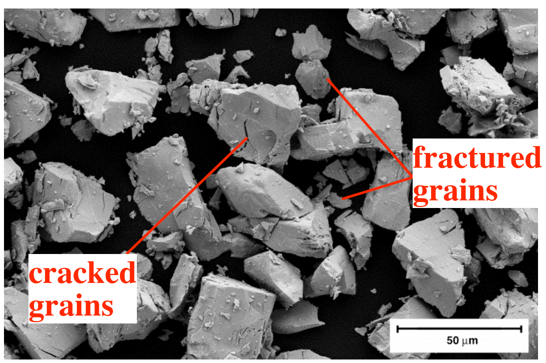
SAND2008-1598P

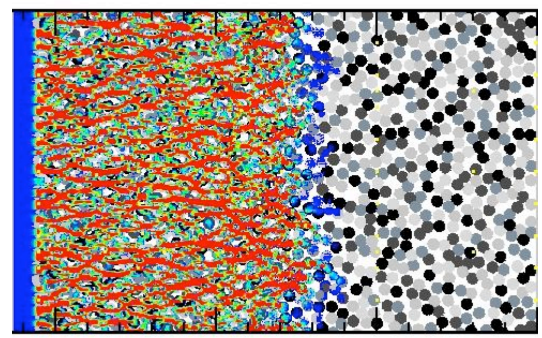
Dynamic Behavior of Granular Ceramics

Tracy Vogler
Solid Dynamics and Energetic Materials Dept.
Sandia National Laboratories

Project Team:
J.P. Borg, D. Sandoval, K. Lappo, T.F. Thornhill, J. Brown, C.S. Alexander, W.D. Reinhart, D.E. Grady, L.C. Chhabildas

AFOSR Workshop on Particulate Mechanics in Extreme Environments
Eglin AFB
January 29-31, 2008





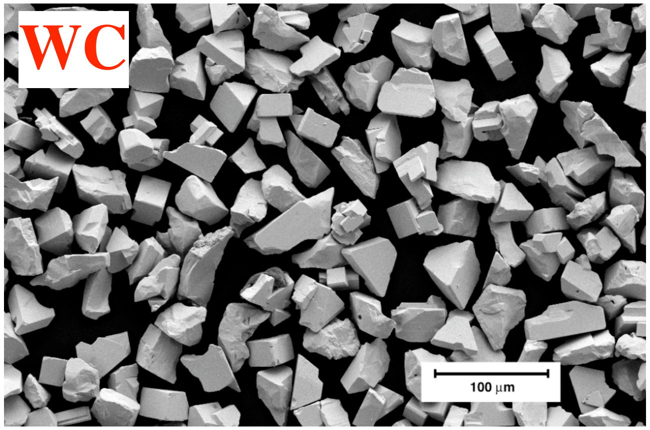
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

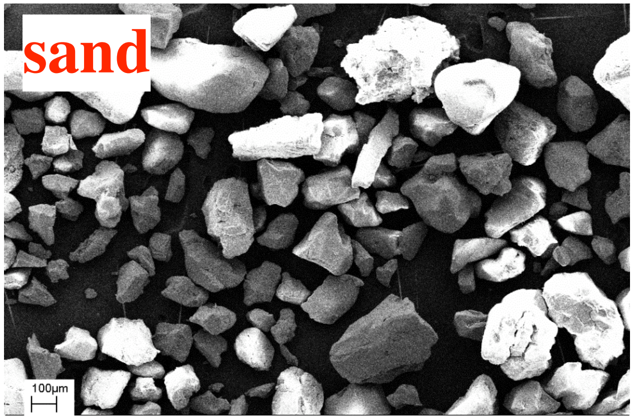
National Nuclear Security Administration

Sandia National Laboratories

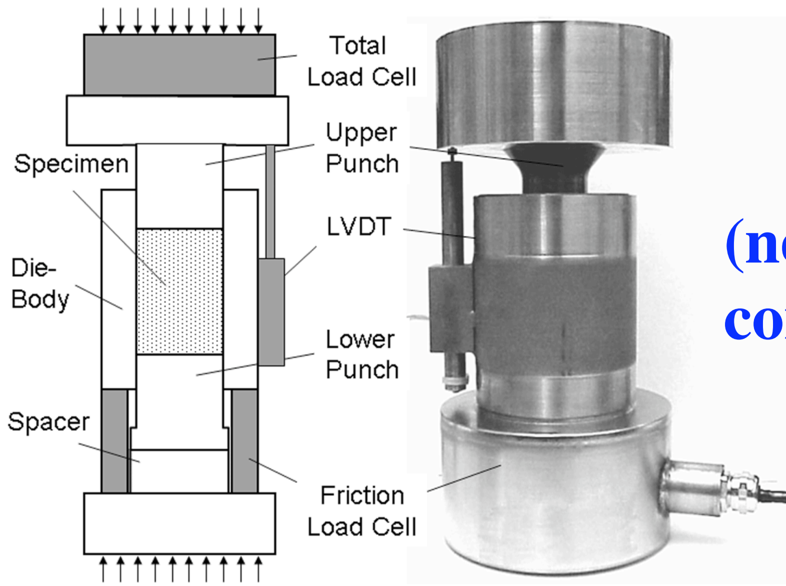
Investigation of Dynamic Behavior of Granular Ceramics

- investigate dynamic compaction behavior of ceramic powders (WC, sand, Al_2O_3, etc.)
- 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





Static Die Compaction Experiments



(nearly) uniaxial strain compaction to ~1.6 GPa

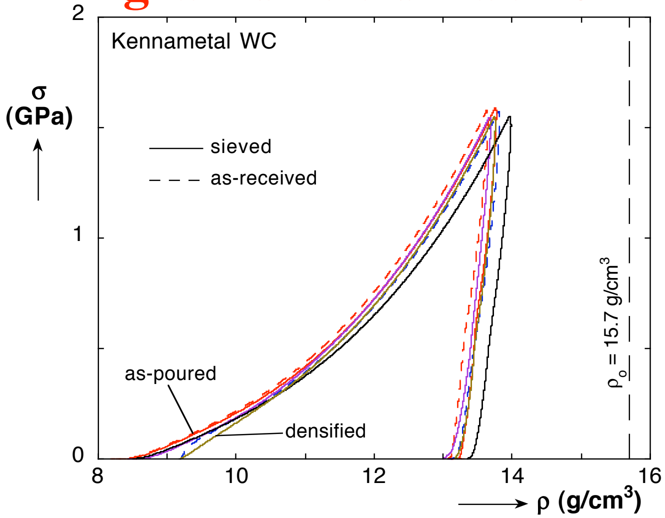
Objectives

- Determine compaction curve functional form
- Examine effects of experimental parameters (grain size, grain size distribution, grain shape, initial density, loading path, etc.)
- Correlate with dynamic results

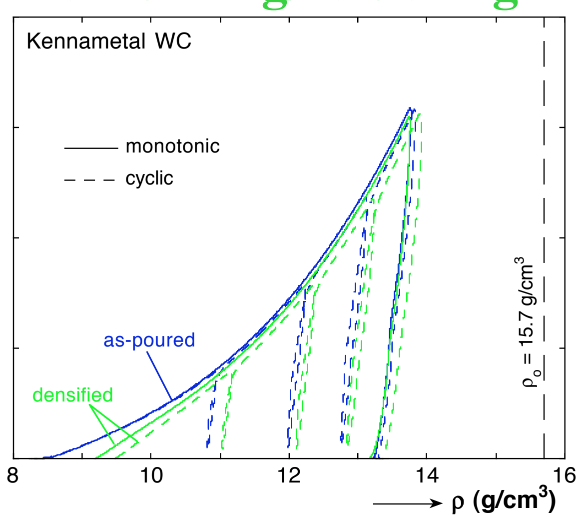
Static Compaction Results

evaluate effects of important variables on loading response

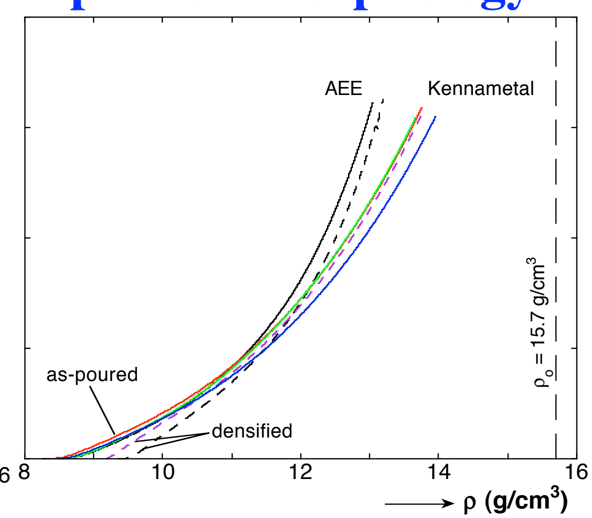
grain size distribution



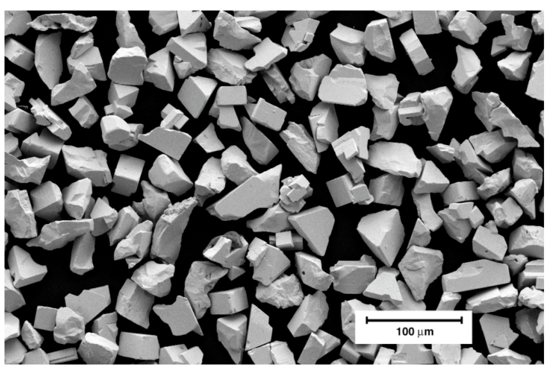
unloading/reloading



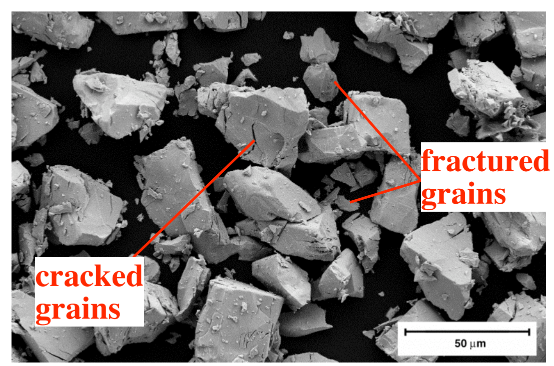
particle morphology



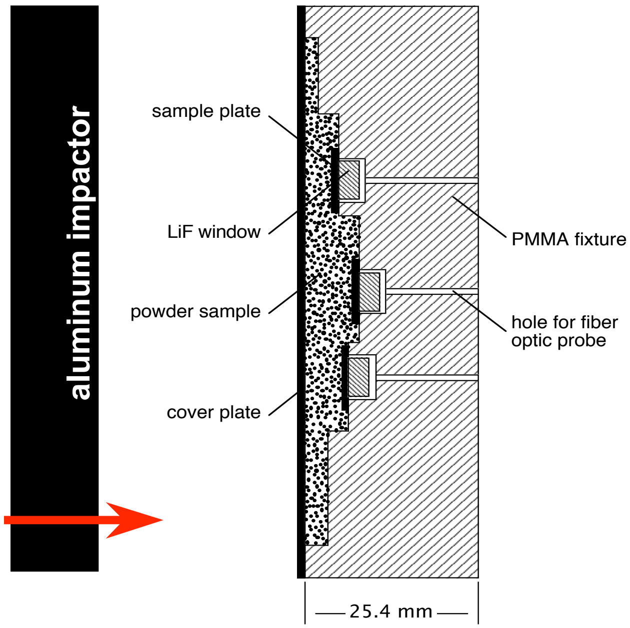
pre-compaction

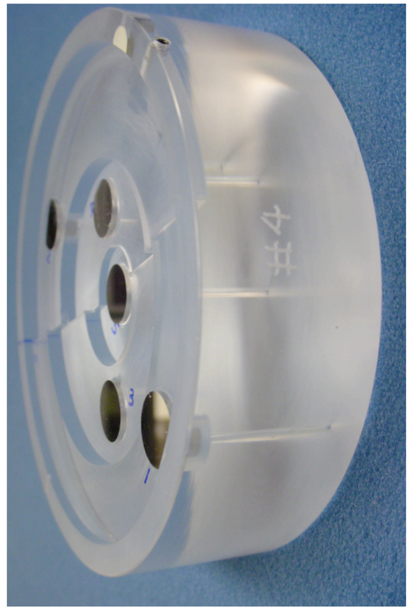


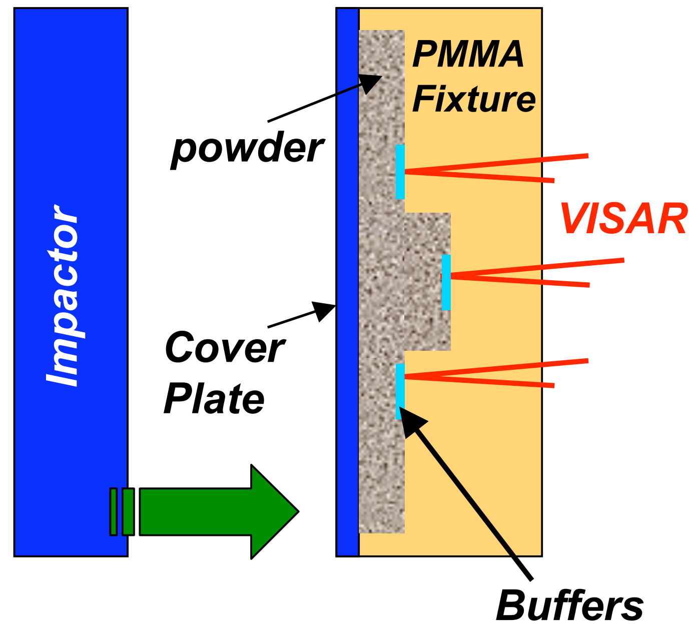
post-compaction



Planar Impact Experiments on Granular Materials





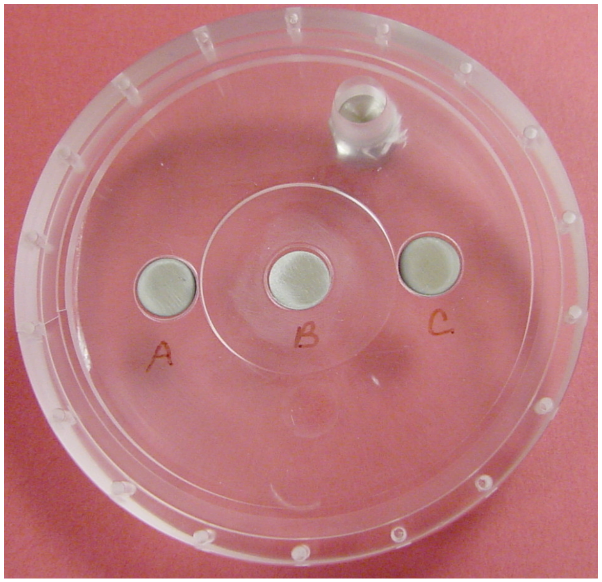


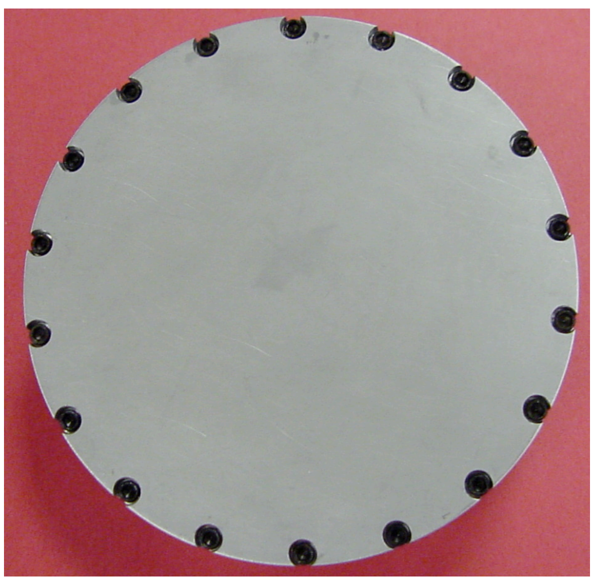
multiple sample thicknesses on the same experiment for accurate shock velocity and uniform powder density; sealed capsule allows fluid / powder mixtures

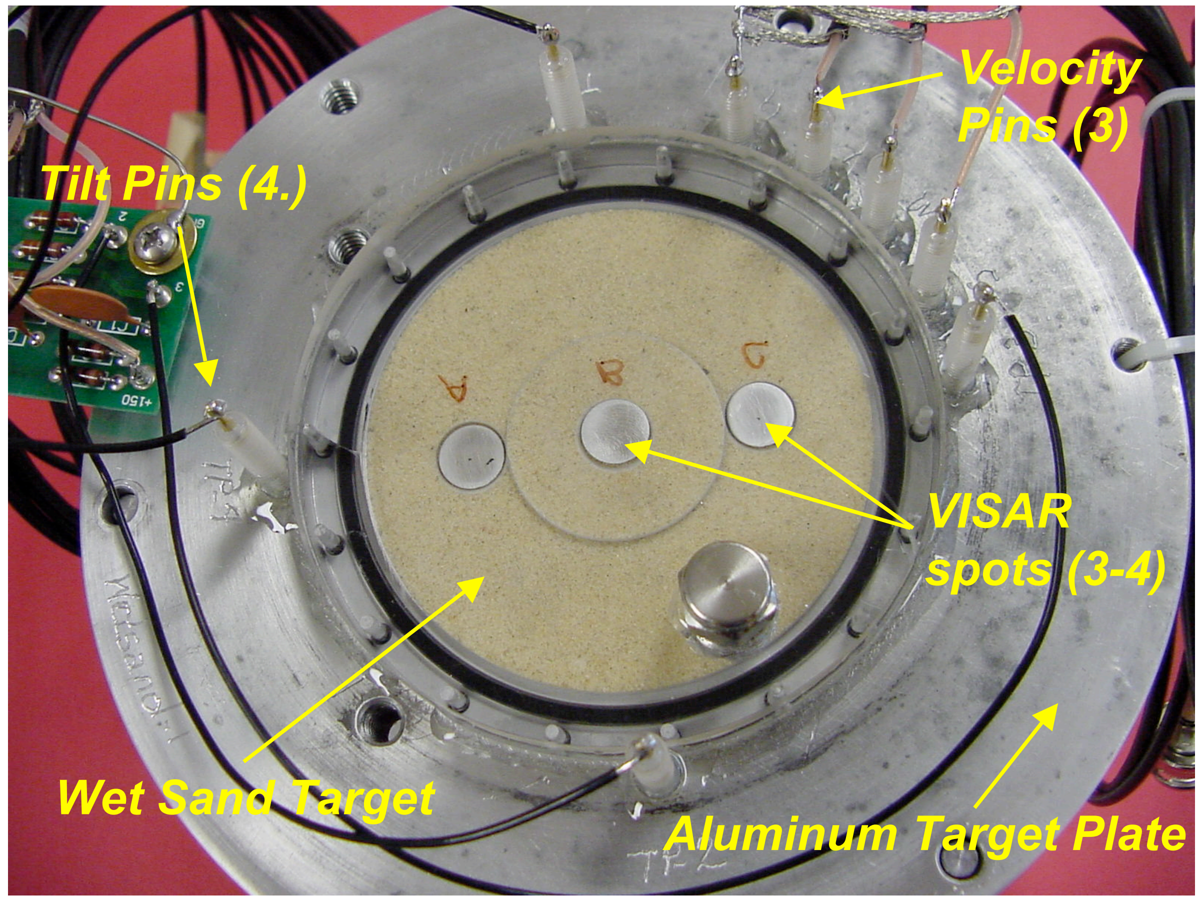
Vogler, T.J., Lee, M.Y., Grady, D.E., 2007. "Static and dynamic compaction of ceramic powders." *International Journal of Solids and Structures* **44**, 636-658.

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.

Wet Sand Targets

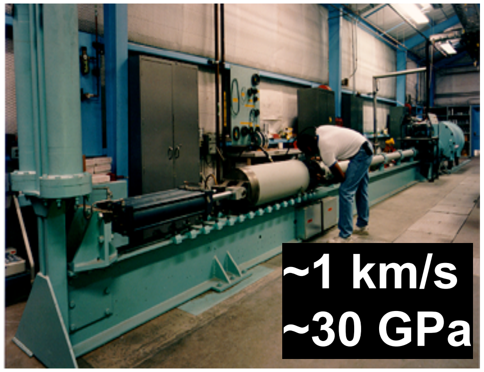


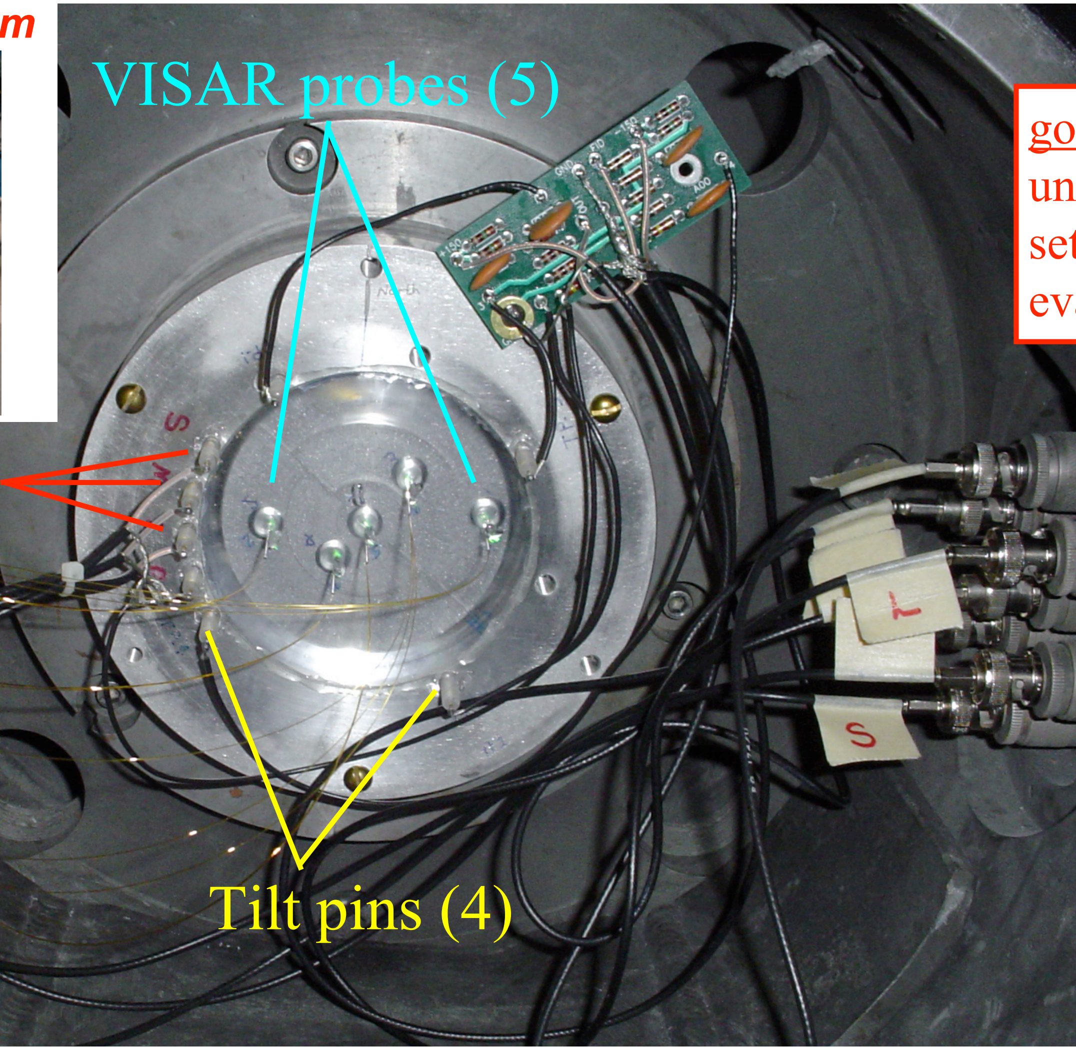




Target Mounted in Gas Gun

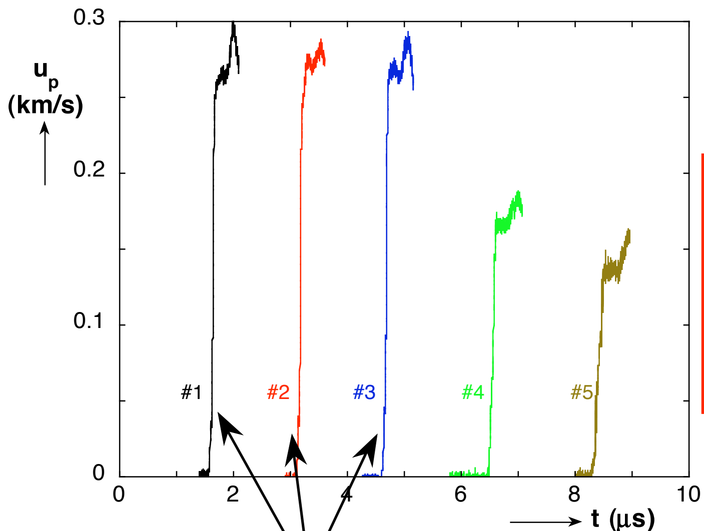
Single Stage Gun 100mm



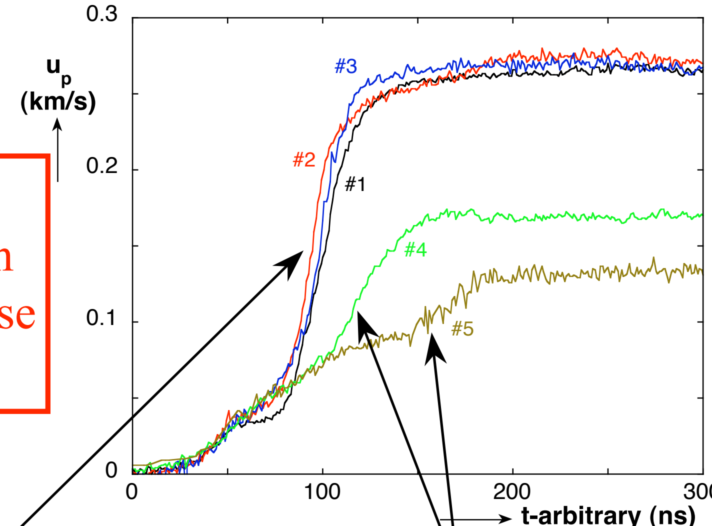


<u>gotcha's:</u>
uniformity
settling
evacuation

Measured Steady Waves



gotcha's:
attenuation
edge release
steadiness



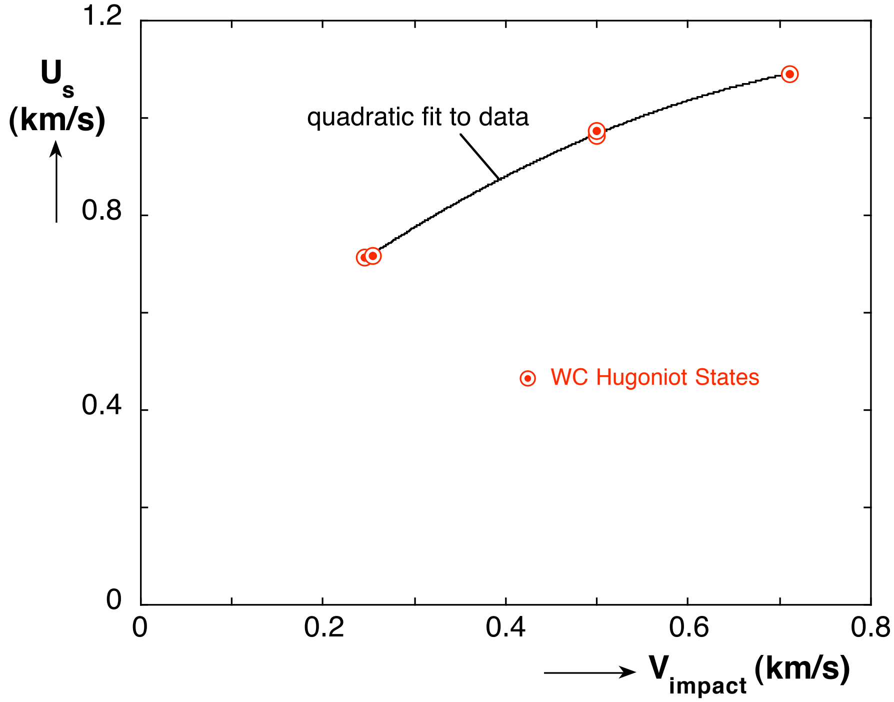
shock velocity calculated based on powder thicknesses and arrival times

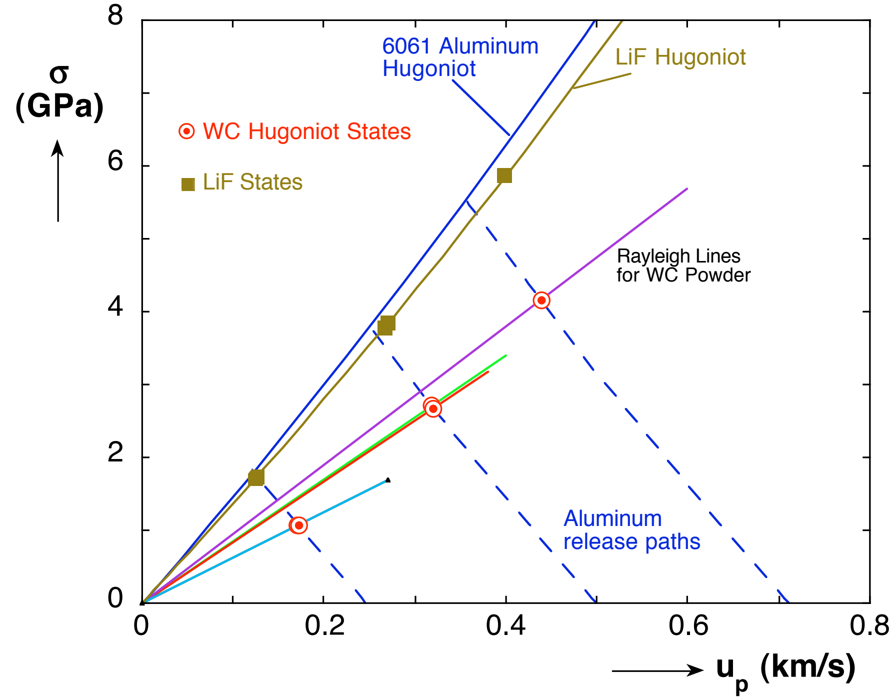
steady, structured waves

attenuated waves

- seem to be first time-resolved measurements of steady waves in granular materials
- since waves are steady, Rankine-Hugoniot jump conditions can be used even though waves have finite rise times

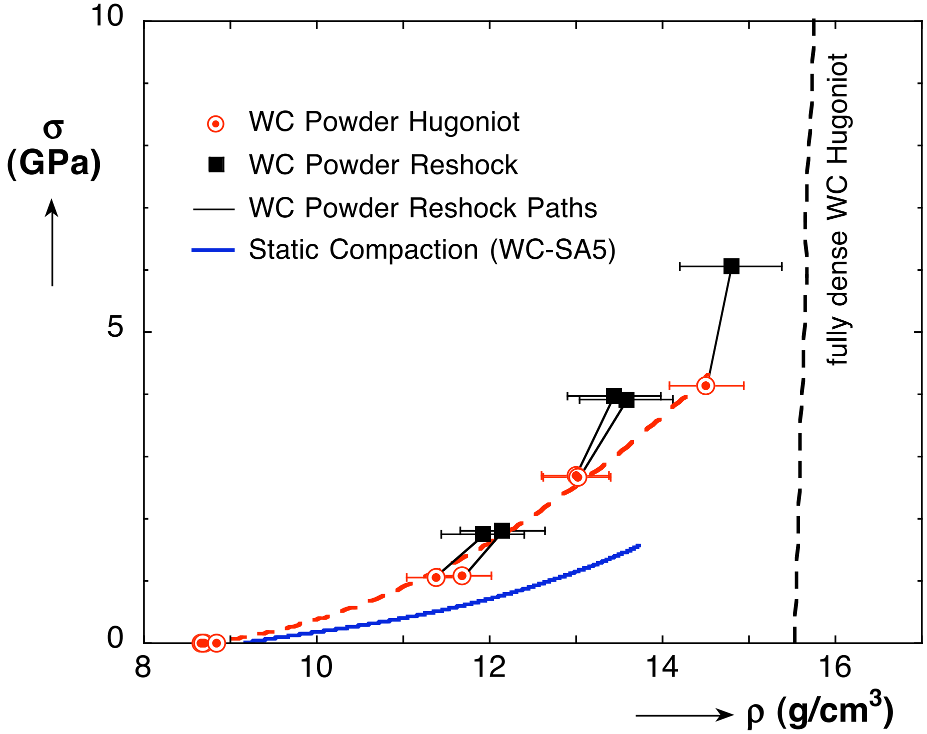
Shock Velocities and Hugoniot States

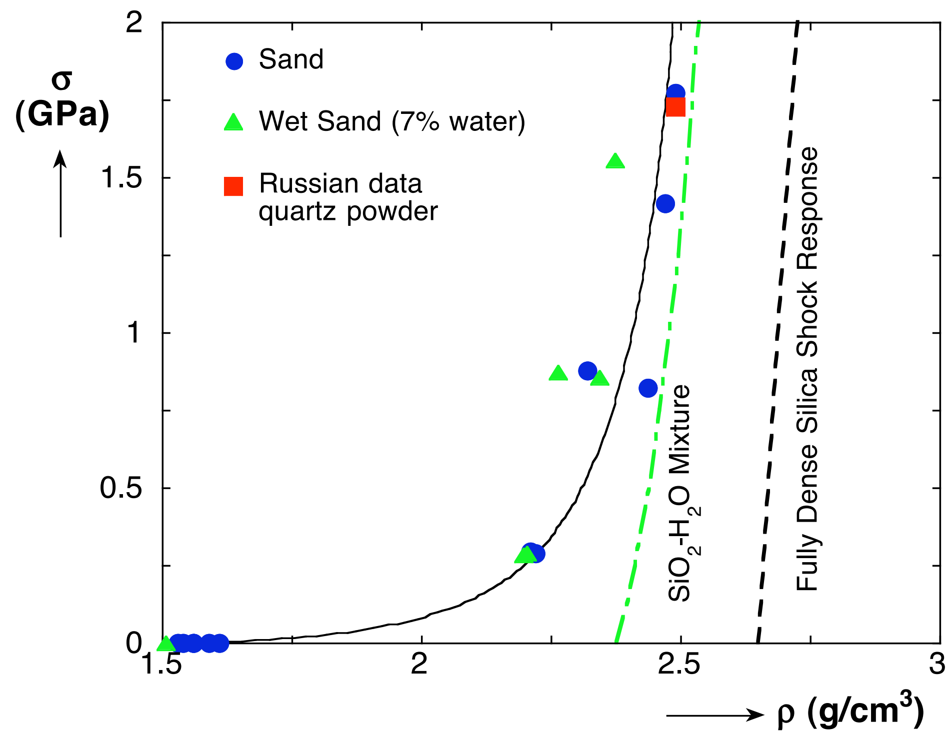




- impedance matching to aluminum impactor used to determine Hugoniot stress and particle velocity ($\sigma = \rho_o U_s u_p$)
- density then calculated from $\rho = \rho_o U_s/(U_s\text{-}u_p)$

Compaction Response for WC and Wet/Dry Sand

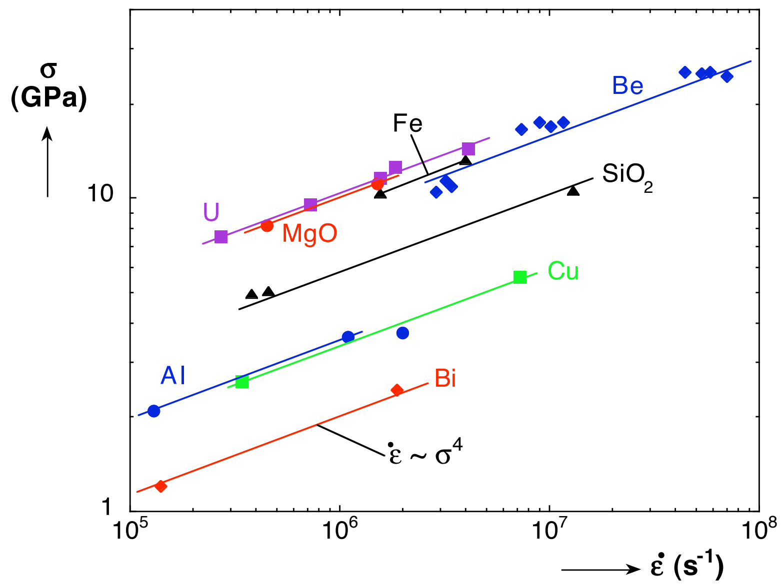




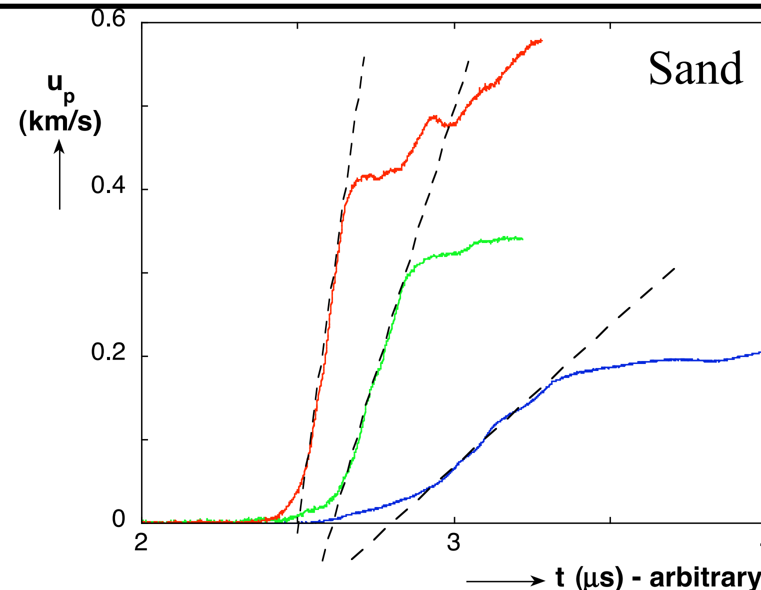
- first reshock state lies above Hugoniot suggesting elastic response of compacted material
- the difference between static and dynamic responses appears to be due to the relatively thin compaction front over which deformation occurs

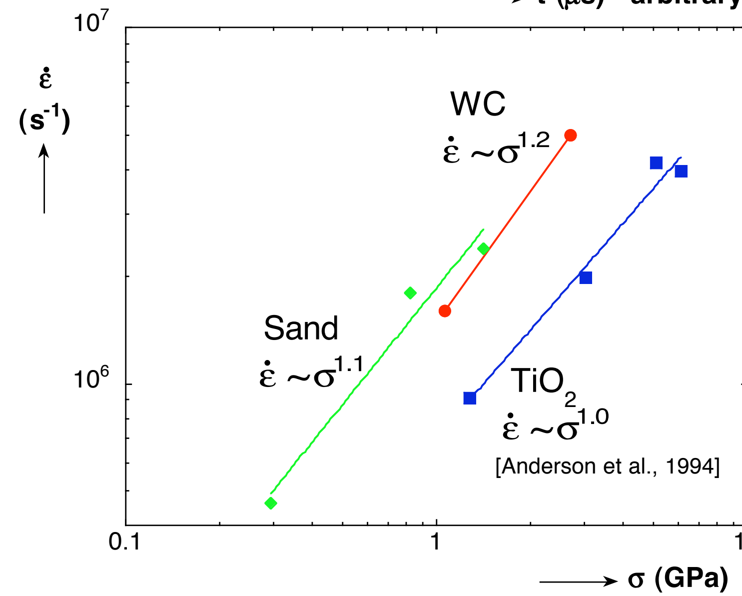
Scaling Between Rise Time of Wave and Stress

for many fully dense materials (Al, Be, Bi, Cu, Fe, MgO, SiO_2, U), rise times of steady waves scale as $\dot{\varepsilon} \sim \sigma^4$ (Swegle & Grady, 1985)



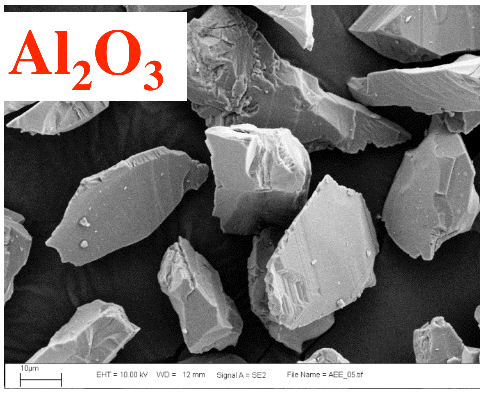
data on three granular ceramics suggest a linear scaling between stress and strain rate

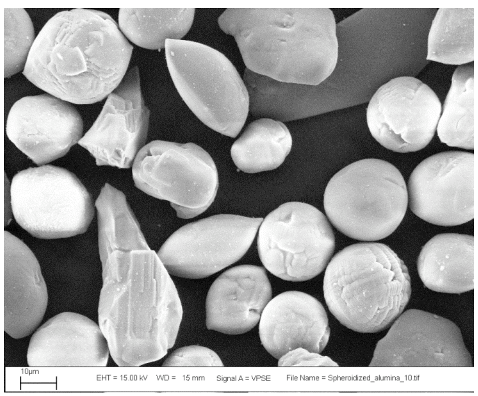


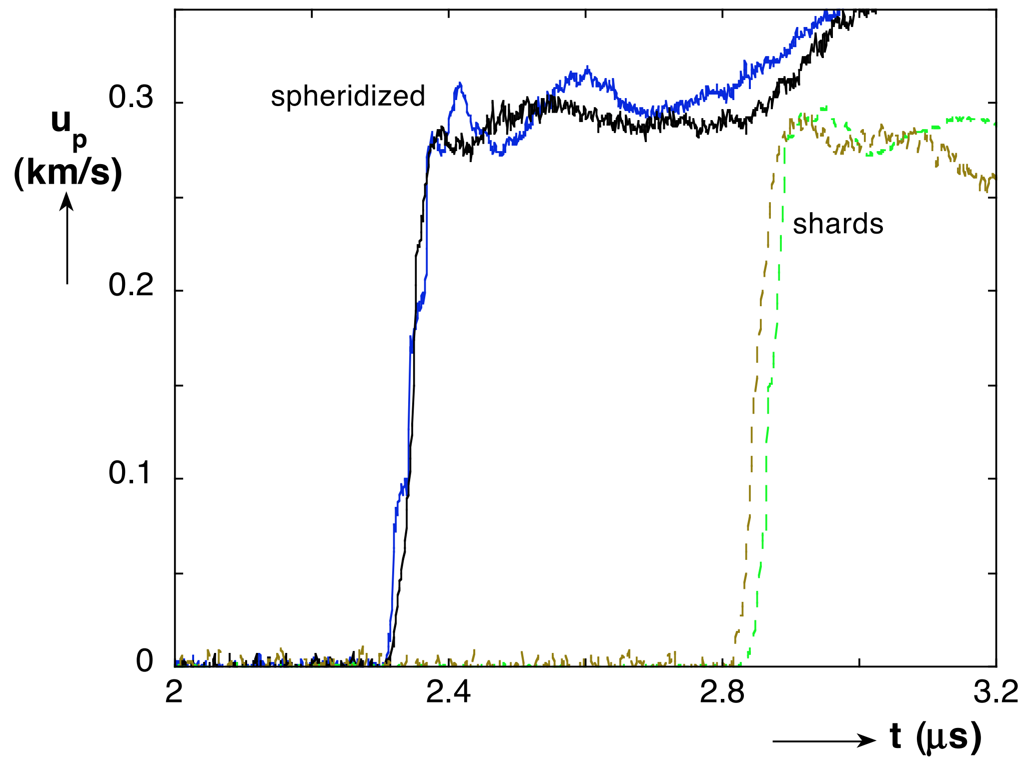


Effect of Particle Morphology

plasma processing used to create spheres, changing particle morphology



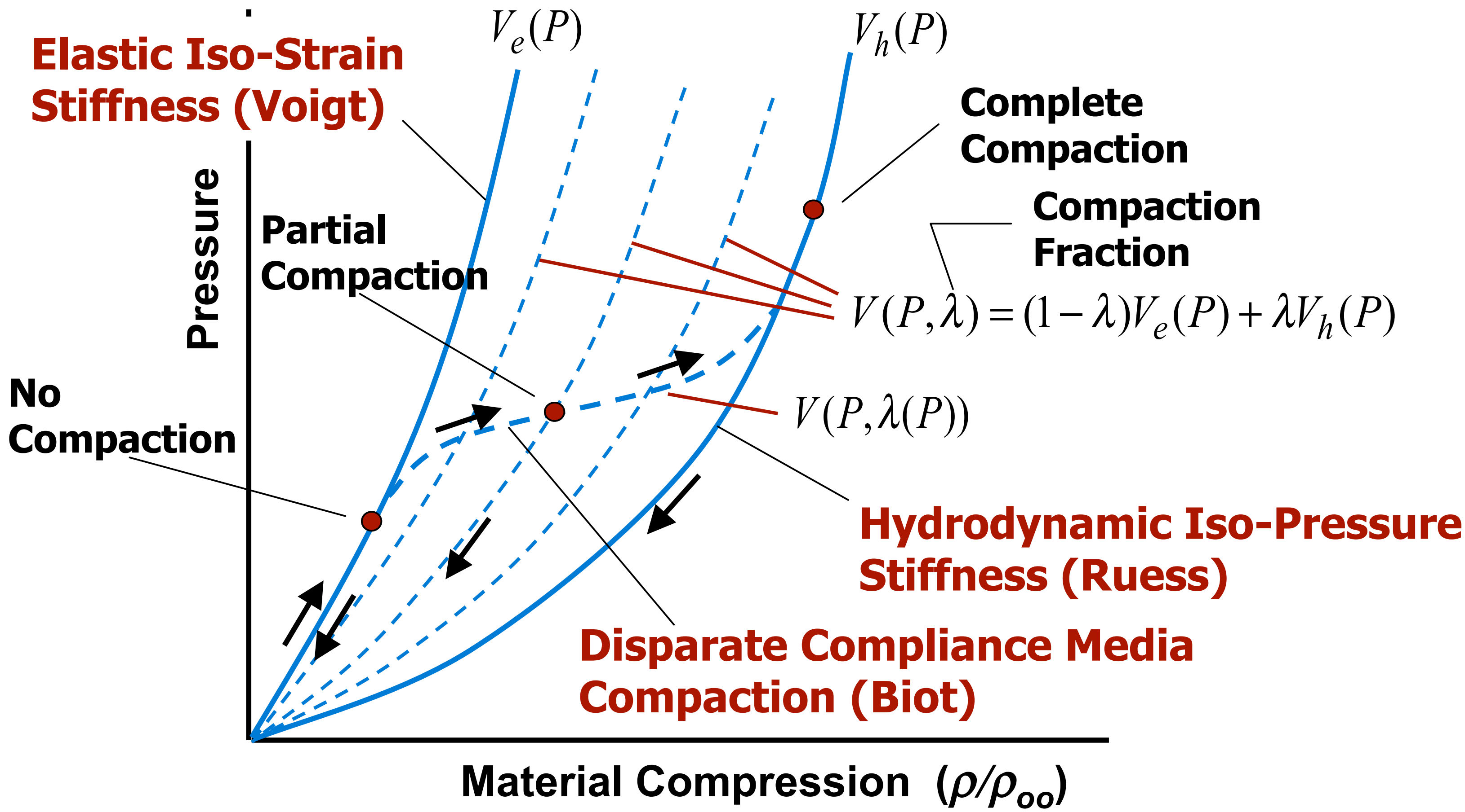




compaction results indistinguishable, but small differences in VISAR records; other materials with more significant morphology changes show greater differences in VISAR (but none in compaction)

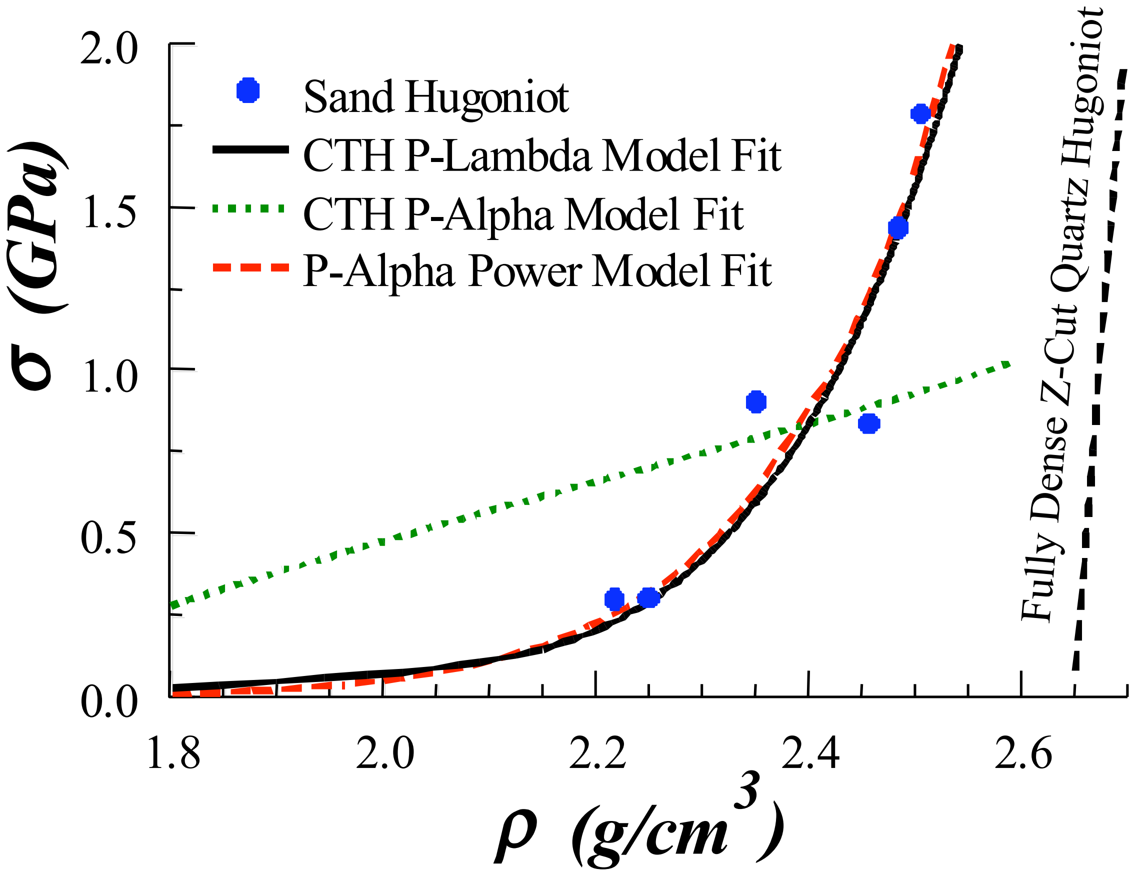
Continuum P-λ Model

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).

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



$$\nu_m(p) = \lambda \nu_R(p) + (1-\lambda)\nu_V(p)$$

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

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

CTH form

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

alternate form

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

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 WC

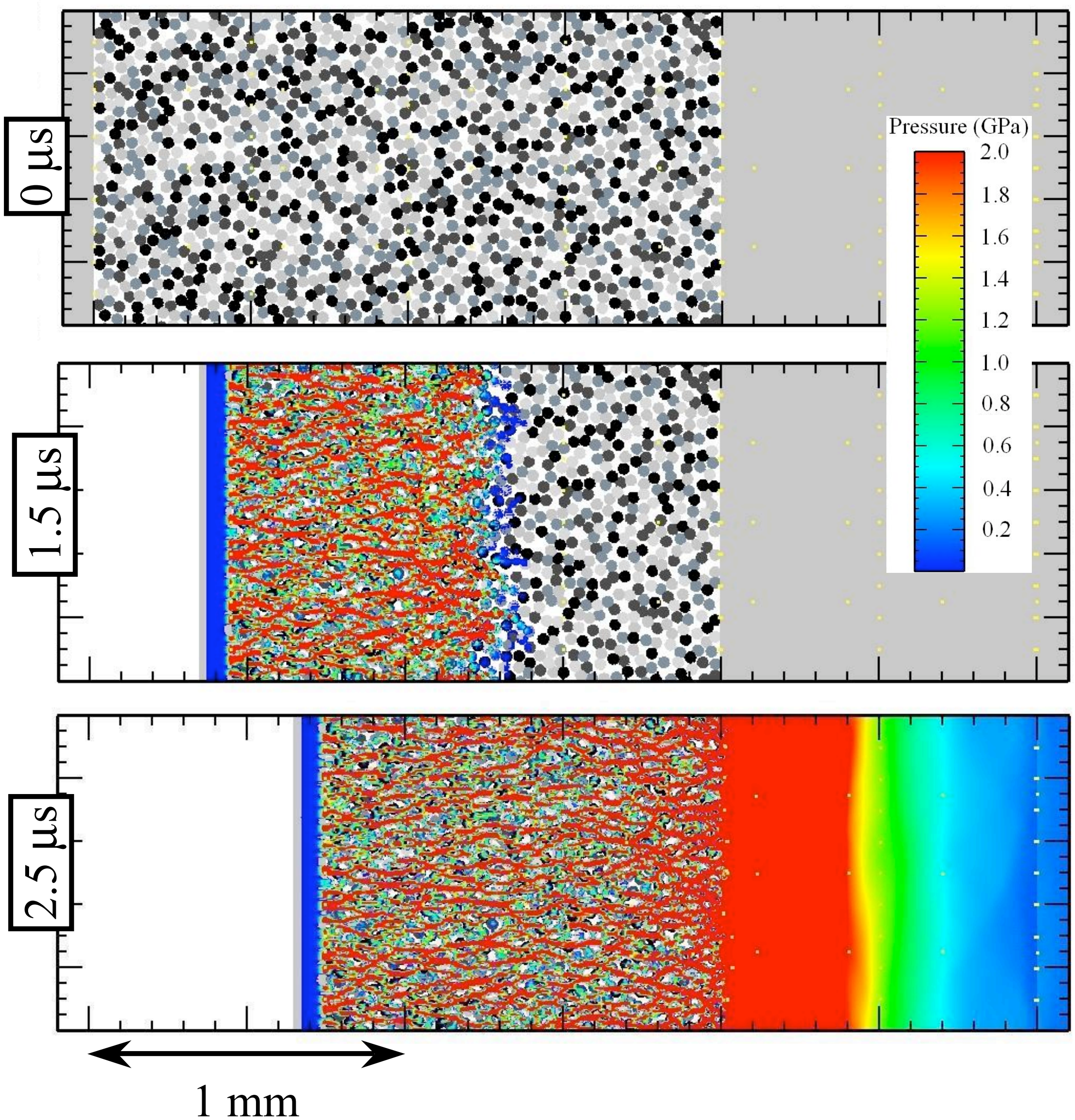
Borg, J.P., Vogler, T.J., (2008). "Mesoscale calculations of the dynamic behavior of a granular ceramic." *International Journal of Solids and Structures* (in press).

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.

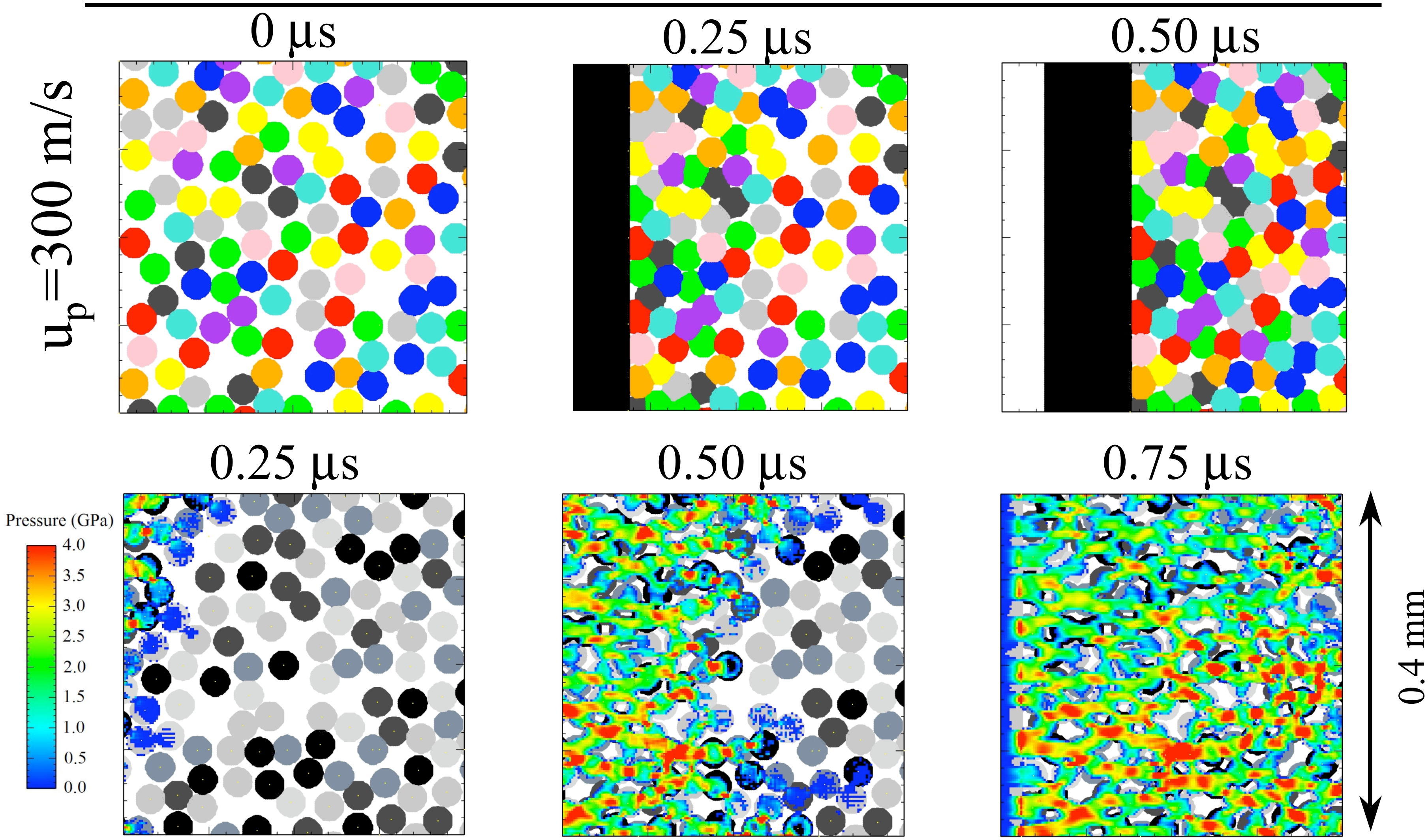
get at underlying physics of granular materials

Computational Dynamic Compaction



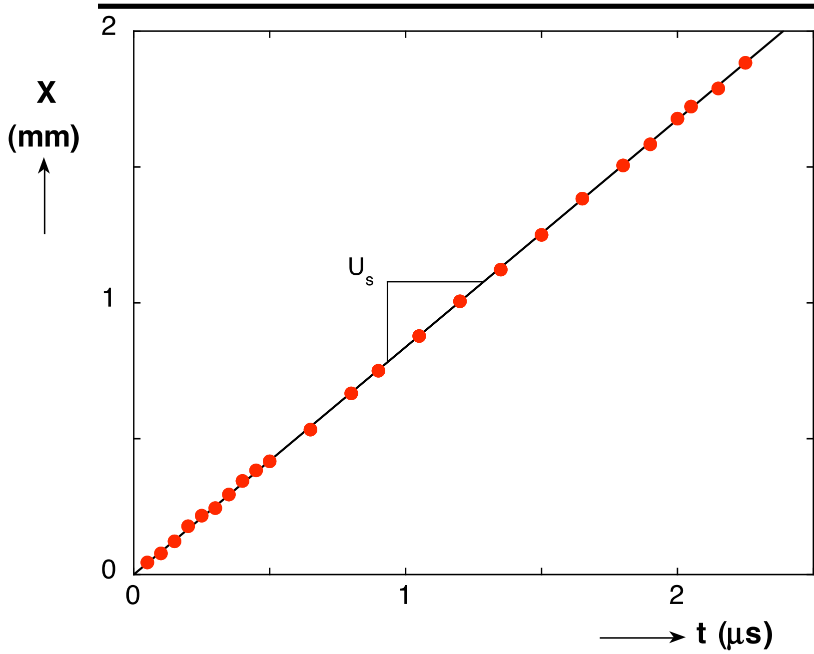
- driver plate velocity u_p=300 m/s
- shock thickness on the order of ~2-5 particles
- strong force chains observed
- wave smooths in aluminum buffer

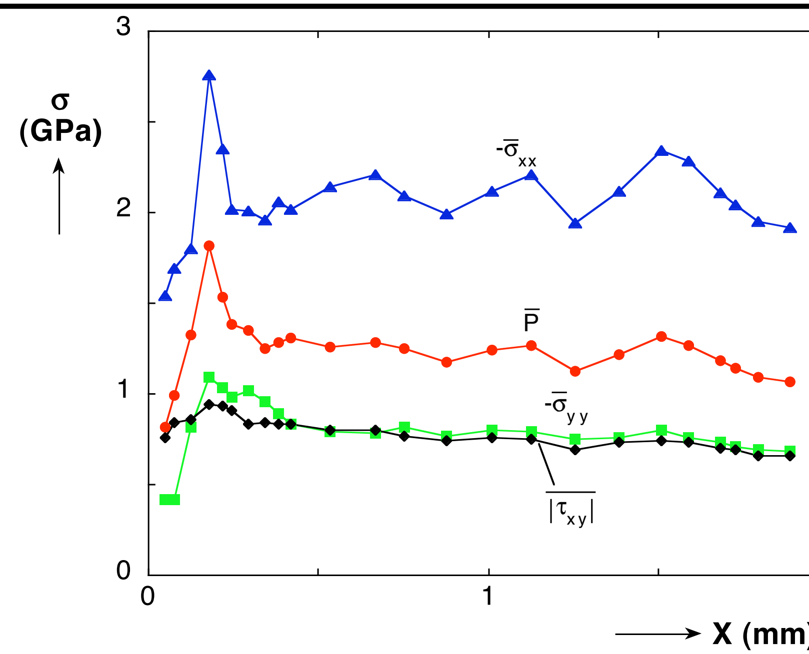
Close-Up of Compaction Process



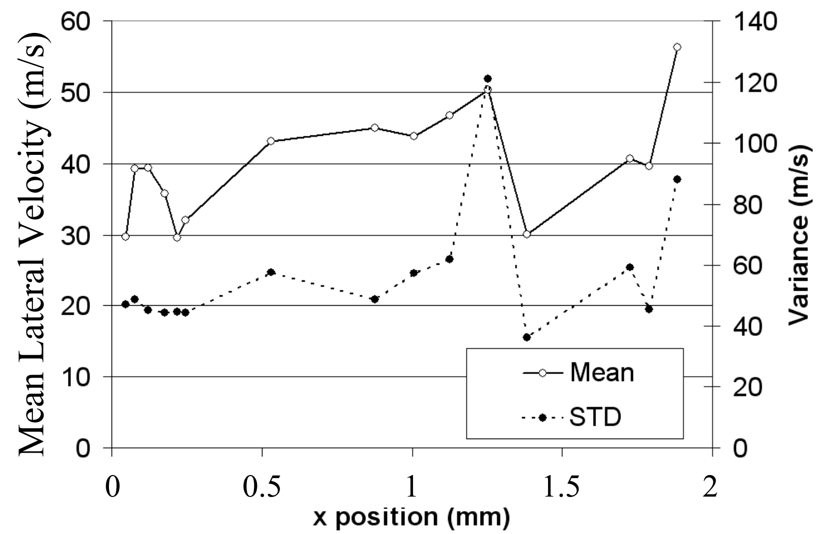
no jetting or vortices so deformation is "*quasi-static*"
(Benson et al., 1997)

Properties of Propagating Wave

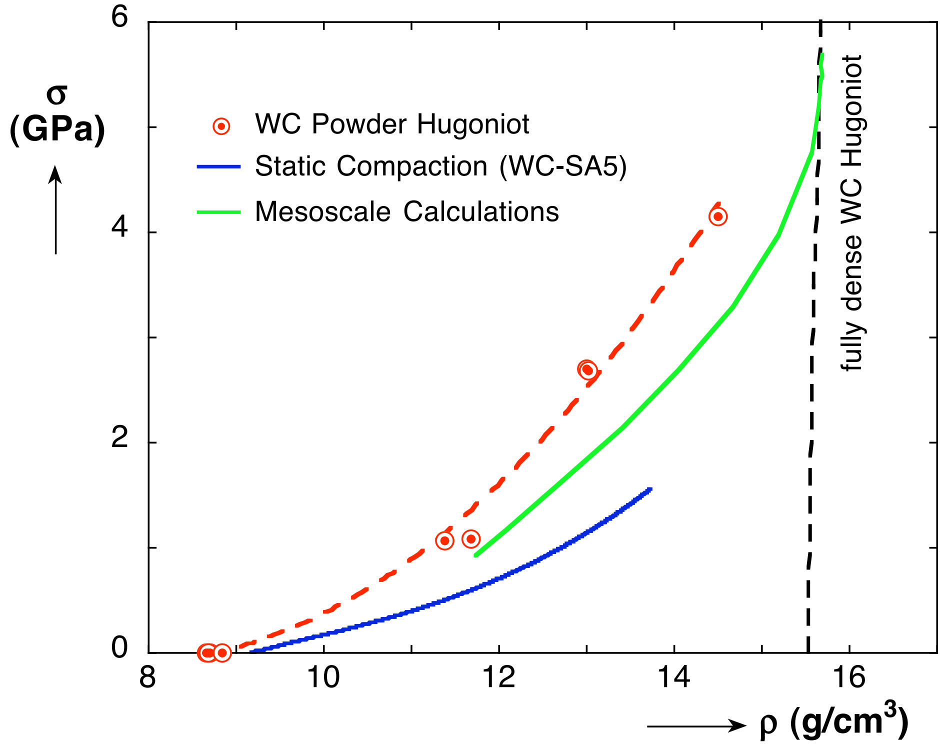




- arrival time of wave suggests steadiness at all times
- stresses in wave front indicate nearly 0.5 mm required to reach steady state
- lateral motion >10% of longitudinal velocity



Calculated Hugoniot from Literature Parameters

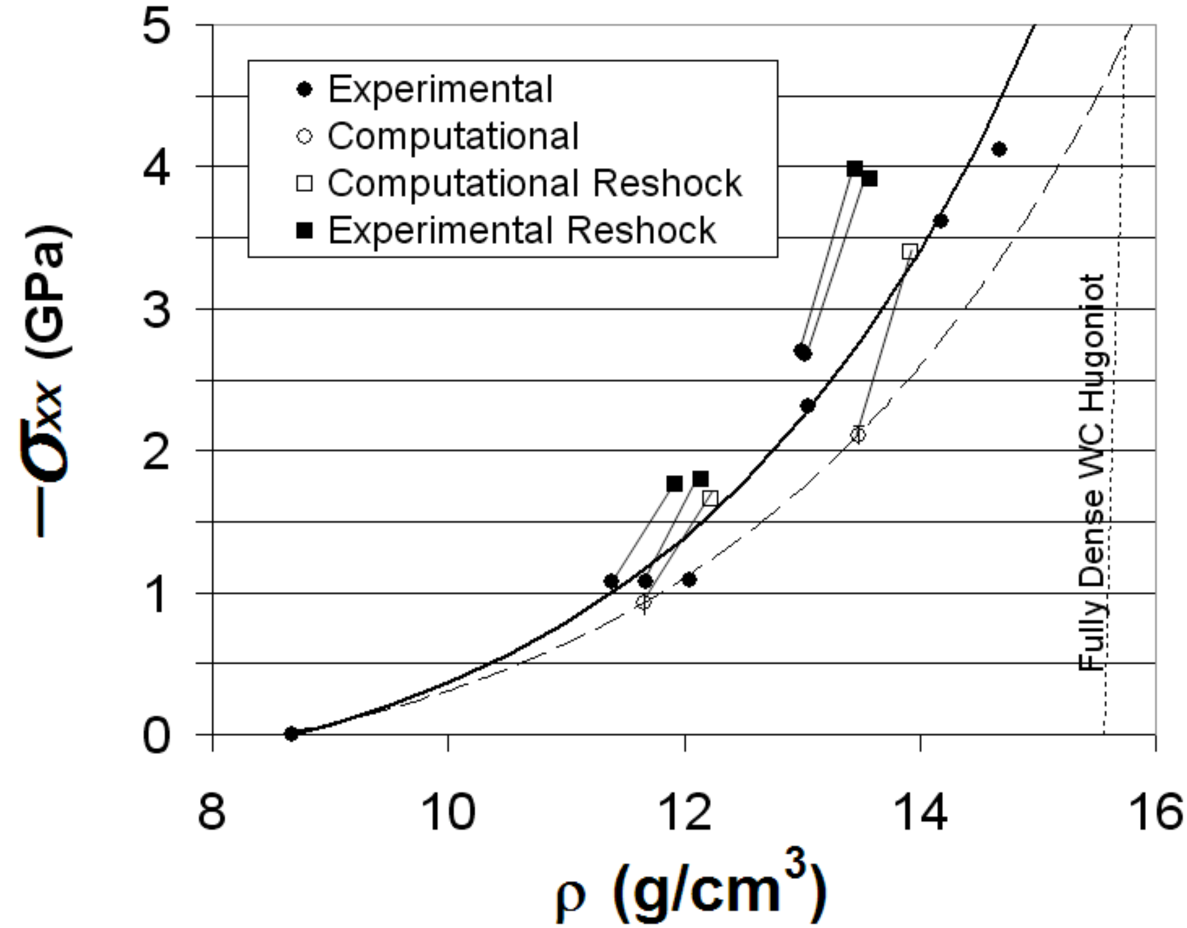


$$\sigma = \rho_o U_s u_p$$

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

- 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

Reshock Behavior of Simulations



reshock behavior of the model agrees well with the experiments

Sensitivity to Simulation Parameters

Material Properties

- Particle size distribution (negligible effect)
- Dynamic yield strength (strong effect)
- Material EOS (negligible effect)
- Spall strength (strong effect but threshold)

Two-Dimensional Properties

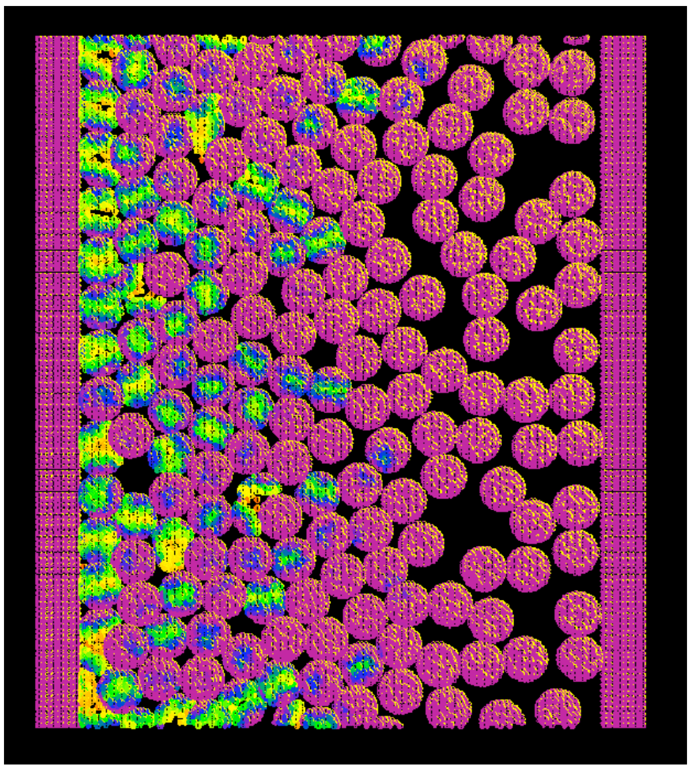
- Material distribution (strong effect)
- Variations in boundary conditions (small effect)

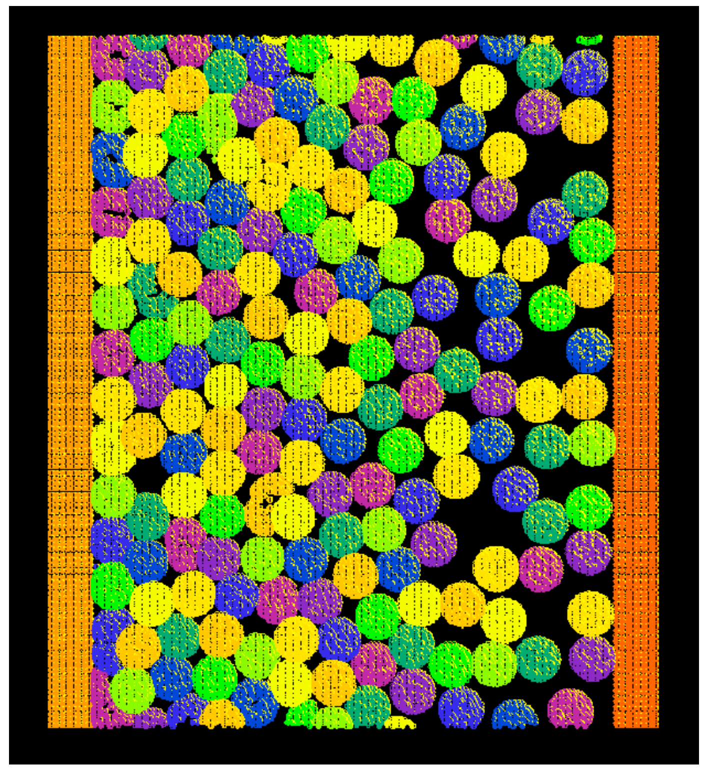
Hydrocode Behavior

- Mixed cell strength (very strong effect)

Initial Mesoscale Calculations with Peridynamics

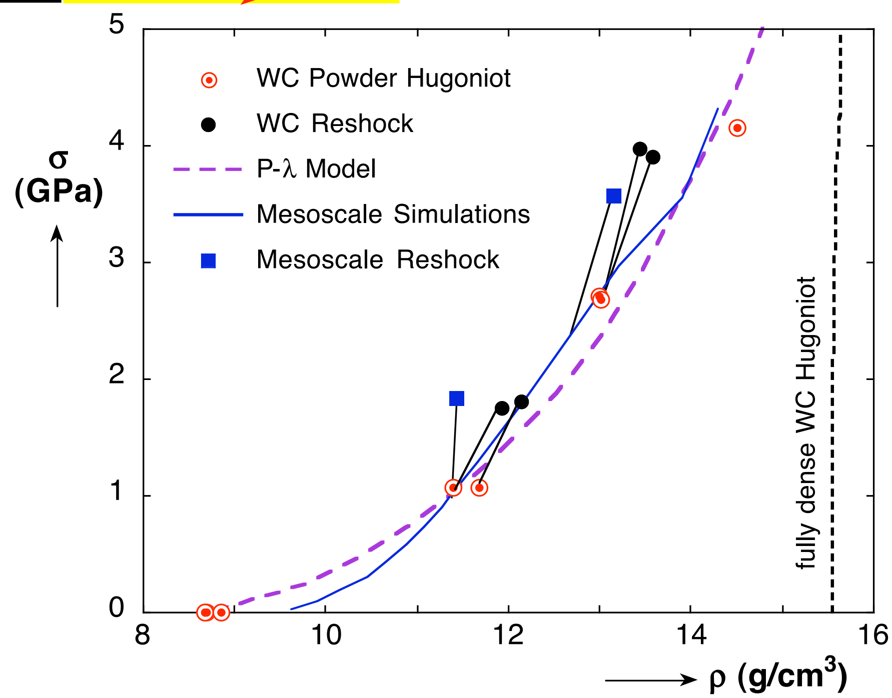
- non-local method based on reformulation of governing equations in integral form
- model framework still under development
- includes fracture and contact missing from CTH
- interaction between fracture and plasticity complicated





Validation Experiments: Attenuating Waves

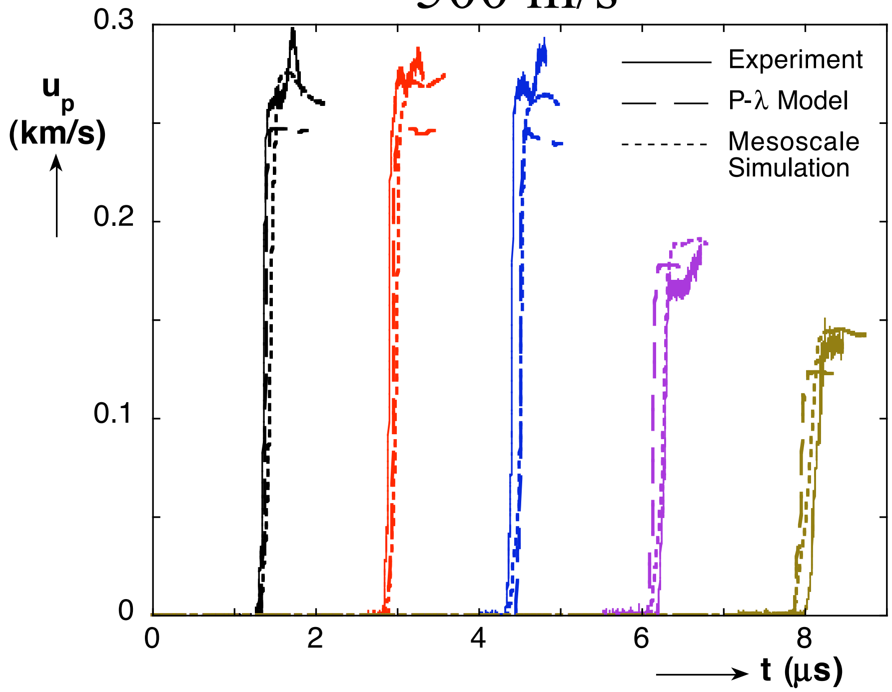
- P-λ model calibrated to WC data
- mesoscale strength set to 8 GPa to match data
- duplicate geometry of experiments for 1 mm wide slice
- velocity averaged at nine points along buffer/window interface



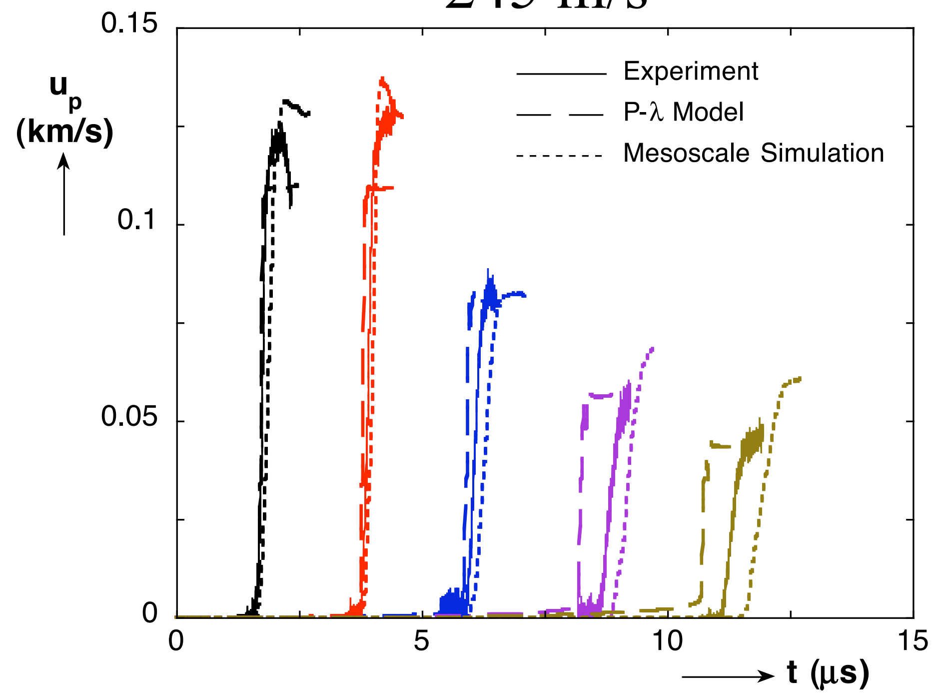
Vogler, T.J., and Borg, J.P. (2007). "Mesoscale and continuum calculations of wave profiles for shock-loaded granular ceramics," in Shock Compression of Condensed Matter – 2007, American Institue of Physics, 291-294.

Attenuating Waves: Comparison to Experimental Profiles

500 m/s

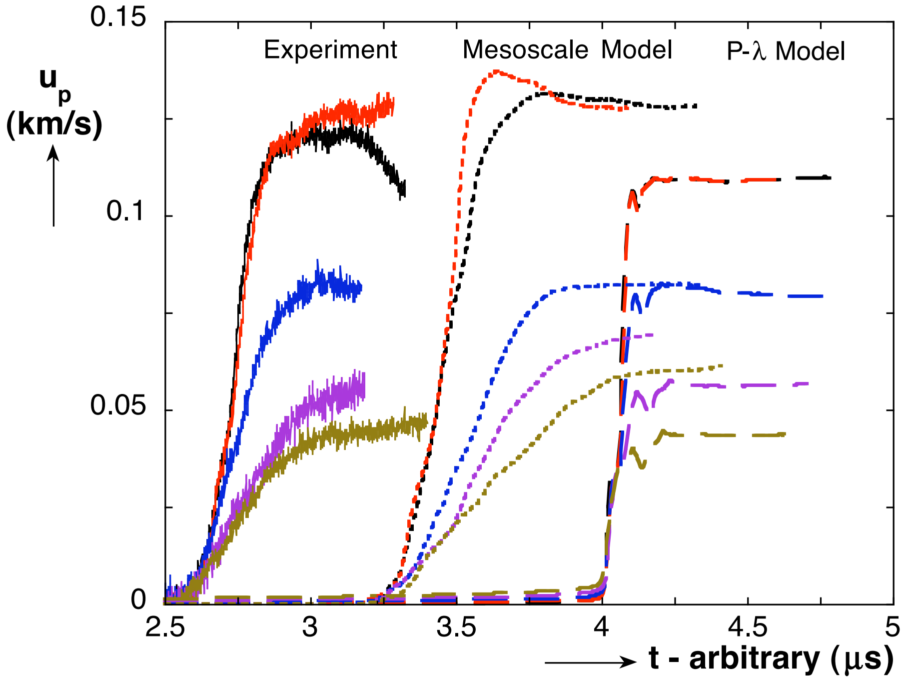


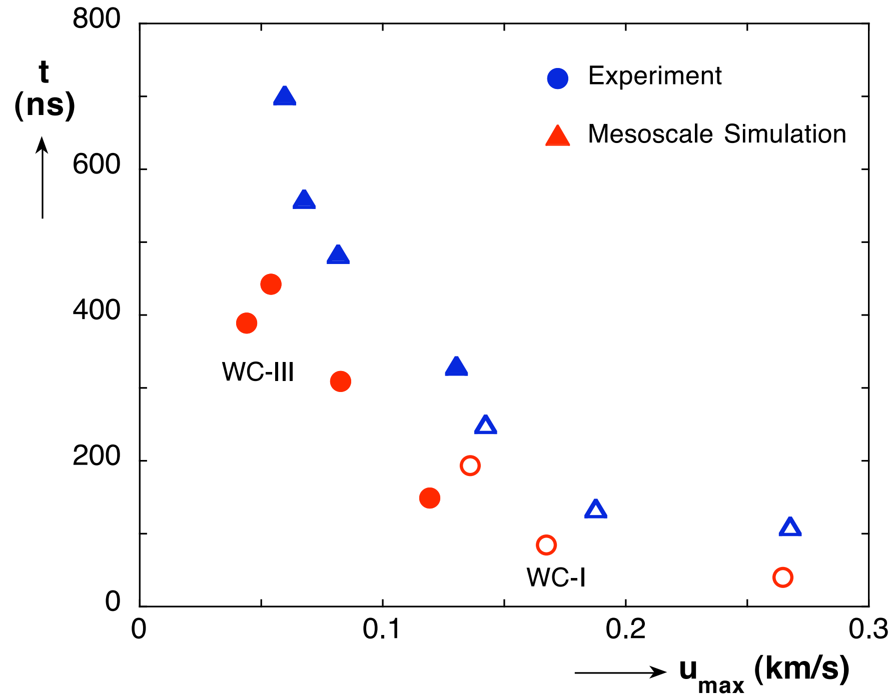
245 m/s



- steady wave arrival times good for both models, but amplitudes more accurate with mesoscale model due to stiffer reshock
- attenuating wave arrivals slightly better with mesoscale
- low stress levels seem to lie between mesoscale and P-λ, sampling regime where there is no data

Attenuating Waves: Wave Shapes

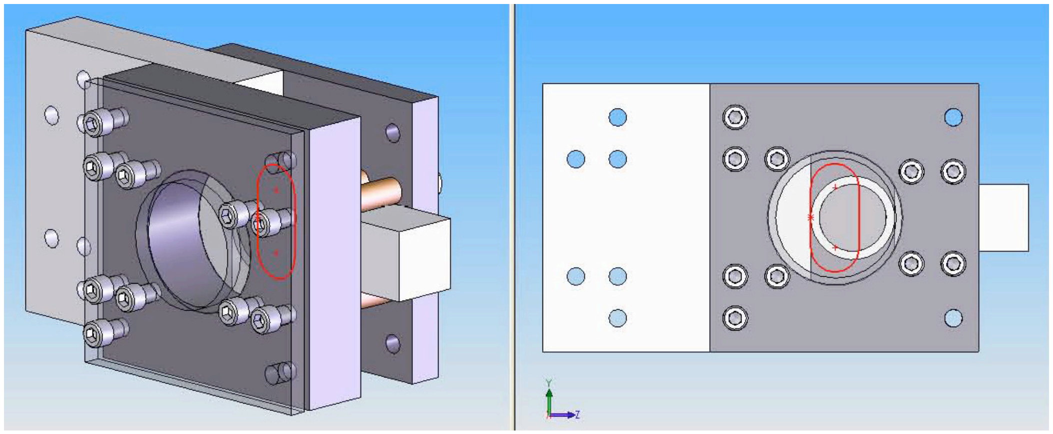


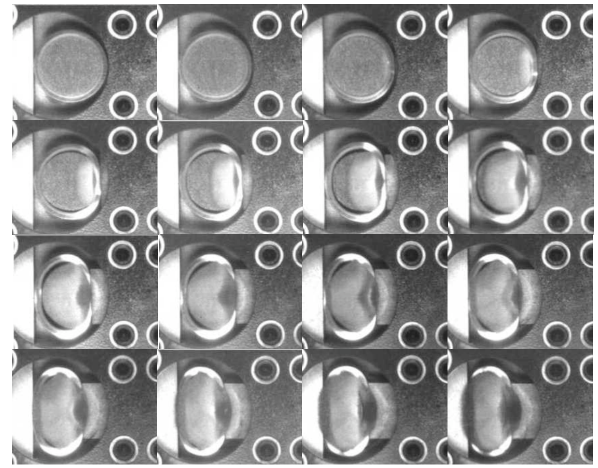


- shape from mesoscale approx. correct; P-λ inaccurate
- rise time seems to depend only on current amplitude

Validation Experiments: Ring Compaction

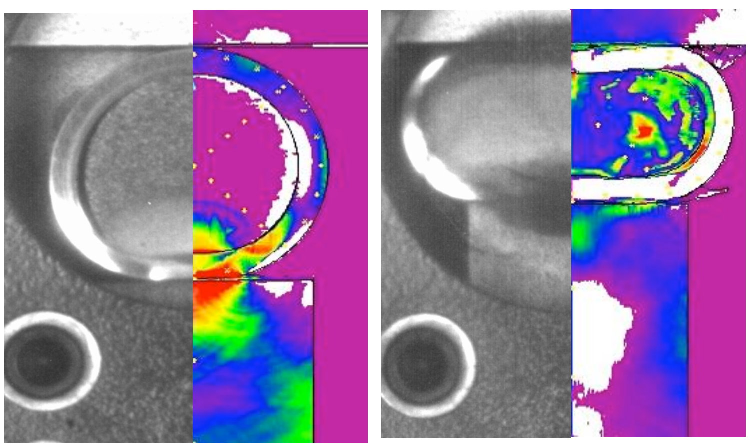
ring compaction experiments provide data for non-planar deformation

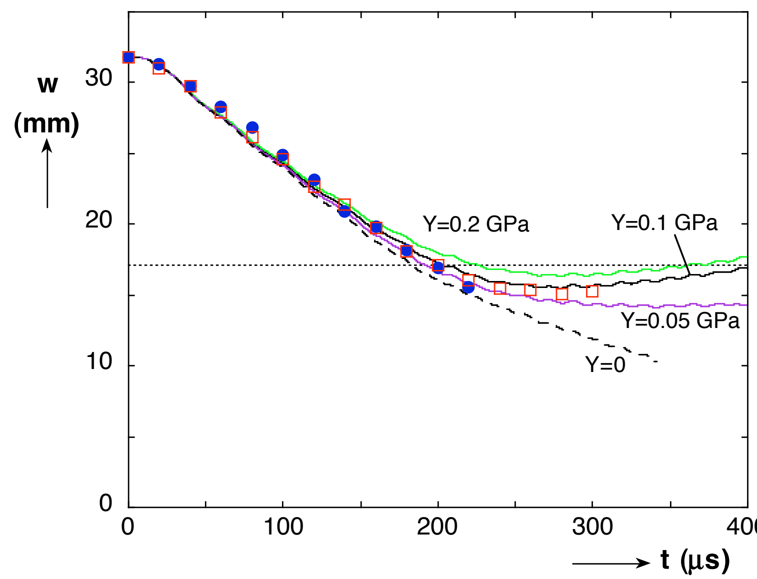




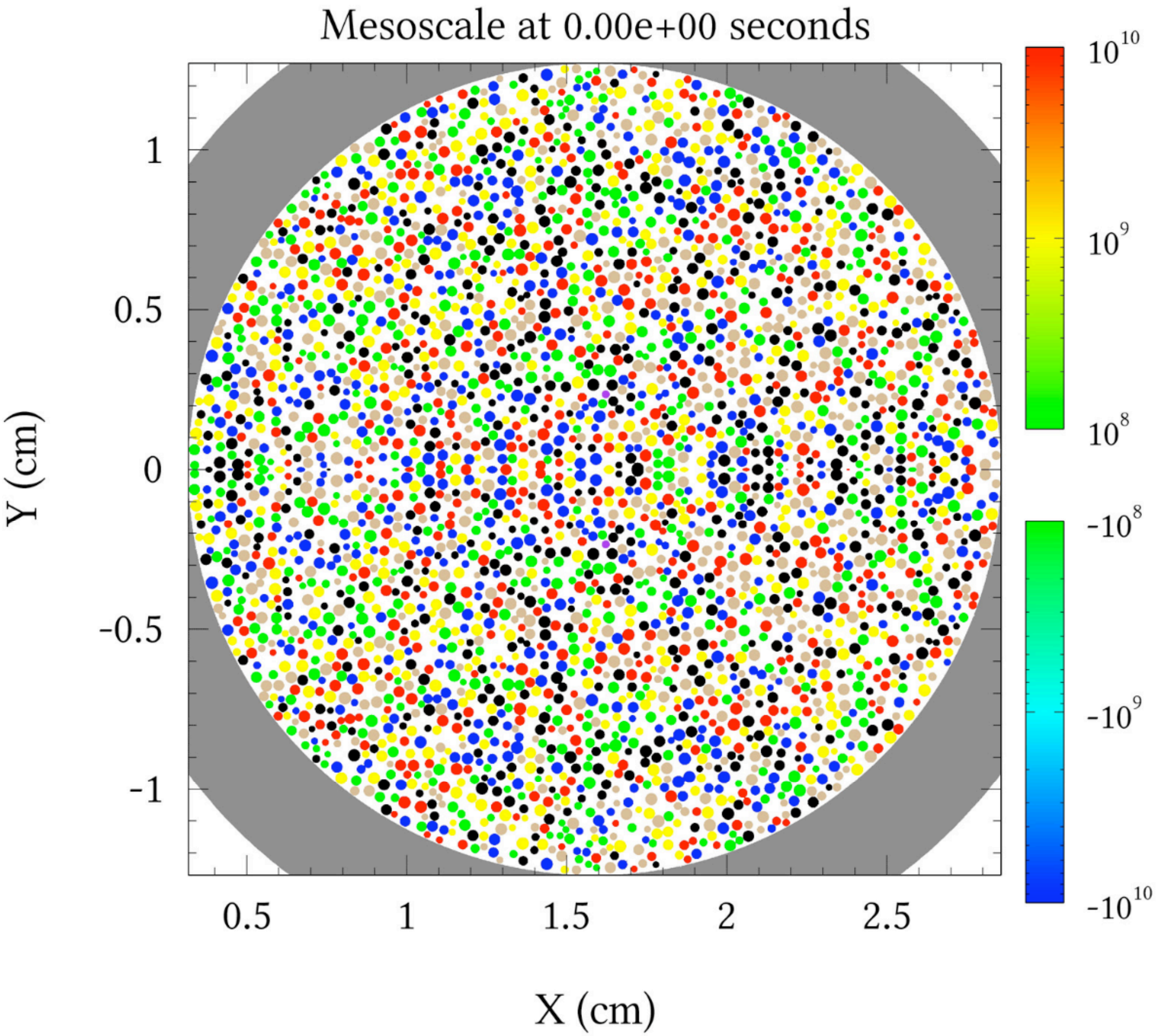
10 µs interframe time

2-D CTH continuum calculation

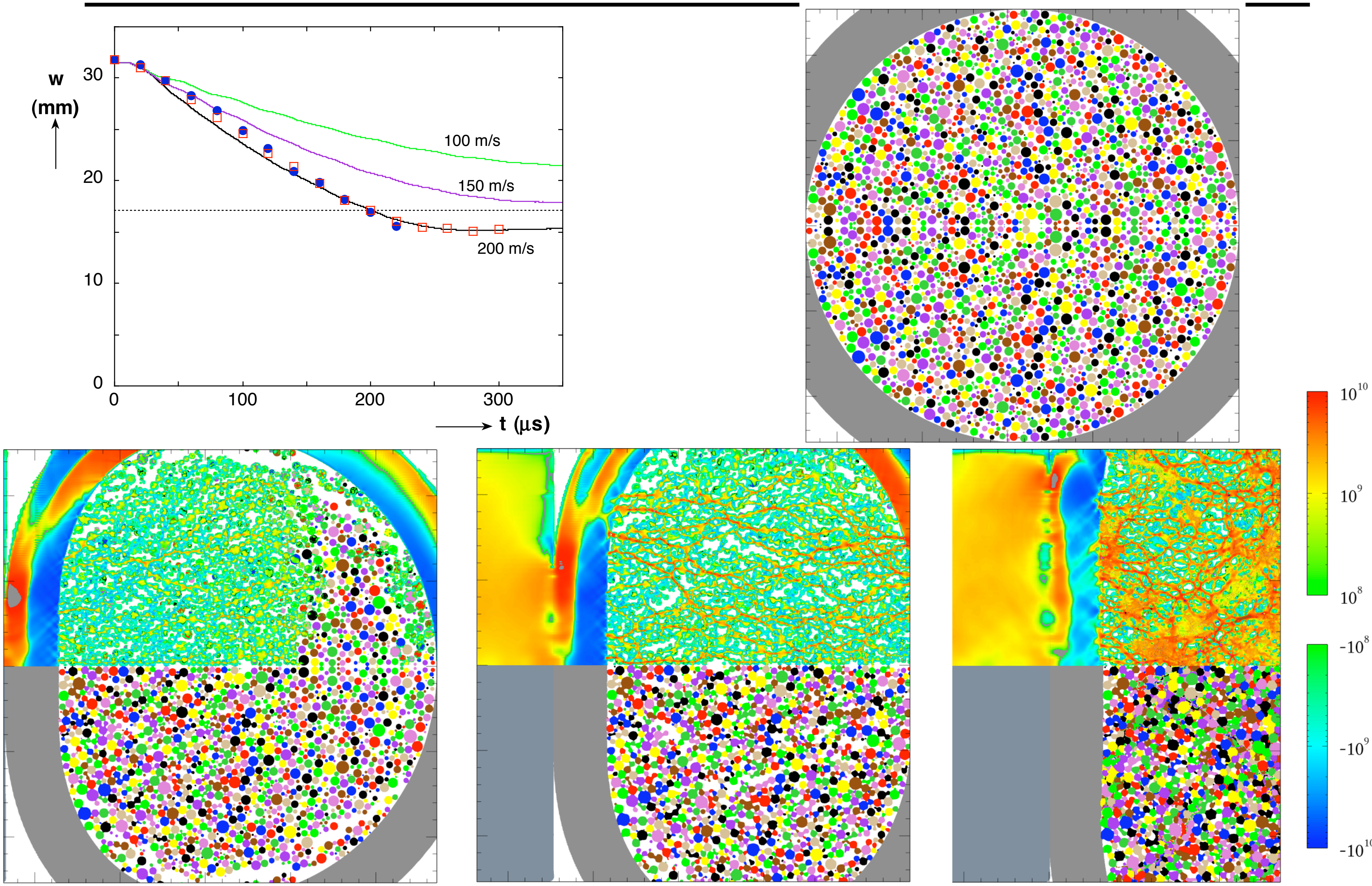




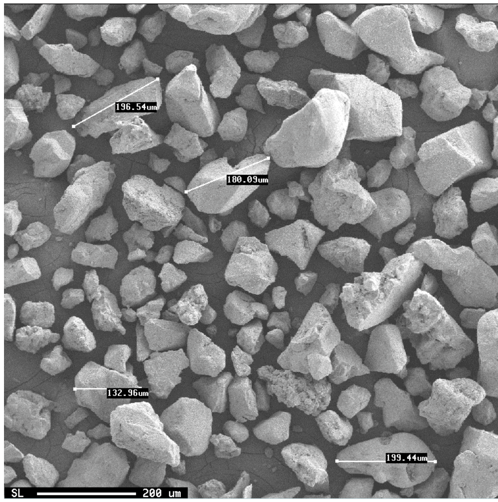
Mesoscale Simulations of Rings (movie)



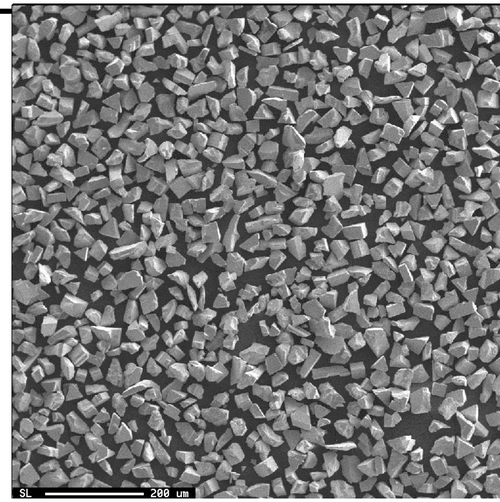
Mesoscale Simulations of Rings



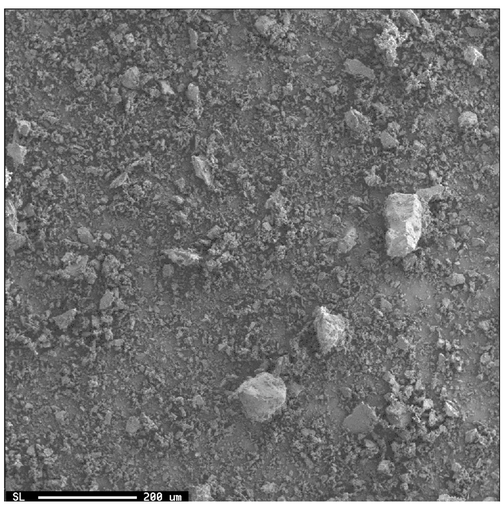
Evolution of Particle Size Distribution



Sand



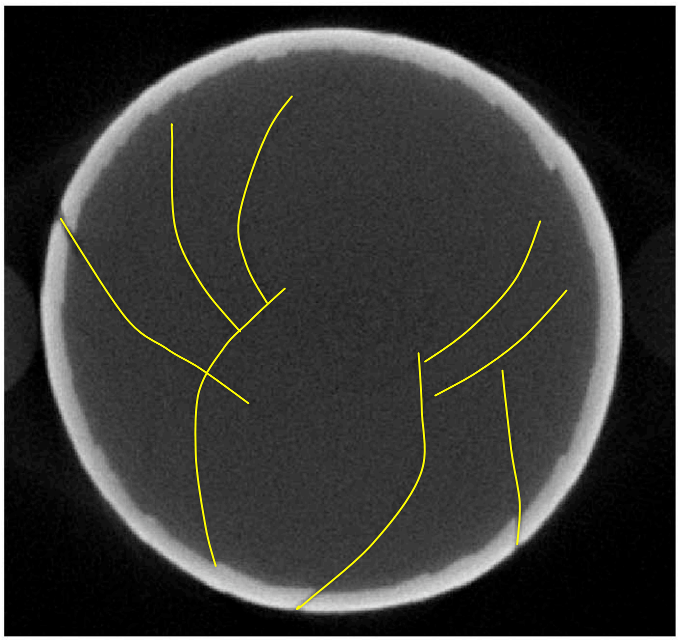
WC



Impacted Sand

Name	Tap Density (g/cc)	Solid Crystal Density g/cc	Mean Particle Size _m	Particle Size St. Dev.
Sand	1.53	2.56	298.1	169.8
Sand Impacted	2.25		28.7	280
WC	7.7	15.7	39.9	11.6
WC Impacted			28.0	13.5

Validation Experiments: Explosively Loaded Cylinder

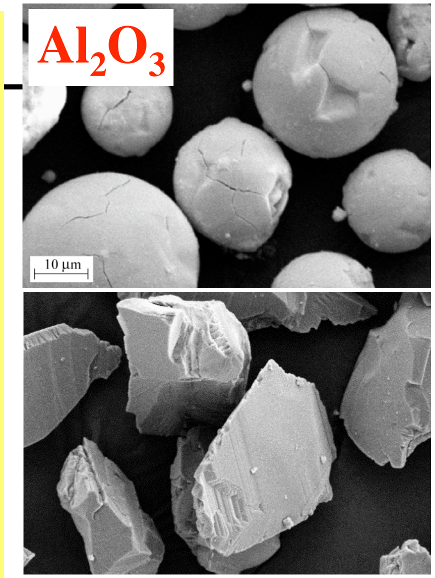


- explosively compacted cylinders to allow comparison with simulations and analytic solutions
- more difficult than expected; also late time effects
- tomographic analysis of compaction difficult and reveals localizations

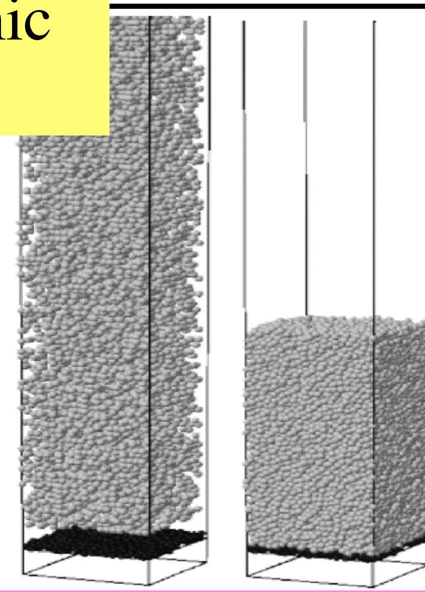
Conclusions

- **planar waves in granular ceramics:**
  - very slow wave speeds
  - steady waves observed for several sample thicknesses
  - waves have finite rise times; strain rate ~σ
  - reloading stiffer than loading
  - dynamic response significantly stiffer than static response
- **validation experiments:**
  - suggest shortcomings of P-λ model
  - wave attenuation, shape, and amplitude can constrain models
  - additional validation experiments needed
  - must rely on real-time diagnostics (VISAR, photography, etc.)
- **mesoscale simulations:**
  - nonuniform stress distribution (force chains) and localizations
  - significant lateral motion and distance to reach steady state
  - techniques such as peridynamics needed to capture missing physics
  - may be suitable for some macroscopic simulations

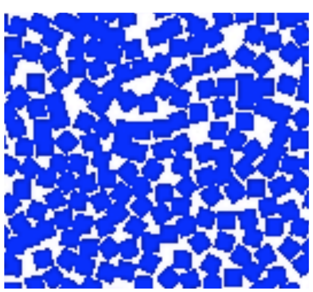
Future Work



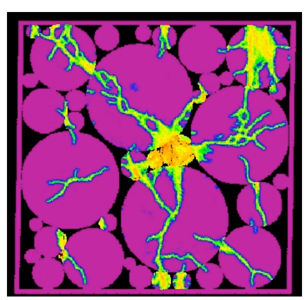
- further work on validation experiments with improved diagnostics
- additional study of morphology effects
- probe full compaction region
- characterize comminution of grains in recovered material
- predictive capability for variations in material
- understand relationship between static and dynamic behavior

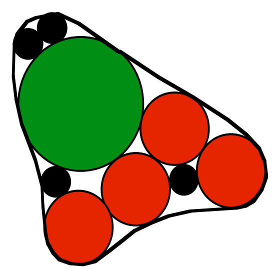


- mesoscale modeling of validation experiments
- 3-D simulations with spheres and other shapes
- determine suitability of peridynamics



Silling, 2007





Jensen et al., 2001

Silbert, Ertas, Grest, Halsey and Levine, **Physical Review E, 65**, 031304**,** 2002