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Title: Abaqus Simulations of Rock Response to Dynamic Loading

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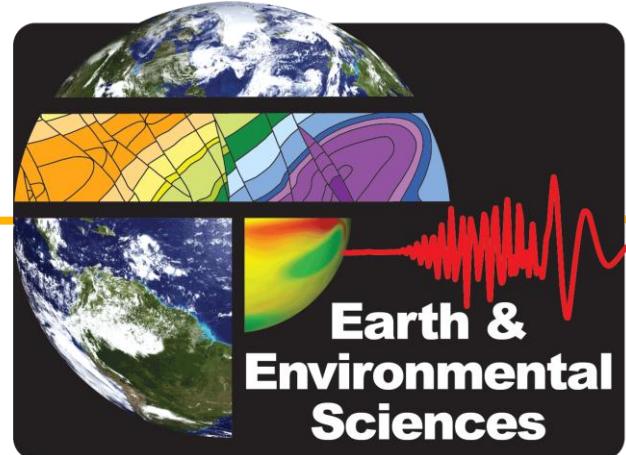
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Abaqus

Simulations of Rock Response to Dynamic Loading

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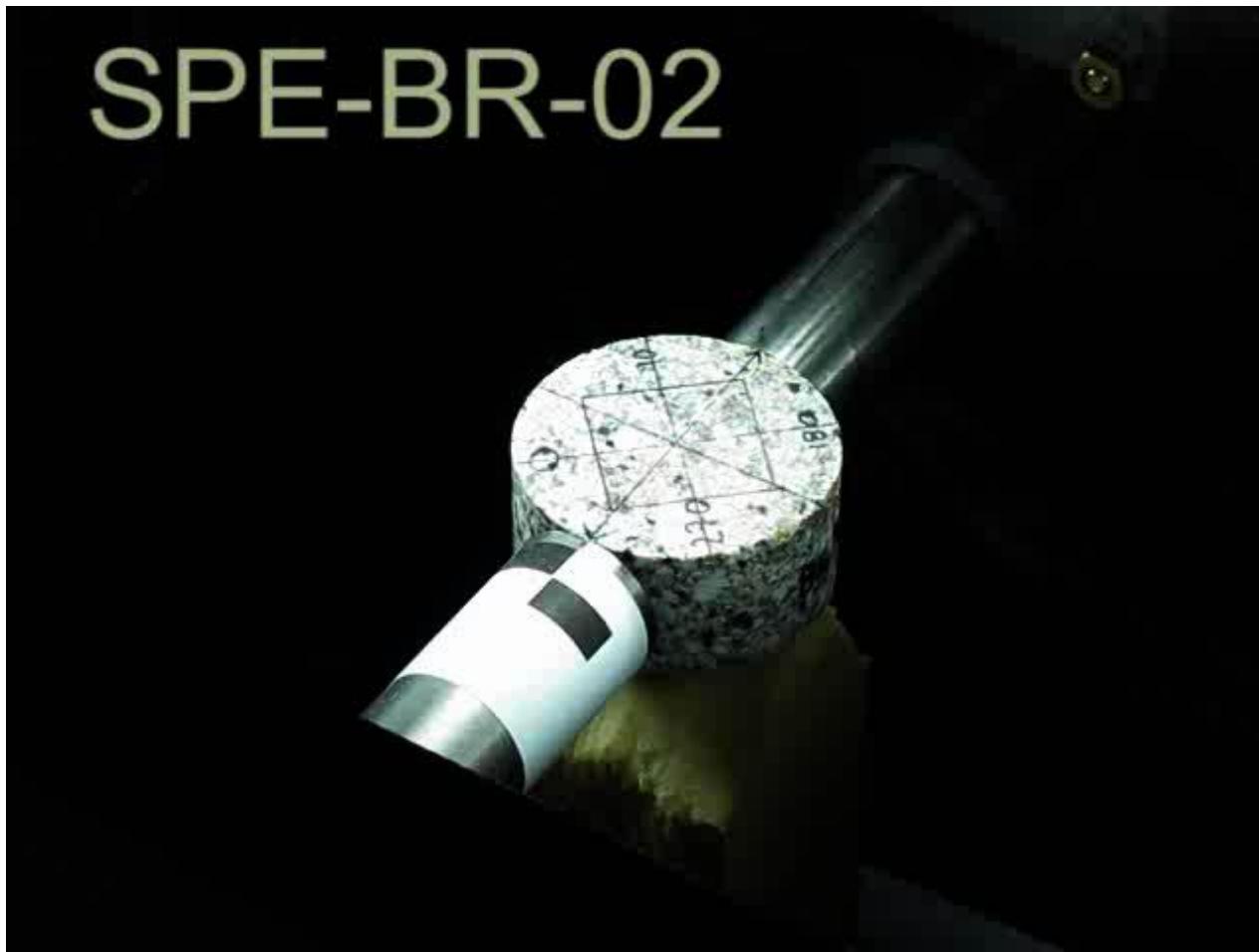
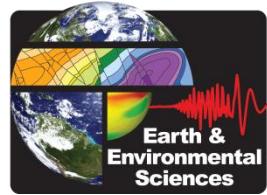


Geoqus 2012
21-23 August

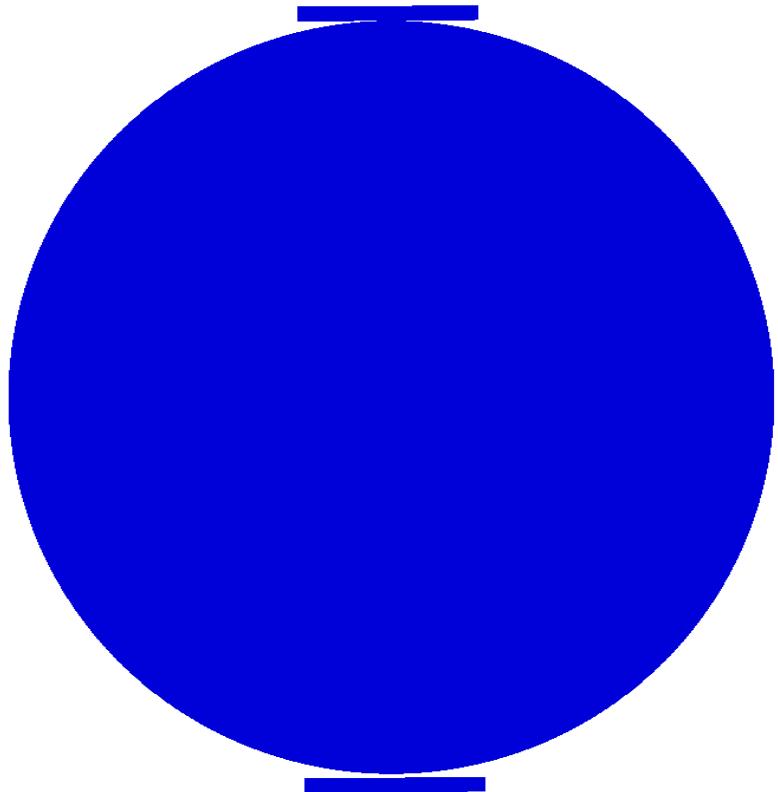
Outline

- **Dynamic rock properties**
 - Brittle failure
 - Non-linear EOS and strength
- **Some historic LANL Abaqus simulations**
- **Complex geologic structure**
 - GAMUT to CAE
 - Blocks and faults
 - Recent shock response simulation

Rock Fracture – Dynamic Brazilian Test



Abaqus Rock Fracture Simulation

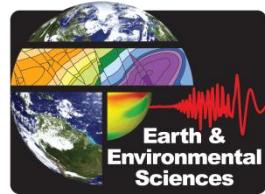


Simulation

Failed Core

Rock Constitutive Response

- The wide range of loading regime in explosive shock requires specialized material models
- Non-linear $P-\mu$ EOS coupled to a 3-invariant yield model in P-Q space
- Properties based on laboratory specimen from formations of interest
- Accessed as an Abaqus user model



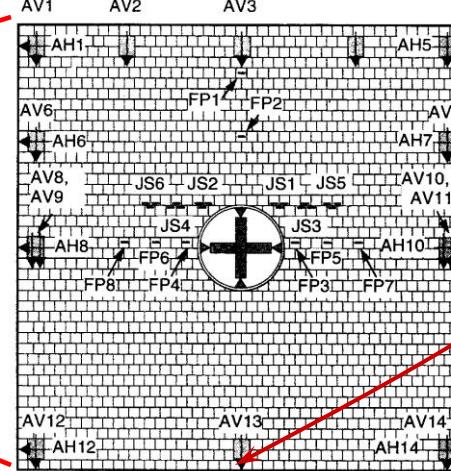
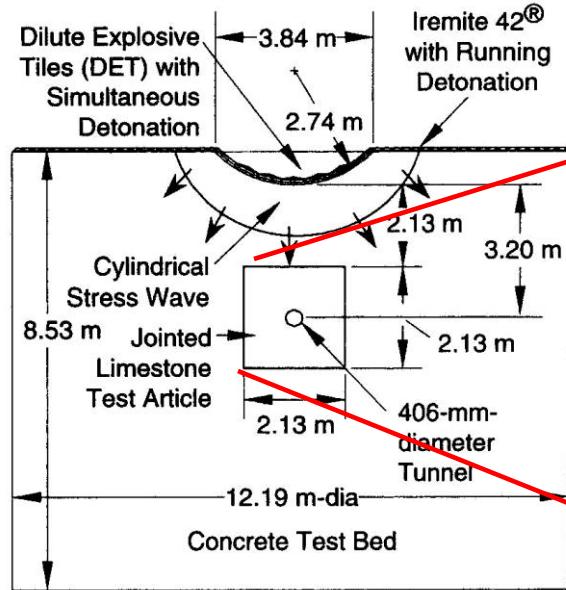
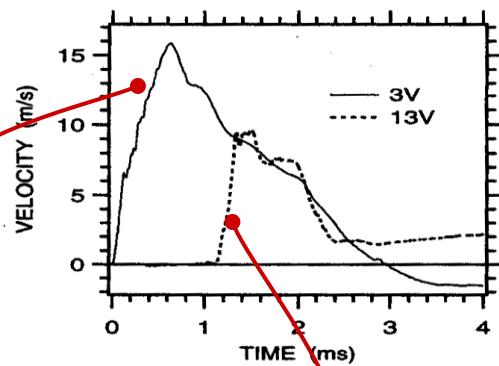
Generic Rock Response Model

- The wide range of loading regime in explosive shock requires specialized material models

“2-D” Dynamic Lab-Scale Test

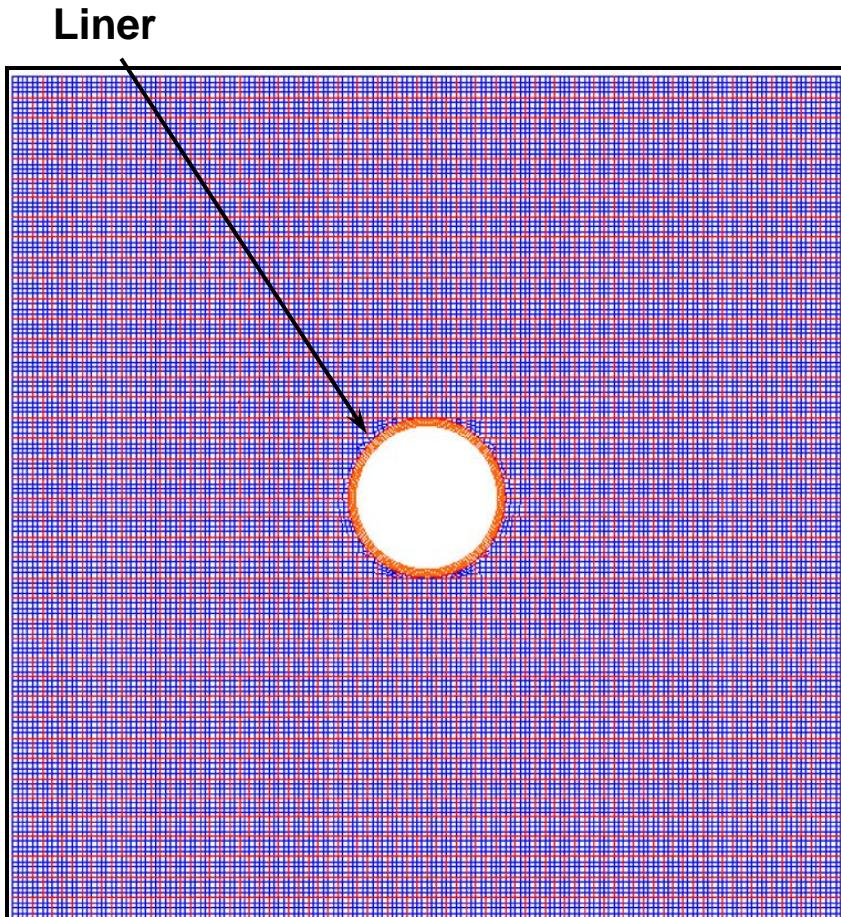
- 5-cm square milled limestone bars
- Stacked around a 0.406-m ϕ aluminum tube
- Embedded in a concrete test bed
- Loaded by shaped cylindrical charge

Measured Velocities
used as BCs



Ref: J. K. Gran, et. al.,
“Dynamic Response
of An Opening in
Jointed Rock,”
*Int. J. Rock. Mech.
Min. Sci.*, 35,
1021-1035, 1998.

2-D Plane Strain Abaqus Model

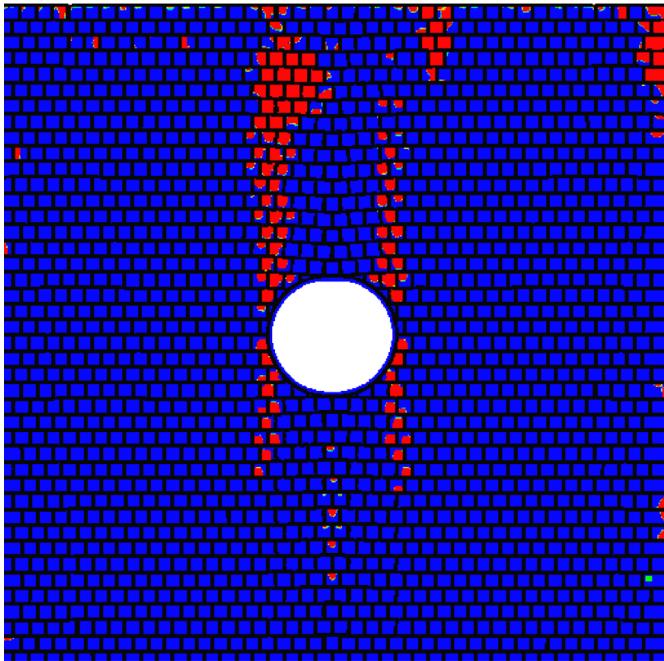


- **Brittle material model**
 - tensile and shear failure
 - w/strain softening
- **Boundary condition**
 - velocity boundary data
- **Aluminum liner**
 - Continuum elements
 - Elastic-plastic response

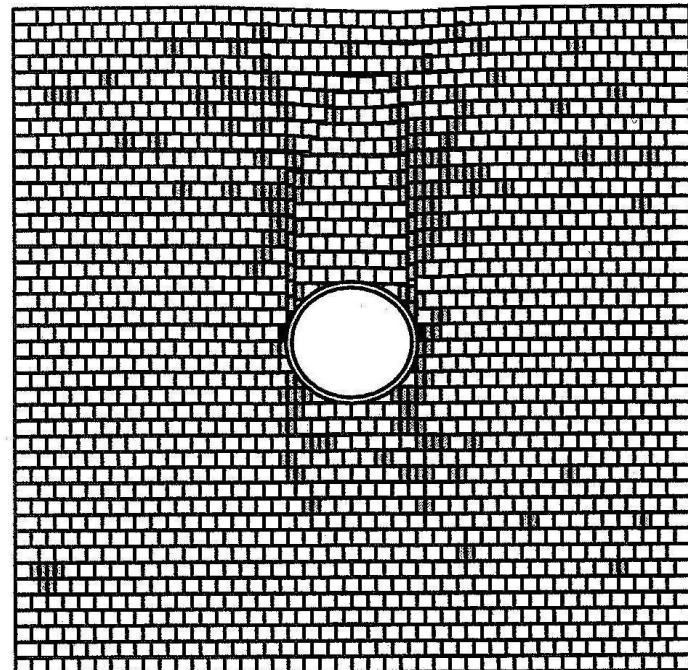
— = Individual Elements
— = Contacts

2-D Model Response- Rock Response

- Brittle cracking/failure
- Block movement within “chimney”



Abaqus Model

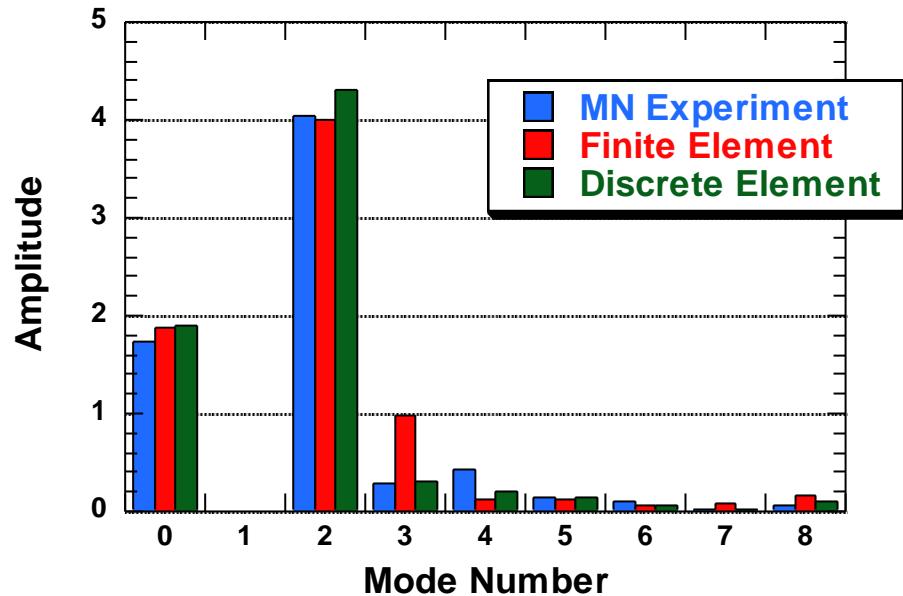


Deconstructed Test Bed

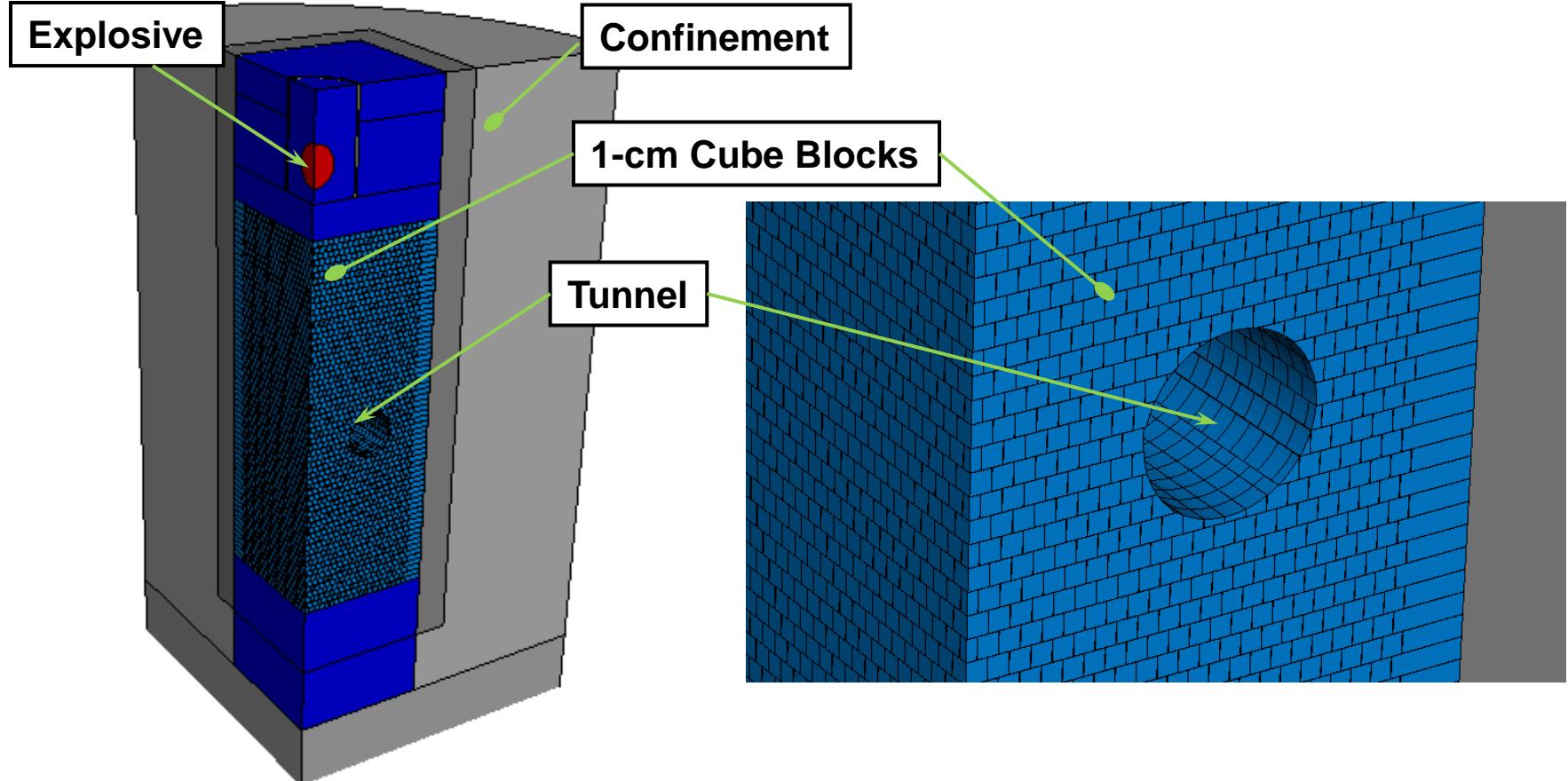
2-D Model Response- Liner Response

- Primary modal response matched
- Deformation:

Liner Deformation	Measured (mm)	Computed (mm)
Crown to Invert	11.4	12.9
Springline to Springline	3.5	3.5

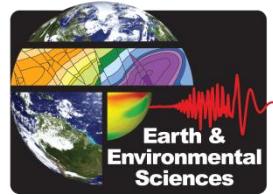


3-D Dynamic Lab-Scale Test

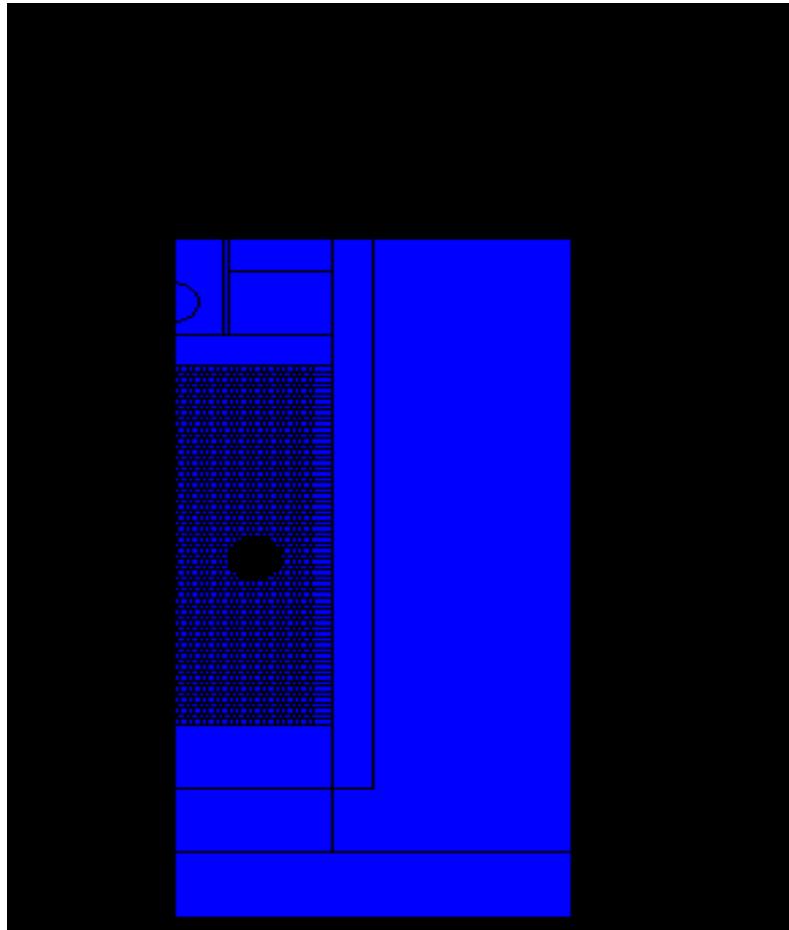


$\frac{1}{4}$ -symmetry Abaqus Model

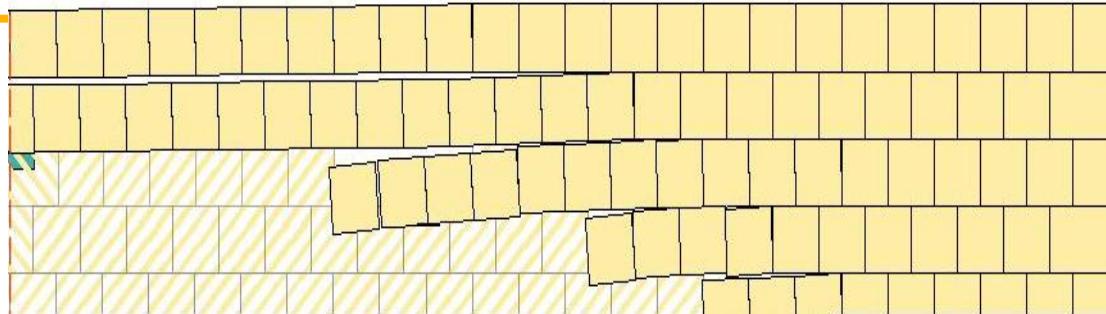
Close-up of Tunnel Region



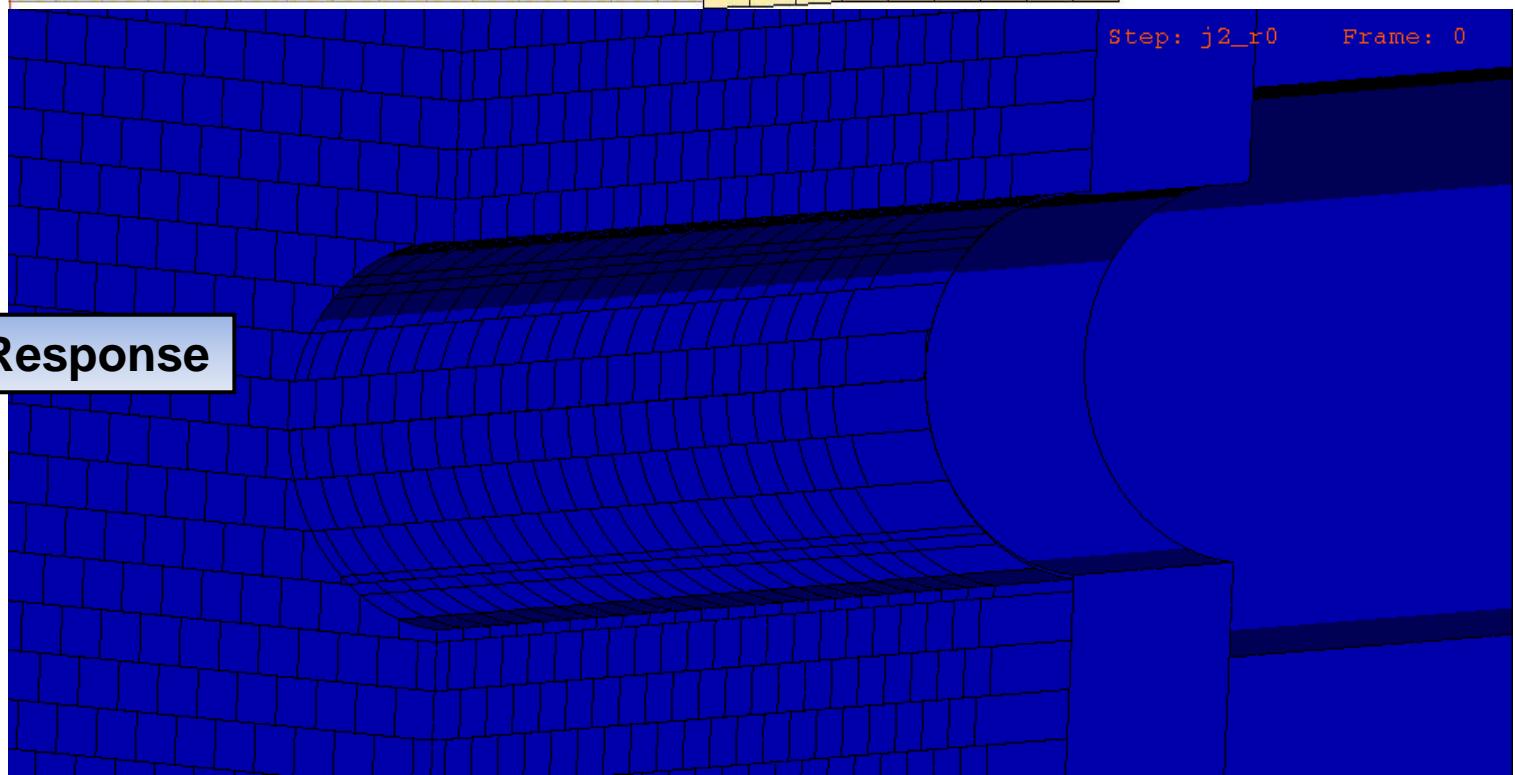
3-D Test Response— Full Model



3-D Test Response—along Tunnel Axis

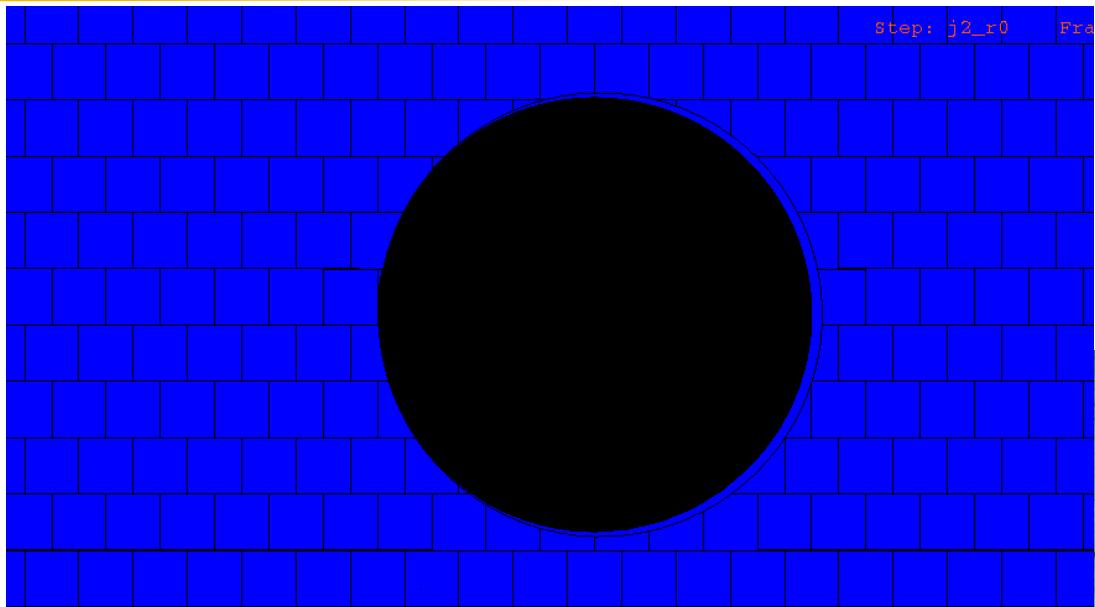


Damage Map



Computed Response

3-D Test Response—End On



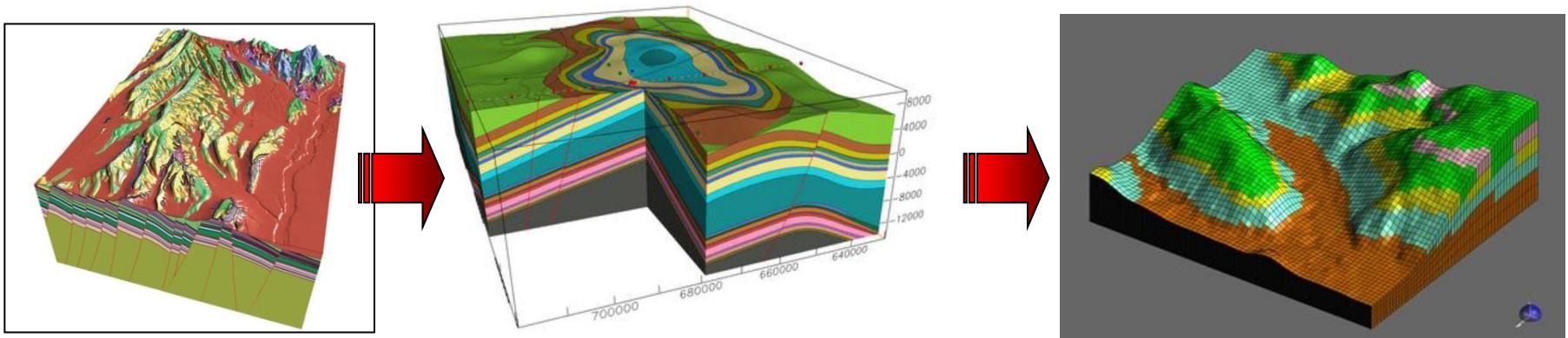
Computed Block Motion

Block Motion Photo



The GAMUT Tool for Geologic Models

- Geologic Assessment Methodology for Underground Targets
- Input = geologic information
- Output = geometric volumes
- Import to CAE for model building and meshing



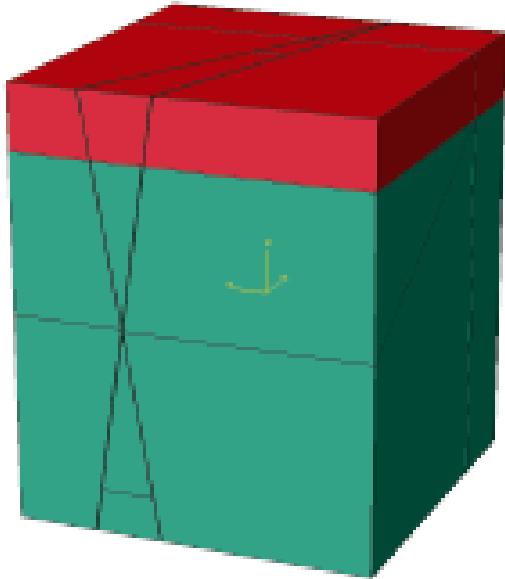
Geologic
Structure

Geologic
Framework
Model

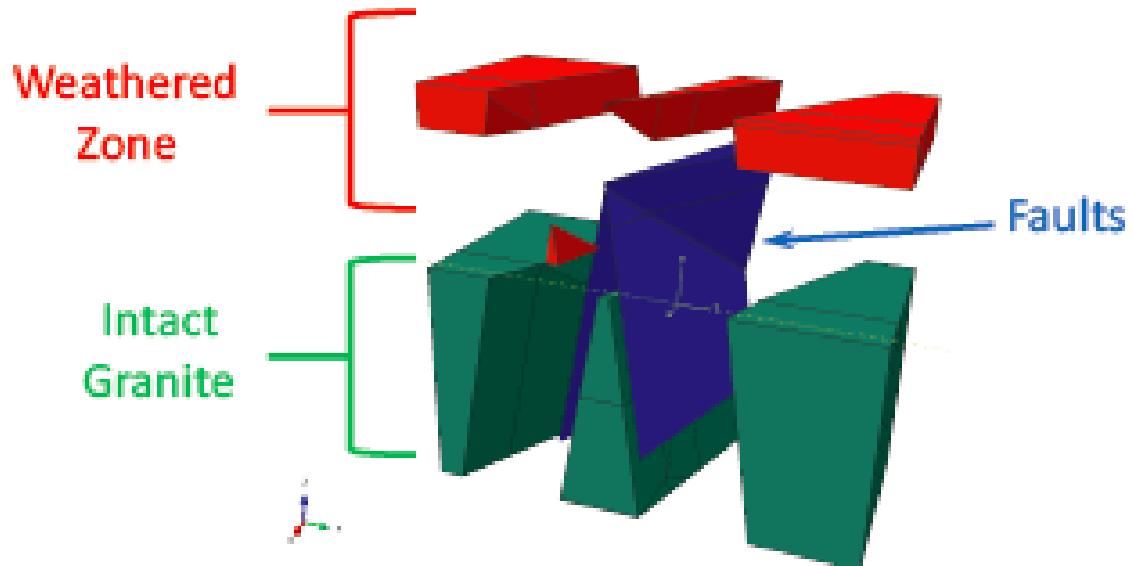
Model for
Numerical
Analysis

GAMUT Model for Field Test

- Includes weathered/intact granite layers and near source faults
- Modeled faults as a shell structure
- Material properties derived from tests on cores
- Includes Eulerian explosive region for fully coupled CEL* simulation



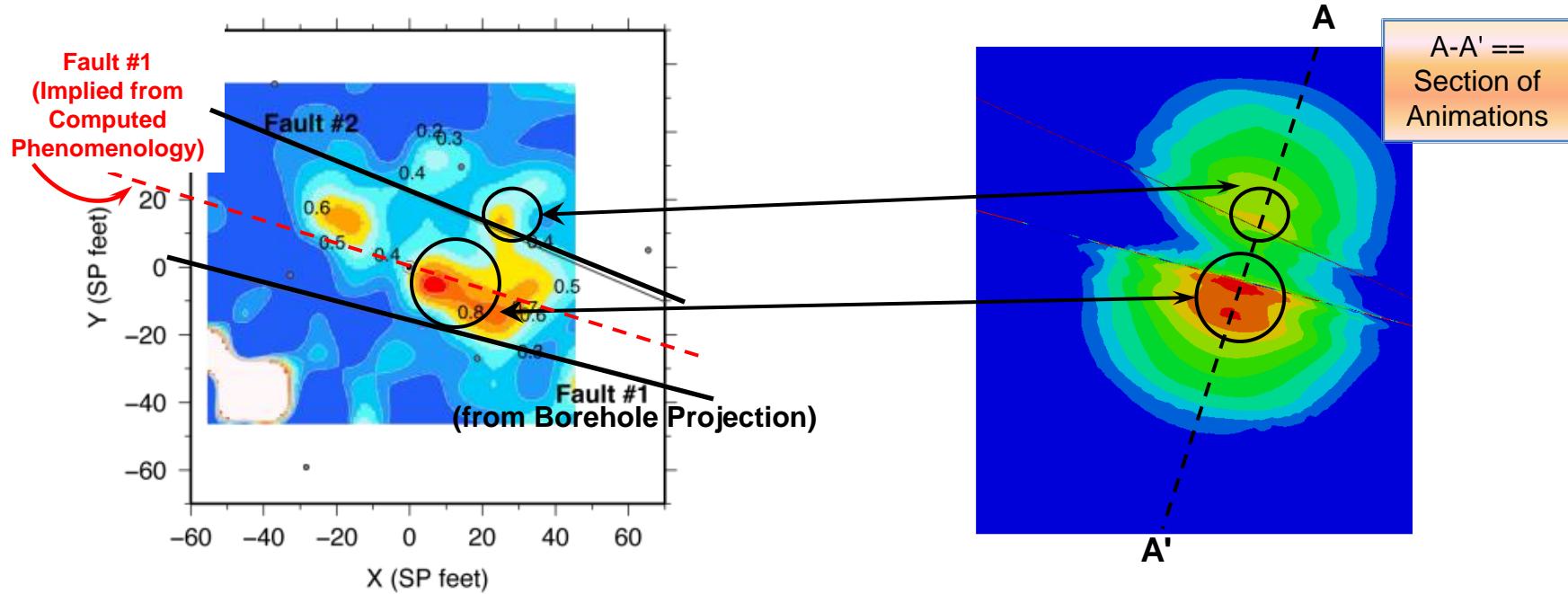
a. Full Model



b. Exploded View

Displacement Contours Comparison

- Qualitatively similar patterns
- Appear to correspond to location of faults
 - Fault locations based on projection from borings
 - Fault #1 may be incorrect based on simulation results

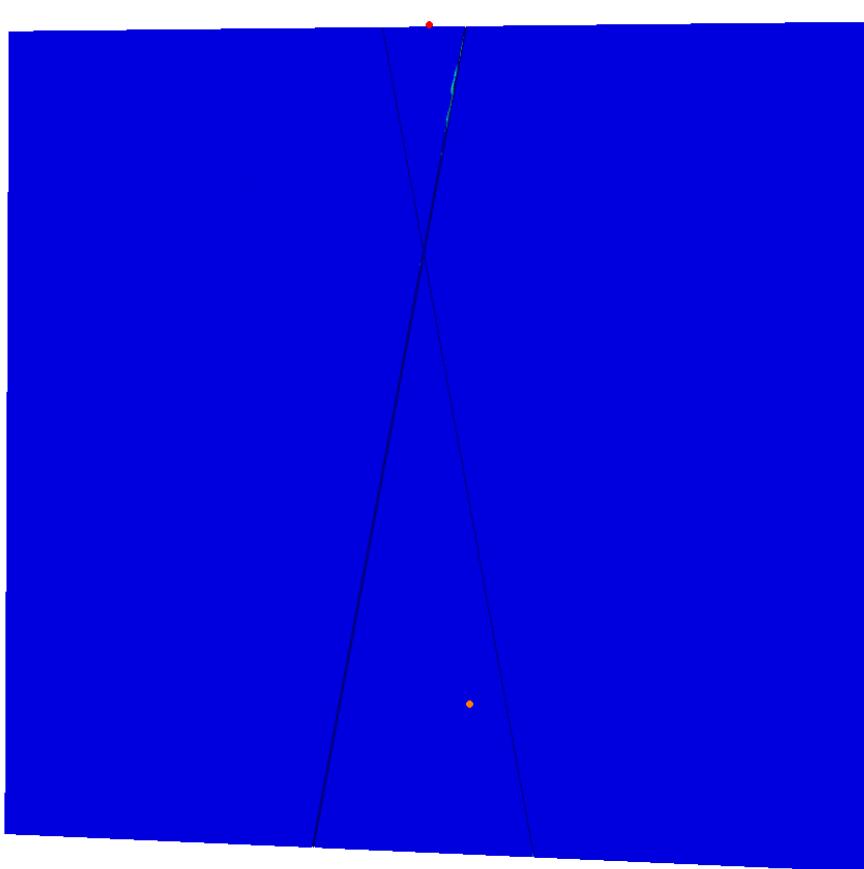
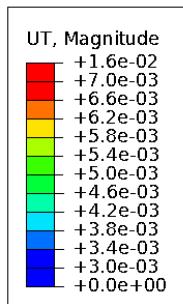


Change Determined by LIDAR

Final Computed Values

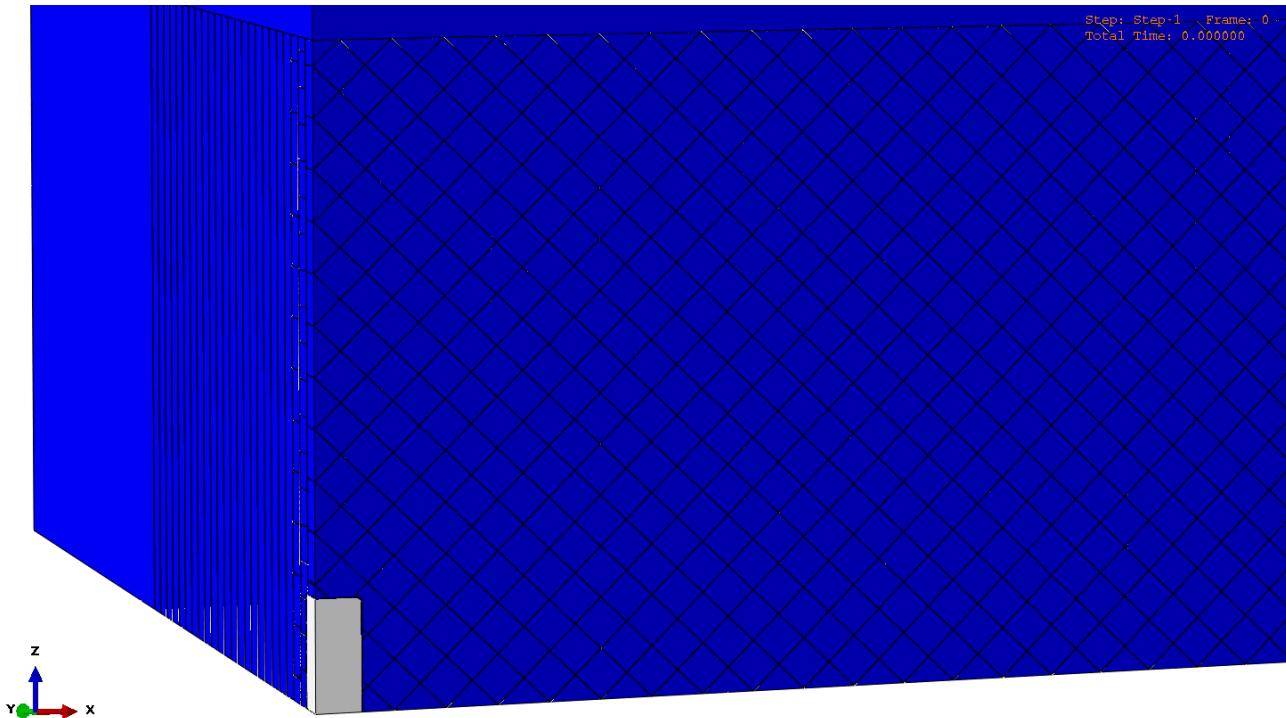
Abaqus Displacement Animation

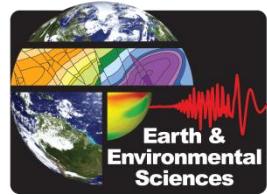
- Development of the surface expression of displacement relative to the faults is seen



Simulation of Explosive in Jointed Rock

- Next step is to include joint sets
- Include material failure and element deletion to simulate expanding explosion product gases





Summary

- The LANL Geodynamics Team has been applying Abaqus modeling to achieve increasingly complex simulations
- Advancements in Abaqus model building and simulation tools allows this progress
- We use Lab-developed constitutive models, the fully coupled CEL Abaqus and general contact to simulate response of realistic sites to explosively driven shock