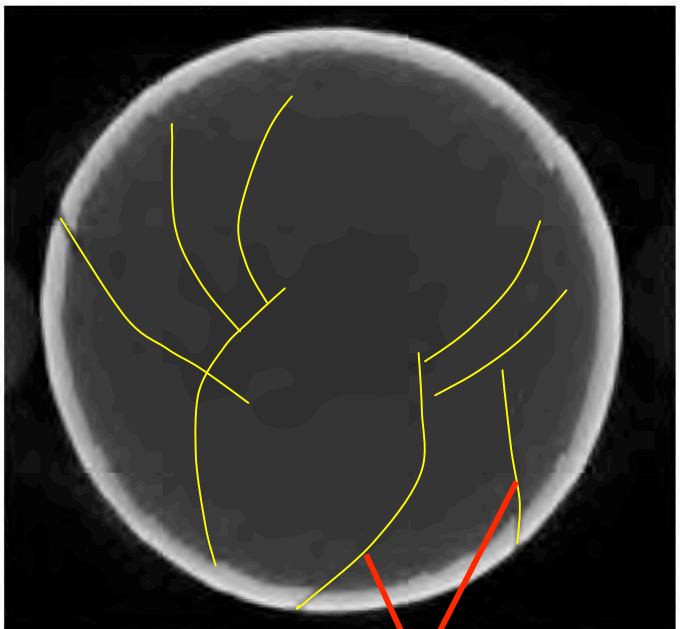
Mesoscale Simulations of Rings



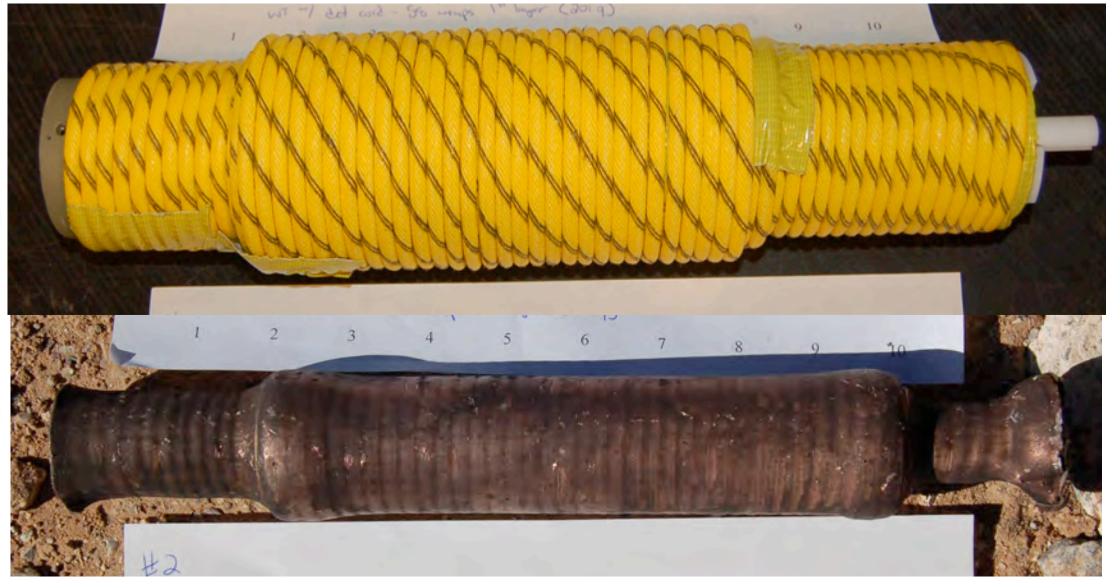




Validation Experiments: Explosively Loaded Cylinder



compaction bands



- explosively compacted cylinders to allow comparison with simulations and analytic solutions
- more difficult than expected; also late time effects
- tomographic analysis of compaction difficult and reveals localizations

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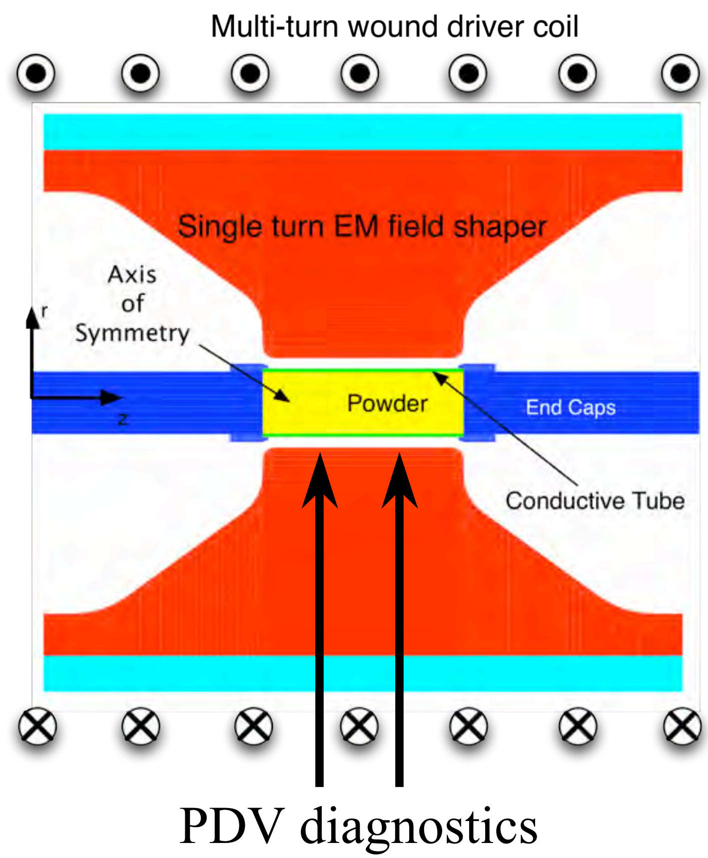
Magnetically Driven Cylindrical Compaction

in collaboration with G. Daehn (Ohio State Univ.) and G. Fenton (ARA)



will provide high-quality dynamic measurements
in a simple (but non-planar) configuration

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Summary and Future Work

- constructed capsule for wet sand experiments; completed planar impact tests on 7% wet sand; tests on 14% underway
- provided calibration of P-α and P-λ models for dry sand (modification to P-α underway)
- particle morphology appears relatively unimportant
- particle fracture does not appear to be important
- layered or nonuniform targets may have significant effects

Future Work

- planar impact tests for clayey sand
- validation experiments (additional ring crush and magnetically-driven compaction); continuum and mesoscale modeling
- additional study of morphology effects
- extend mesoscale simulations to 3-D

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