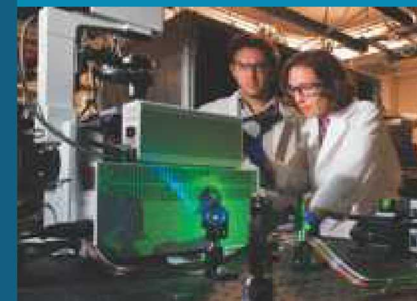
SAND2019-4824PE

Empty Room Closure Research Plan



Benjamin Reedlunn

Jake Koester

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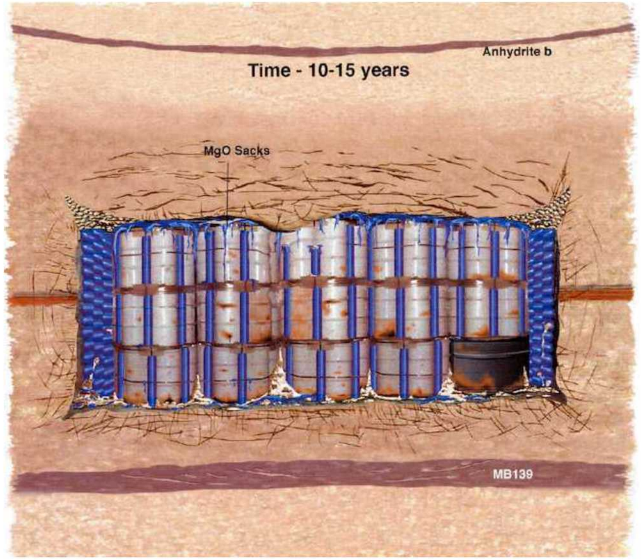
Outline

Motivation

Filled Room Closure vs. Empty Room Closure

Filled Rooms



Empty Rooms

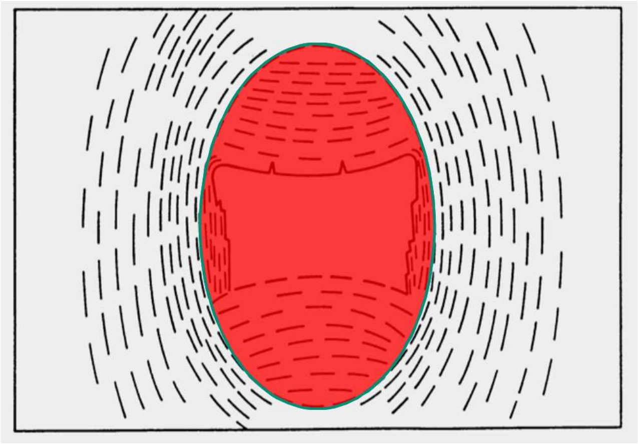
Fracturing Around Empty Rooms

1. Controls the size and character of the rubble pile.

Lower Horizon

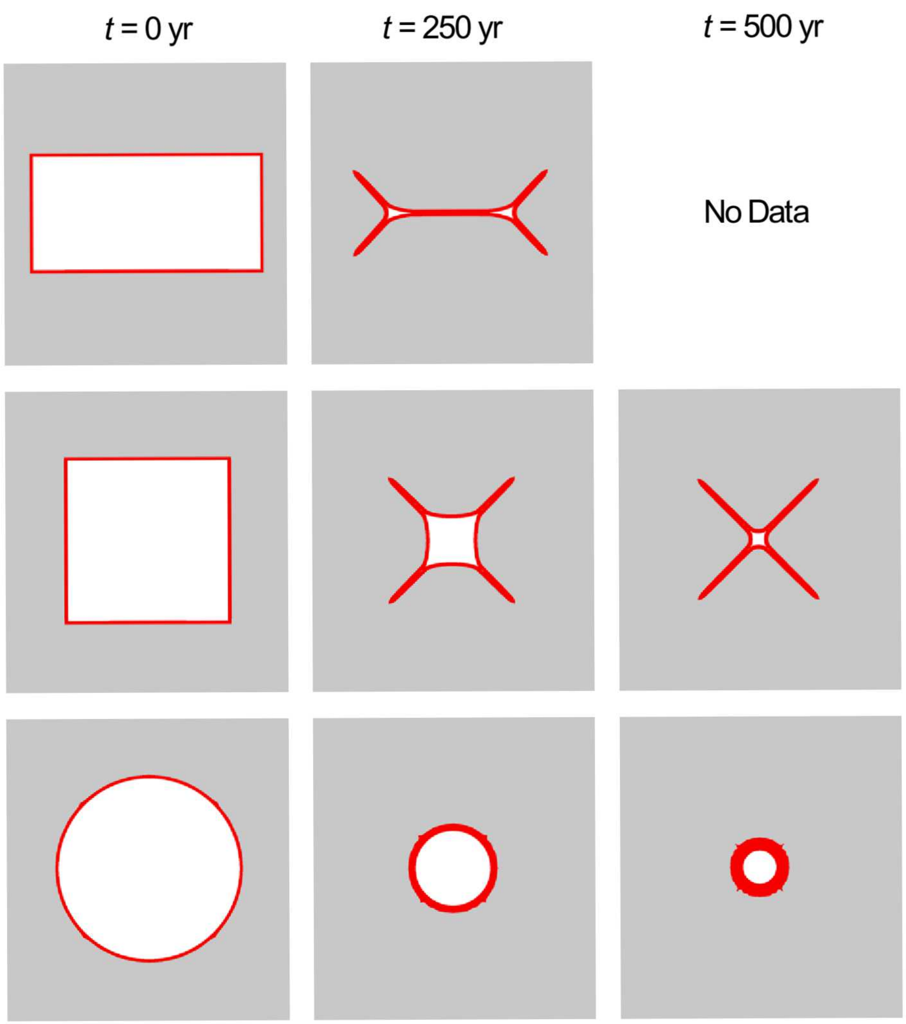
Upper Horizon

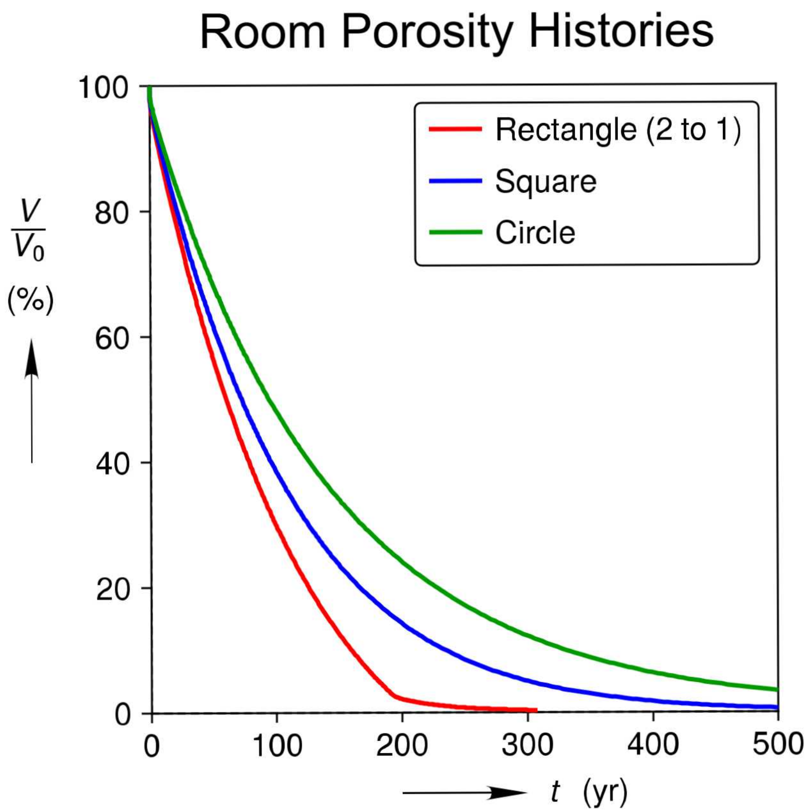
2. Changes room cross-section to a more stable, enduring, shape.



Borns, D.J. and J.C. Stormont. (1989) (Modified)

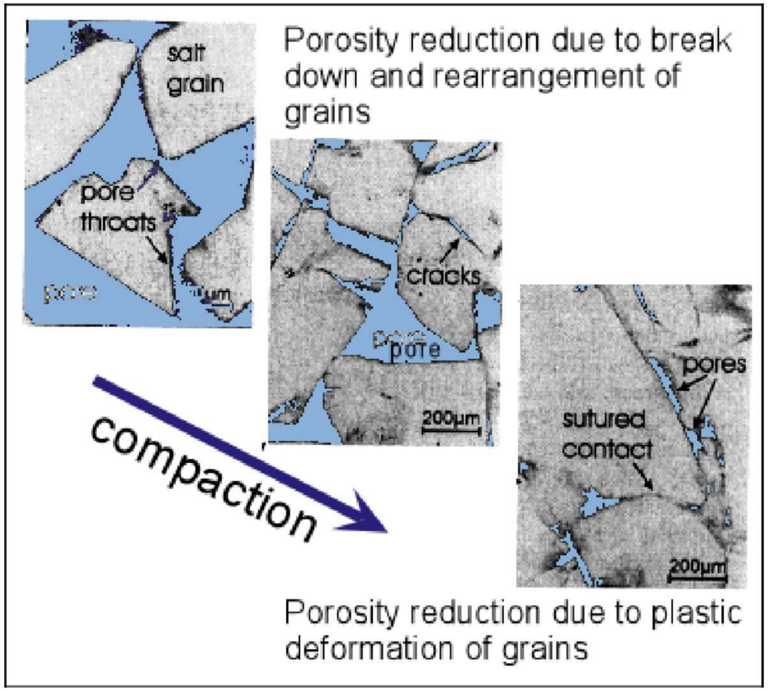
Room Shape affects Creep Closure





Rubble Pile Compaction

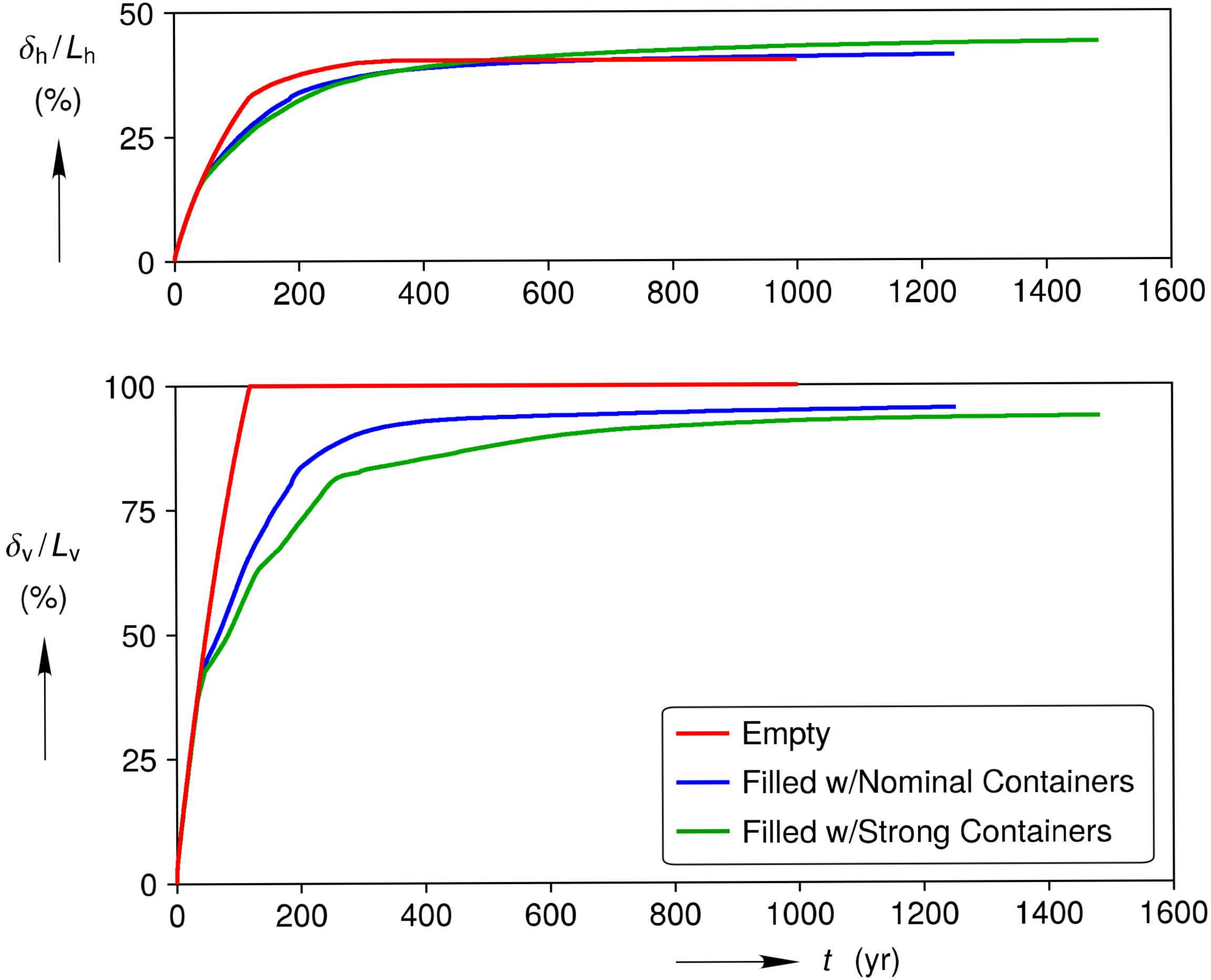
1. Important Processes
   a. Rubble reorganization
   b. Rubble fracture
   c. Creep
      i. Dislocation
      ii. Pressure solution



Spangenberg (1998) (Modified)

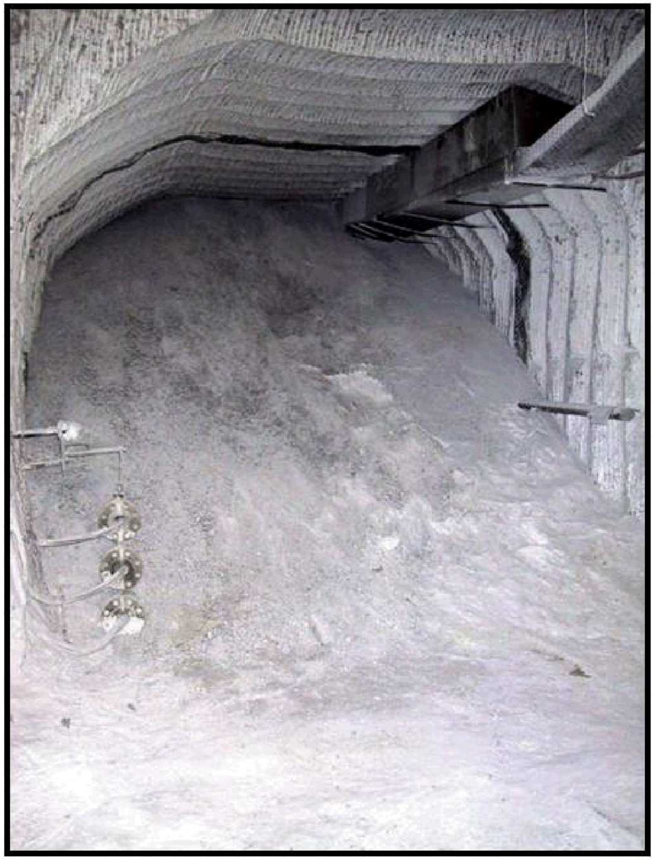
2. Impact
   a. Compaction processes control flow pathways
      i. Two samples with same porosity can have different permeability
   b. Rubble pile supplies back pressure to surrounding rock formation
      i. Larger rubble likely compacts slower than smaller rubble

Filled Rooms Creep Closed More Slowly



Crushed Salt vs. Rubble Pile

Crushed Salt



Bechthold, W., et. al. (2004). Backfilling and Sealing of Underground Repositories for Radioactive Waste in Salt (BAMBUS II Project), Final Report. European Commission, EUR 20621 EN

Rubble Piles

Research Plan Outline

Plan

1. Creep closure
   a. Already partially validated by room D, G, and Q data

2. Roof falls
   a. Attempt to predict size and shape of roof falls
      i. Stochastic distribution of defect sites?
   b. Validate against lab-scale room collapse experiments and observations at WIPP

3. Rubble pile compaction
   a. Flow channels
      i. Explicitly represent macroflow channels
      ii. Implicitly represent microflow channels
   b. Ignore healing for now
   c. Validate against crushed salt experiments
      i. Vary grain size distribution
      ii. Vary temperature and compaction pressure

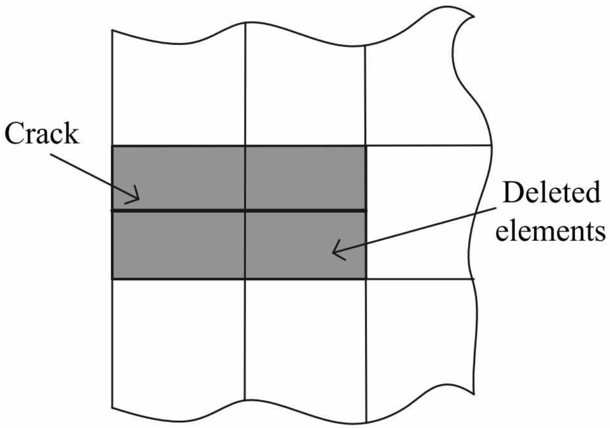
Potential Numerical Approaches

Potential Numerical Methods

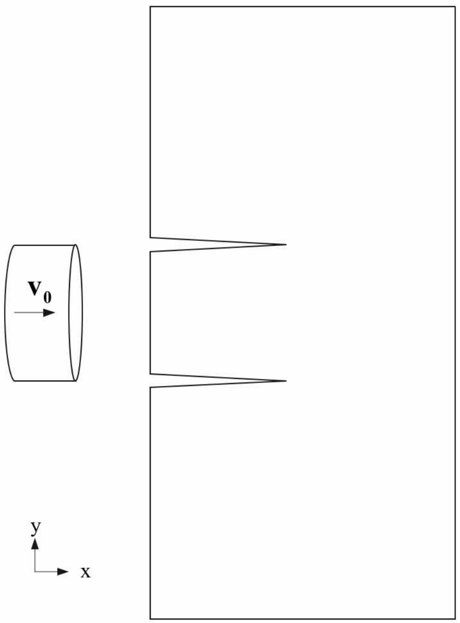
1. Fundamental issue: we are trying to capture a discrete crack with a continuum level model
2. Potential numerical issues
   a. Mass loss
   b. Mesh structure dependence
   c. Mesh size dependence
3. Candidate numerical methods
   a. Finite elements with element death
   b. Finite element with interelement cracks
   c. Particle methods
   d. Meshless methods

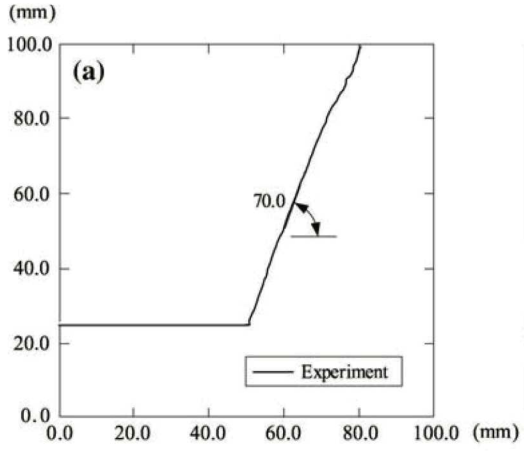
Element Death

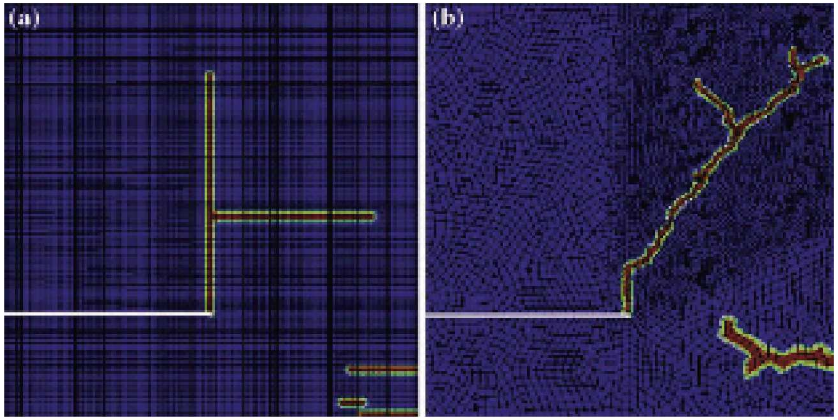
Mass Loss



Mesh Structure Dependence



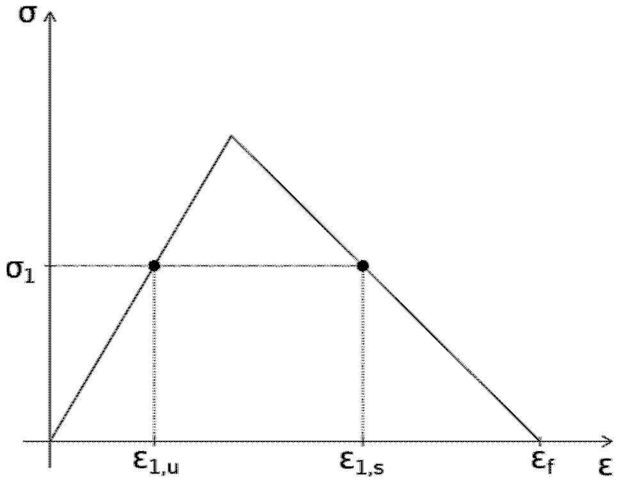




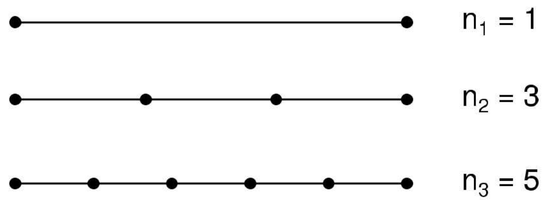
Song, Jeong-Hoon, Wang, Hongwu, and Belytschko, Ted. A comparative study on finite element methods for dynamic fracture. Computational Mechanics. 2008. vol. 42. no. 2. pg. 239—250.

1D Example of Strain Softening Instability

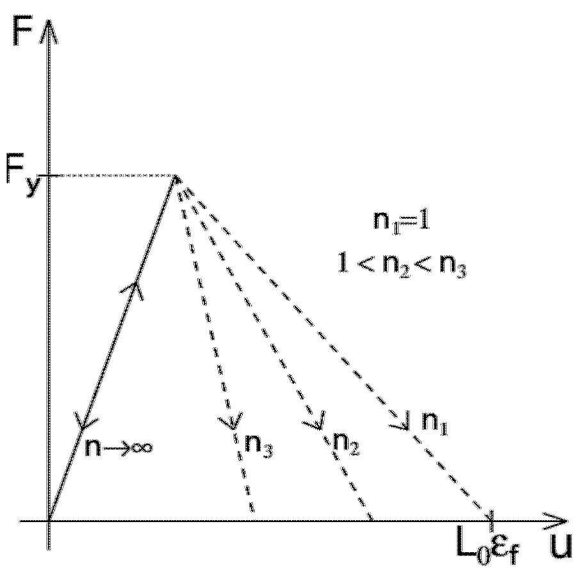
Local Stress-Strain Behavior



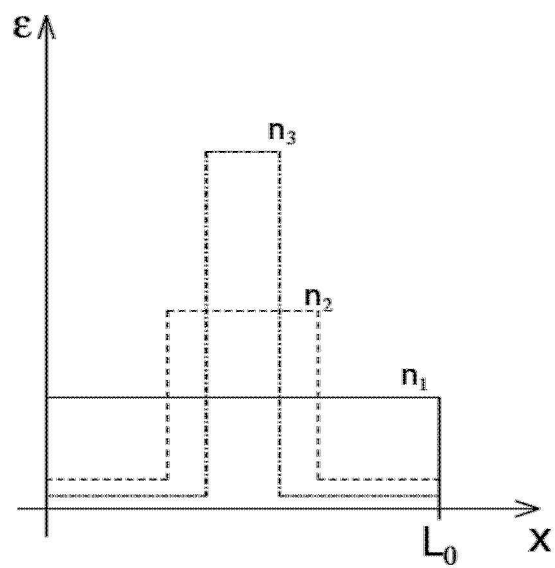
1-D Bar Meshes



Force-Displacement Behavior



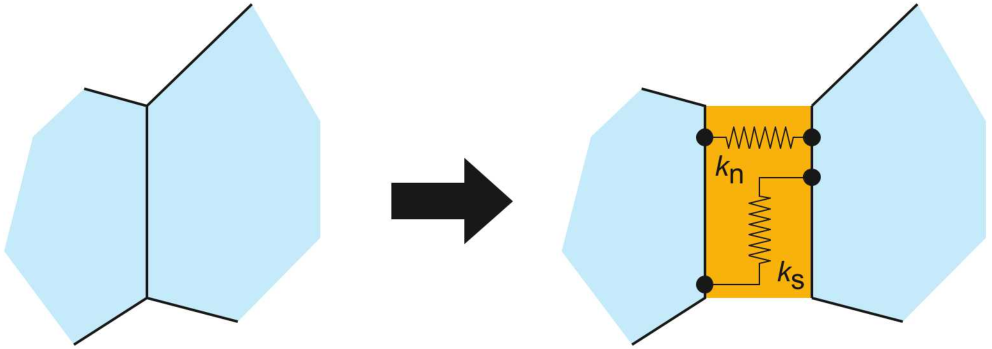
Strain Distribution



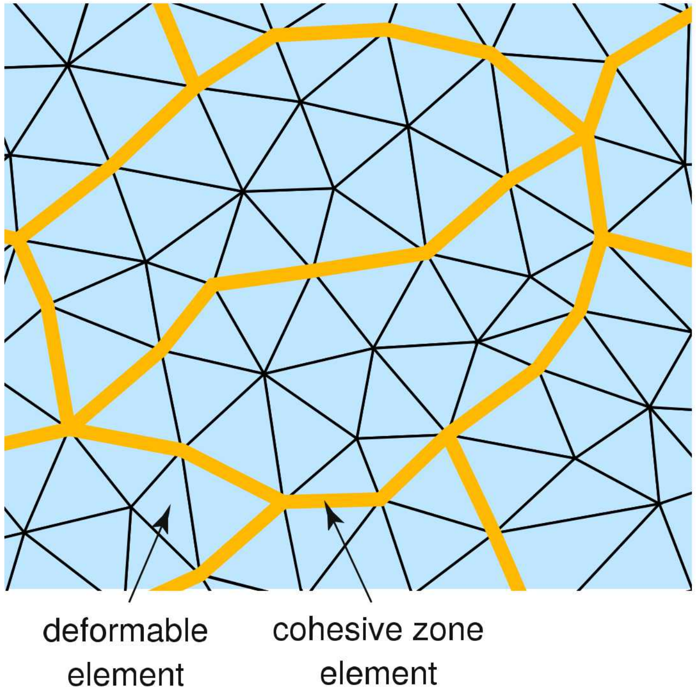
I. de-Pouplana and E. Oñate, An isotropic damage model for geomaterials in the KRATOS framework, Monograph CIMNE (2015). M153 URL https://www.scipedia.com/public/Pouplana_2015

Interelement Crack Method

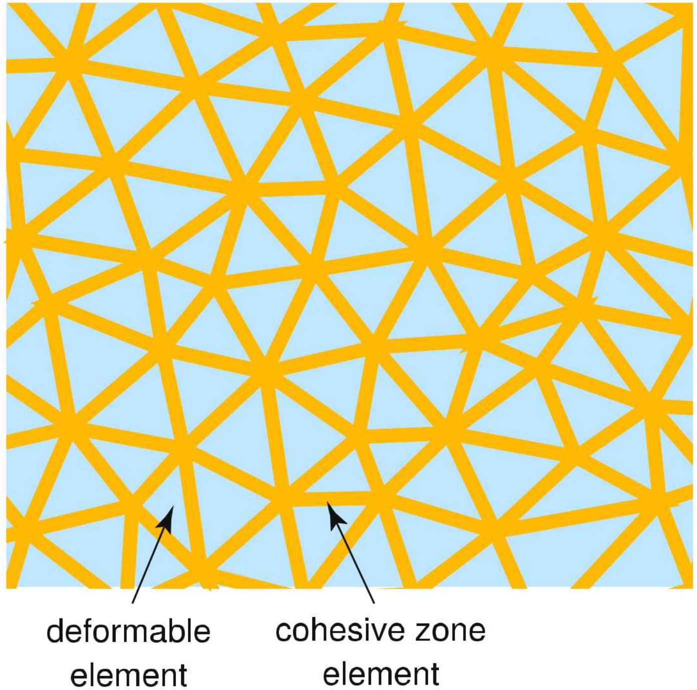
Cohesive Zone Element Insertion



Selective Insertion

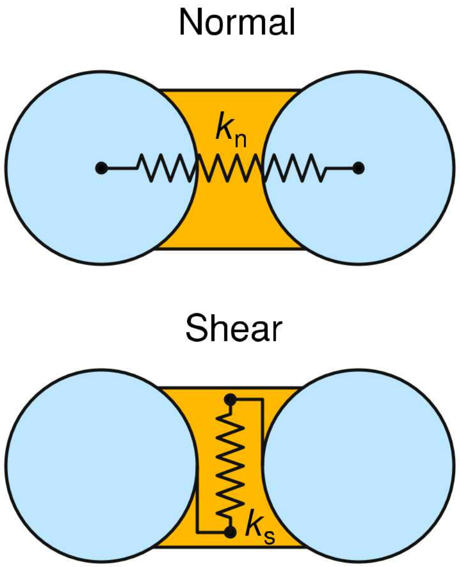


Blanket Insertion

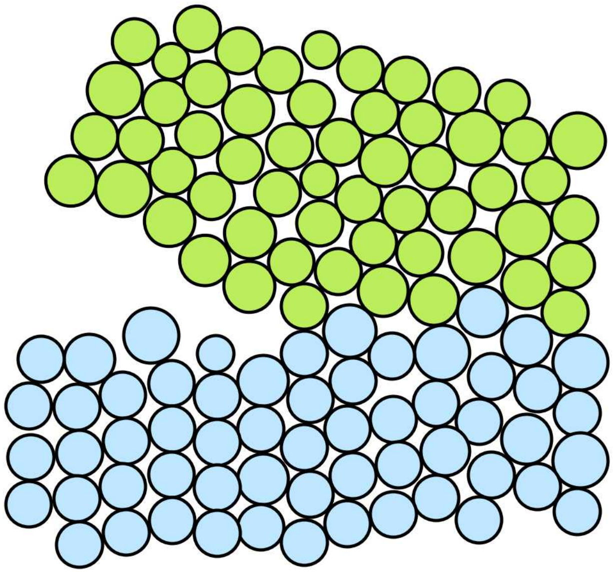


Particle Methods

Particle-to-Particle Interactions



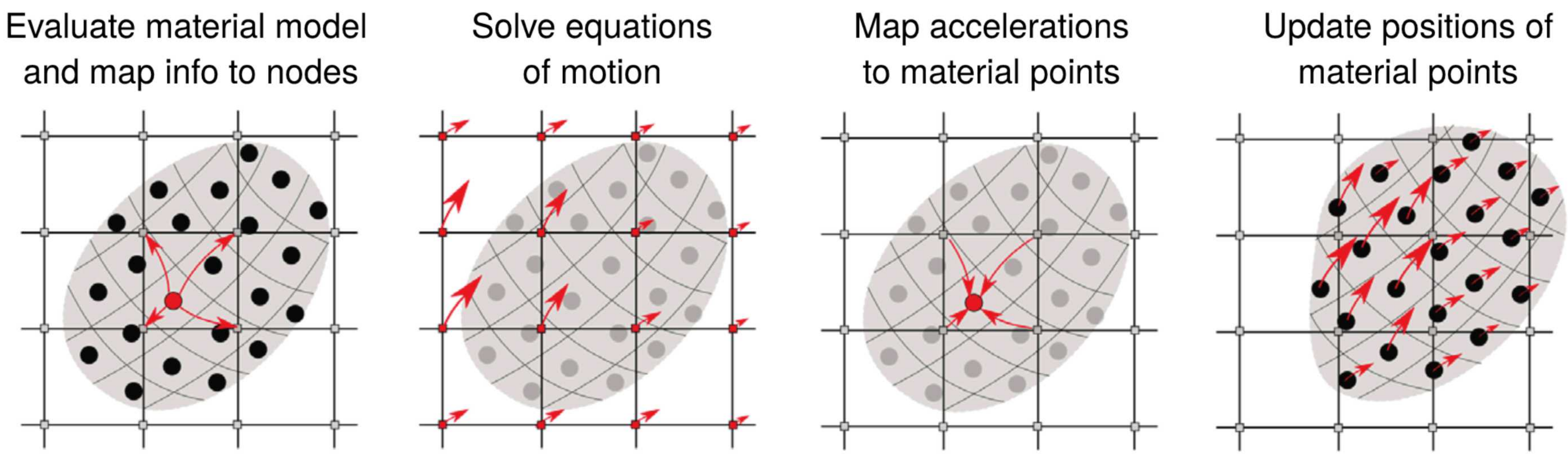
Particle Method Fracture



Material Point Method (MPM)

1. Descendent from Particle in Cell (PIC) method.
2. First published paper in 1994. Cited 943 times.
3. Codes
   i. MPM Sim (Commercial)
   ii. Anura3D (International Collaboration)
   iii. Uintah (Open Source)
4. Miscellaneous
   i. Used heavily by the computer graphics community
   ii. Fern, J., et al. The Material Point Method for Geotechnical Engineering: A Practical Guide. 2019. CRC Press

Material Point Method (MPM)



Rohe, A., Pinyol, N., Ceccato, F., Yerro, A., Fern, J., and Chmelnizkij, A., Modelling large deformation and soil–water–structure interaction with Anura3D, GiD Convention Workshop, UPC Barcelona, 2018 (Modified)

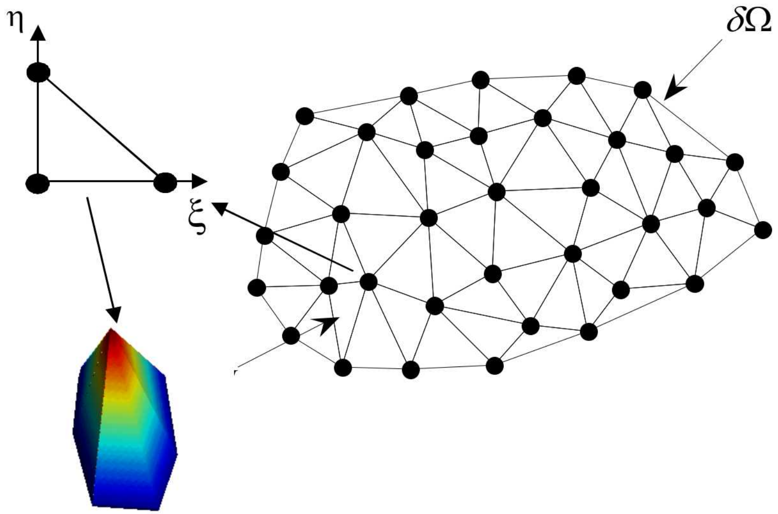
Reproducing Kernel Particle Method (RKPM)

1. Descendent from Smoothed Particle Hydrodynamics (SPH)
2. First published paper in 1996. Cited 828 times.
3. Codes
   a. LS-DYNA has a RKPM capability
   b. Sierra has a fledgling RKPM capability
4. 1500 has two staff who studied RKPM for their doctorate

Reproducing Kernel Particle Method (RKPM)

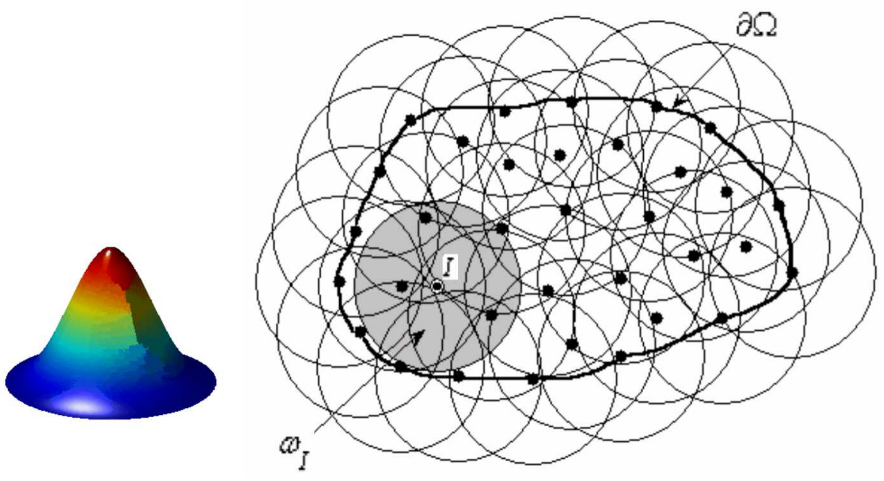
Finite Element Method

Shape functions and integration are both defined on the element domain.

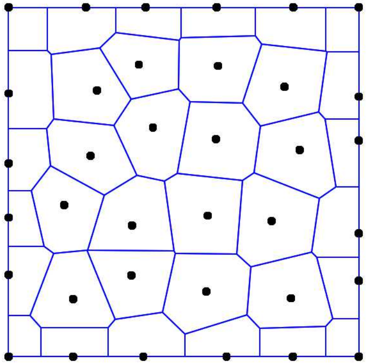


RKPM

Shape Functions



Domain Integration



Littlewood, D., Hillman, M., Yruex, E., Bishop, J., Beckwidth, F., Chen, J.S., Implementation and Verification of RKPM in the Sierra/Solid Mechanics Code. ASME IMECE Conference. 2015. (Modified)

Meshless Methods

1. Primary advantages
   a. Designed to handle severe deformation (>100 % strain)
   b. Inherently captures normal contact without expensive interface tracking
   c. Regularization techniques are relatively easy to implement
   d. Adaptive particle insertion and deletion is relatively easy
   e. Can utilize classical continuum material models
   f. Healing just needs to be added to the material model
2. Primary drawbacks
   a. Potential longer run times
   b. Sliding contact is challenging
   c. Surfaces must sufficiently separate to stop interacting
3. Sandia's nuclear weapon program will likely continue to invest in meshless methods

Assessment of Meshless Methods

Project Scope

1. Goal: Assess whether meshless methods are well suited to the simulation empty underground room closure in rock salt.
   a. Identify which approaches work and which do not

2. Capability demonstration, not intensive code development
   a. Minor code development is OK

3. Collaborate with Sandia to incorporate successful approaches into Sandia code(s).
   a. Approaches should be implemented with an eye on production

Problem #1: Creep Closure

1. Supplied by Sandia:
   a. Creep material model
   b. Initial boundary value problem
   c. Finite element results
2. Assess whether a chosen meshless method can accurately simulate 2D room closure due to creep alone (no fracturing)
   a. Show discretization convergence
   b. Record total CPU time
3. Compare discretization converged meshless simulation against a finite element simulation
   a. Horizontal and vertical closure histories
   b. Room porosity histories

Simple Odqvist Creep Model

Strain Decomposition

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\text{el}} + \dot{\boldsymbol{\varepsilon}}^{\text{vp}}$$

Isotropic, Linear, Hypoelasticity

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{\mathcal{C}} : \dot{\boldsymbol{\varepsilon}}^{\text{el}}$$

$$\boldsymbol{\mathcal{C}} = (B - 2\mu/3)\,\boldsymbol{I} \otimes \boldsymbol{I} + 2\mu\,\boldsymbol{\mathcal{I}}$$

Associated Flow Rule

$$\dot{\boldsymbol{\varepsilon}}^{\text{vp}} = \dot{\bar{\varepsilon}}^{\text{vp}} \frac{\partial \bar{\sigma}}{\partial \boldsymbol{\sigma}}$$

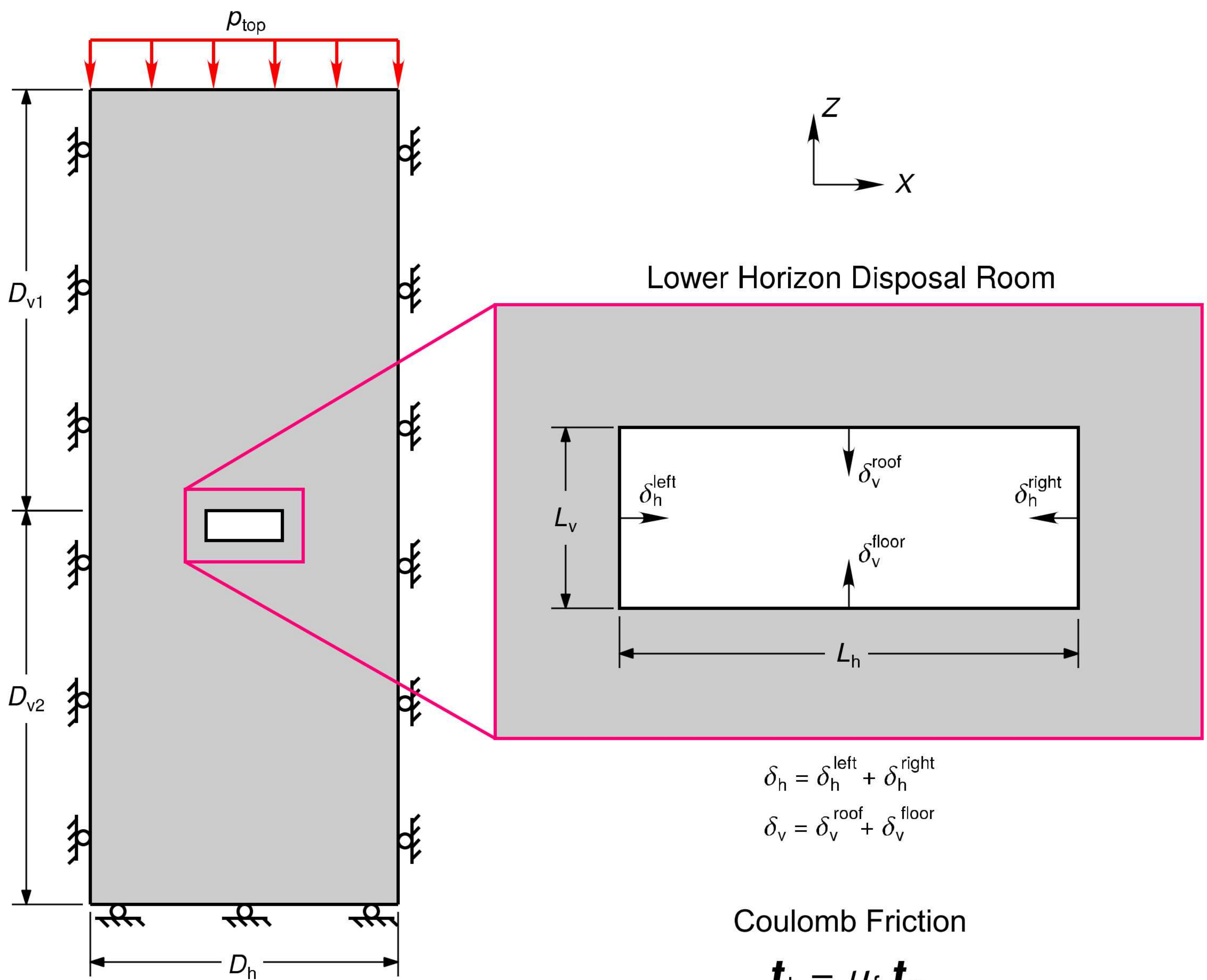
von Mises Equivalent Stress

$$\bar{\sigma} = \sqrt{3\,J_2}$$

Equivalent Viscoplastic Strain Rate

$$\dot{\bar{\varepsilon}}^{\text{vp}} = \sum_{i=1}^{2} A_i \left(\frac{\bar{\sigma}}{\mu}\right)^{n_i}$$

Creep Closure Simulation Setup



$$\delta_h = \delta_h^{left} + \delta_h^{right}$$

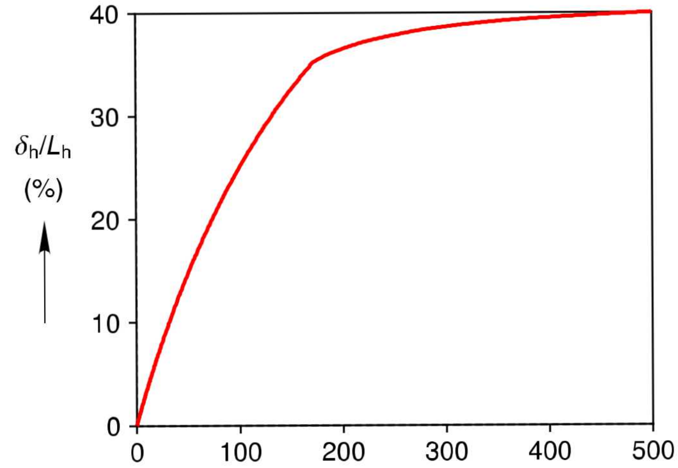
$$\delta_v = \delta_v^{roof} + \delta_v^{floor}$$

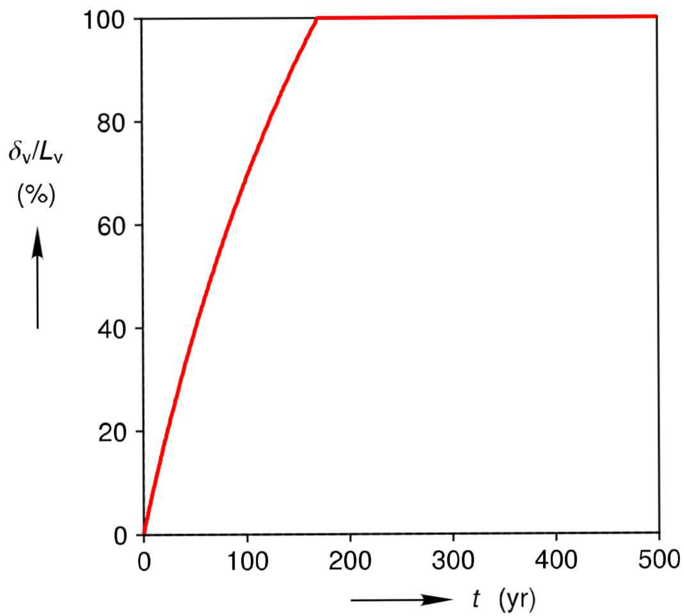
Coulomb Friction

$$\boldsymbol{t}_t = \mu_f \, \boldsymbol{t}_n$$

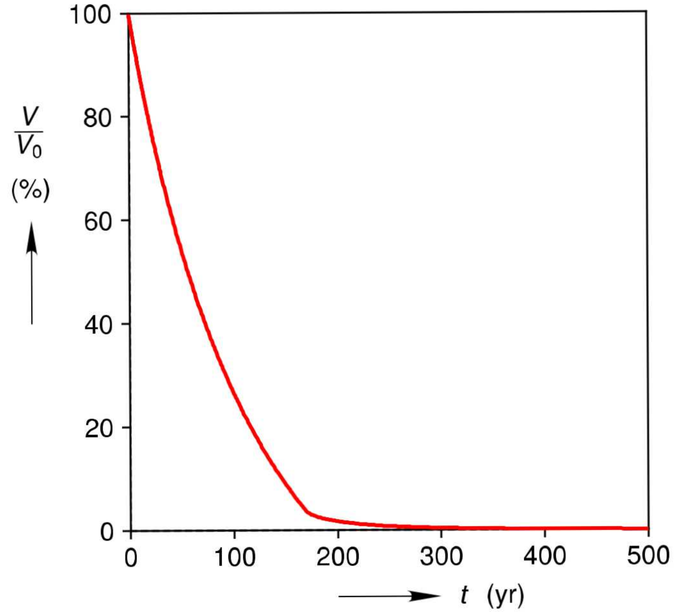
Finite Element Solution

Horizontal and Vertical Closure Histories

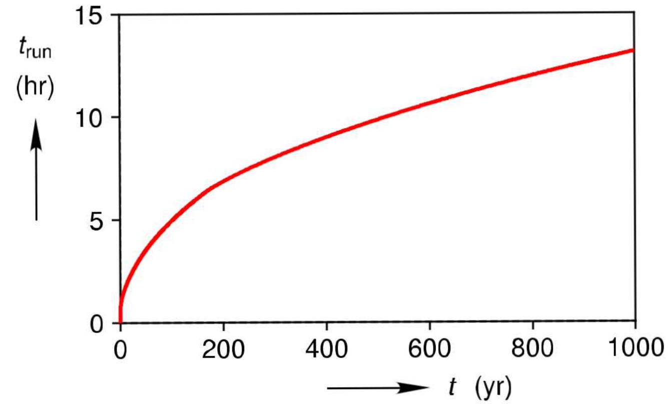




Room Porosity History



Run Time



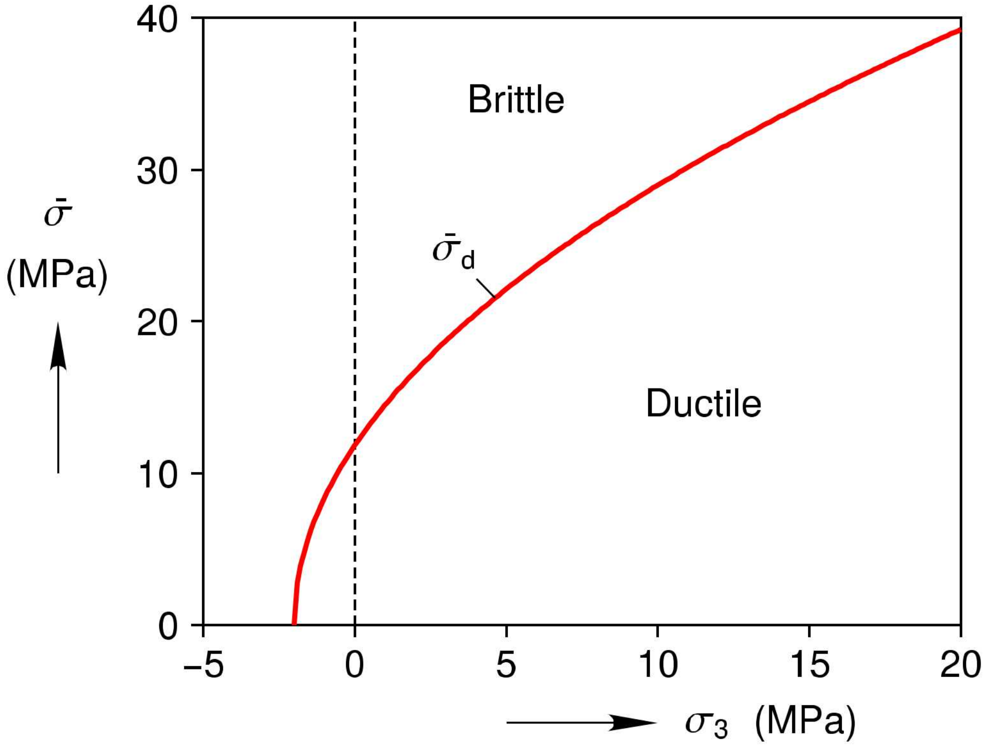
Problem #2: Fracturing and Roof Falls

1. Supplied by Sandia:
   a. Damage material model
   b. Initial boundary value problem

2. Assess whether a chosen meshless method can simulate 2D fracturing around a room and roof falls
   a. Show discretization convergence
   b. Record total CPU time

3. Demonstrate 3D fracturing around a room and roof falls
   a. Record total CPU time

Tentative Simple Damage Model



$$\bar{\sigma}_d = \sqrt{C\,(\sigma_3 - B)}$$

$$\dot{\omega} = \frac{\langle \bar{\sigma} - \bar{\sigma}_d \rangle \, \dot{\bar{\varepsilon}}^{vp}}{D}$$

$$\dot{\boldsymbol{\sigma}} = (1 - \omega)\, \mathcal{C} : \dot{\boldsymbol{\varepsilon}}^{el}$$

$$\dot{\bar{\varepsilon}}^{vp} = \sum_{i=1}^{2} A_i \left[\frac{\bar{\sigma}}{\mu\,(1-\omega)} \right]^{n_i}$$

Problem #3: Rubble Pile Compaction

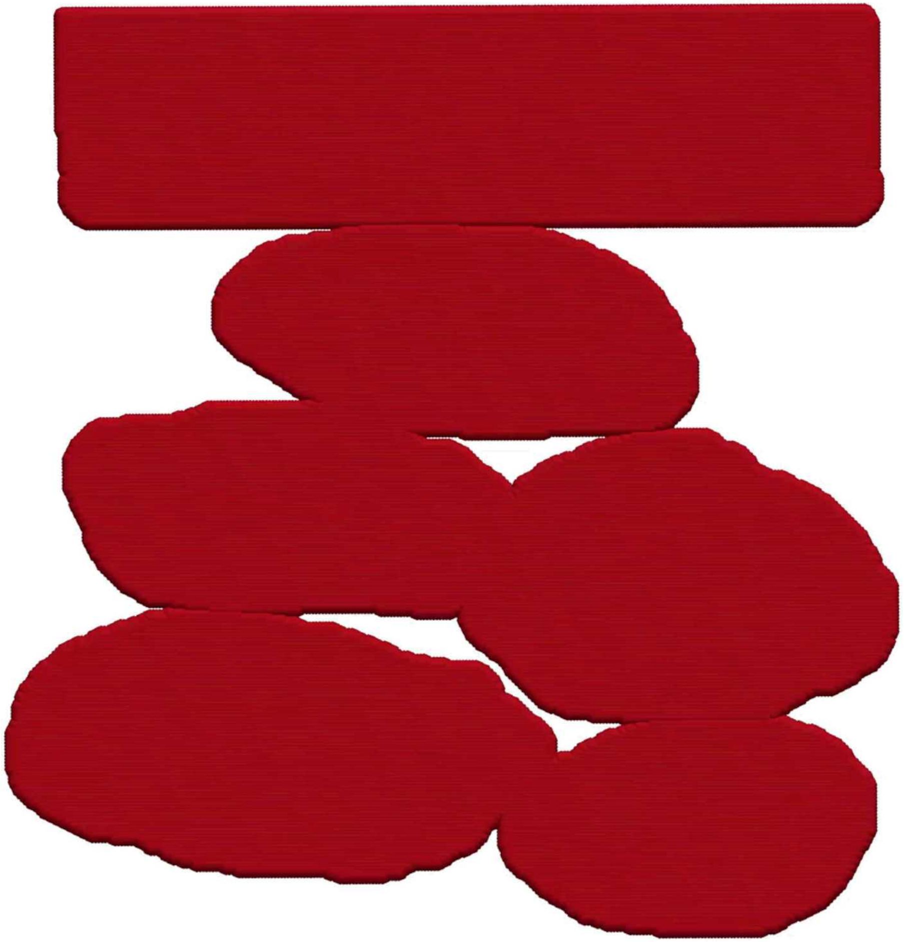
1. Supplied by Sandia:
   a. Initial boundary value problem

2. Assess whether a chosen meshless method can simulate 2D rubble pile compaction due to room closure
   a. Show room porosity discretization sensitivity
   b. Record total CPU time

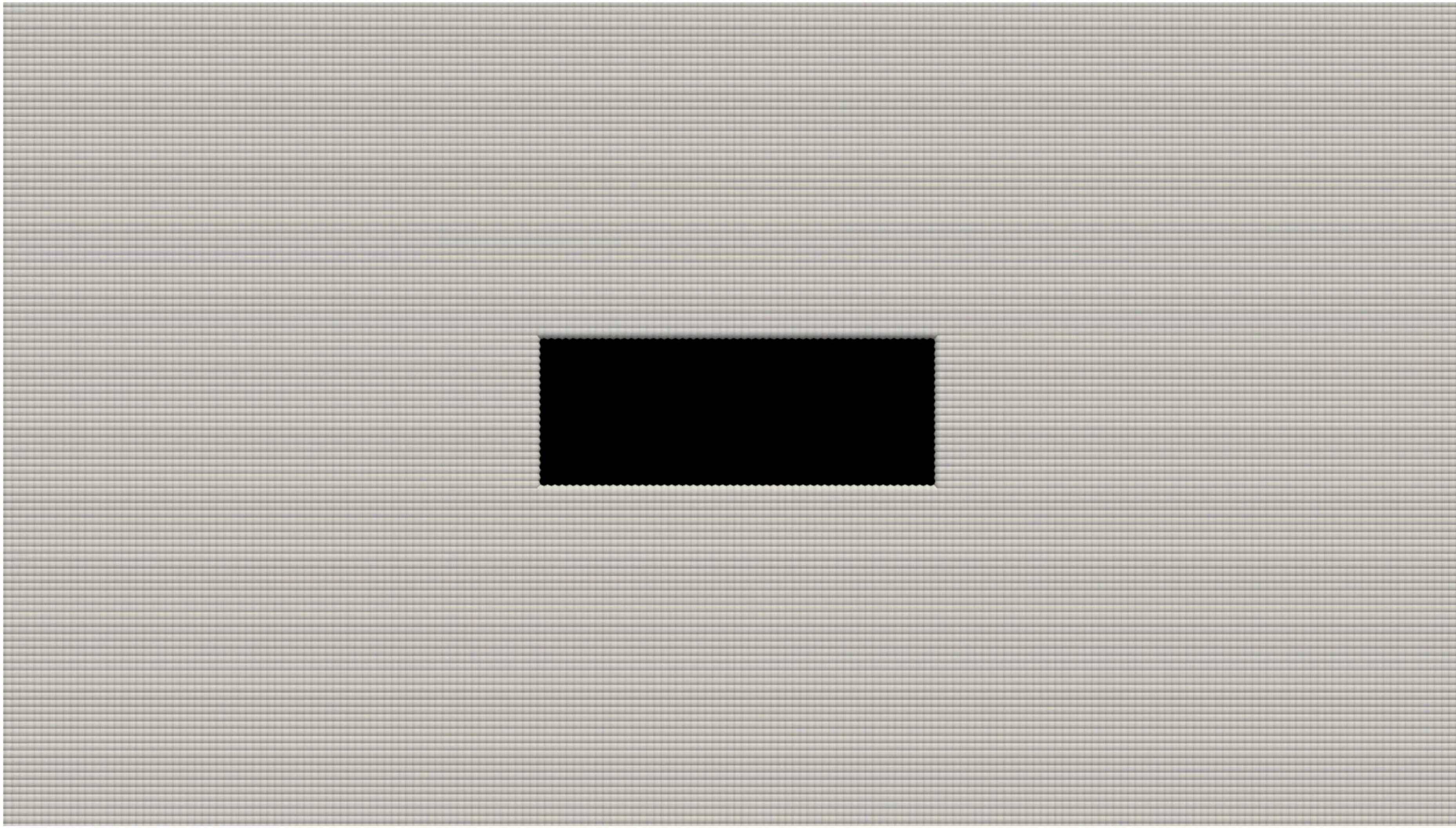
3. Demonstrate 3D rubble pile compaction
   a. Compute room porosity history
   b. Record total CPU time

Meshless Method (Pre-)Preliminary Results

MPM Team (Pre-)Preliminary Results

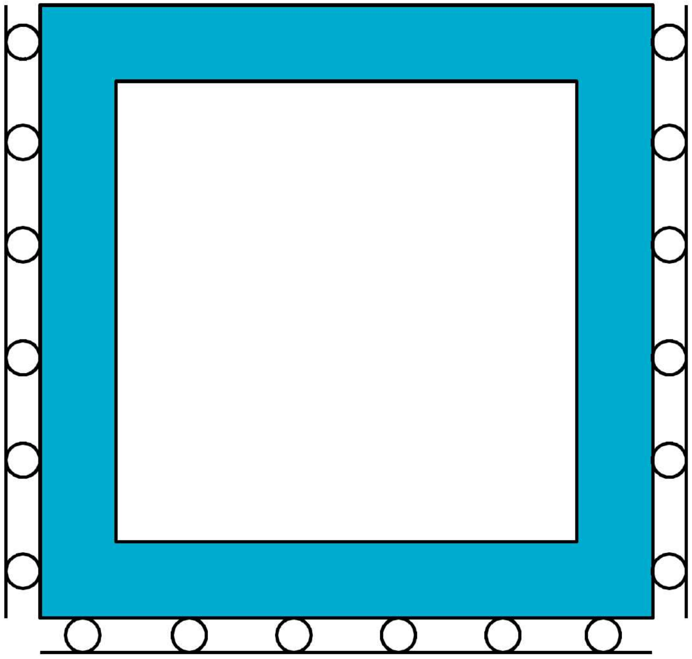


MPM Team (Pre-)Preliminary Results

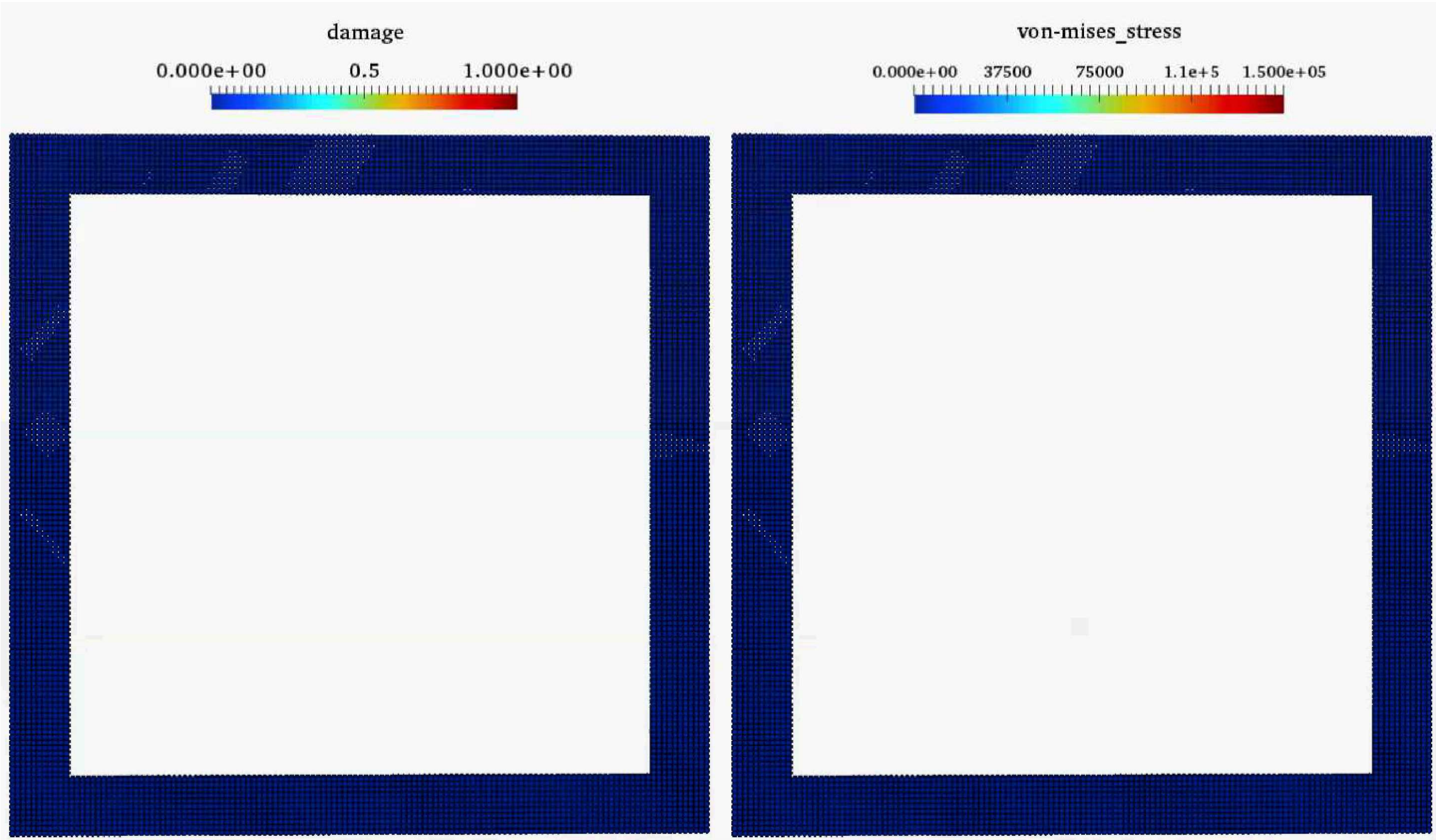


RKPM Team (Pre-)Preliminary Results

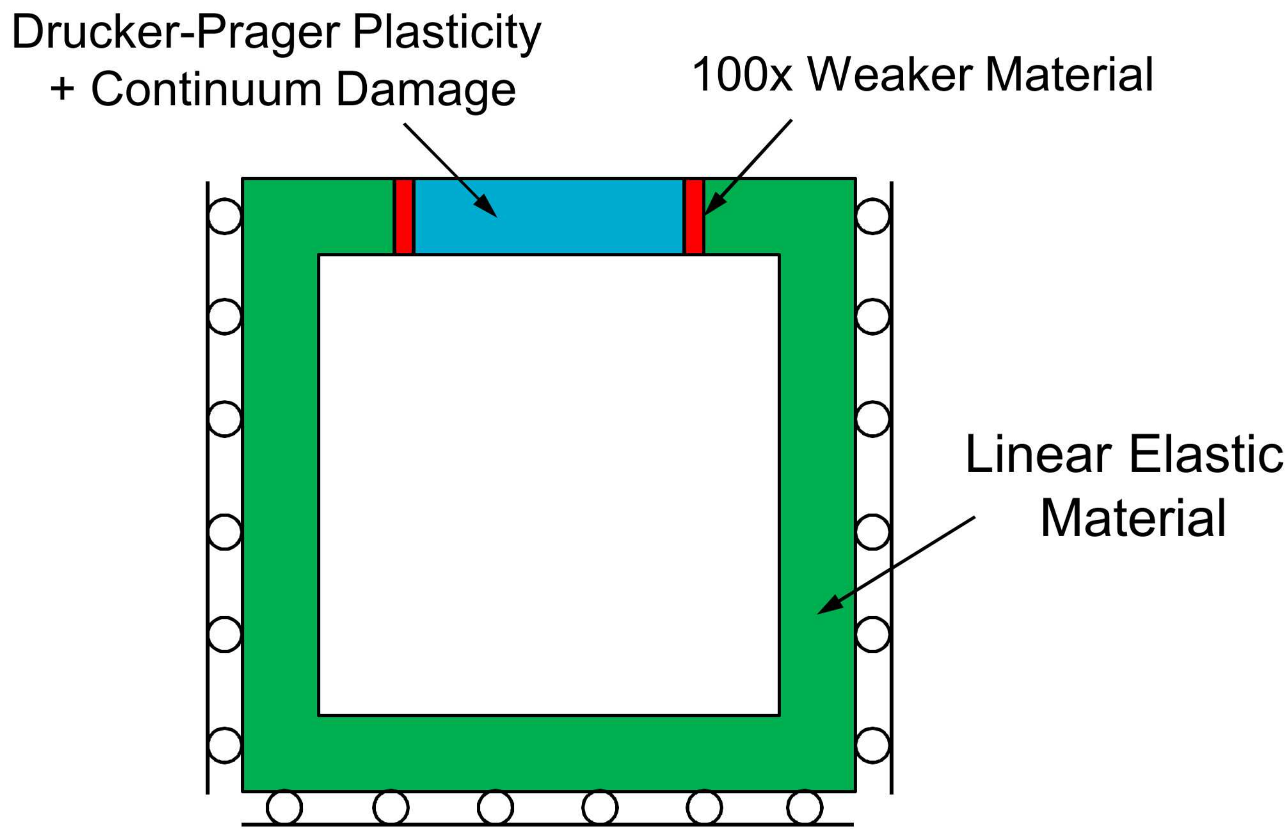
Homogeneous Material:
Continuum Damage + Drucker-Prager Plasticity



RKPM Team (Pre-)Preliminary Results

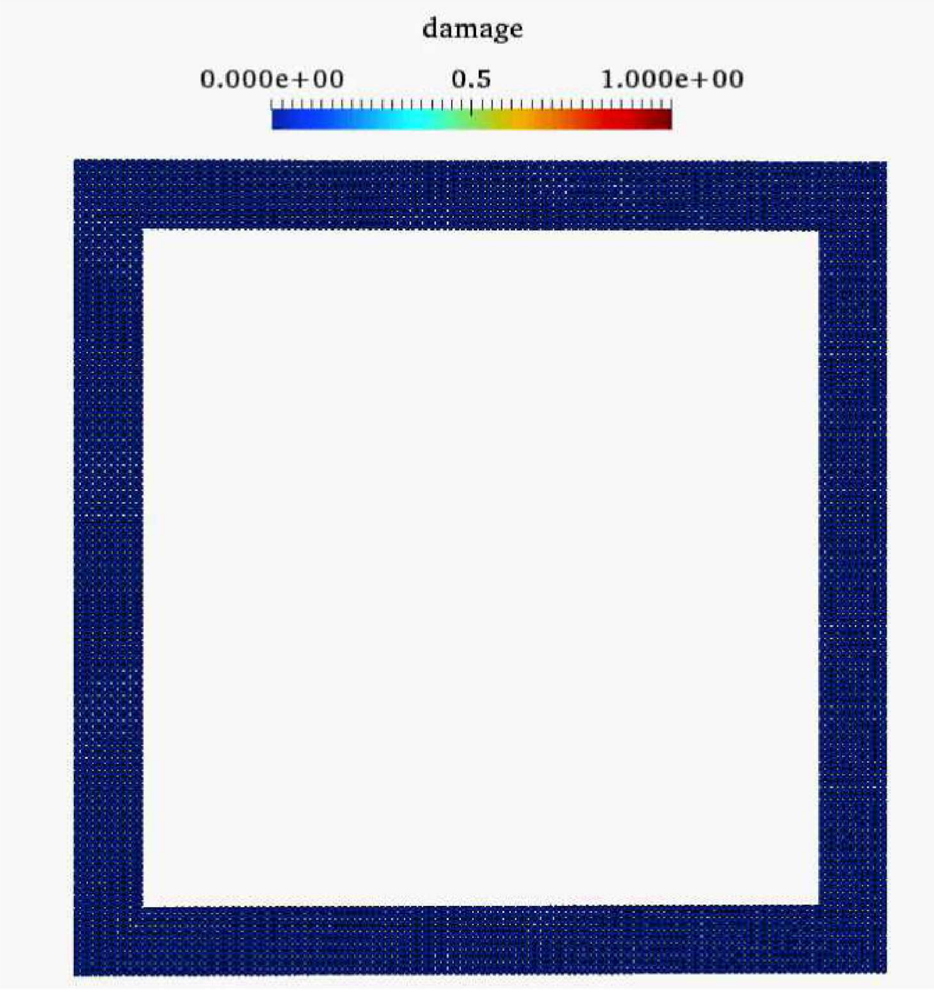


RKPM Team (Pre-)Preliminary Results

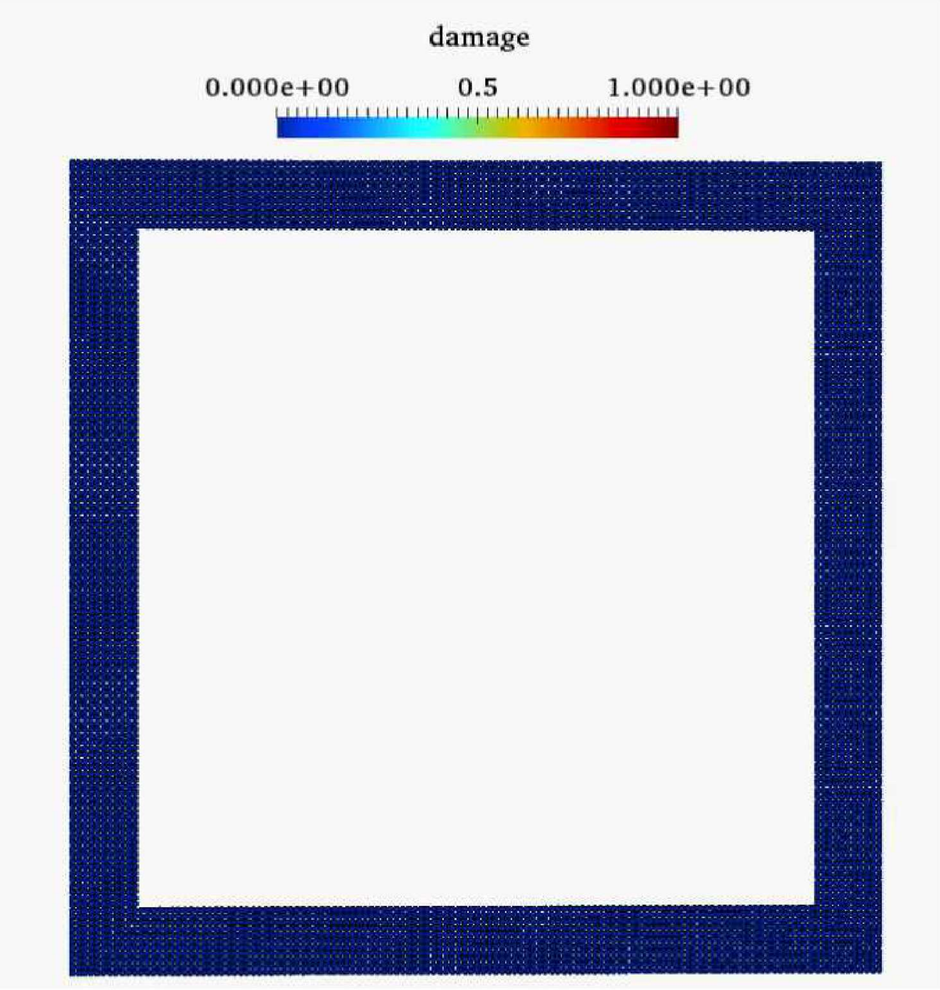


RKPM Team (Pre-)Preliminary Results

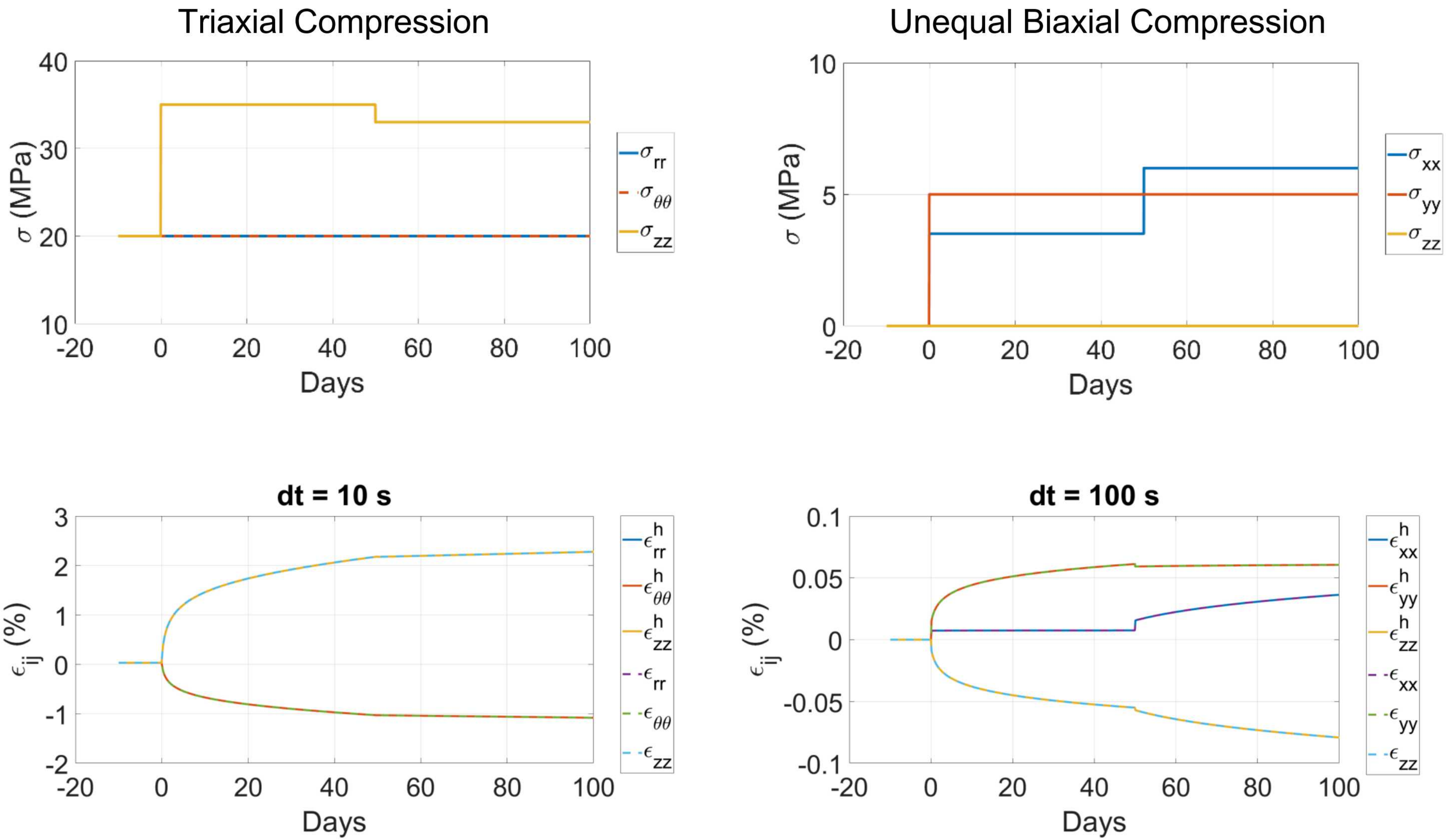
$k_i = 5 \times 10^{-3}$



$k_i = 1 \times 10^{-2}$



RKPM Team Ported and Verified M-D Model



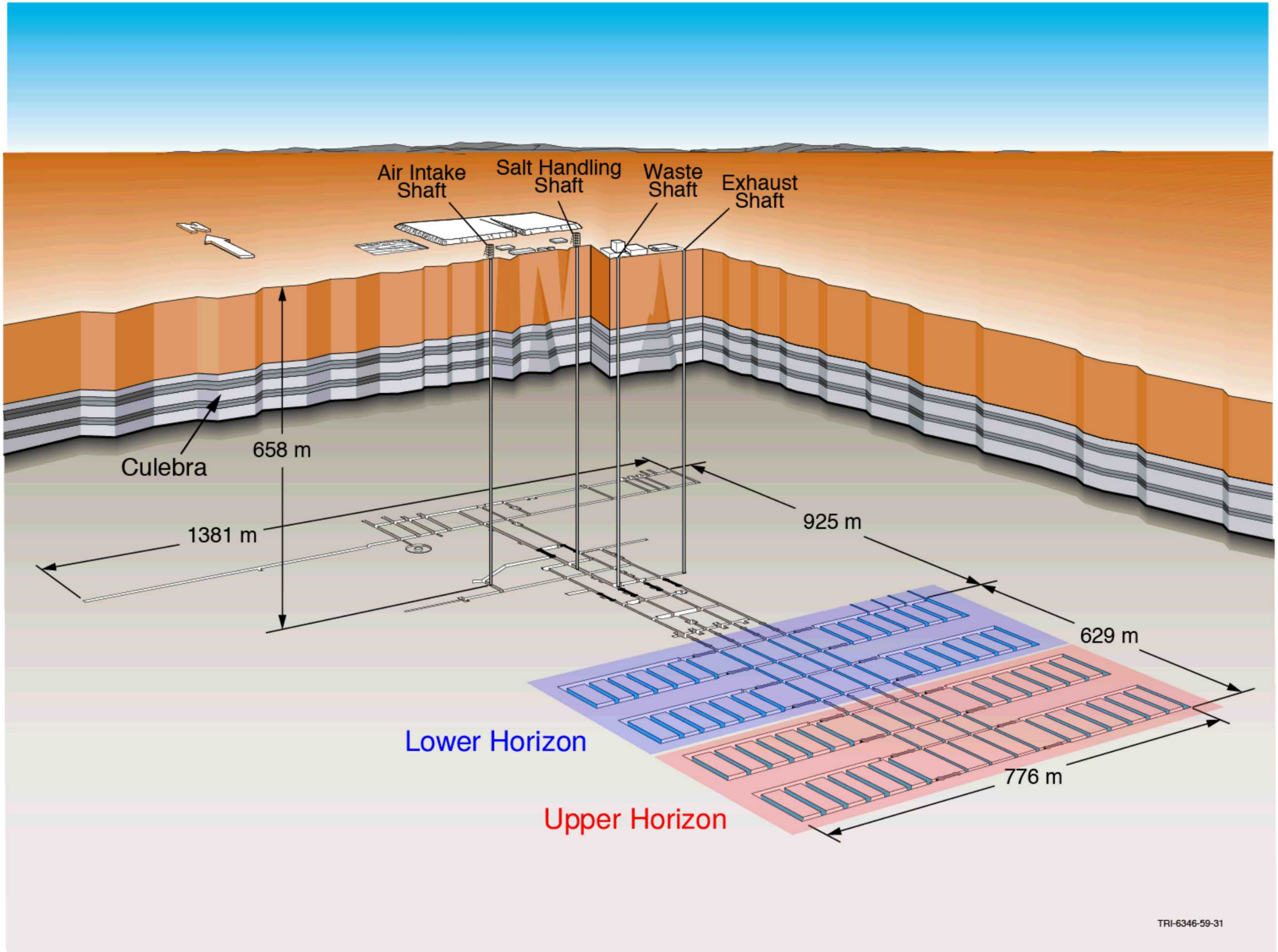
Tentative Project Schedule

Rough Project Schedule

1. Numerical method
   a. Investigation: April – September 2019
      i. One day workshop in ABQ during week of Sept 23rd?
   b. Implementation: April 2019 – April 2020
2. Continuum damage model
   a. Preliminary model: May 2019
   b. New model development: June – December 2019
   c. New model implementation: January – April 2020
3. Empty room demonstration simulations
   a. Proof-of-concept: June 2019 – April 2020
   b. Semi-polished: April 2020 – ?
4. Crushed salt validation simulations
   a. Proof-of-concept: June 2019 – April 2020
   b. Semi-polished: April 2020 – ?

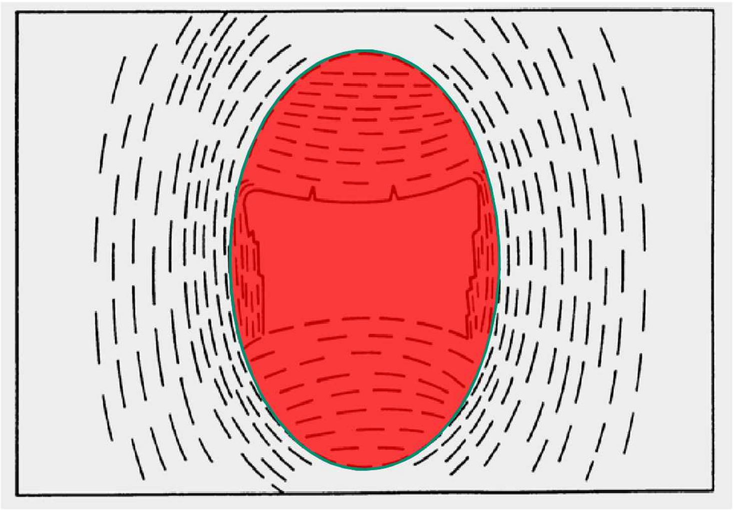
Extra Slides

Upper vs. Lower Horizon



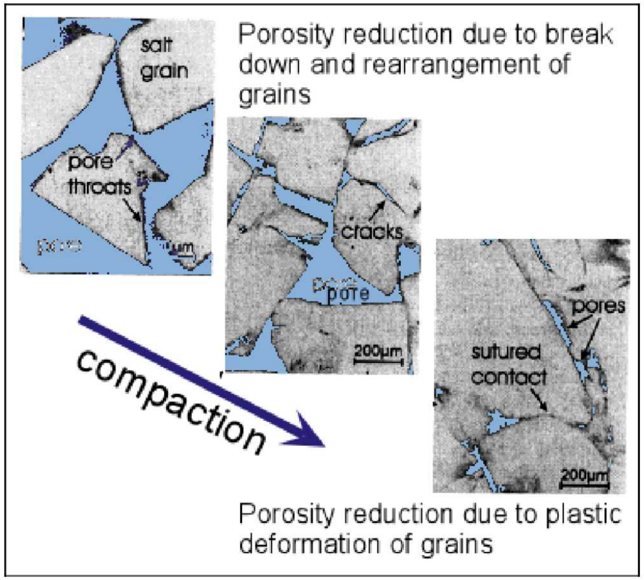
Empty Rooms Close More Slowly

1. Fracturing around room
   a. Changes the room cross-section from a rectangle to a more enduring, stable shape
   b. Controls the size and character of the rubble pile



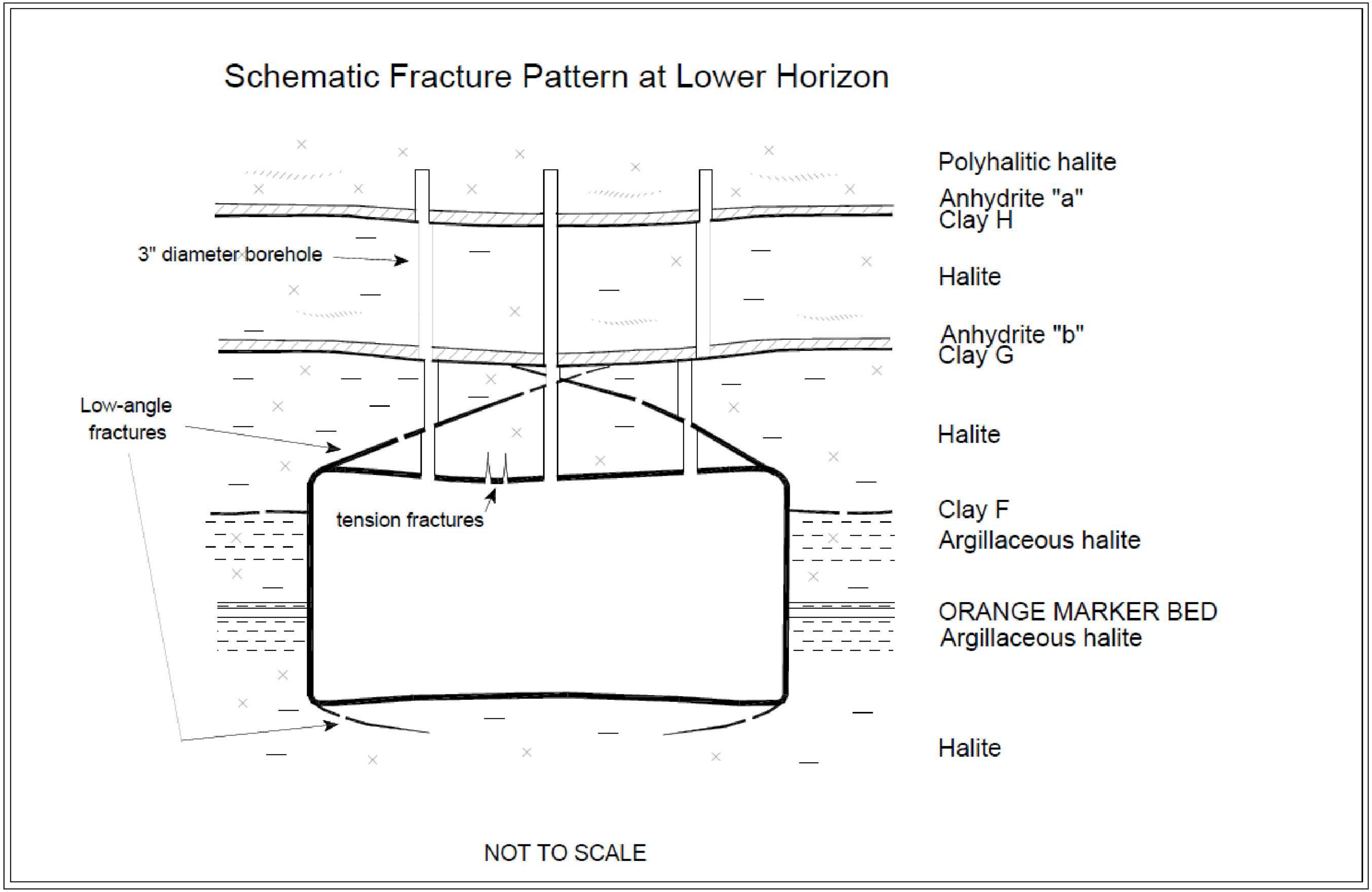
Borns, D.J. and J.C. Stormont. (1989) (Modified)

2. Rubble pile compaction
   a. Involves reorganization, fracturing, and creep
   b. Compaction processes control flow pathways
   c. Rubble pile supplies back pressure to surrounding rock formation



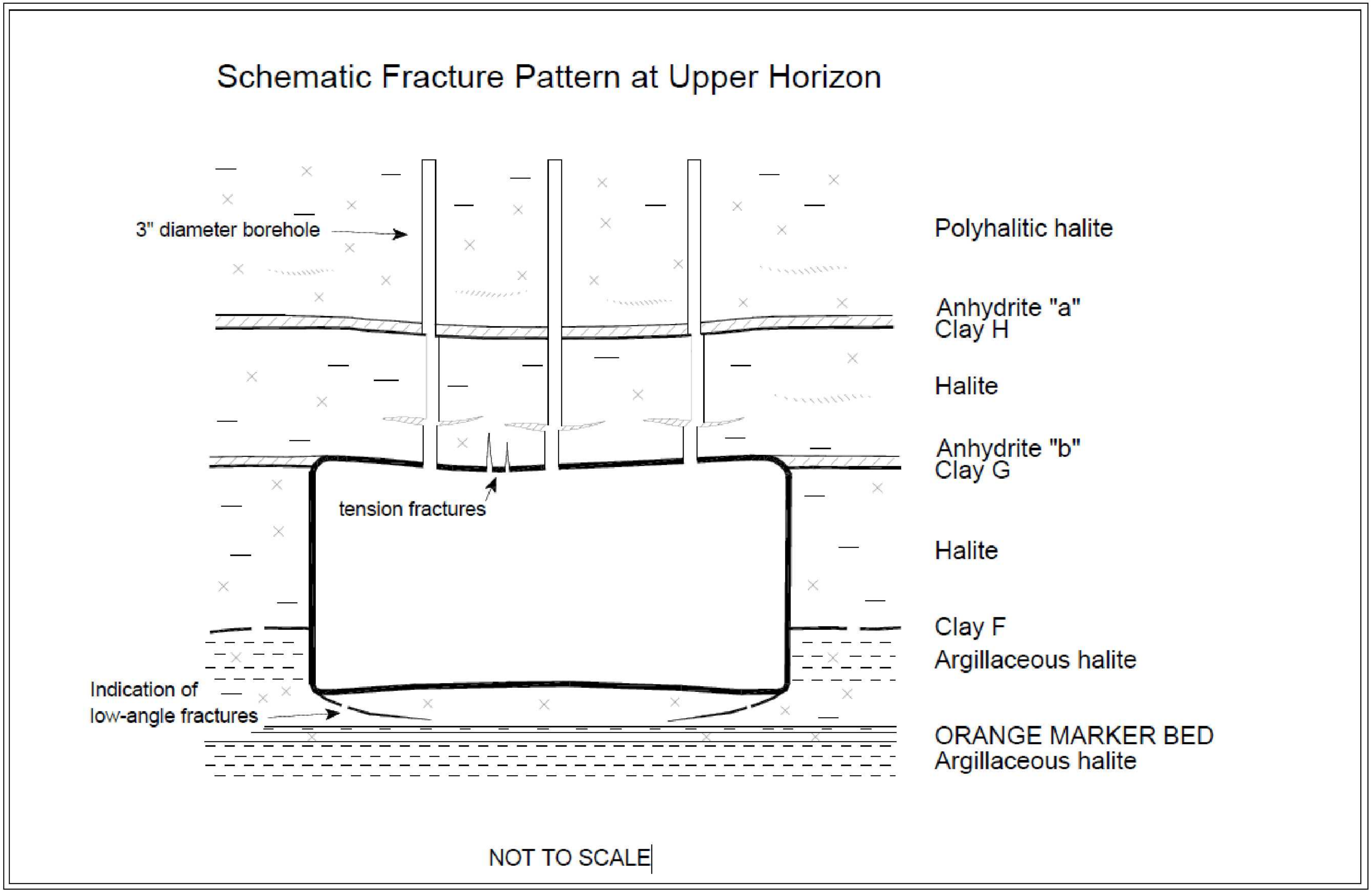
Spangenberg (1998) (Modified)

Typical Fractures on Lower Horizon



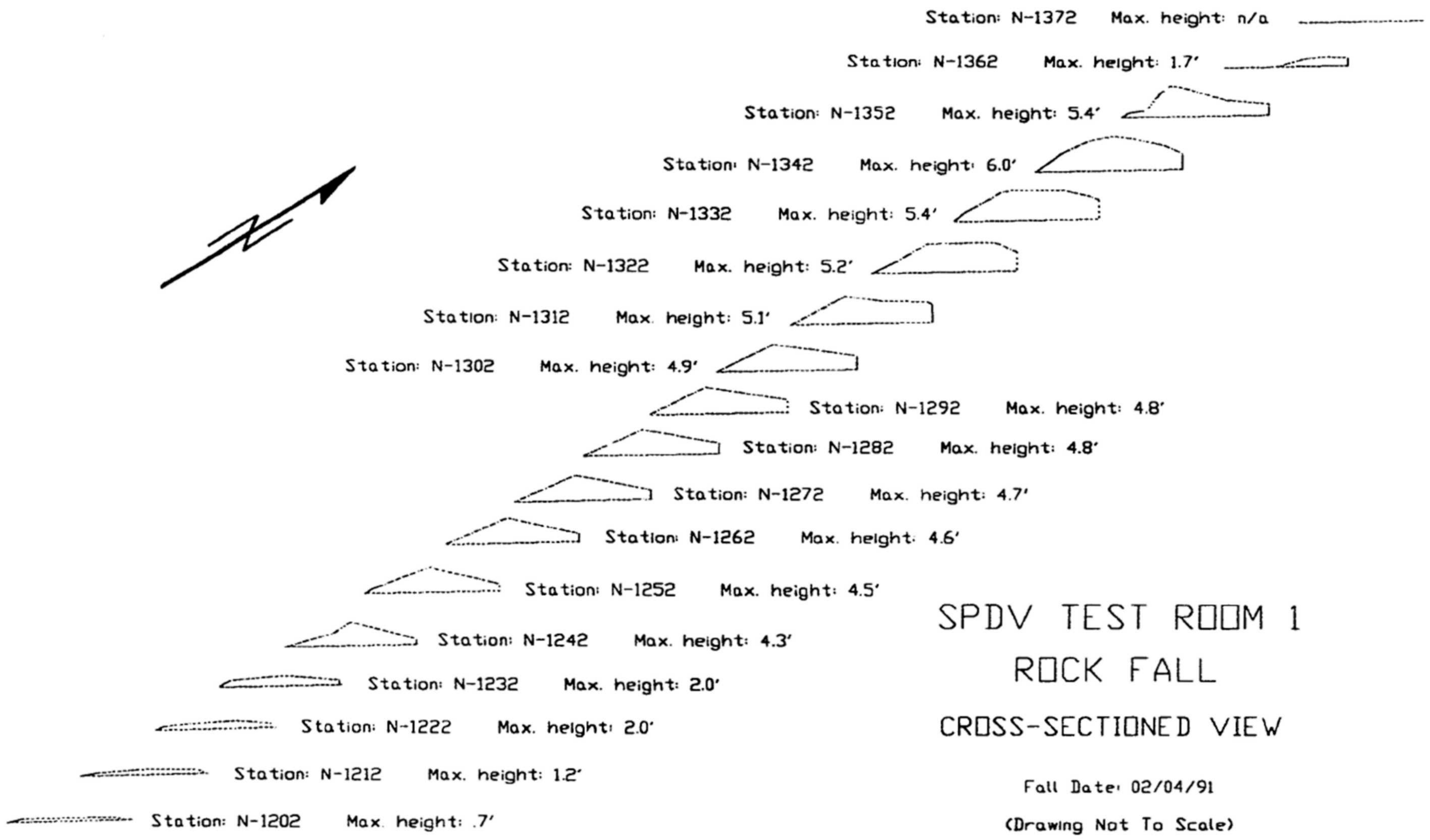
DOE (2016) Waste Isolation Pilot Plant Geotechnical Analysis Report, Vol. 1. DOE/WIPP-16-3569

Typical Fractures on Upper Horizon



DOE (2016) Waste Isolation Pilot Plant Geotechnical Analysis Report, Vol. 1. DOE/WIPP-16-3569

Fallen Block Shapes (Lower Horizon)



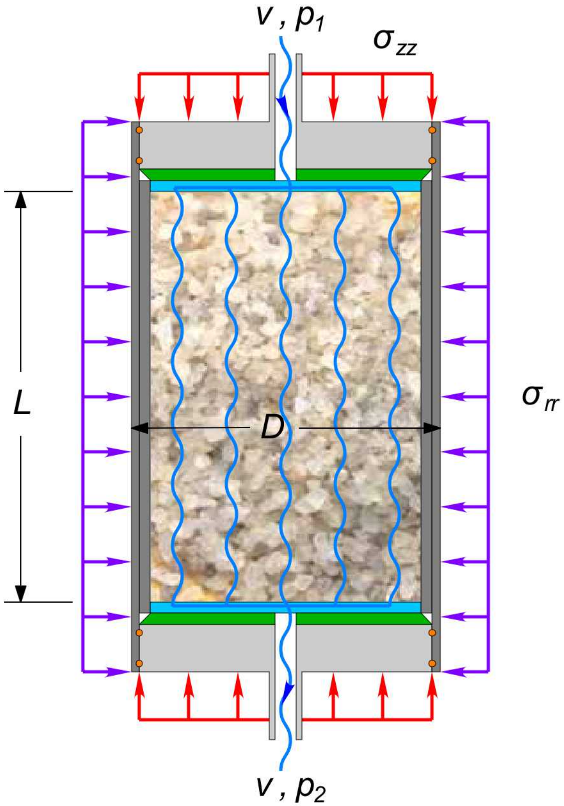
U.S. DOE. (1993). The Current Bases for Roof Fall Prediction at WIPP and a Preliminary Prediction for SPDV Room 2. DOE/WIPP 93-033.

Crushed Salt Laboratory Testing

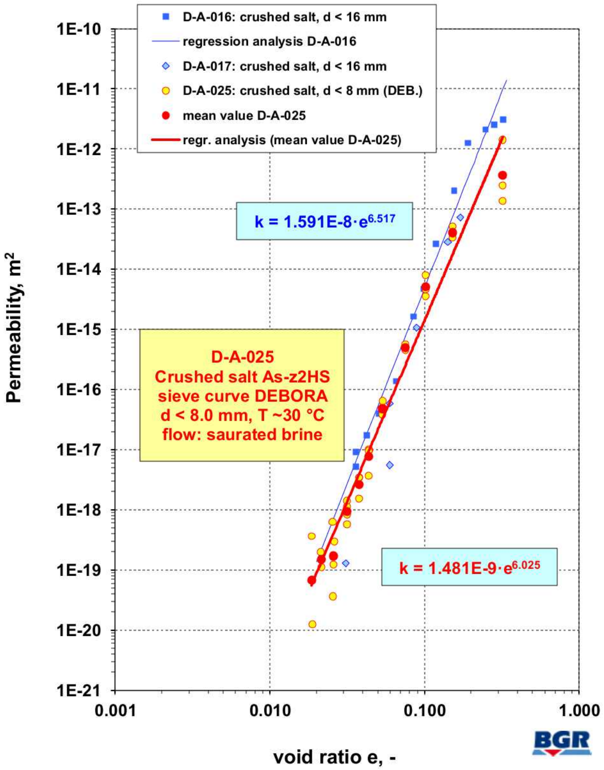
Specimen preparation

Photo courtesy of Scott Broome

Triaxial compression while measuring permeability



Permeability vs. Void Ratio (Porosity)

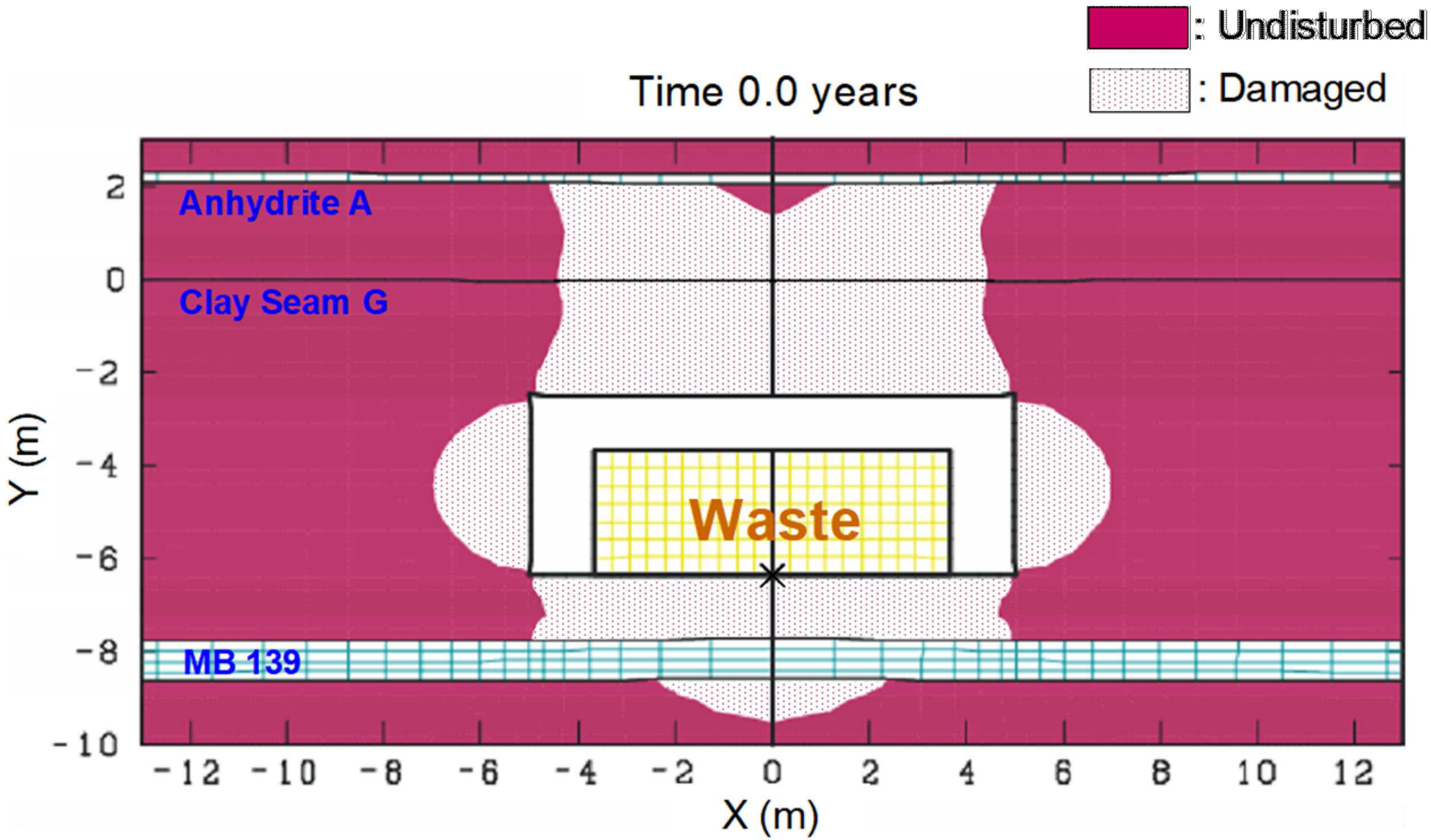


Kroehn, KP, et al. Mechanical and hydraulic behaviour of compacting crushed salt backfill at low porosities. Project REPOPERM. Phase 2. GRS GmbH. GRS – 450. 2017

Examples of Fracture on Lower Horizon

Roof Fall on Upper Horizon

Estimation of Excavation Damaged Zone

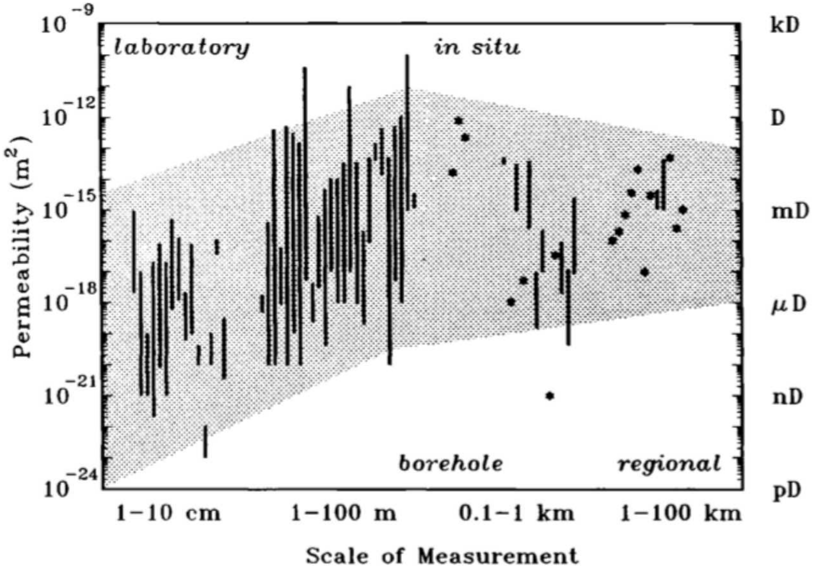


Herrick, C.G., et al. (2009). Estimating the Extent of the Disturbed Rock Zone around a WIPP Disposal Room. Paper ARMA 09-82. 43rd US Rock Mechanics Symposium, Ashville, NC. June 28 – July 1, 2009.

Scale Effects

Compaction Scale Effect

Permeability Scale Effect



Clauser, C. (1992). Permeability of crystalline rocks. Eos, Transactions American Geophysical Union, 73(21), 233-238.

Speeding up the Viscoplasticity

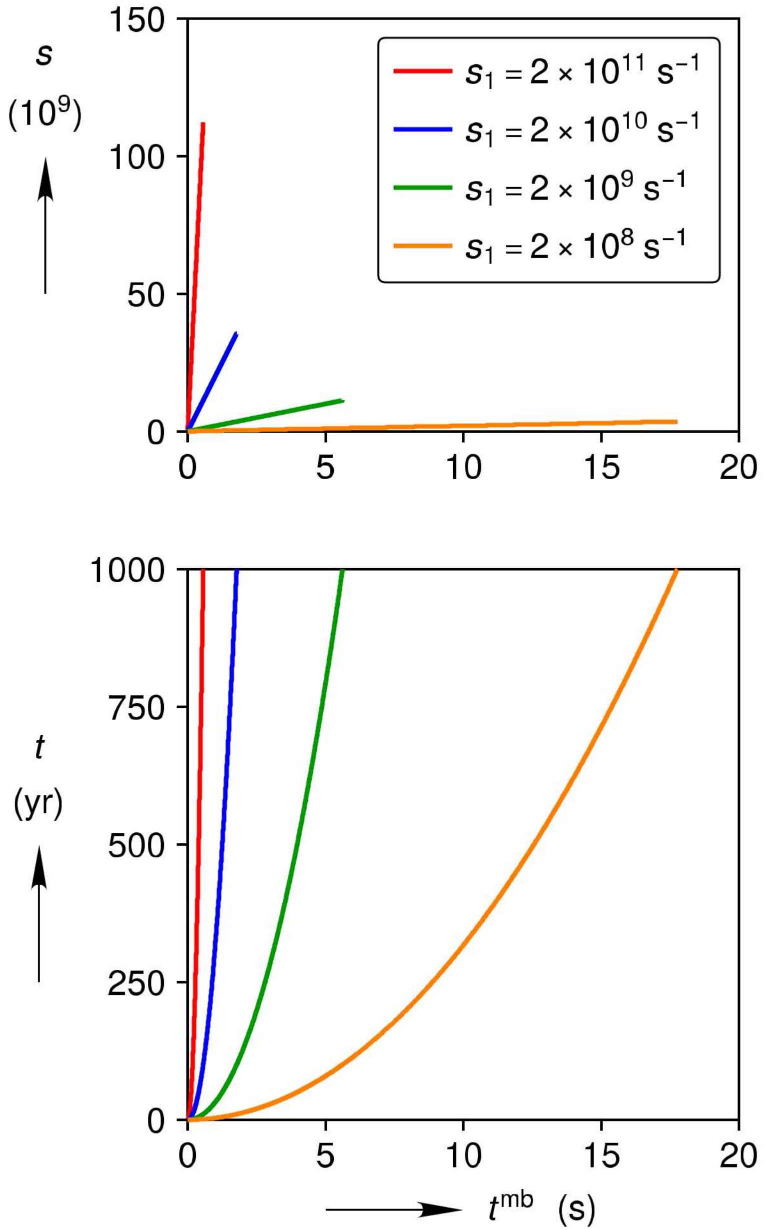
$$\dot{\bar{\varepsilon}}^{\mathrm{vp}} = \sum_{i=1}^{2} A_i \left(\frac{\bar{\sigma}}{\mu}\right)^{n_i}$$

$$\Downarrow$$

$$\dot{\bar{\varepsilon}}^{\mathrm{vp}} = s \sum_{i=1}^{2} A_i \left(\frac{\bar{\sigma}}{\mu}\right)^{n_i}$$

$$\mathrm{d}t = s\, \mathrm{d}t_{\mathrm{mb}}$$

$$s = s_0 + s_1\, t_{\mathrm{mb}}$$



Scaling Ramp Rate Selection