Sandia National Laboratories

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PHYSICAL LARGE CENTRIFUGE MODELING OF UNDERGROUND CHEMICAL EXPLOSIONS

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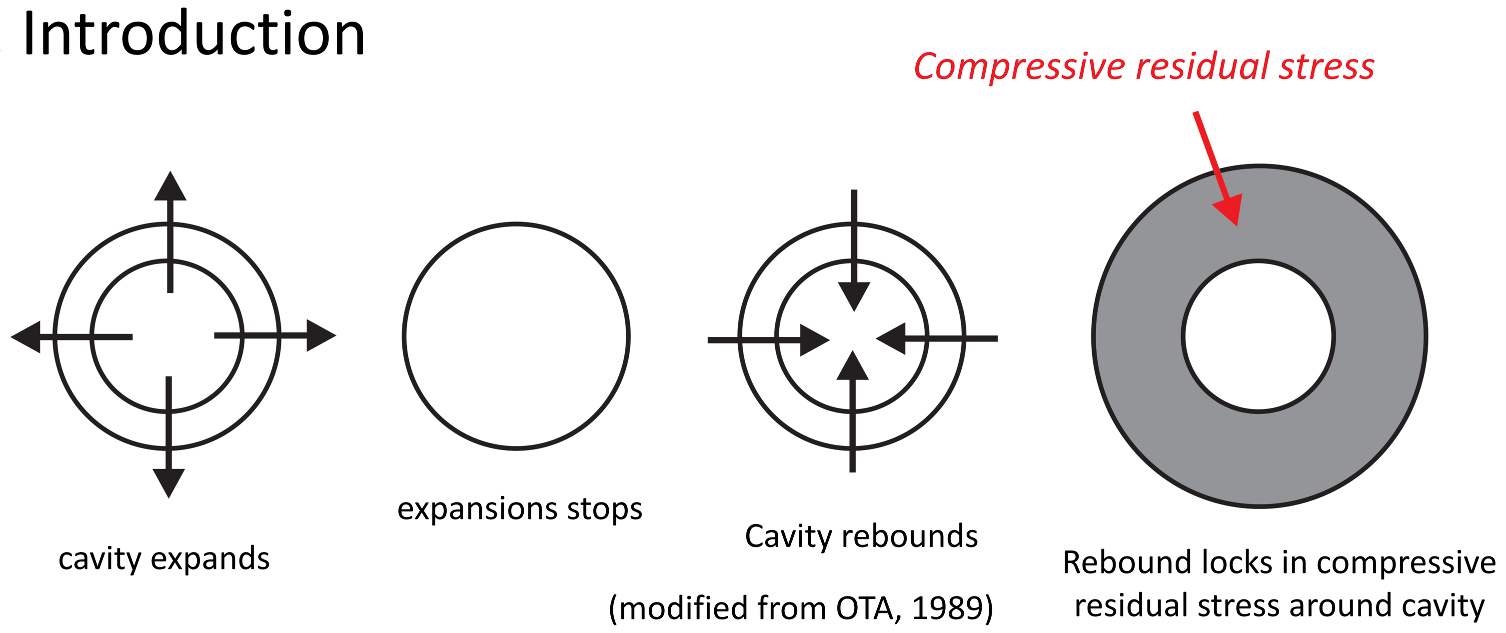
1. Introduction



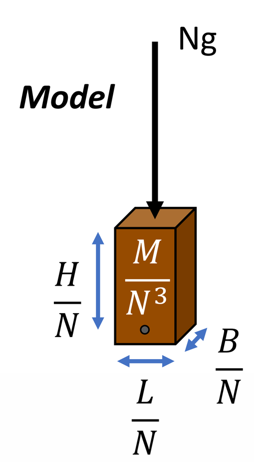
(modified from OTA, 1989)

Formation of a compressive residual stress cage around an explosively formed subsurface cavity acts to close fractures and contain debris, including liquids, gases, and particulates. We have developed a new ***meso-scale*** geomechanics capability using an 8.84-m (29-ft) radius centrifuge for physically simulating underground chemical explosions and potential stress cage processes in scaled geologic models.

Development goals for this meso-scale capability:

- model size represents key domains of 3D real-world system
- high-strain rate dynamic events captured with real-time data collection
- high-resolution pre/post X-ray CT comparison for rock deformation

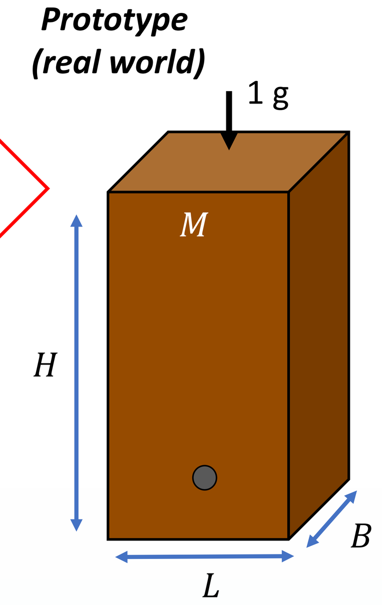
2. Centrifuge Scaling



Scaling: represent prototype with model

Place 1/Nth model in increased gravity field of N × earth's gravity

See Kuhlman and Heath, 2023, Scaling Containment on a Large Centrifuge, SAND2023-02634



1:1 Stress Similitude

$$\sigma_v = \frac{force\ (ma)}{area} = \frac{\frac{M}{N^3} \times Ng}{\frac{L}{N} \times \frac{B}{N}} = \frac{Mg}{L \times B} \quad \Longleftrightarrow \quad \sigma_v = \frac{force\ (ma)}{area} = \frac{M\ g}{L \times B}$$

$$\frac{L_m}{L_p} = \frac{1}{N} \qquad \frac{A_m}{A_p} = \frac{L_m^2}{L_p^2} = \frac{1}{N^2} \qquad \frac{V_m}{V_p} = \frac{L_m^3}{L_p^3} = \frac{1}{N^3}$$

Length, area, and volume scaling

$$\frac{F_m}{F_p} = \frac{M_m g_m}{M_p g_p} = \frac{M_m N g_p}{M_p g_p} = \frac{N}{N^3} = \frac{1}{N^2}$$

Force scales as N^2

$$\frac{E_m}{E_p} = \frac{F_m L_m}{F_p L_p} = \frac{1}{N^2 \cdot N} = \frac{1}{N^3}$$

Energy scales as N^3

Explosive scaling: specific energy is constant; total energy is the product of that with density and L^3. Thus, one gram of explosives at 100 applied g or *N* = 100, scales to 1,000,000 grams or one metric ton.

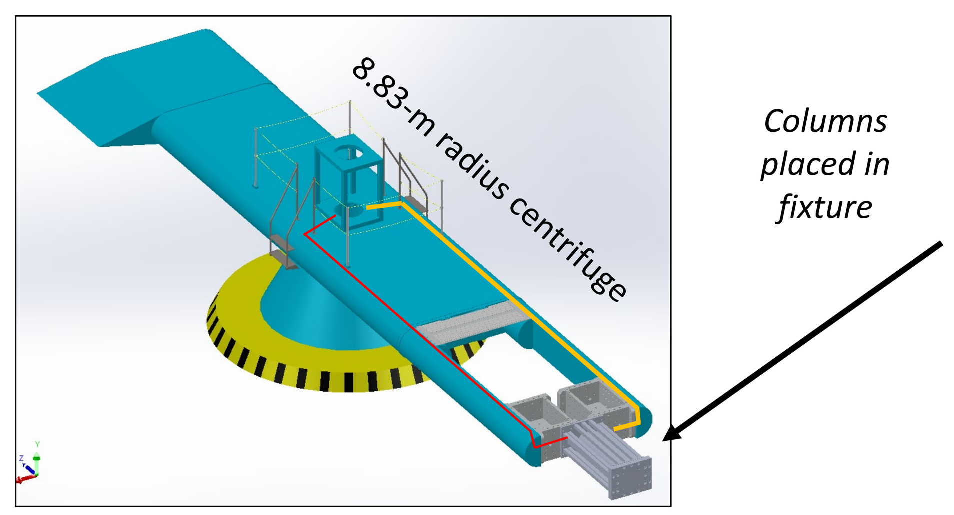
3. Methods

Centrifuge testing was performed on two mechanical "rock-matching" grout columns with embedded chemical explosives in different seismic coupling configurations, accelerometers, and strain indicators.

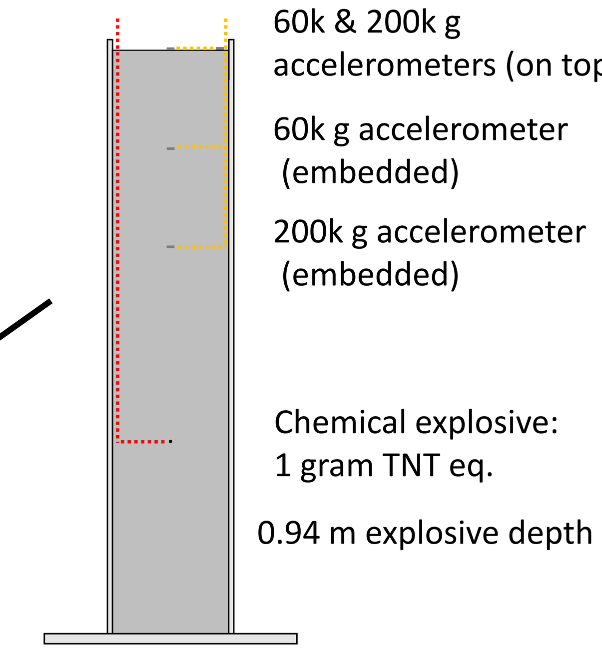
Centrifuge test matrix at 100× normal Earth's gravity or N = 100

Coupling	Explosive	Scaled explosive	Foam chamber diam.	Scaled cavity diameter
Fully	1 gram	1.0 metric ton TNT eq.	NA	NA
Partially	1 gram	1.0 metric ton TNT eq.	2 cm	2 m

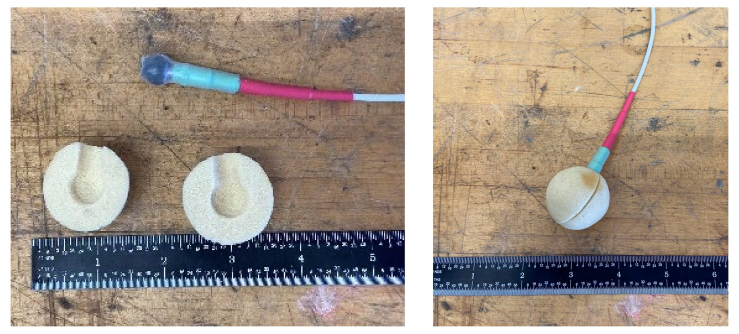
Energy scales as N^3



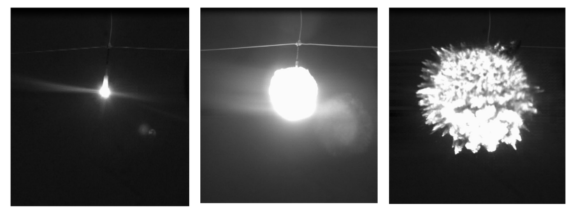
Test time: 12 minutes, which scales to 83.3 days



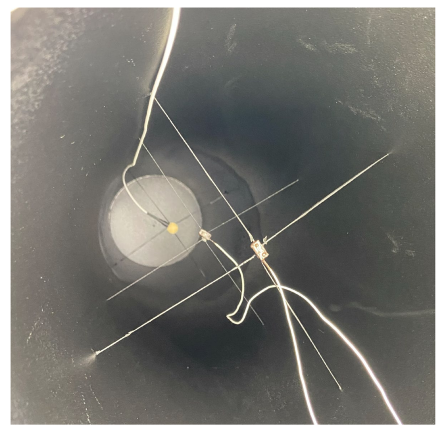
1.45-m by 0.3-m (4.75' by 12") coated Al tubes with rock-matching grout



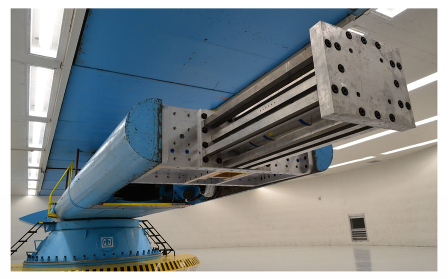
PRIMASHEET 1000 (63% PETN) shaped as a sphere, on RP-2 detonator; 7,100 m/s det. velocity (EBAD, 2020)



Progression of spherical explosion in air per explosive design (not in foam)



View of coated Al tube prior to filling with grout, with 1-gram partially-coupled chemical explosive



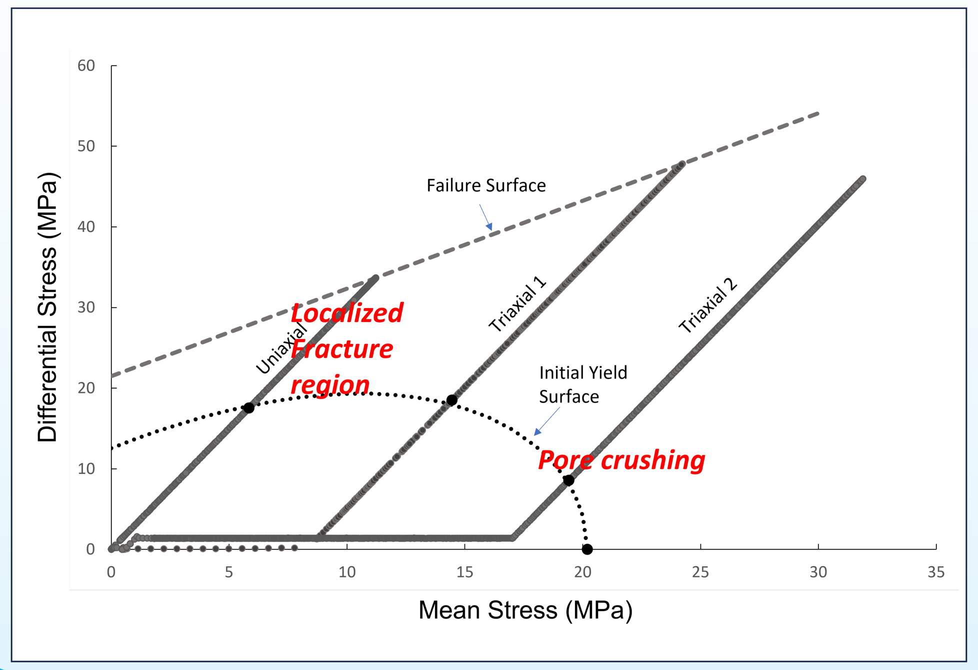
Sandia's 8.84-m radius centrifuge

- 300 g max. (limited by fixture)
- 7257 kg (16,000 lb) max payload
- 1.6 million g-lb capacity
- 2.1-m (7-ft) wide attachment

Column/grout characterization:

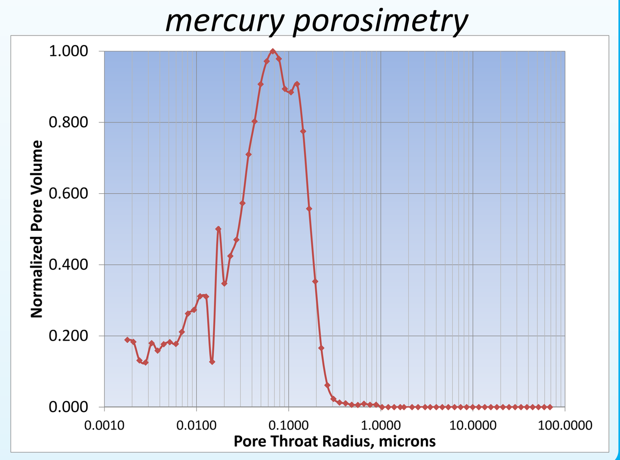
- Strain indicators: steel balls (1.588-mm diameter) in grout
- Pre/post X-ray CT
- Standard lab geomechanical and hydrological testing on molds from batches of grout

4. Results – Material Properties of Grout Samples



Yield and failure surfaces for multiple stress paths performed on grout plugs (from cast molds)

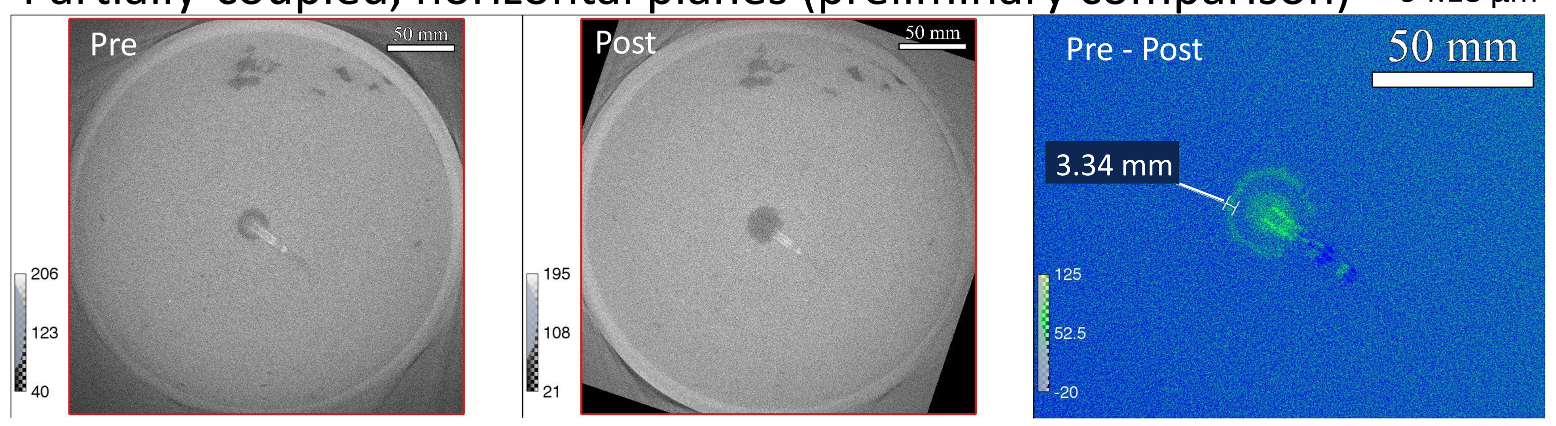
Pore size distribution from mercury porosimetry



5. Results – Pre/Post X-ray Computed Tomography

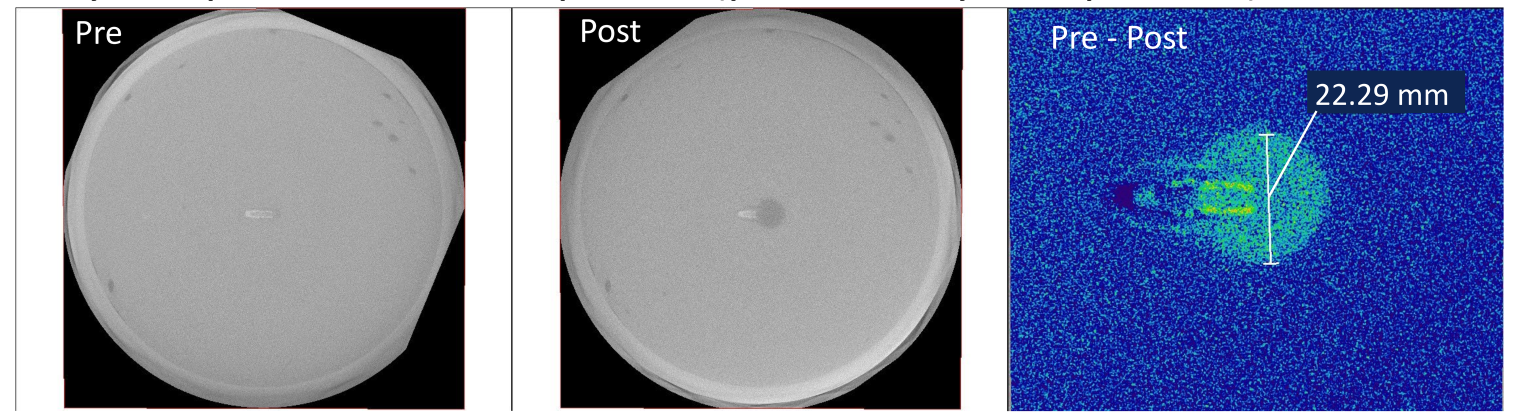
Voxel size: 94.18 µm

Partially-coupled, horizontal planes (preliminary comparison)



Supporting CTH modeling of peak shock pressure on foam chamber/grout interface: 0.83 GPa

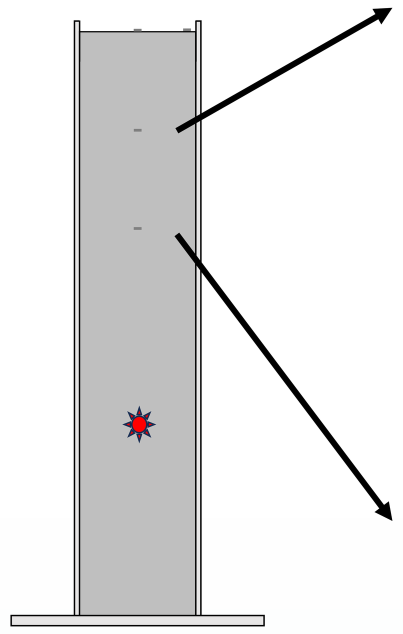
Fully-coupled, horizontal planes (preliminary comparison)

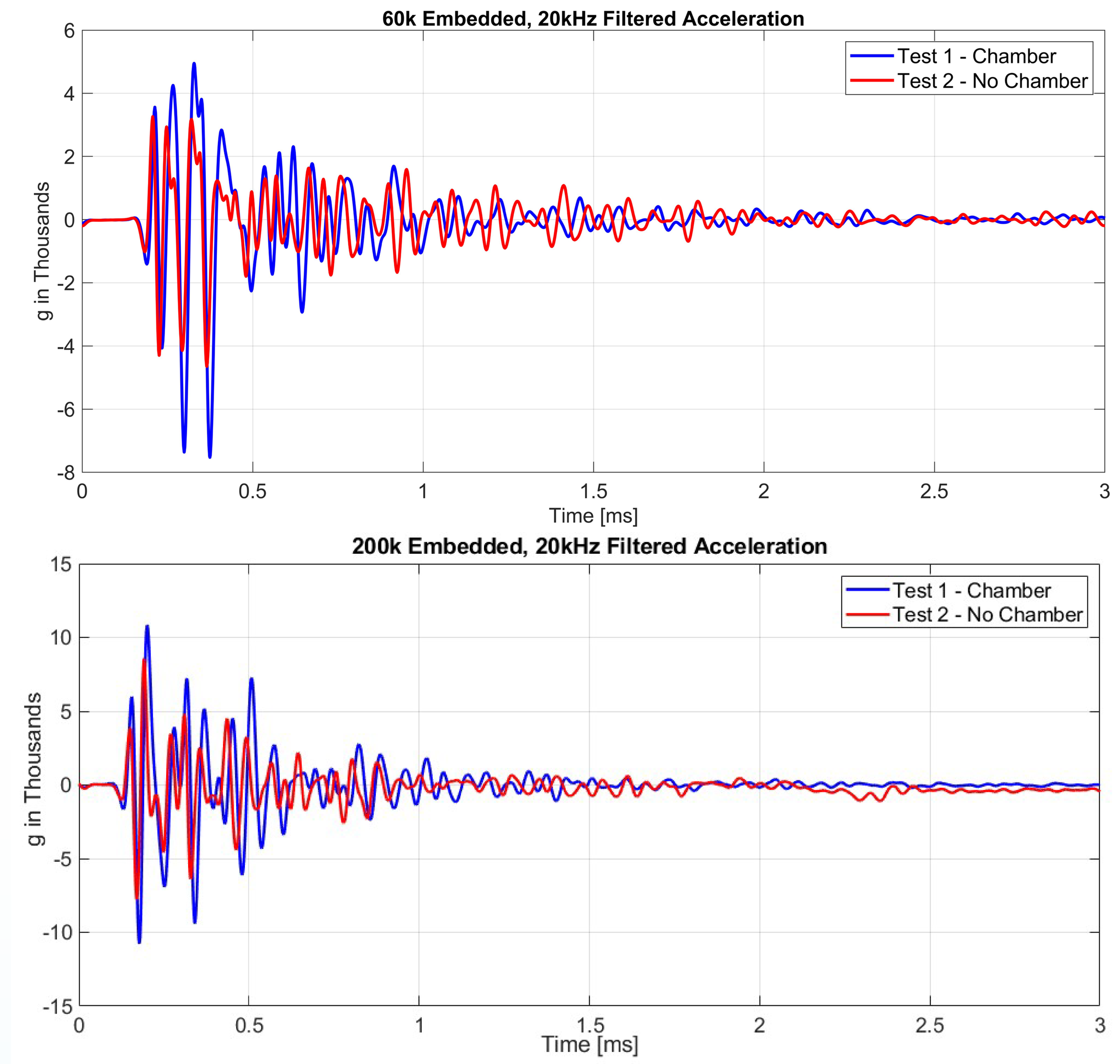


PRIMASHEET explosive peak shock pressure in contact with the grout: ~20 GPa (Cooper, 1996)

6. Results – Accelerometers

Foam chamber corresponds to partially coupled
No foam chamber corresponds to fully coupled





7. Conclusions, Impact, and Future Work

- Demonstrated explosions at high g, X-ray CT for quantifying damage (i.e., pore crush), and good return on accelerometer data
- Accelerometer signal larger in partially-coupled configuration
- Estimation of residual stress in progress
- This year: test 2-gram fully/partially coupled columns at 100 & 225 g
- This capability has configurability, high-resolution characterization, and reasonable economics to augment field campaigns

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References: Cooper, P.W. 1996. Explosive Engineering. VCH Publishers, Inc., New York, New York, 460 p.; Ensign-Bickford Aerospace and Defense (EBAD). 2020. Primasheet 1000 Flexible Explosive (Datasheet Flexible Explosive); Kuhlman, K.L., Heath, J.E. 2023. Scaling Containment on a Large Centrifuge. SAND2023-02634, Sandia National Laboratories, Albuquerque, NM, 36 p.; Office of Technology Assessment (U.S. Congress; OTA). 1989. The Containment of Underground Nuclear Explosions. OTA-ISC-414, U.S. Government Printing Office, Washington, DC, 89 p., https://nnss.gov/wp-content/uploads/2023/04/OTA-ISC-414.pdf.

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