The Dynamic Compaction of Sand and Related Porous Systems

Quasi-static to Shock

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Aims

- Apply techniques to determine the high-pressure and low-pressure response of sand
- Use a natural sand (marine)
- Present data on sand over a wide range of strain rates.
- Establish trends
- Provide data for validation of models
- Increase predictive capability

Modelling

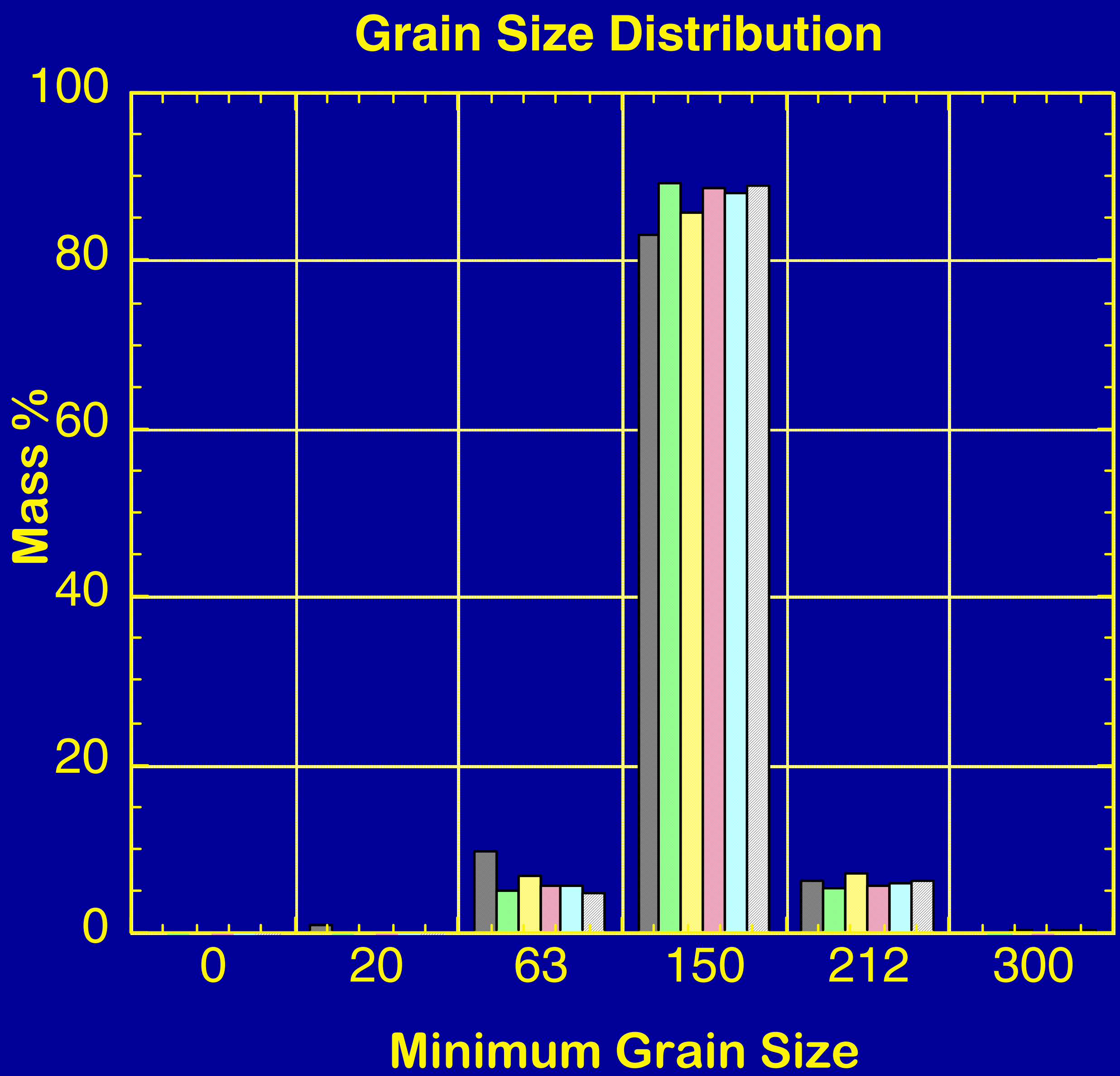
Several groups of models exist -

- P-alpha model (volume-based)
- P-lambda model (length-based)
- Porter-Gould (potential-based)
- Thouvenin (laminar-based)

Parameters / Techniques

- **Dry Sand - heated in oven.**
- **5%, 10%, 20%, 22% by *mass* water,**
- **Instron**
- **Dropweight**
- **Hopkinson Bar**
- **Plate Impact**

Size Distribution (natural sand)



Sand - bi-modal mix

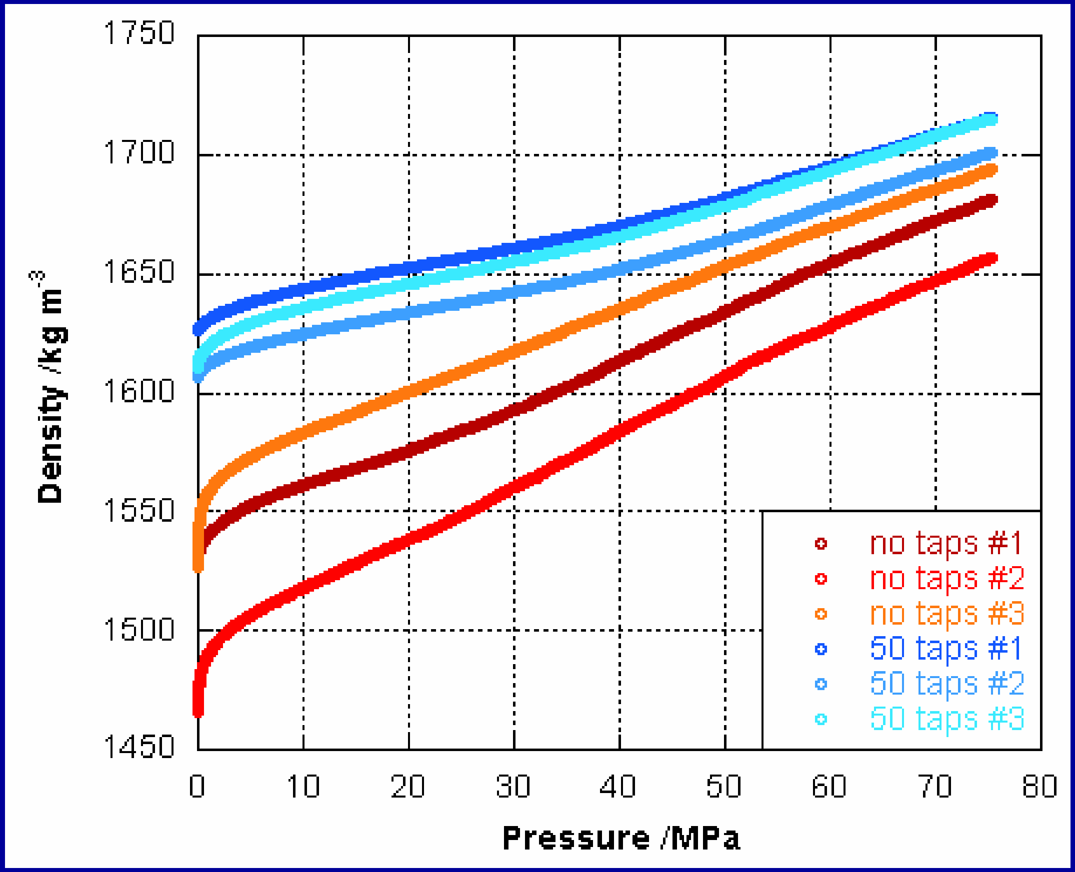
- Bimodal sand - 150-210 micron + 50-63 micron particles
- No significant difference found with the natural "mix".
- Both materials will be referred to as "sand"

Instron - Quasi-Static

Parameter Space

- 10 kN load capacity
- Water content 0, 5 or 10 %mass.
- 6 g samples
- Stainless steel cell
  - 13 mm inner diameter
- Piston driven in at 5 mm/min.

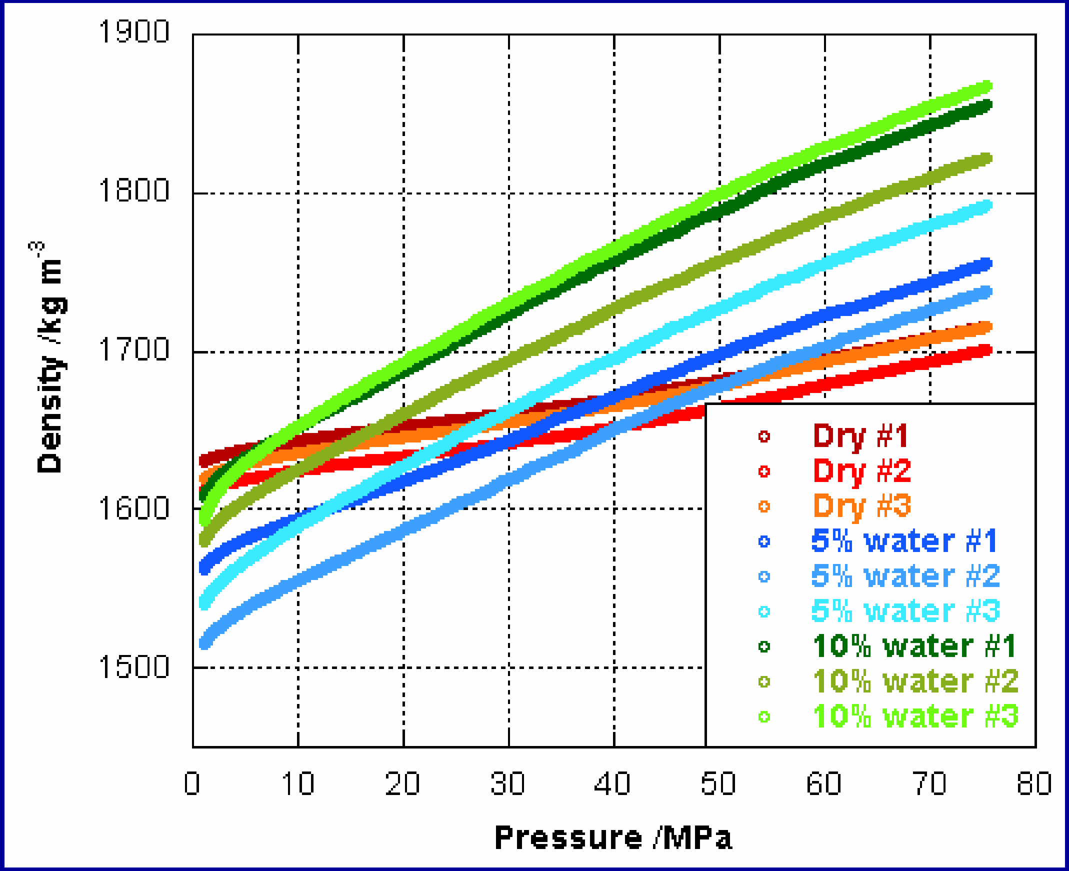
Instron - Results



Starting Density

- Obviously important
- In range the materials move closer together
- Do not become identical
- Friction between the grains
- Lock-up with pressure
- Movement of particles
- Force Chains within the sample
- Skeletal Strength

Moisture Content



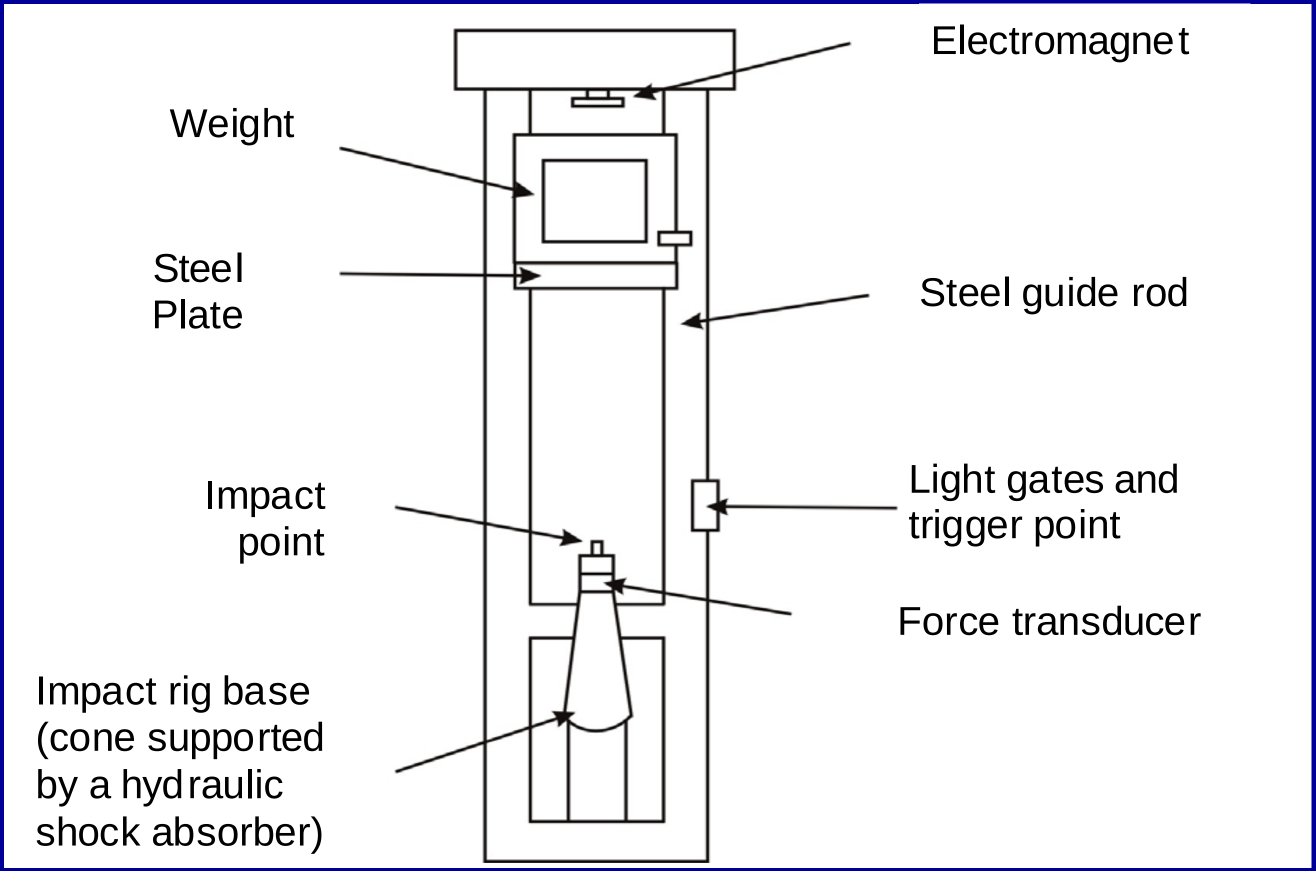
Water Content

- Starting density order
  - Dry > 10% Wet > 5% Wet
- Dry = limited change in density
- Wet = movement in grains
- Wet = move along parallel paths

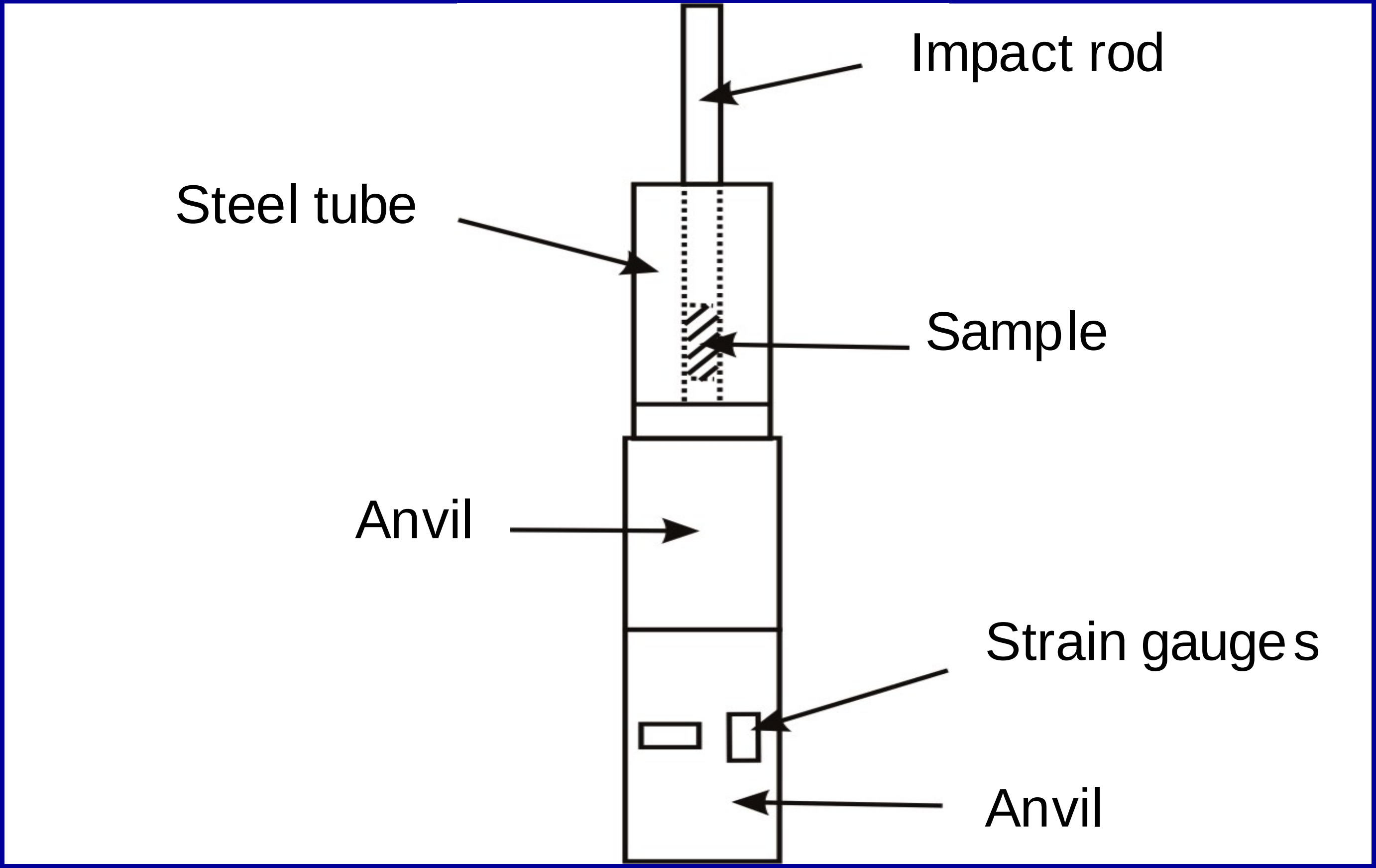
Drop-weight Parameters

- 4 orders strain-rate faster than Instron
- 6.414 kg weight
- Maximum height of 120 cm.
- Guided
- Velocities of up to 5 ms^{-1}
- Sample cell and size - same as Instron

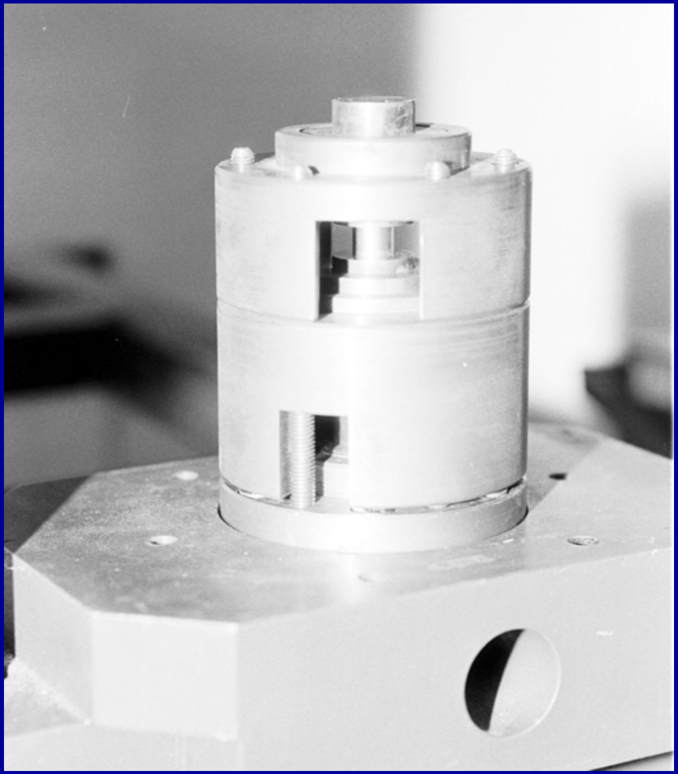
Schematic Drop-weight

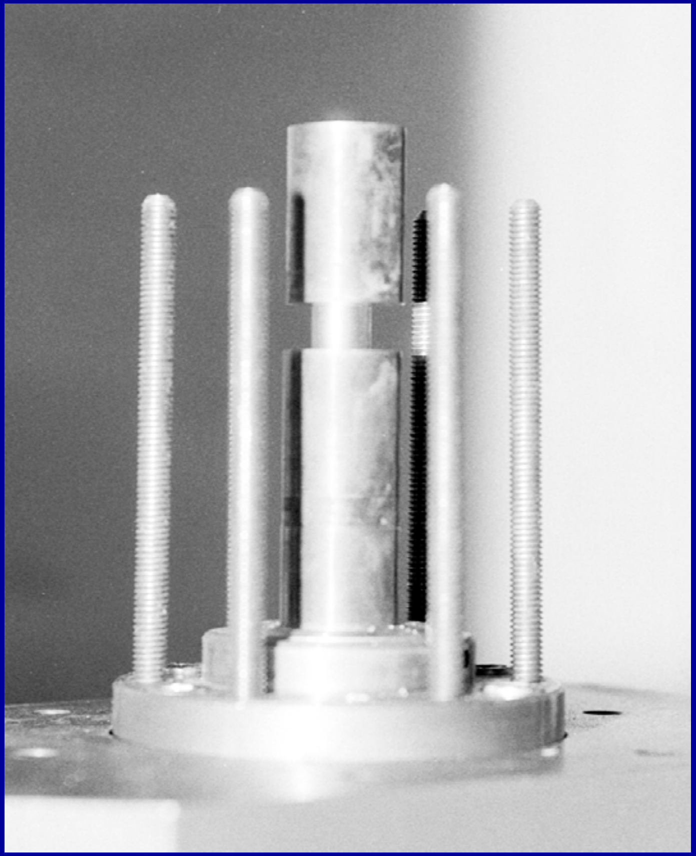


Sample Cell - Stress monitoring

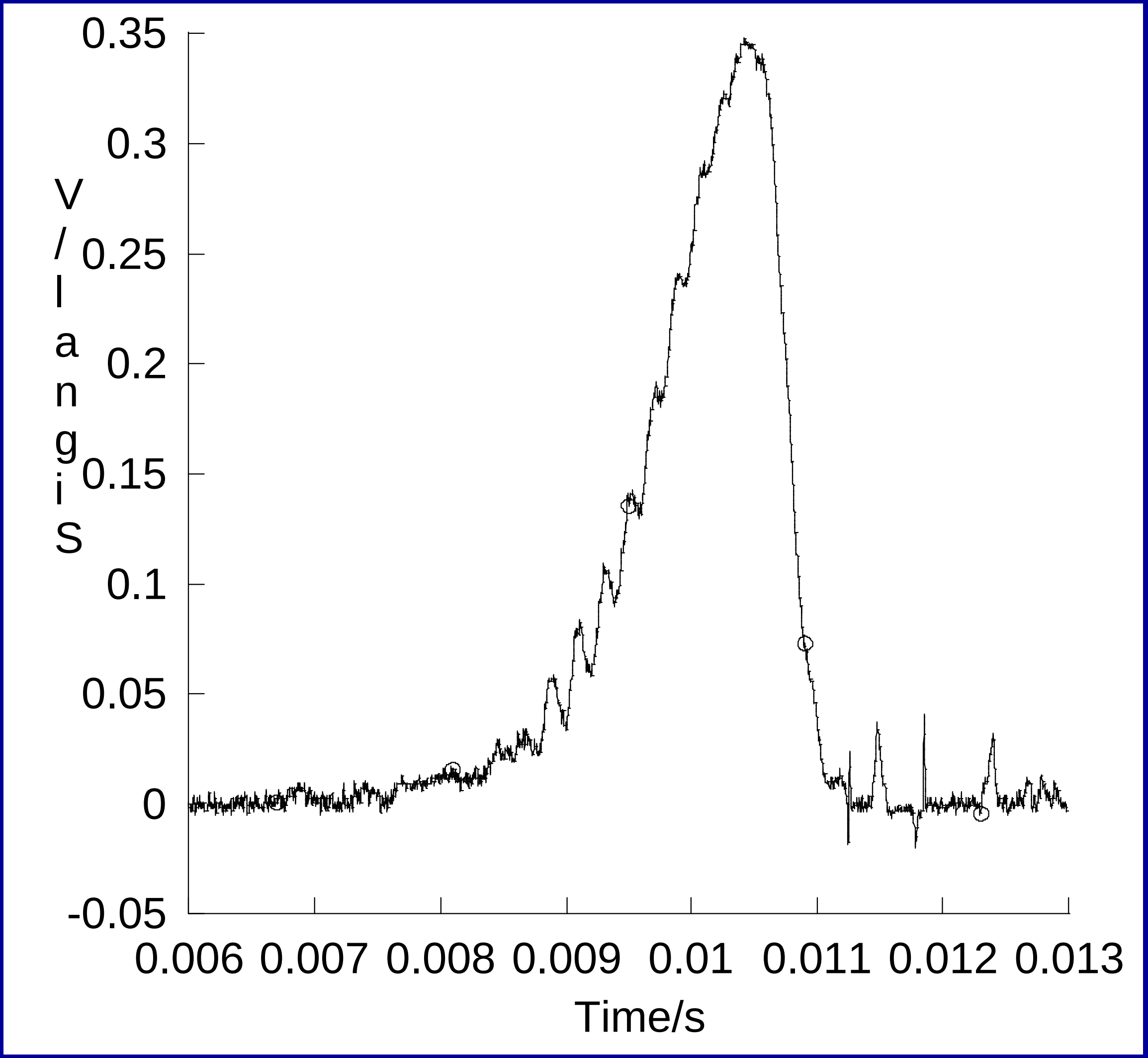


Force transducer



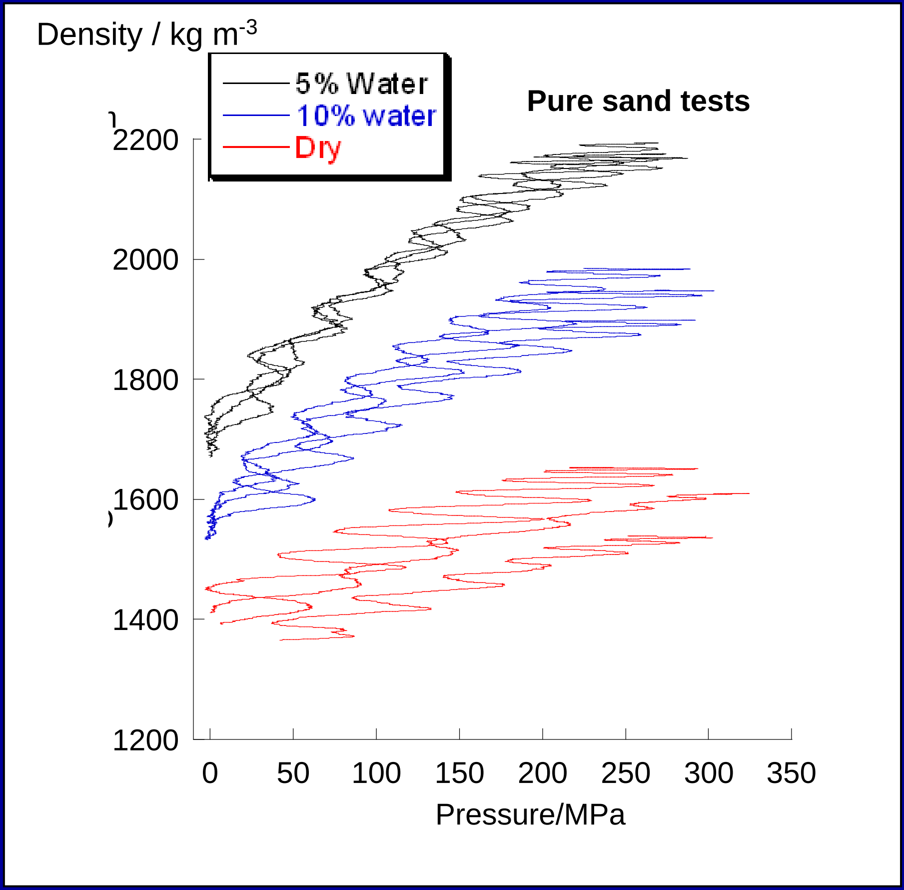


Raw Strain Signal



Stress + Deceleration (distance)

... and the results

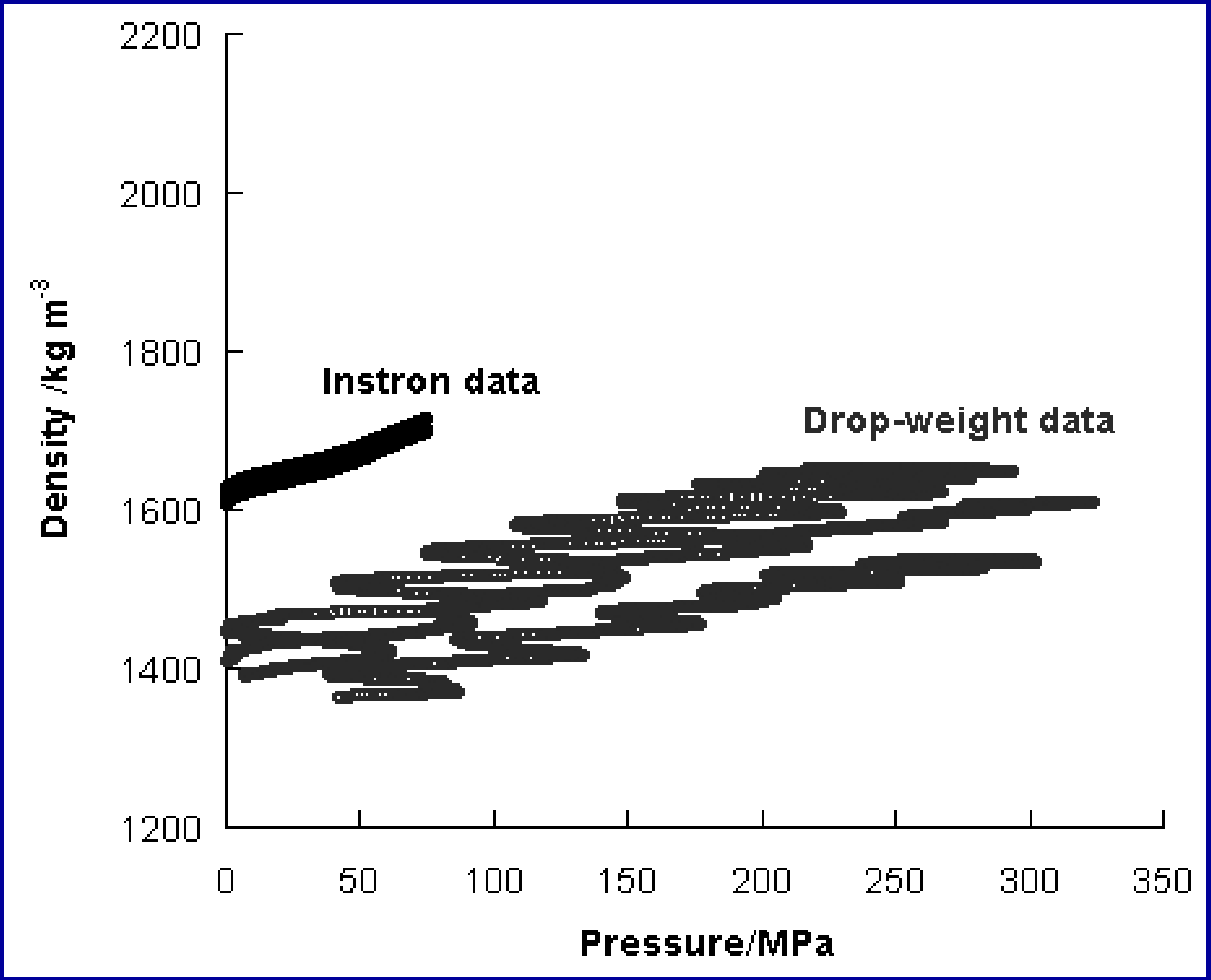


Trends

- Trends
  - Dry sand - little compaction
  - Wet sand - grain movement
  - Lubrication
  - In *all* cases limited fracture
- In Wet samples - see some water flow out of pores

Comparison -

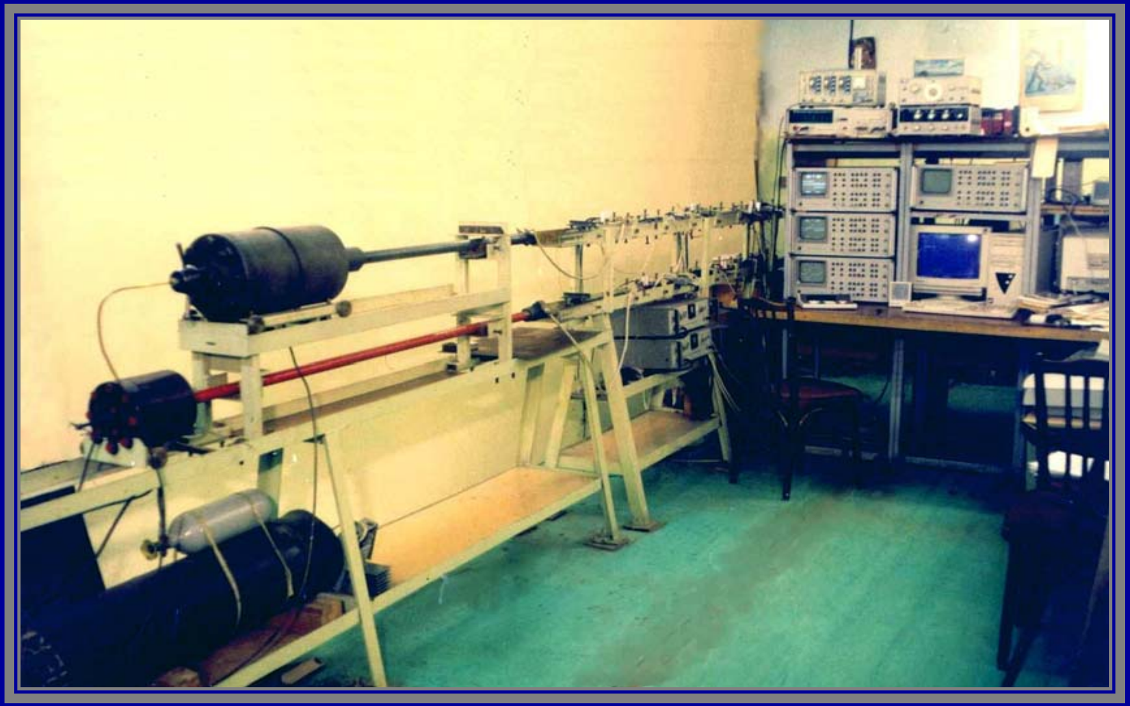
Comparison - Quasi to Dropweight

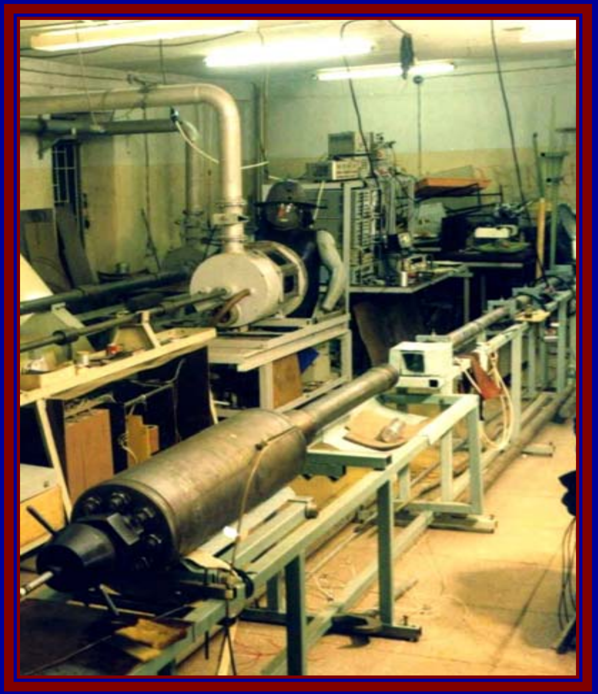


Intermediate Rates
Hopkinson Bar

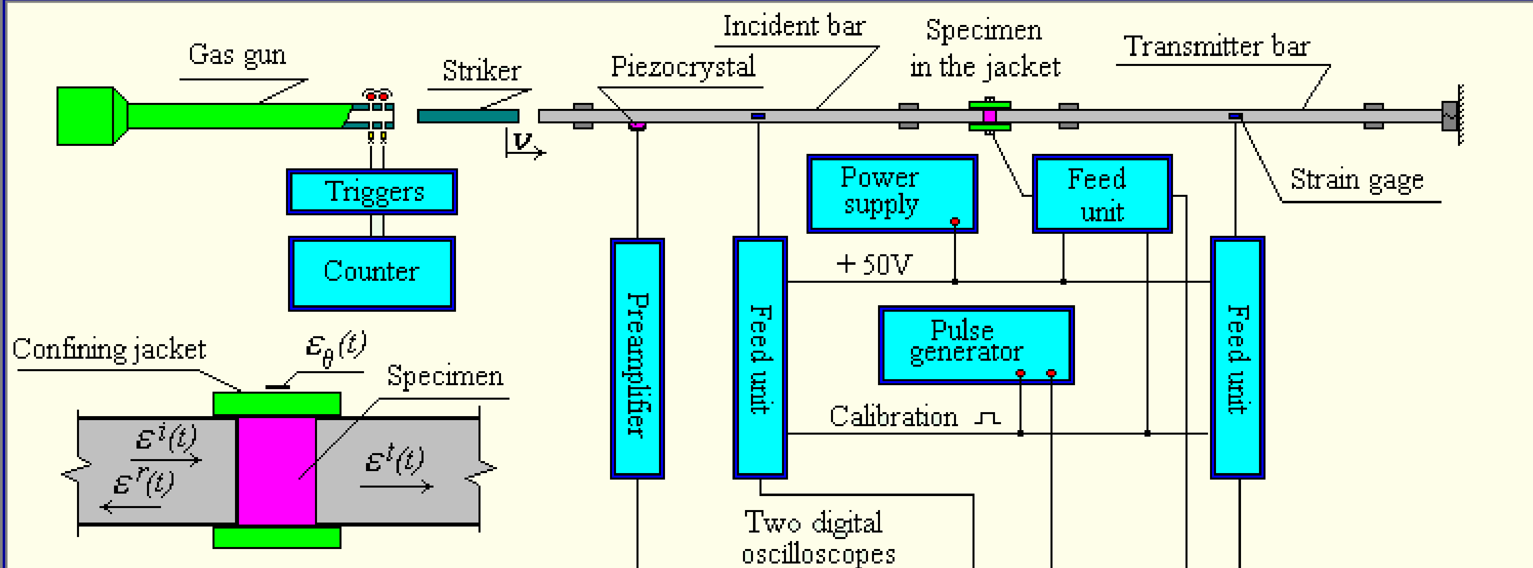
- Strain rate up to 10^4 s^{-1}
- Kolsky / Hopkinson Bar technique
- Bars - elastic waveguides
- Strain gauges on bars
- Stress-time / strain - time

Set Hopkinson pressure bars Diameter of 10/20 /60mm





Modified Kolsky method for poorly coherent and low-density materials



$$\sigma_x(t) = E\frac{A}{A_s}\,\varepsilon^t(t)$$

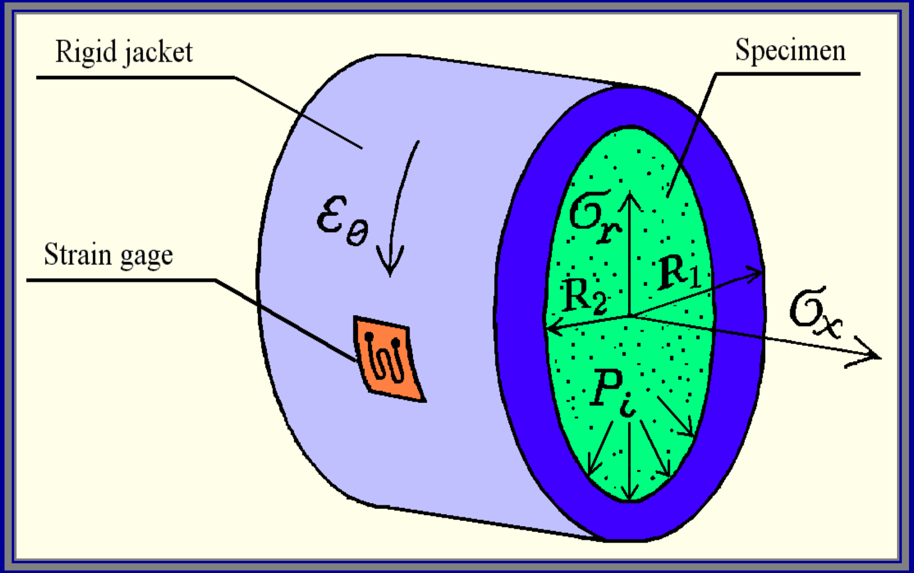
$$\varepsilon_x(t) = -\frac{2C}{Lo}\int_0^t \varepsilon^r(t)\cdot dt$$

$$\dot{\varepsilon}_x(t) = -\frac{2C}{Lo}\,\varepsilon^r(t)$$

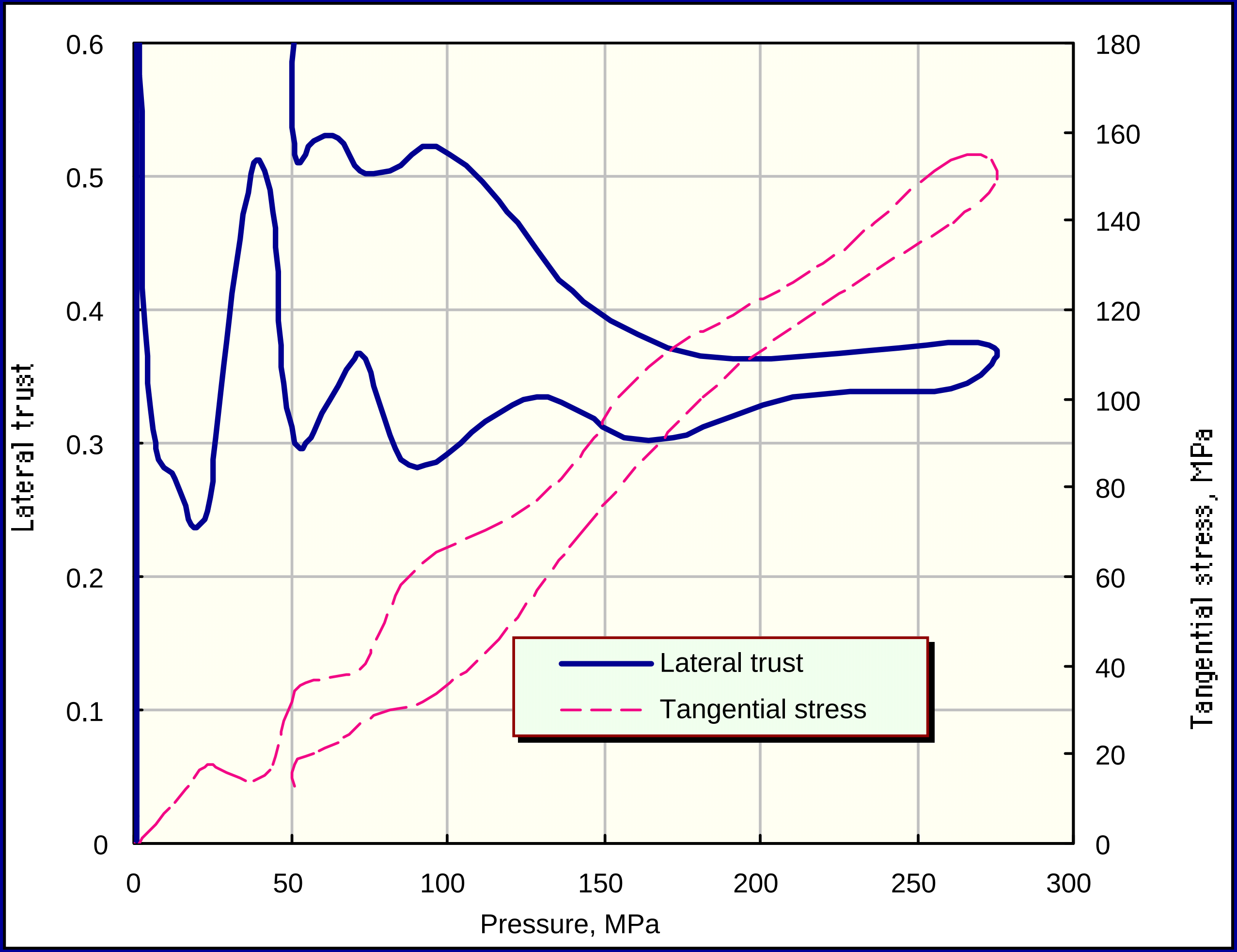
$$\sigma_r(t) = \frac{1}{2R_2^2}\left[E\left(R_1^2-R_2^2\right)\varepsilon_\theta(t)\right]$$

Stress / Strains in the System

Stress components in a specimen and in the confined jacket



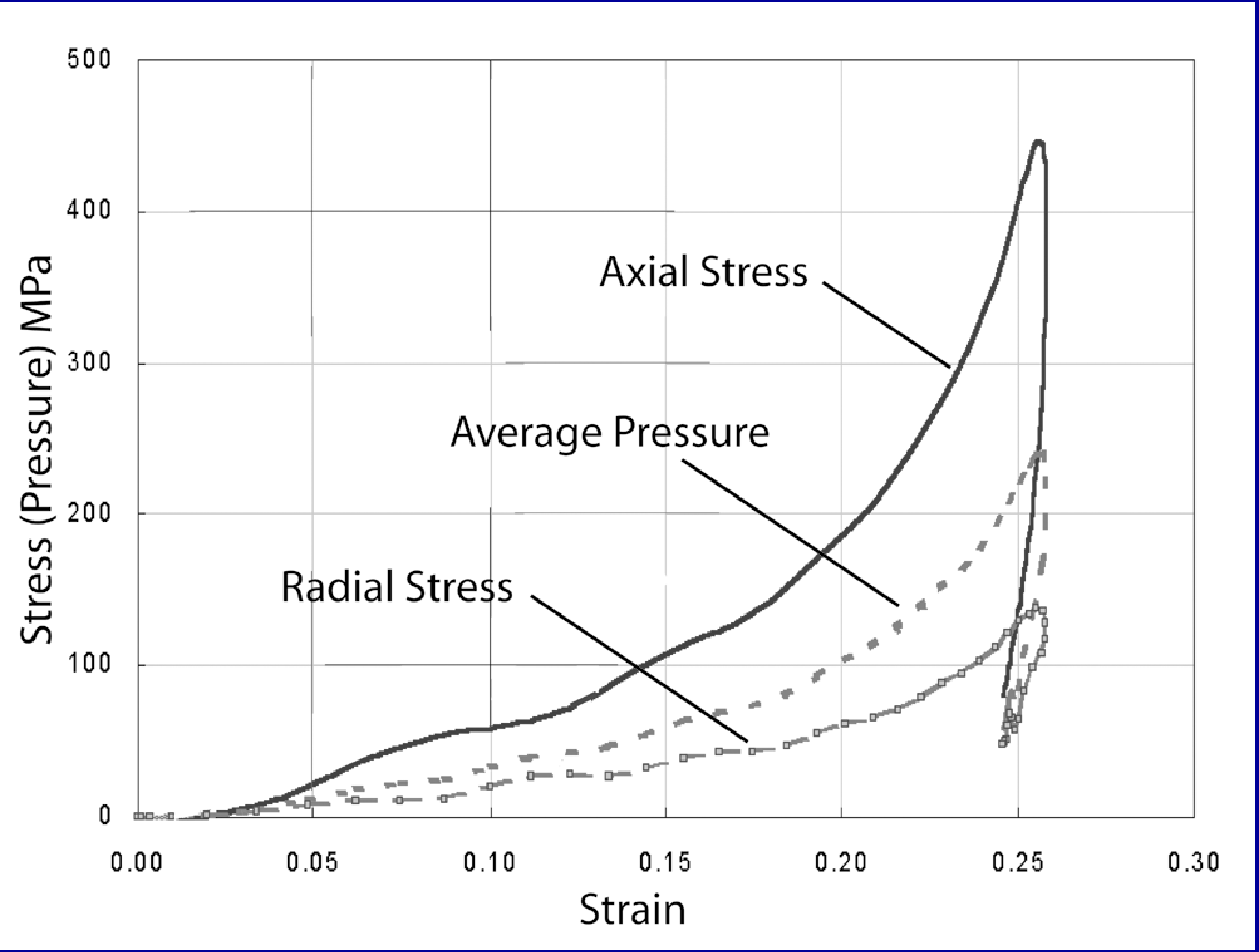
Data from Jacketed Hopkinson System



The Governing Relationships

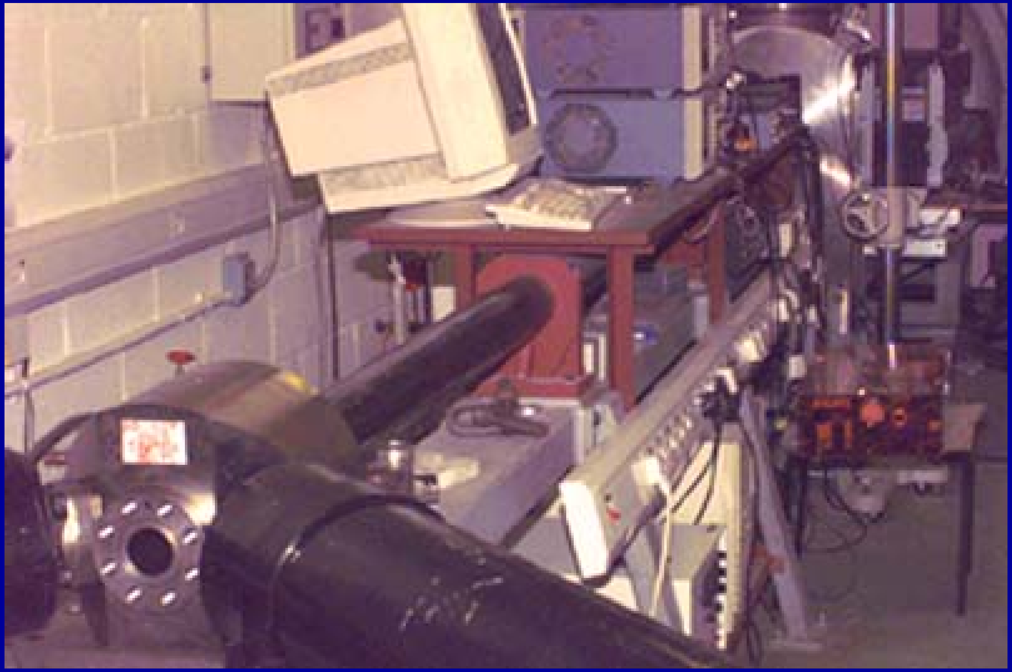
- $\tau = (\sigma_x - \sigma_r) / 2$
- $P = (\sigma_x + 2\sigma_r) / 3$
- $\tau = C + (\tan\psi)P$
- $P = (\sigma_x - {}^4/_3 C) / (1 + {}^4/_3 \tan\psi)$
- Loose soils - C is small - little static shear strength

Data obtained



The Cavendish Gas-Gun Facility

- *50 mm bore / 5 m long barrel*
- *20 l gas reservoirs*
- *350 atm. max. driving pressure*
- *150 - 600 g projectiles*
- *Velocities up to 1.2 km s^{-1}*



Manganin Foil Stress Gauges

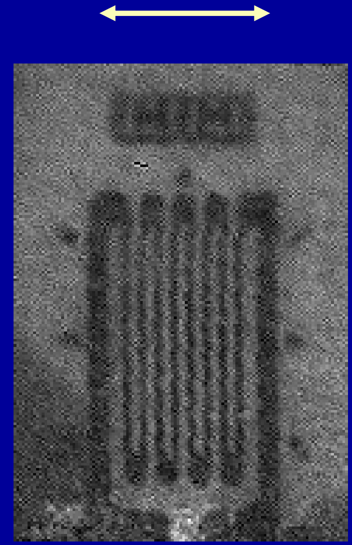
Gauges - piezoresistive

Time resolution 30 - 200 ns dependant on geometry

Accuracy ± 2.5%

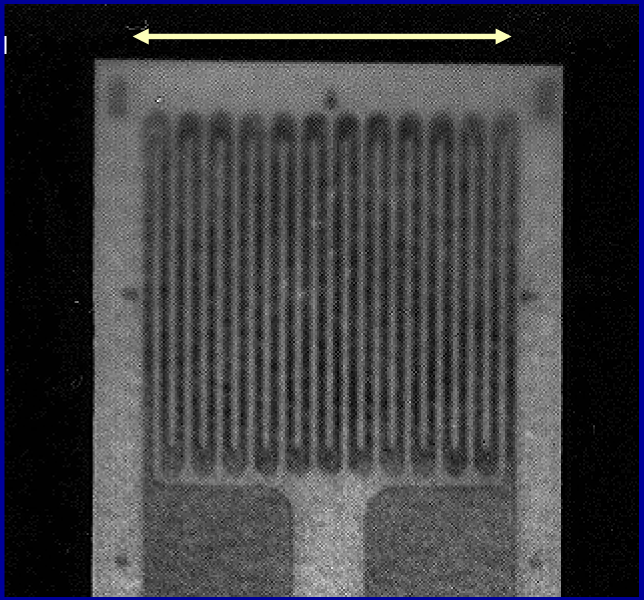
Different sizes available

2.3 mm



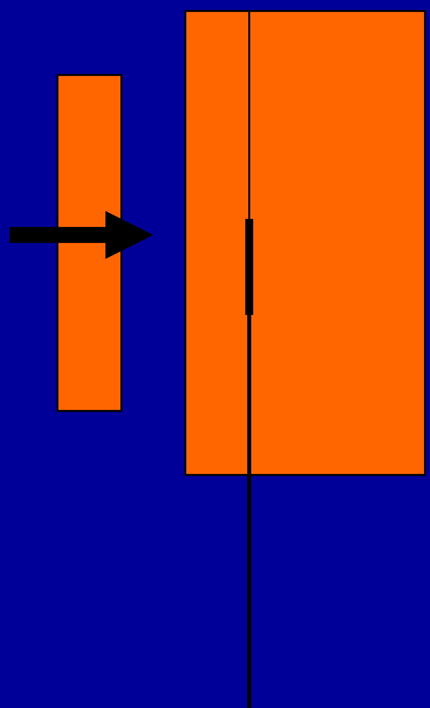
Encapsulated Gauge

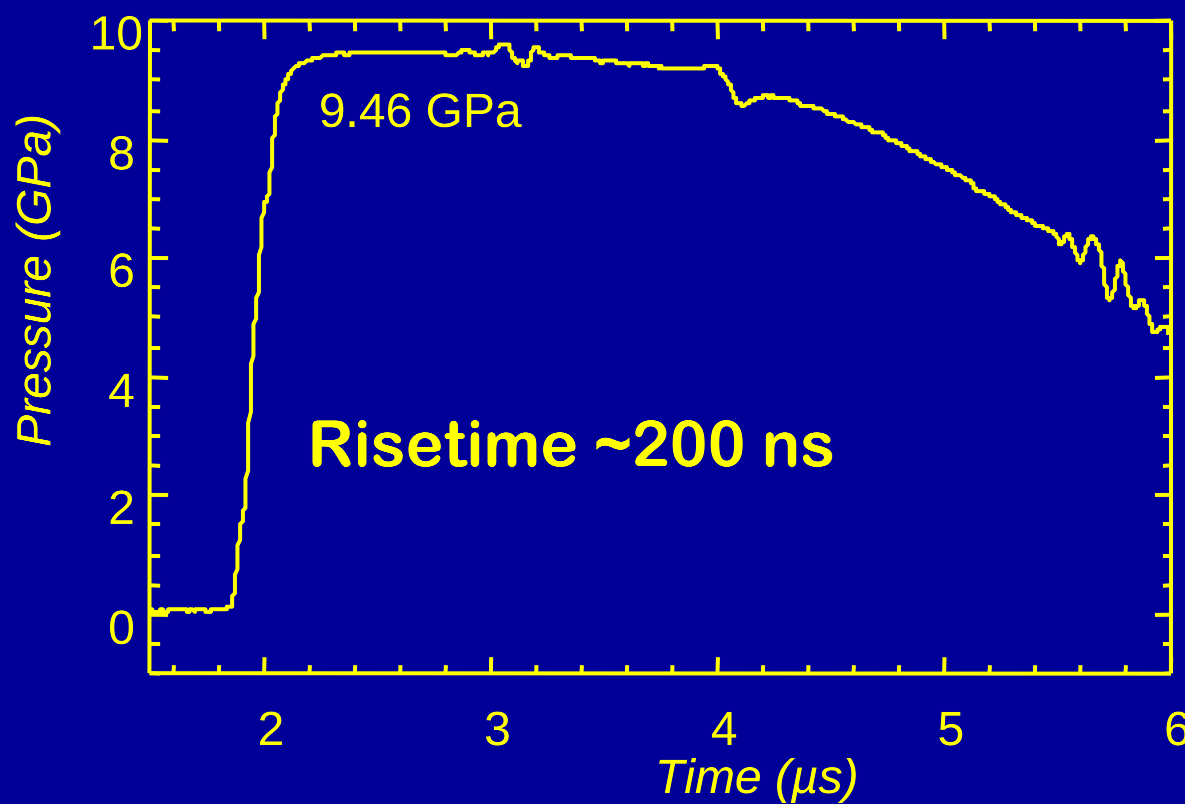
6.0 mm



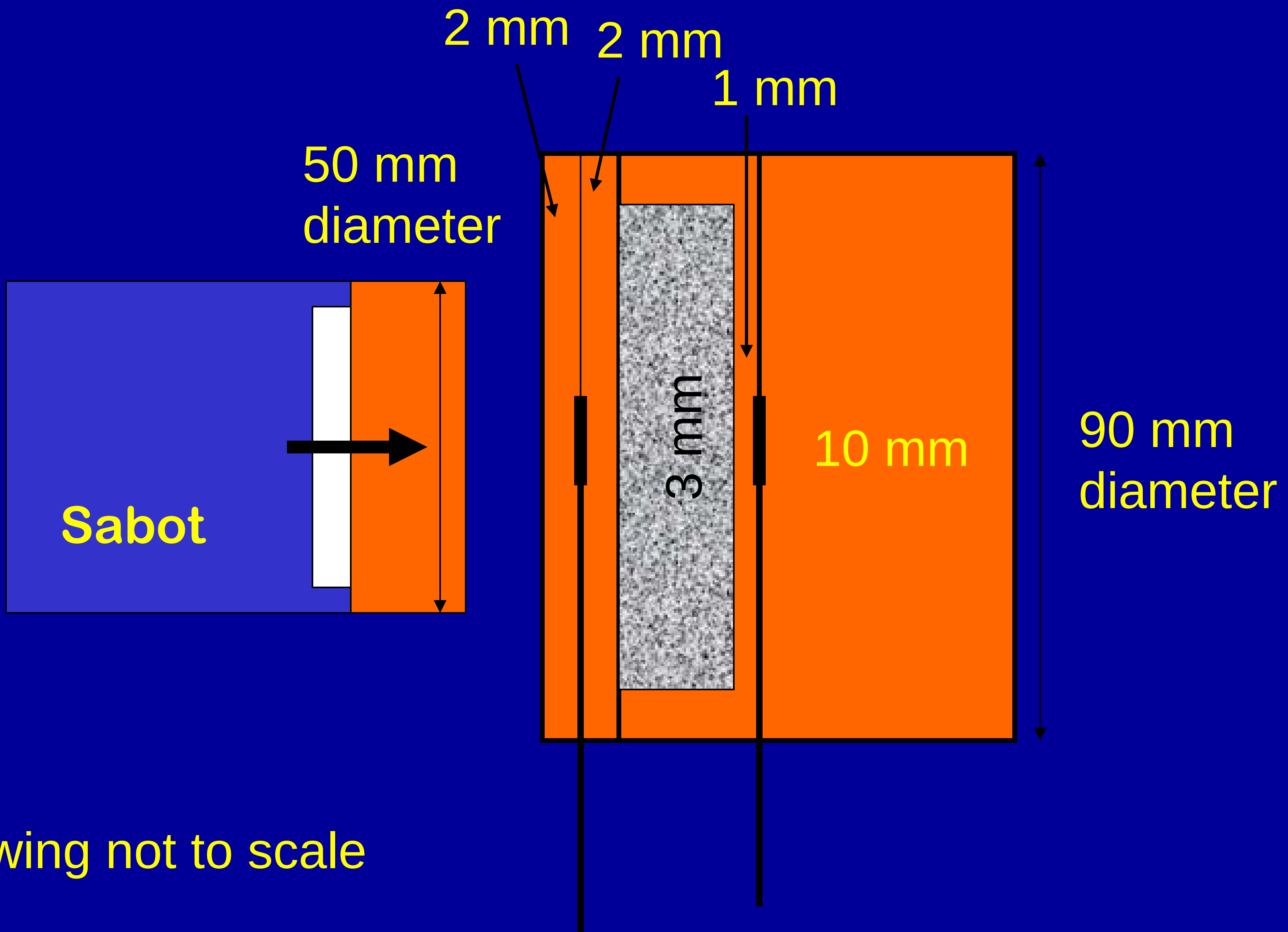
Copper Impactor on Copper Target

- Impact Velocity = 498 m s^{-1}, 10 mm Cu Flier
- Target = Impact Face / 10 mm Cu / Gauge / 20 mm Cu



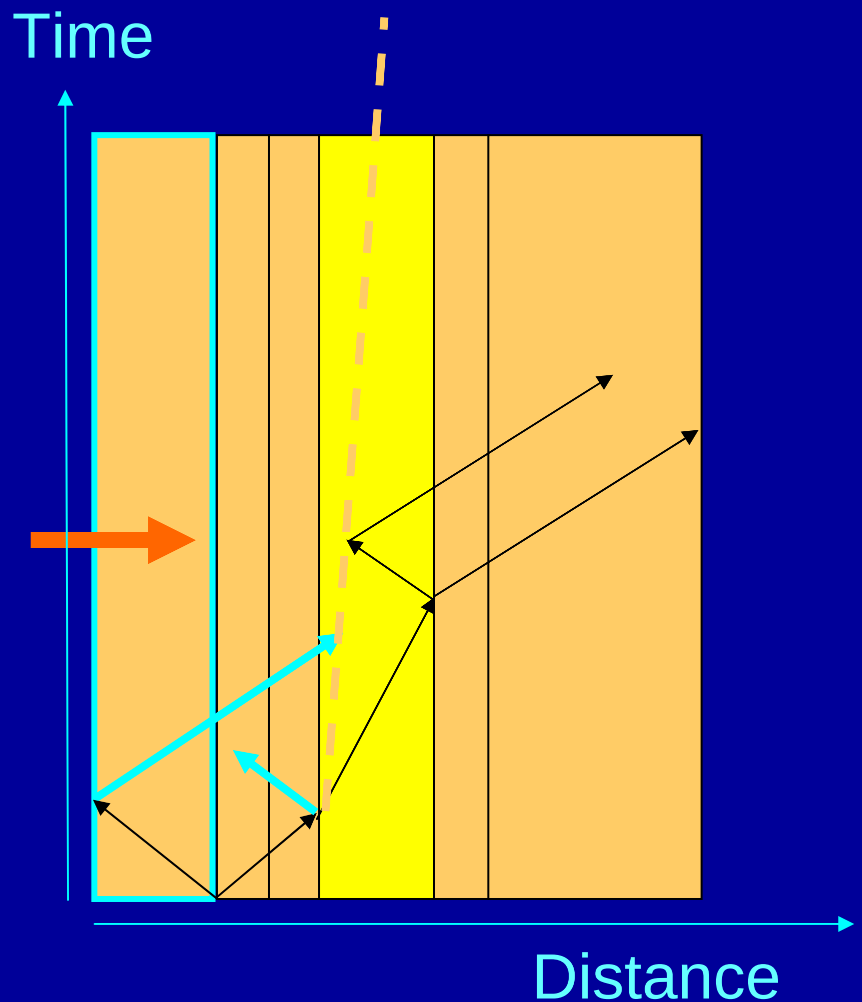


Sample Arrangement



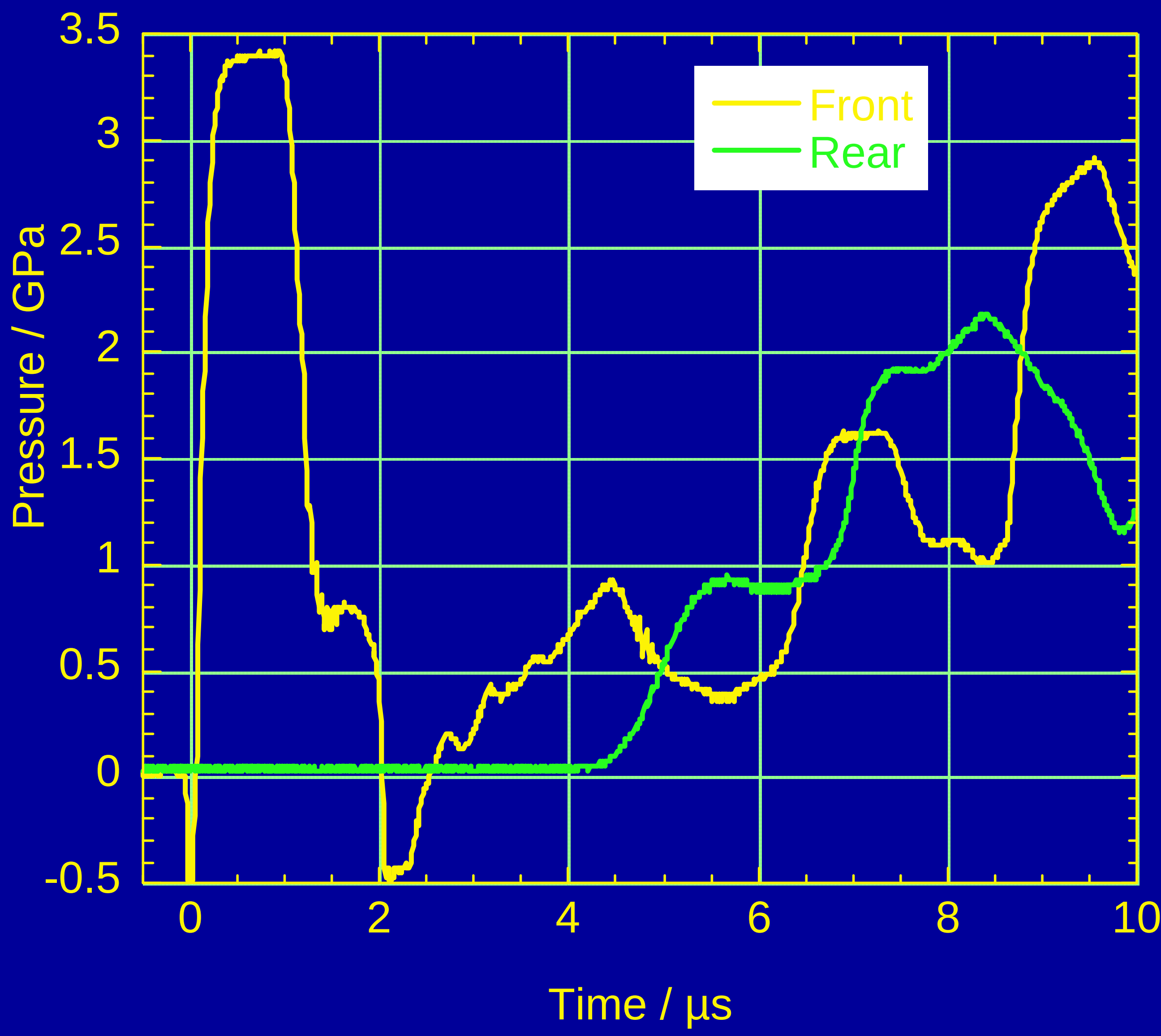
Drawing not to scale

Wave reflection in cell

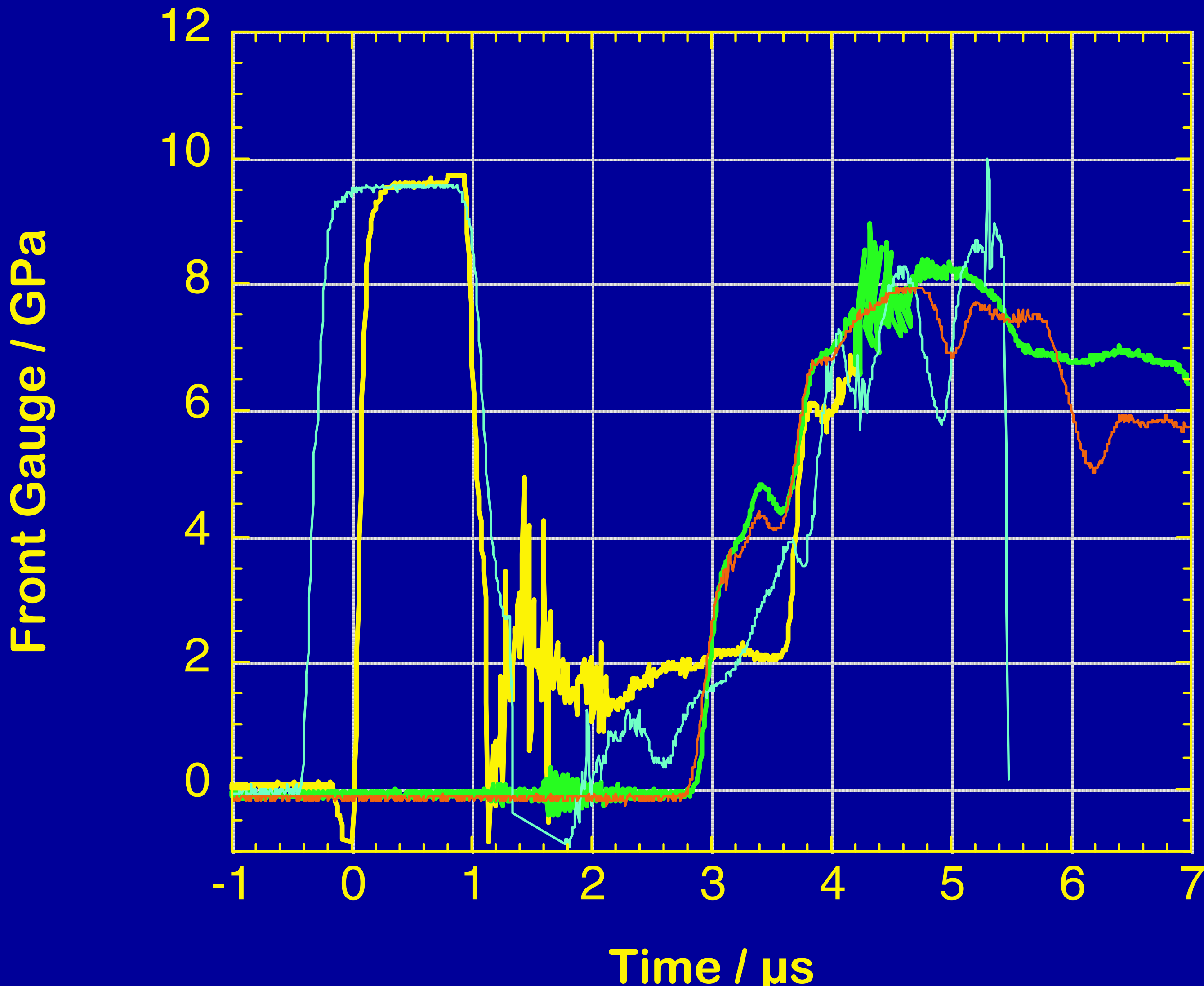


- Shock waves - black lines
- Release waves - blue lines
- Dashed line - indicates compaction

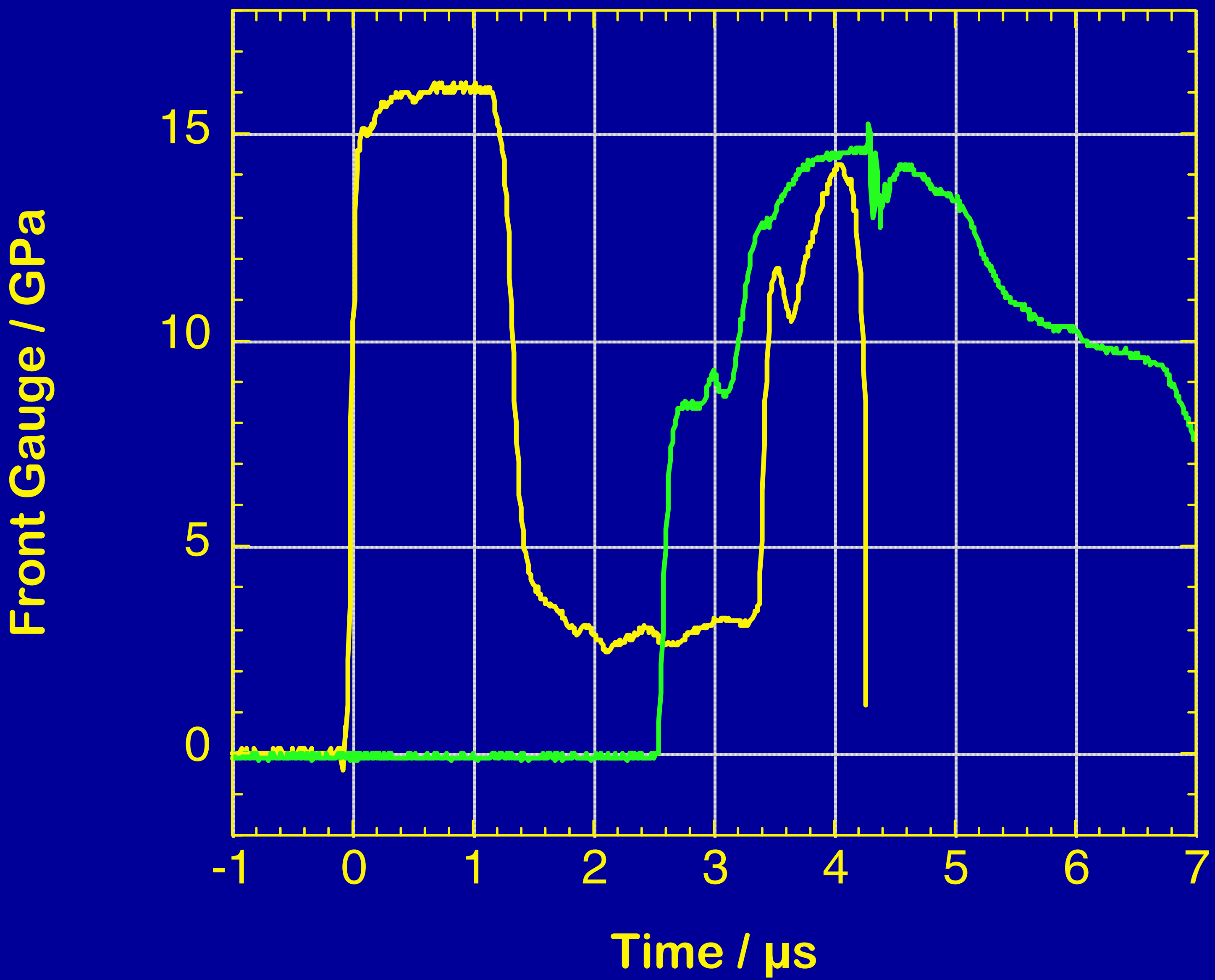
Impact at 200 m s^{-1}



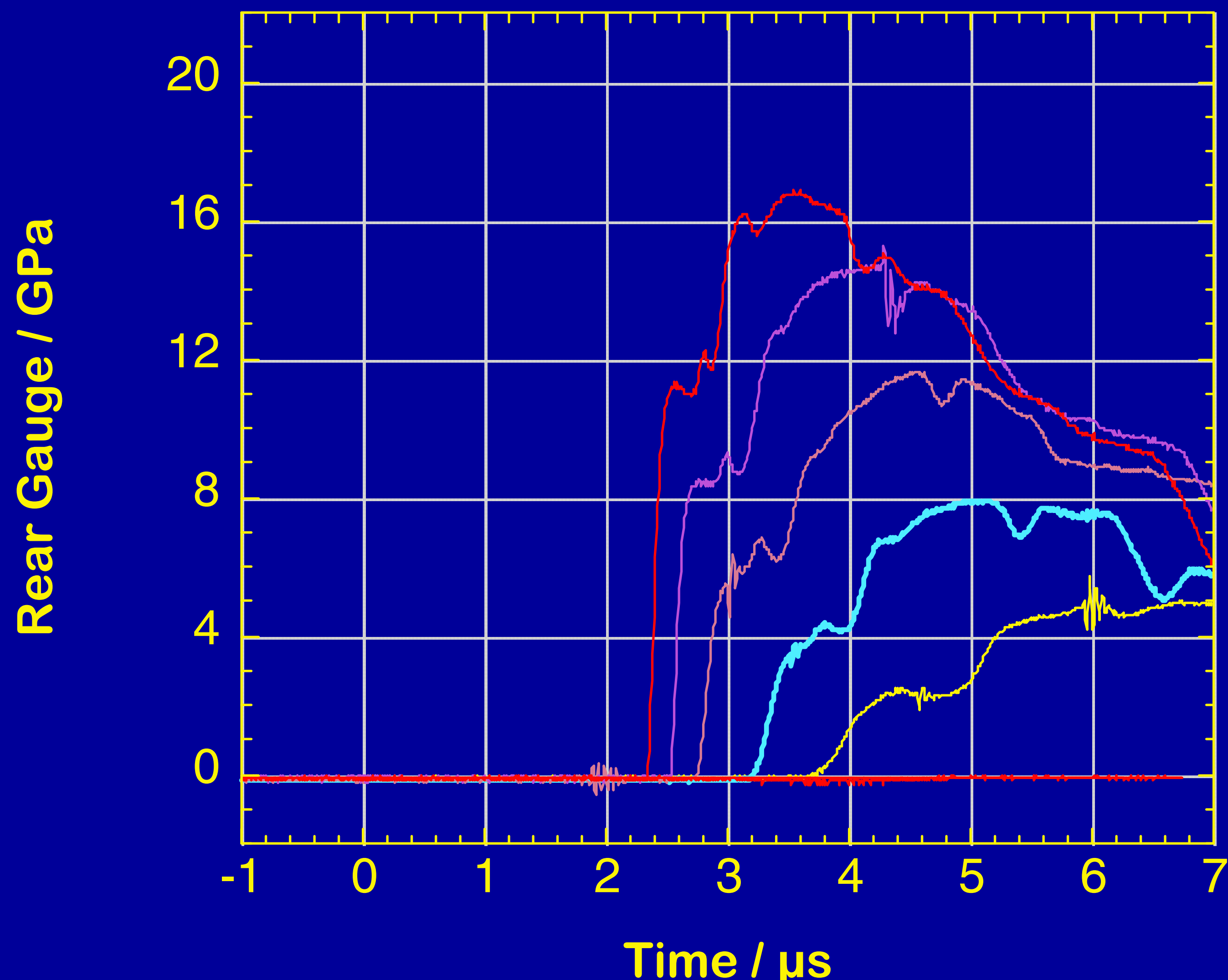
500 + 505 m s^{-1}



$812\ m\ s^{-1}$



Rear Gauge Variation



Features in Output Traces

- Ramping region - pore collapse
- Shock velocity on principal Hugoniot

  time difference between gauges
- 1st Plateau - secondary Hugoniot
- 2nd Plateau - ring-up, wave reflection
- Shock velocity in pre-compressed sand (gauge comparison)

Shock thickness / particle size

- Rise time of first pulse
- Shock velocity

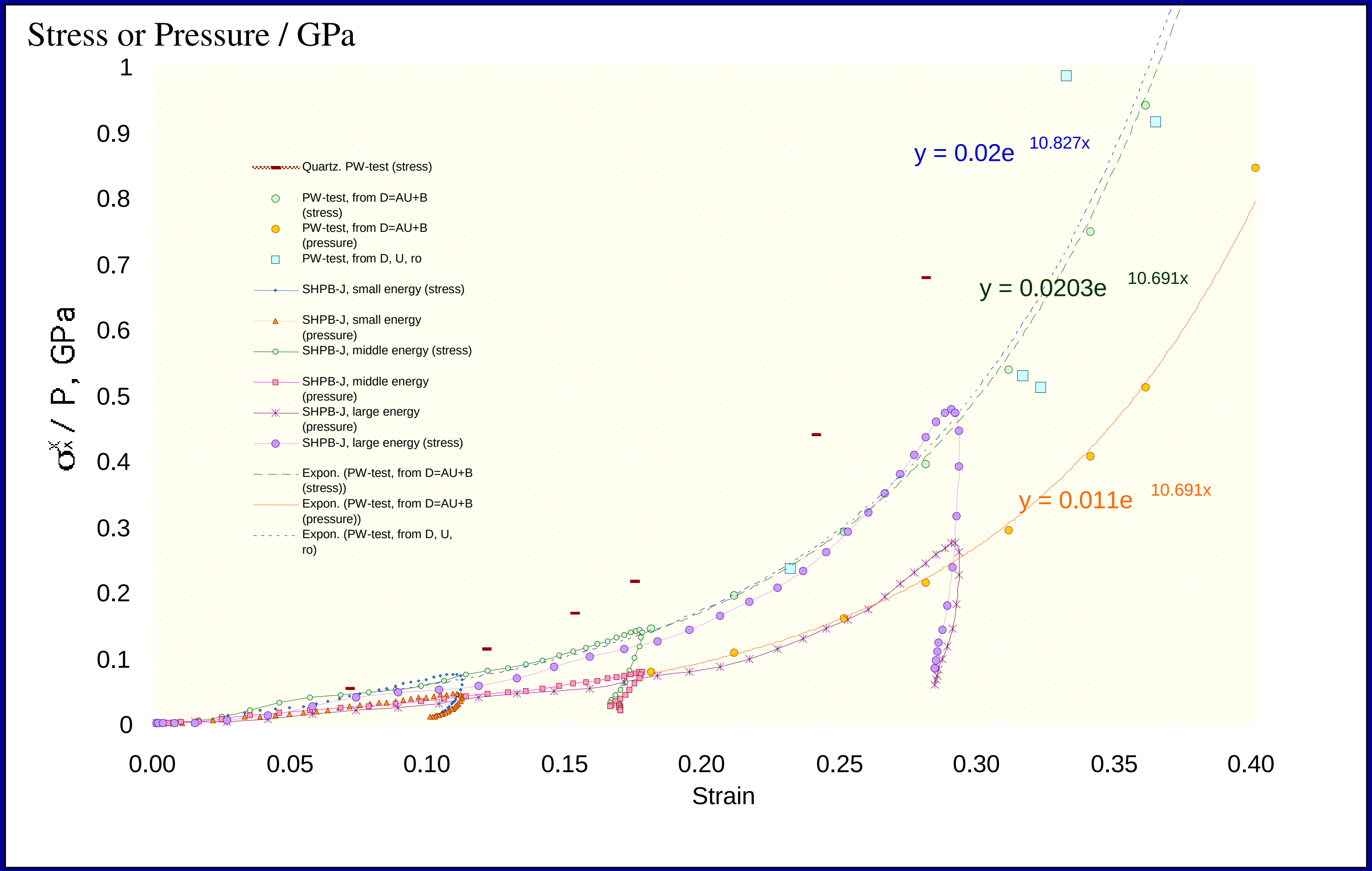
- 200 m s^{-1}
  - 1 μs rise time and U_s 1 mm μs^{-1}
  - 1 mm or 4 grain particles
- 500 m s^{-1}
  - 0.5 μs rise time U_s 1.4 mm μs^{-1}
  - 0.7 mm or 3 grain particles
- 800 m s^{-1}
  - 0.2 μs rise time and U_s 2 mm μs^{-1}
  - 0.4 mm or 2 grain particles
- Need appropriate length-scale model (mesoscopic)

Comparison -
Intermediate to High-rate

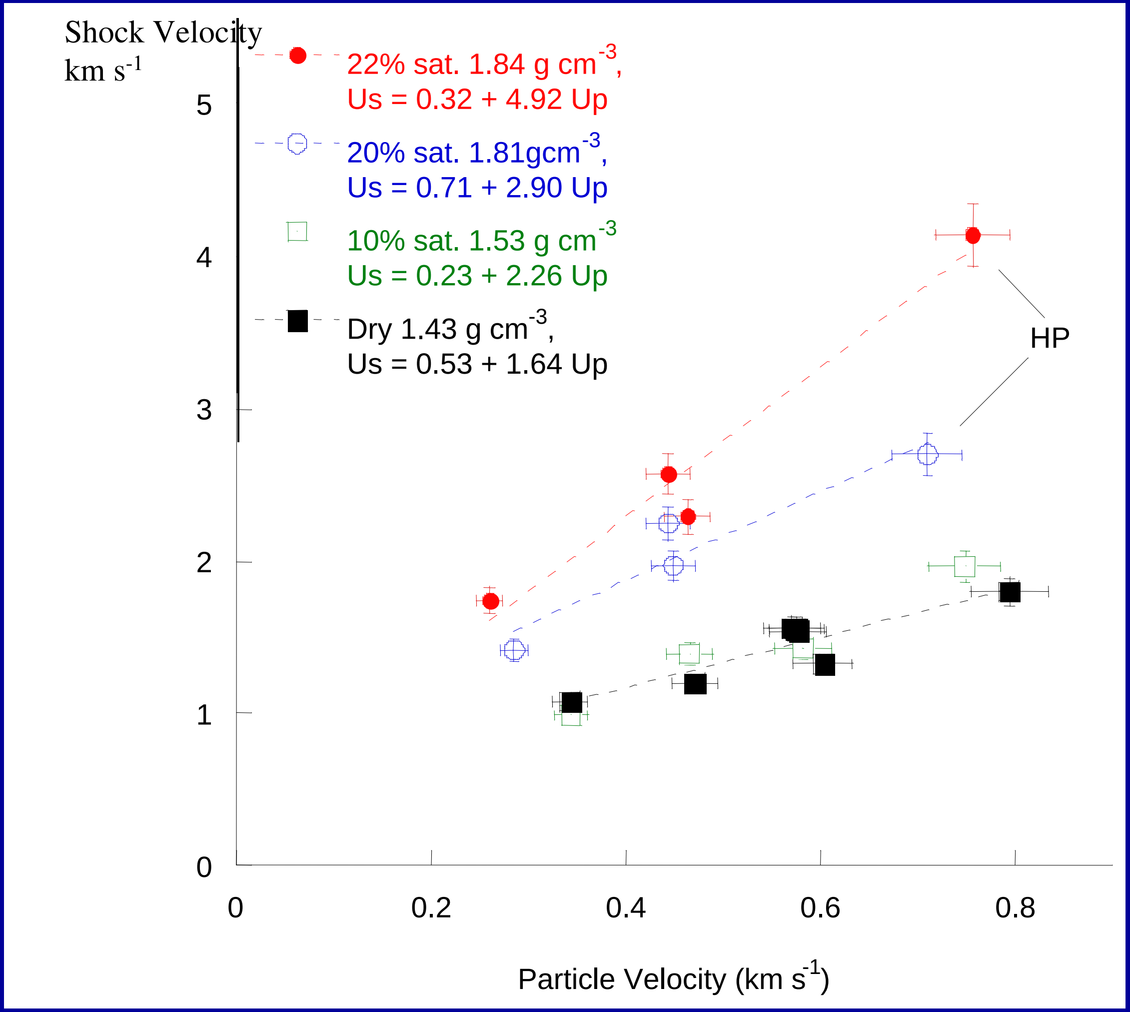
- Assume relationship lateral v. longitudinal stress ~same in shock

- Overlap of stress range of Hopkinson bar with the shock study

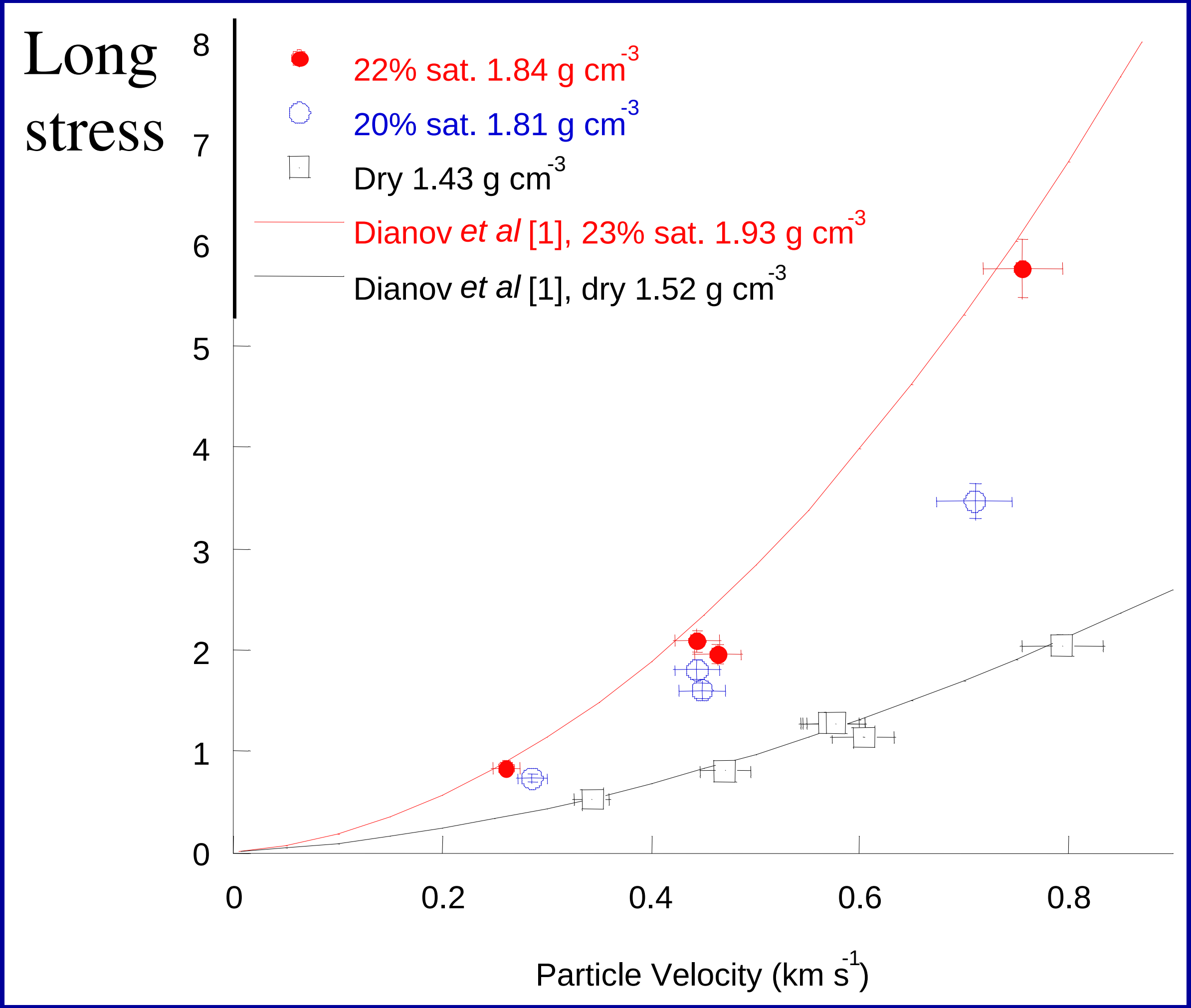
Results Combined Stress + Pressure



Water content Particle Velocity Space



Stress Space



Effect of Water Content

- 0-10% water (weight) ~ dry
- 10 - 20 % marked change
  - Higher level, faster sound speed
- Change 20 to 22% as large as from 10 - 20%

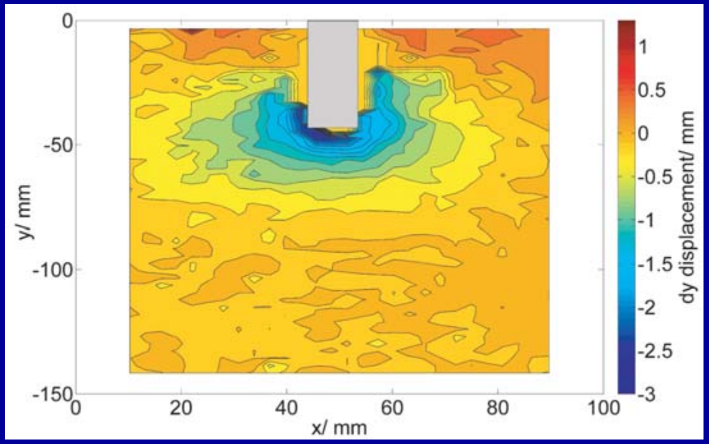
Conclusions

- Sand characterised over a range of conditions
- Low rate = friction / grain movement
- High rate = fracture
- Water content = strain rate dependant,
  - Low rate few % - big effect - lubrication
  - Intermediate rate - stronger effect at higher levels
  - High rate -small % water, no effect (>10%)
  - Large effect small % change at high saturation
- Measured Bulk Response
- Low-density sample shows different strain rate dependance, compaction processes

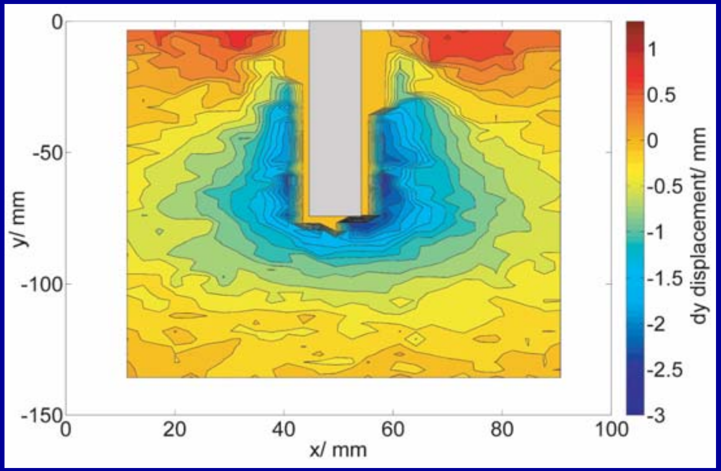
Recent / On-going Areas

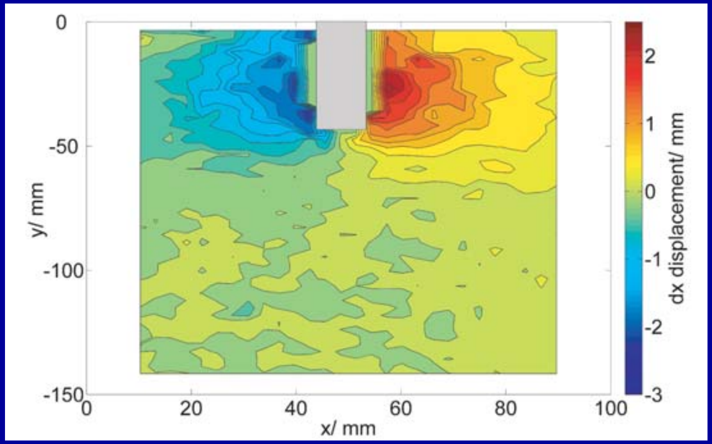
- Grain size over a wider interval
- Find size / volume element that can be used to describe bulk response
- Model the fracture, collapse process
- Meso-level modelling
- Ductile grains

Dyanmic Impact - Longitudinal and Lateral components

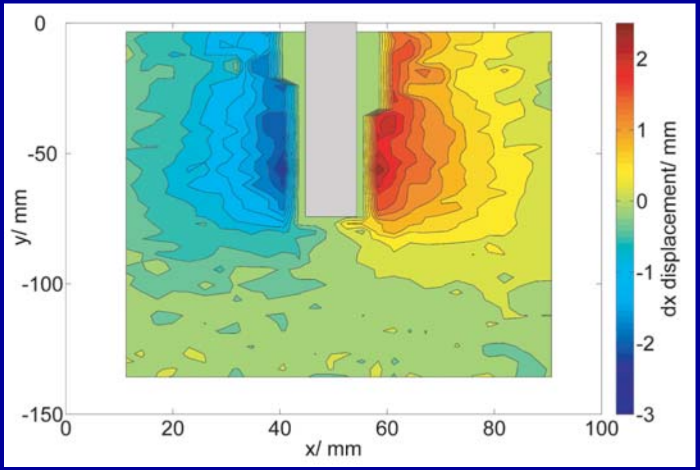


1. Expanding cone shaped area of material moving longitudinally
2. Fixed angle of cone through all images





1. Lateral displacement roughly uniform along rod
2. Same lateral extent of deformation throughout



250us after impact

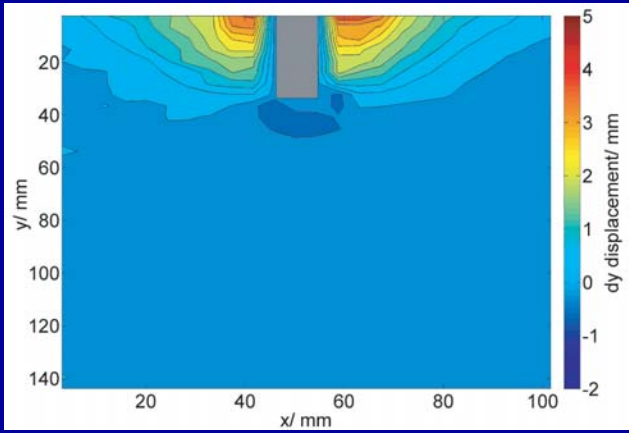
450us after impact

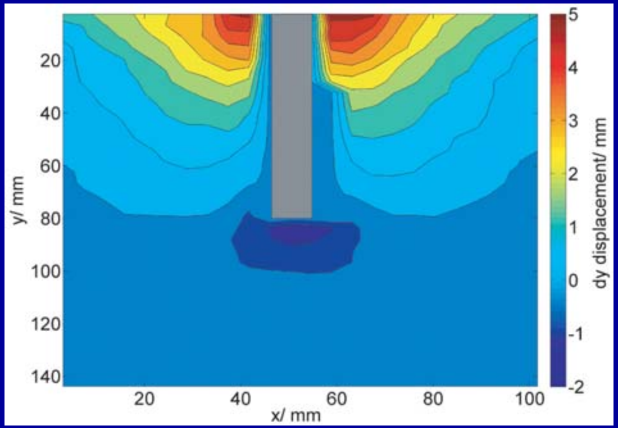
Flow Fields – J. Addiss, Thesis 2009

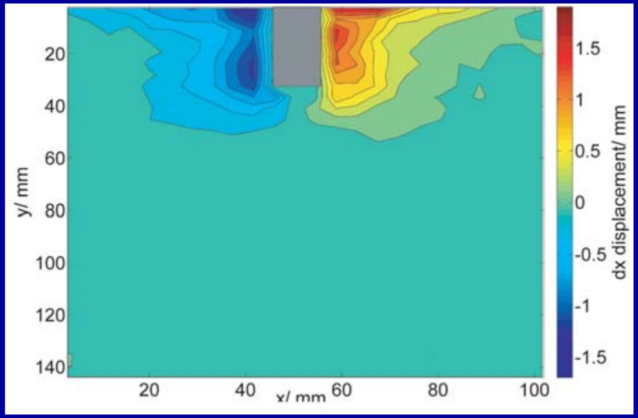
Quasi-static penetration

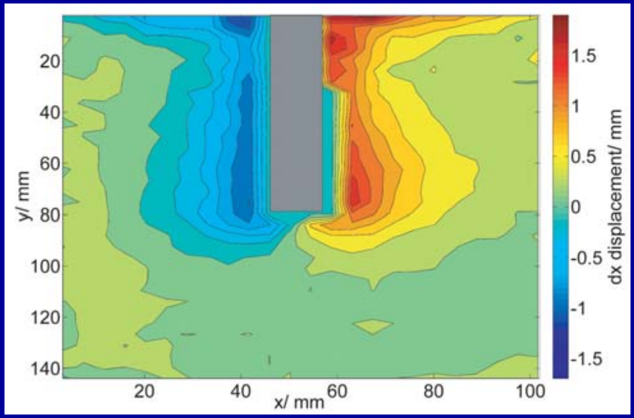
- Penetration carried out at a rate of 1.5 mm/min (2.5×10^{-5} m/s) using an Instron compressive tester.
- Same sample geometry, projectile, x-ray setup etc.
- Looking for rate dependence in the penetration process – will give a fuller understanding of the behaviour of the material

Longitudinal and Lateral components

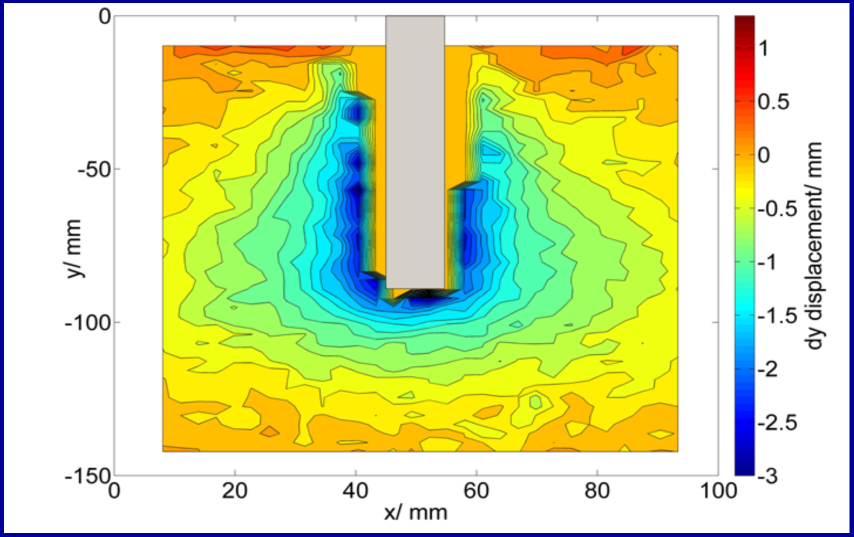


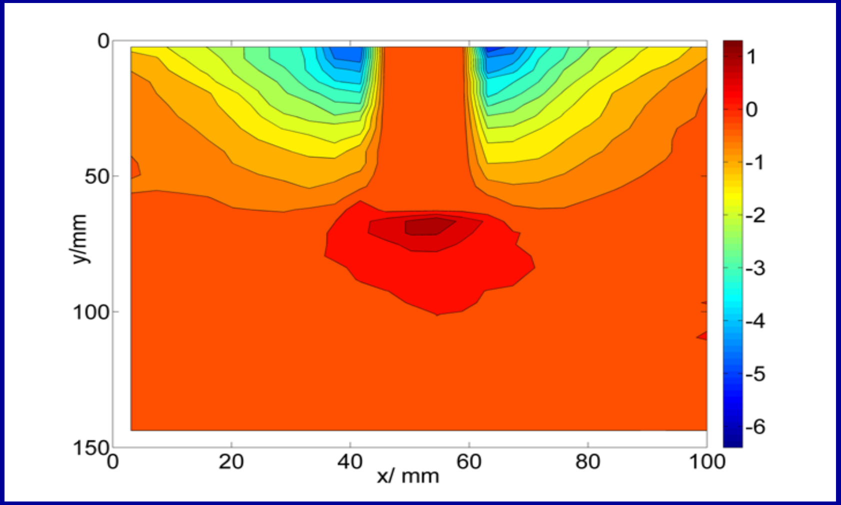






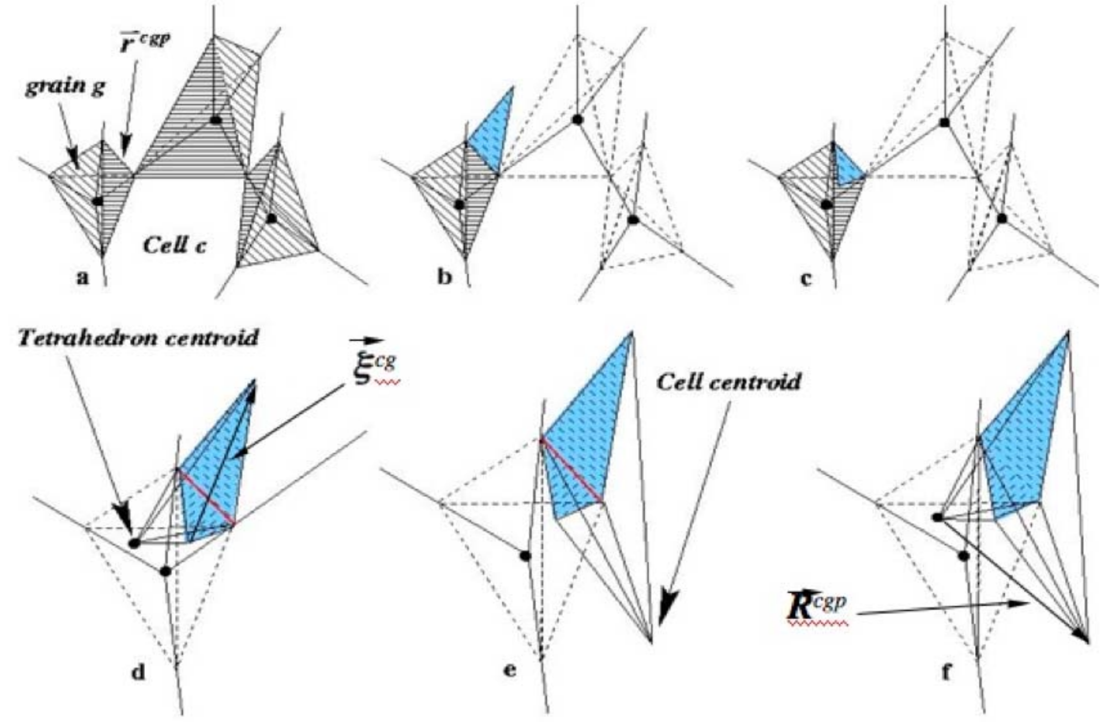
Comparison





- In the quasi-static case most of the material down to the rod tip is moving upwards
- There is no travelling compaction wave in the material

Theoretical Construct
R. Blumenfeld



$$C_{ij}^{cgp} = \left(\vec{\xi}^{\,cgp} \times \vec{r}^{\,cgp}\right)_i R_j^{cg}$$

$$V^q = V^{cgp} = \frac{1}{3} Tr\{\overleftrightarrow{C}^{cgp}\}$$

Acknowledgements

- D.L.A. Cross, R. Flaxman, D. Johnson, R. Marrah - Cavendish Laboratory
- D. Tam and L. Taylor - NSWC - 2002
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