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Initial Simulations of Empty Room Collapse and Reconsolidation

2022 US/German Workshop on Salt Repositories

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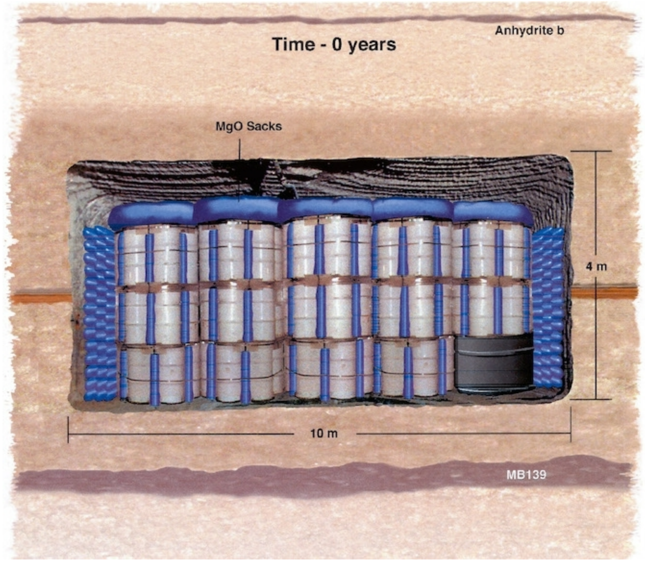
Agenda

1. Background
2. Large-Scale Room Collapse and Reconsolidation Simulations
3. Small-Scale Rubble Pile Reconsolidation Studies
4. Summary and Future Work

Background

Filled vs. Empty Room Closure

Filled Rooms



Empty Rooms

Relevant Physical Phenomena

1. Gradual room closure
   1. Driving force for empty room closure
2. Fracturing around room
   1. Changes room shape and size
   2. Controls the size and character of rubble pile
3. Rubble pile reconsolidation
   1. Involves rearrangement, fracture, dislocation creep, and pressure solution creep
   2. Rubble supplies back pressure
4. Flow through the rubble pile
   1. Depends on flow network as well as pathway size, roughness, and tortuosity.

Large-Scale Room Collapse and Reconsolidation Simulations (items 1–3)

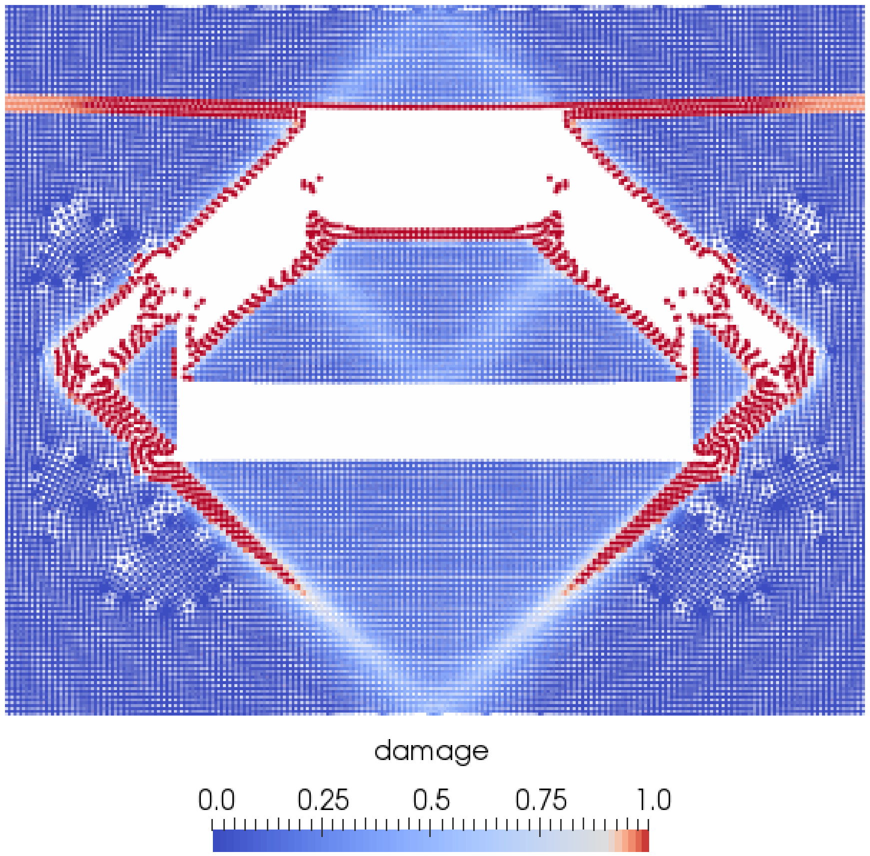
Small-Scale Rubble Pile Reconsolidation Studies (items 3–4)

Large-Scale Room Collapse and Reconsolidation Simulations

Research Plan

1. Assess potential numerical methods
   1. Develop additional capabilities as needed.
2. Attempt to simulate roof falls and subsequent reconsolidation
   1. Stochastic distribution of defect sites?
3. Improve salt constitutive modeling
   1. Add damage and healing
4. Perform sensitivity studies
5. Validate against observations at WIPP and other salt mines
   1. Teutschenthal mine in Germany may be a possibility

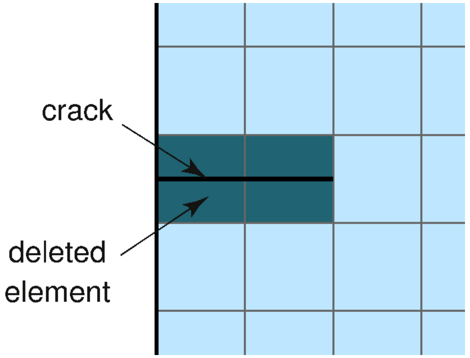
Roof Fall Simulation Snapshot



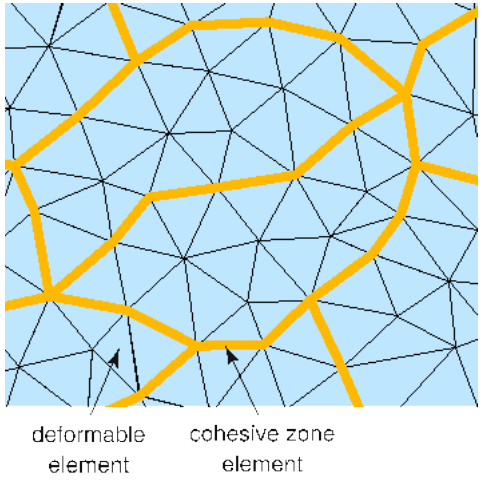
Potential Numerical Methods

1. Fundamental issue: we are trying to capture a discrete crack with a continuum level model
2. Potential numerical issues
   1. Mass / volume loss
   2. Mesh structure dependence
   3. Mesh size dependence
3. Candidate numerical methods

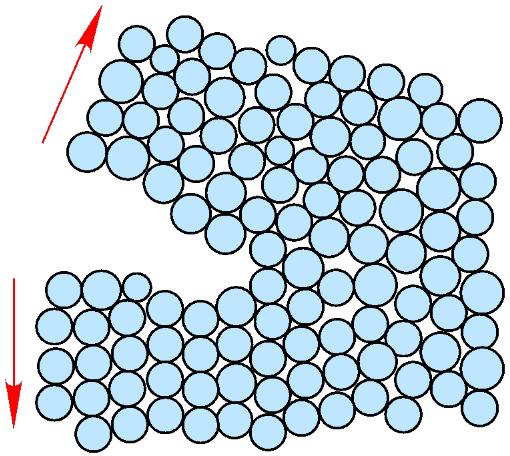
Finite Elements with Element Death



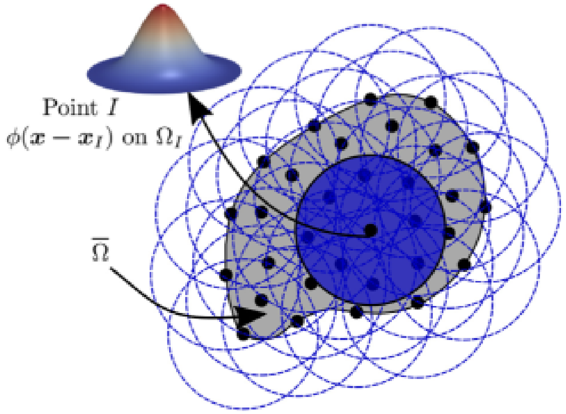
Finite Elements with Interelement Cracks



Particle Methods



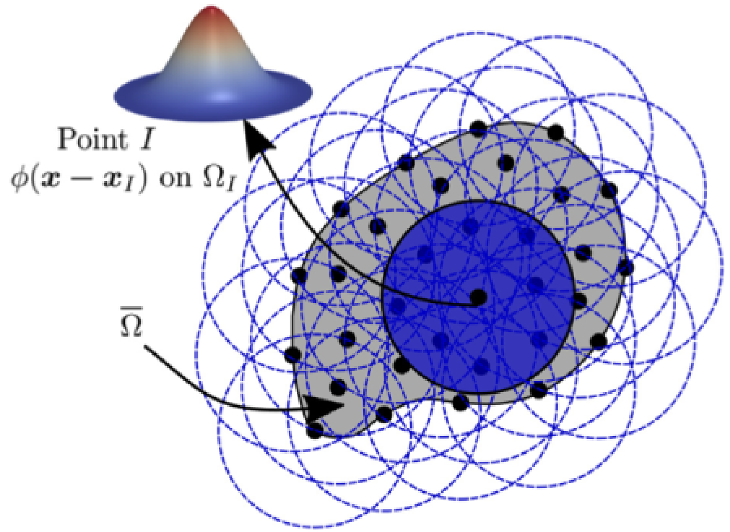
Meshless Methods



Meshless Methods

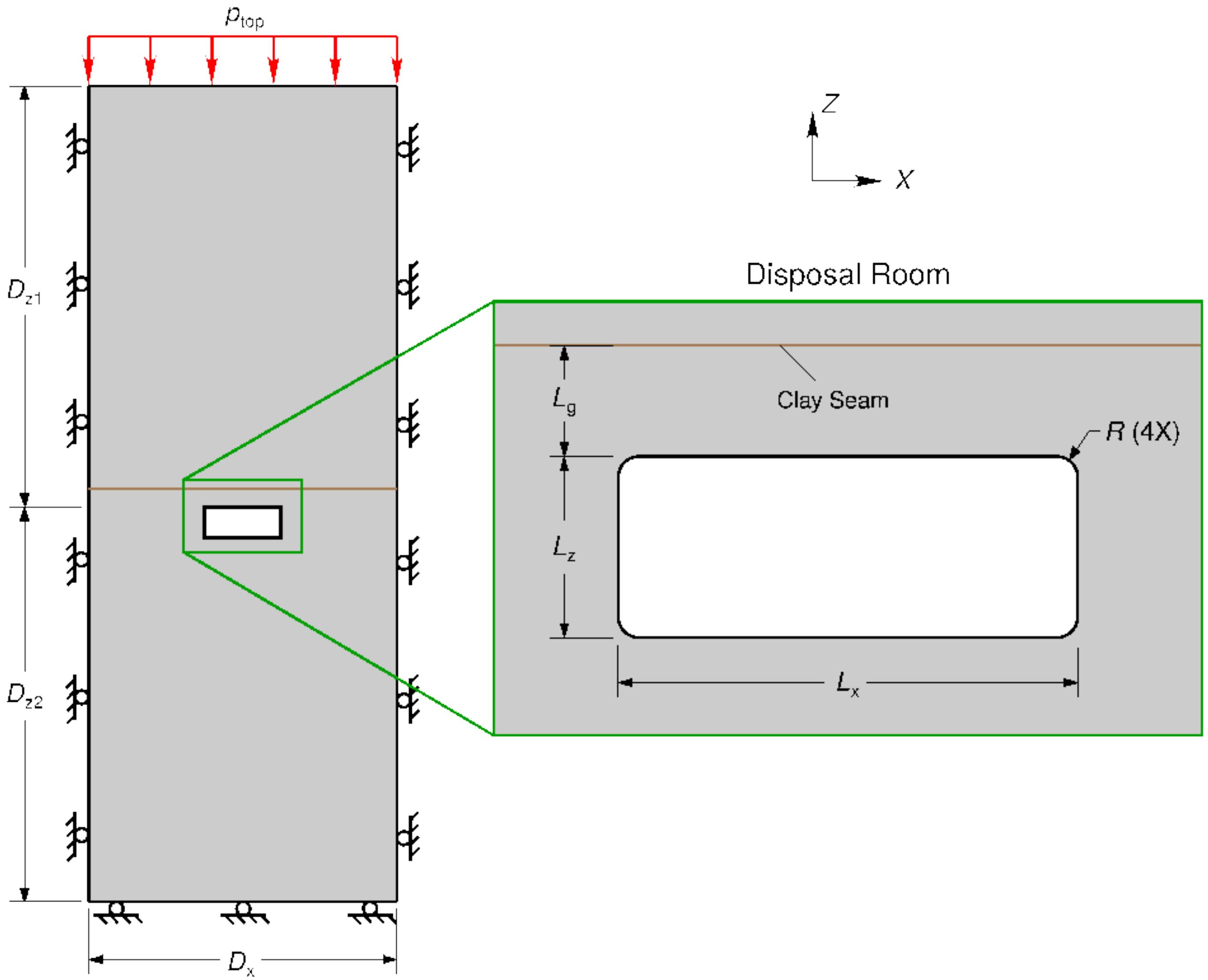
1. Primary advantages
   1. Fracture without mass loss
   2. Fracture plane orientation is less constrained
   3. Can utilize classical continuum material models
   4. Designed to handle severe deformation (>100 % strain)
   5. Regularization techniques are relatively easy to implement
   6. Other Sandia programs will likely continue to invest in meshless methods

2. Primary drawbacks
   1. Accurate frictional contact is challenging
   2. Despite decades of development, meshless methods are not as mature as finite element methods.

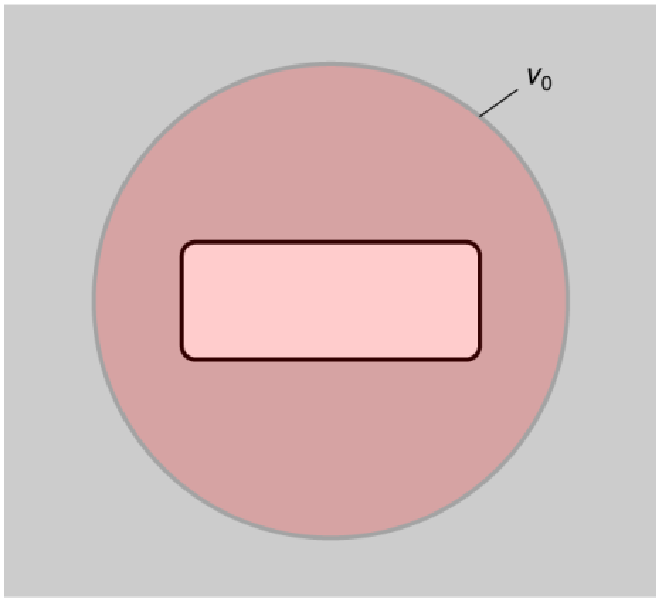


Simulation Setup

Geometry and Boundary Conditions



Porosity Calculation



Room Porosity: $$\phi^{room} = \frac{V_v^{room}}{V_0^{room}}$$

Cylinder Porosity: $$\phi = \frac{V_v}{v_0}$$

Relative Porosity: $$\frac{\phi}{\phi_0} = \frac{V_v / v_0}{V_{v0} / v_0} = \frac{V_v}{V_{v0}}$$

"Toy" Salt Model

Kachanov Stress

$$\hat{\sigma} = \frac{\sigma}{1 - \omega}$$

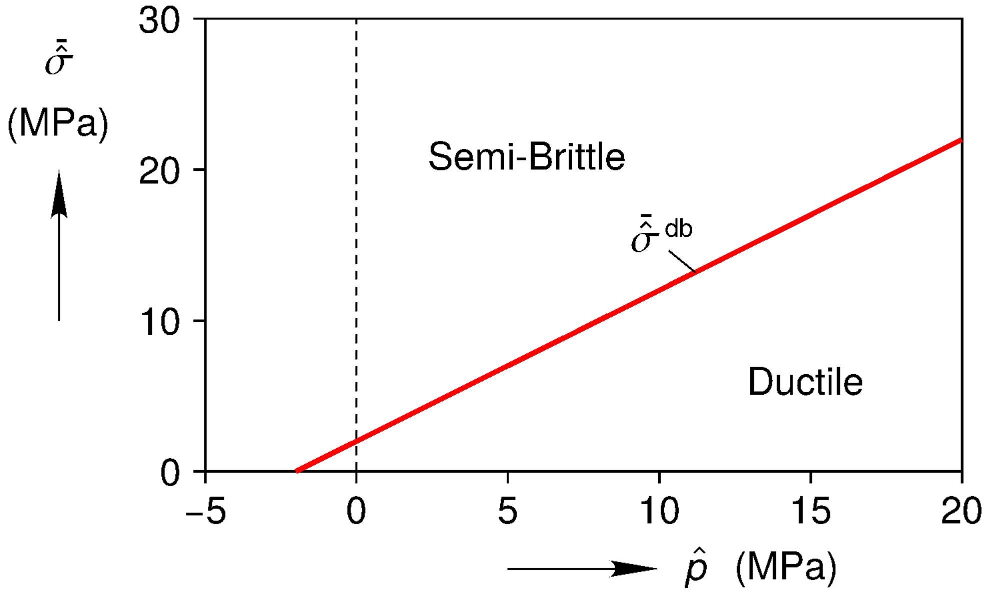
von Mises Equivalent
Kachanov Stress

$$\bar{\hat{\sigma}} = \sqrt{3\,\hat{J}_2}$$

Equivalent Viscoplastic Strain Rate

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

Damage Boundary

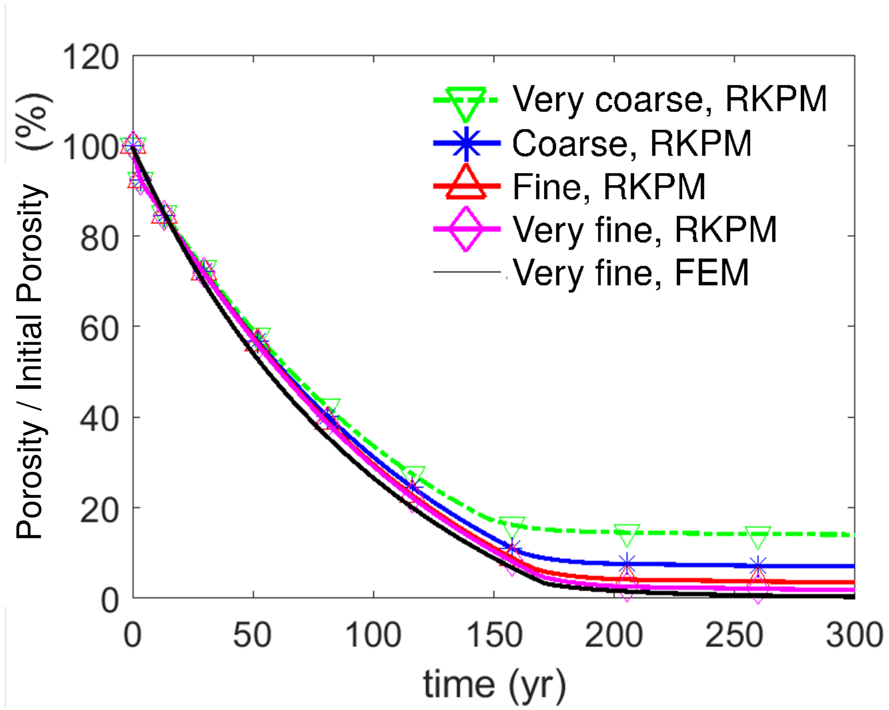


$$\bar{\hat{\sigma}}^{\mathrm{db}} = B_2 \left(\hat{p} - \frac{B_1}{1 - \omega}\right)$$

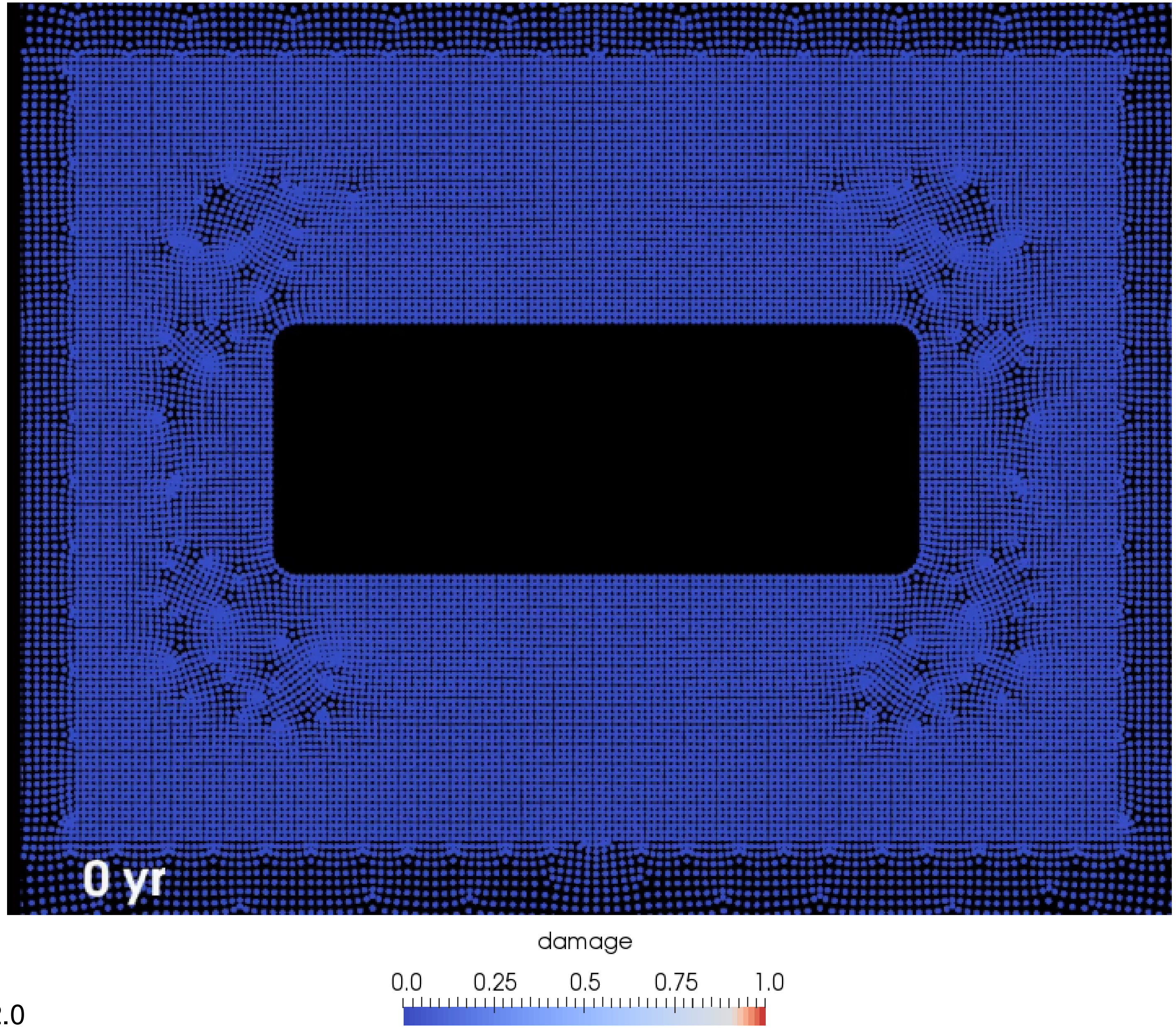
Damage Evolution

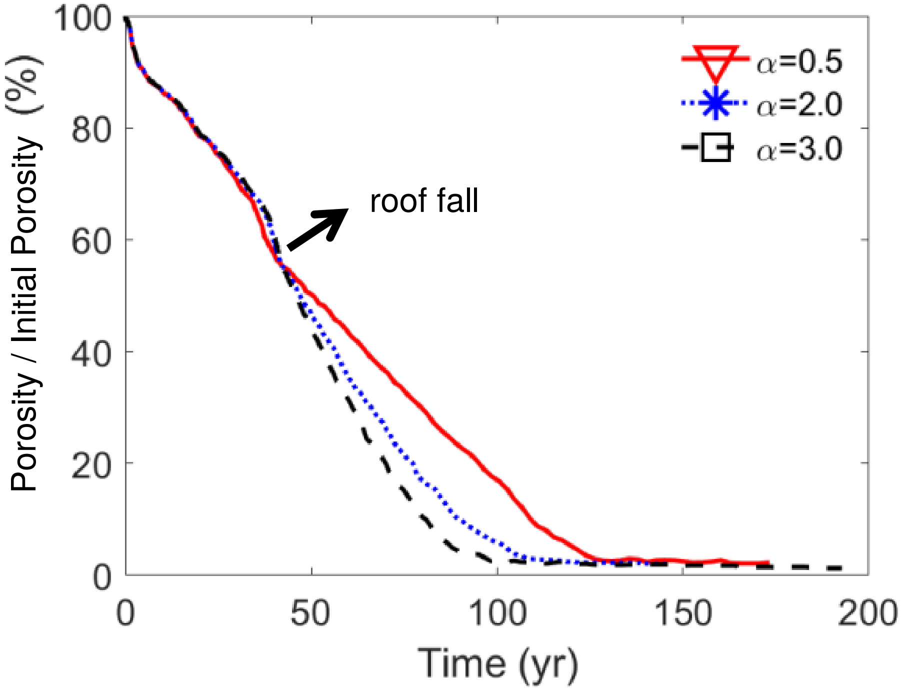
$$\dot{\omega} = \frac{D}{\mu} \left\langle \bar{\hat{\sigma}} - \bar{\hat{\sigma}}^{\mathrm{db}} \right\rangle \left(\dot{\bar{\varepsilon}}^{\mathrm{vp}} + \alpha\, \dot{\bar{\varepsilon}}^{\mathrm{el}}\right)$$

Gradual Room Closure (Without Damage)



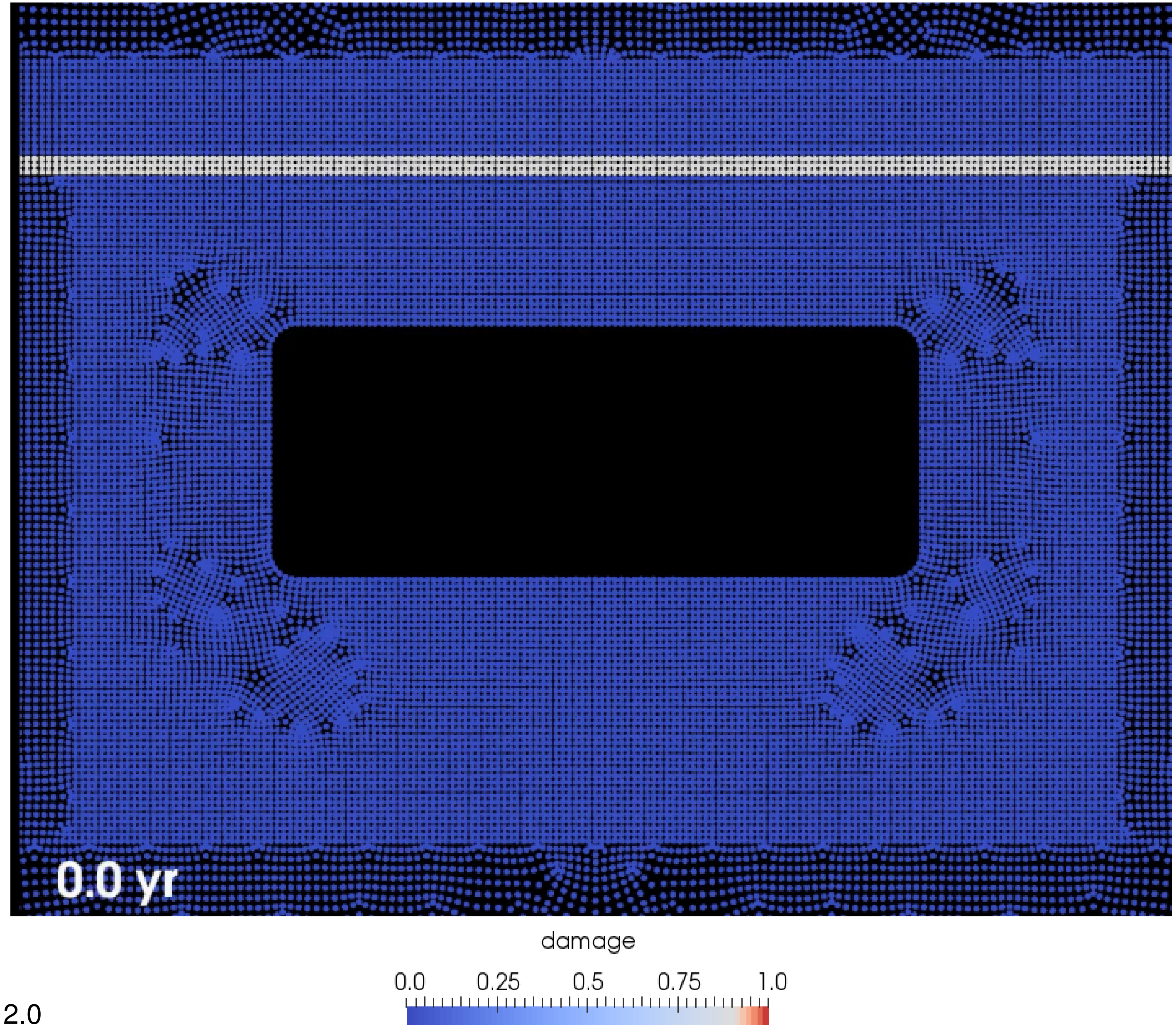
Room Collapse Without Clay Seam

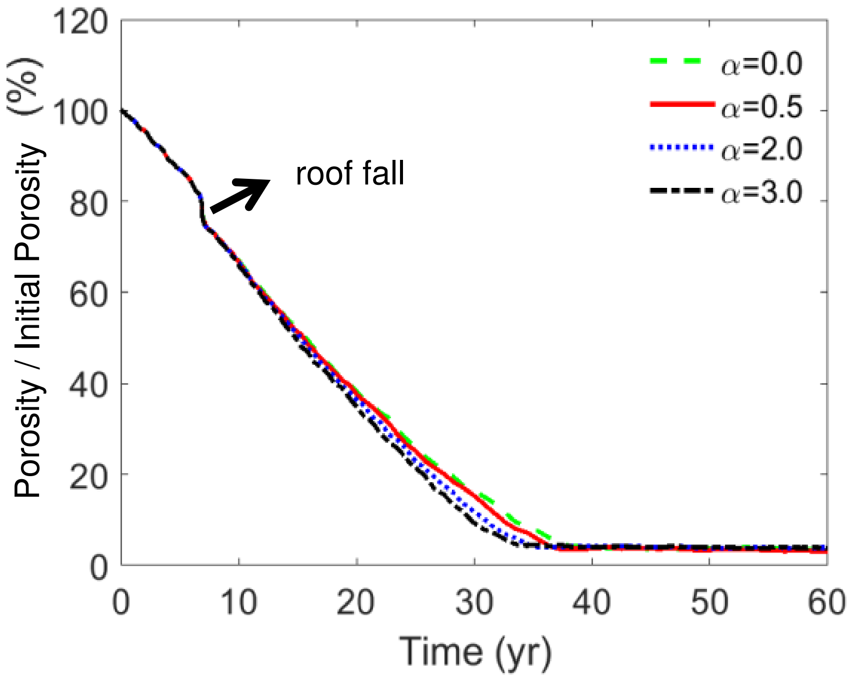




α = 2.0

Room Collapse With Clay Seam

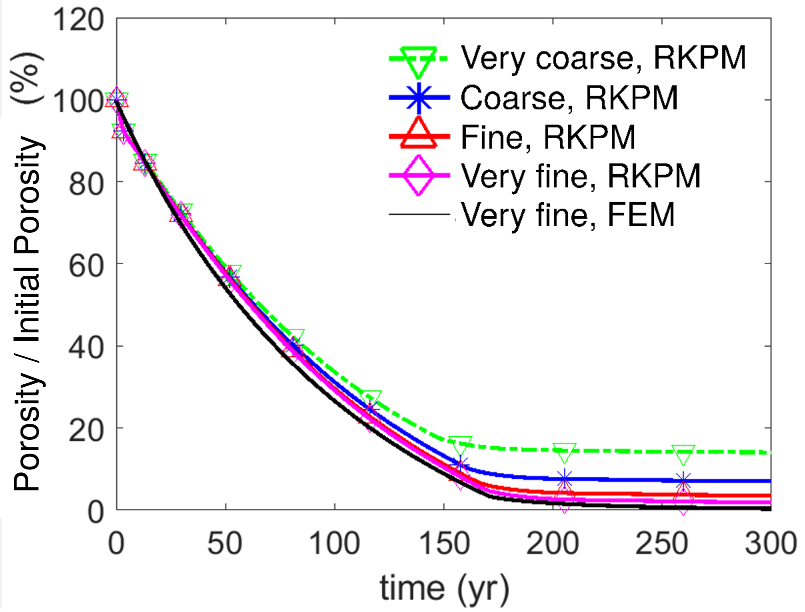




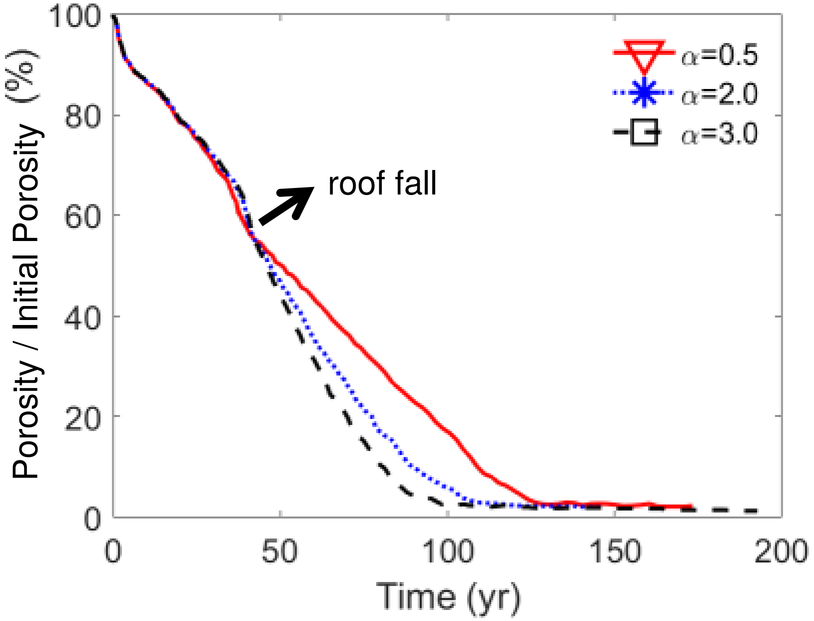
α = 2.0

Compare Relative Porosity Histories

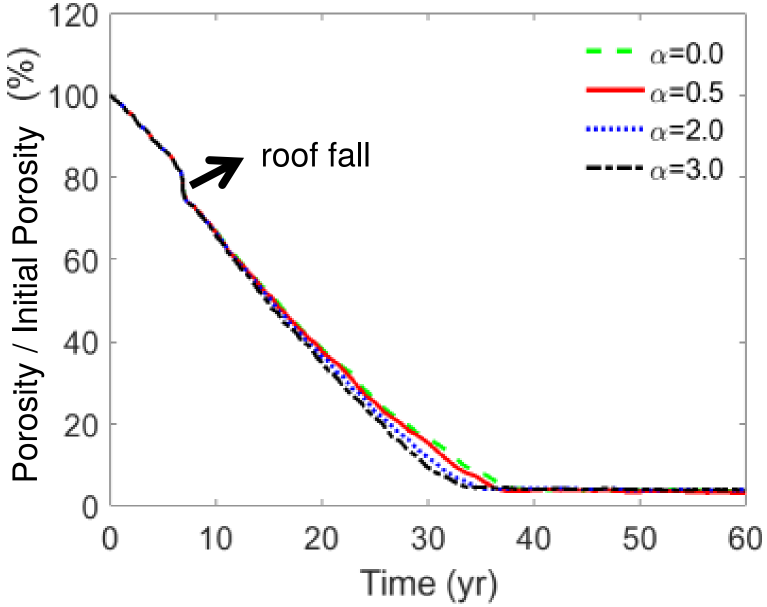
Gradual Room Closure
Without Clay Seam



Room Collapse
Without Clay Seam

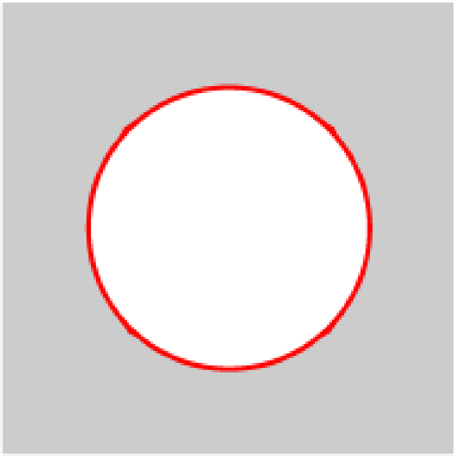


Room Collapse
With Clay Seam



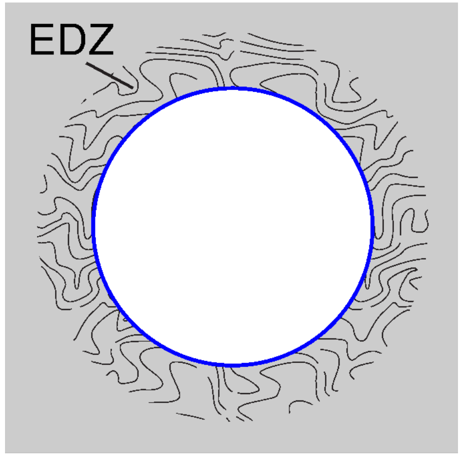
A Mechanism That Speeds Up Closure?

Small Room



vs.

Small Room, Surrounded with EDZ

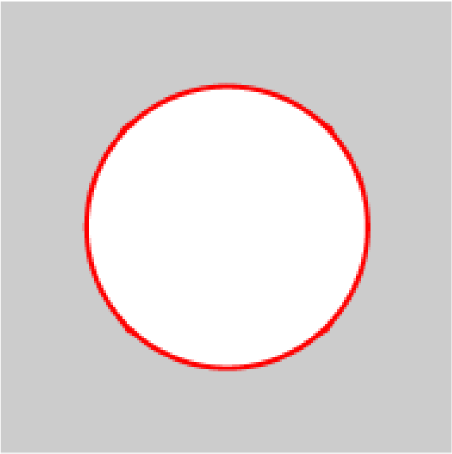


1. The excavation damage zone and roof falls cause the effective room size to increase.

2. Roof falls do not change void space

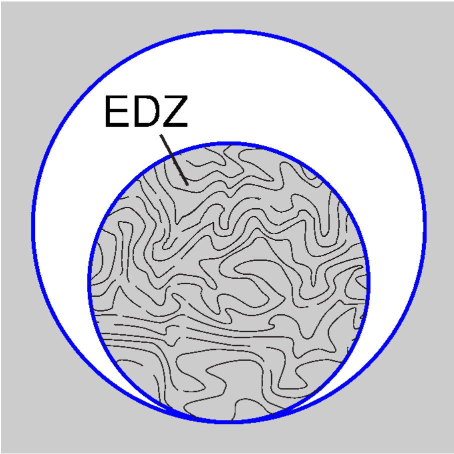
A Mechanism That Speeds Up Closure?

Small Room



vs.

Big Room, Filled with EDZ Rubble

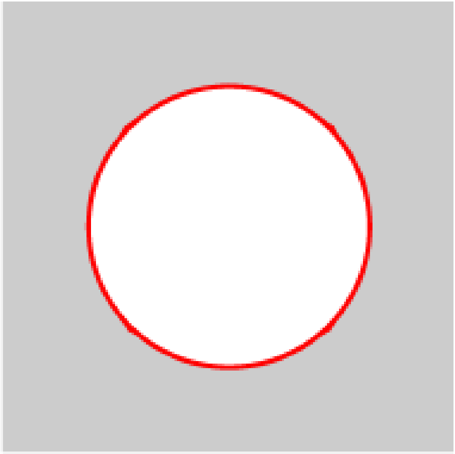


1. The excavation damage zone and roof falls cause the effective room size to increase.

2. Roof falls do not change void space

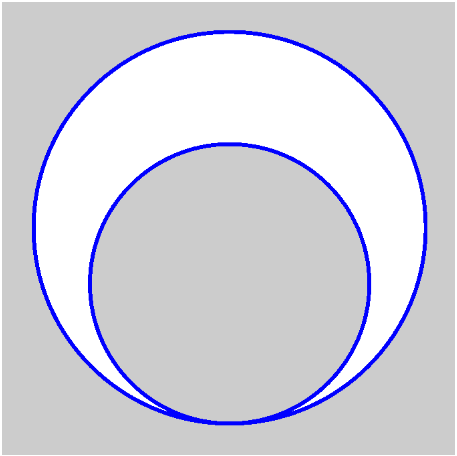
A Mechanism That Speeds Up Closure?

Small Room



vs.

Big Room, Filled with Idealized Rubble



1. The excavation damage zone and roof falls cause the effective room size to increase.

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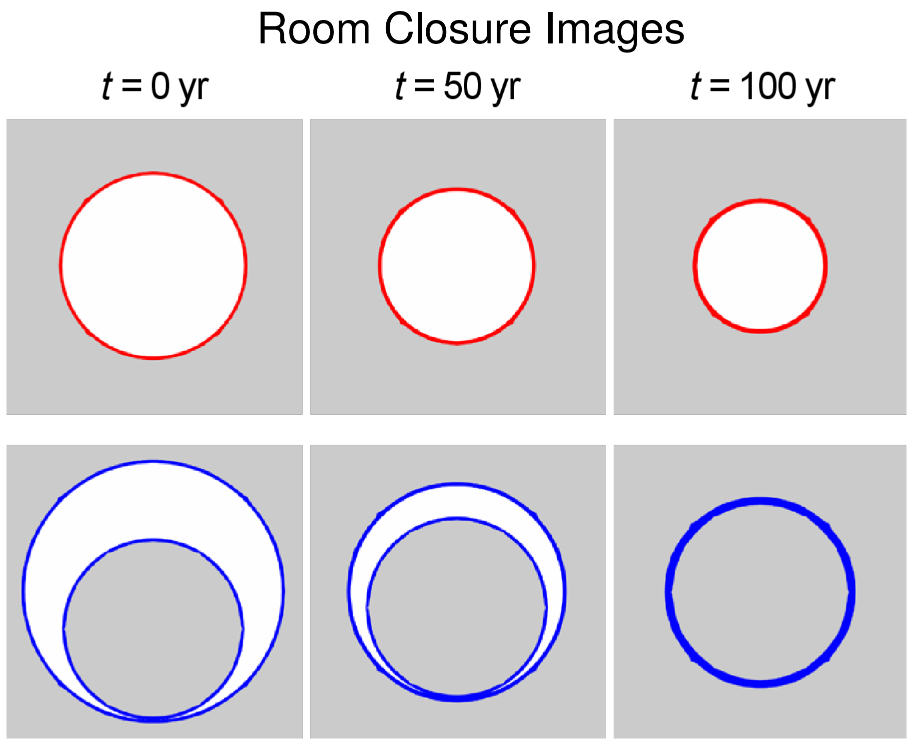
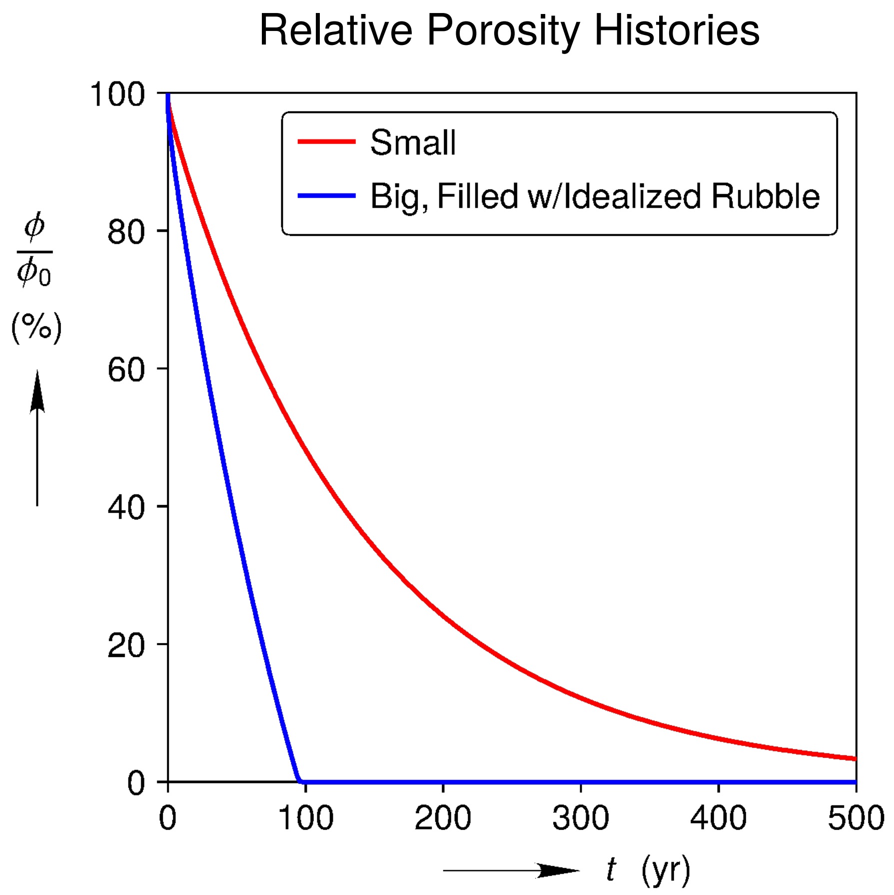
A Mechanism That Speeds Up Closure?



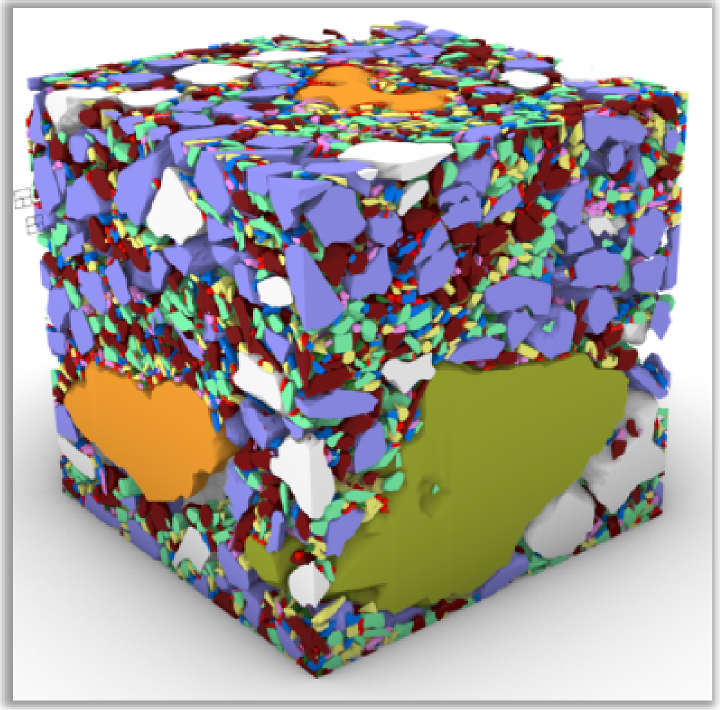


Small-Scale Rubble Pile Reconsolidation Studies

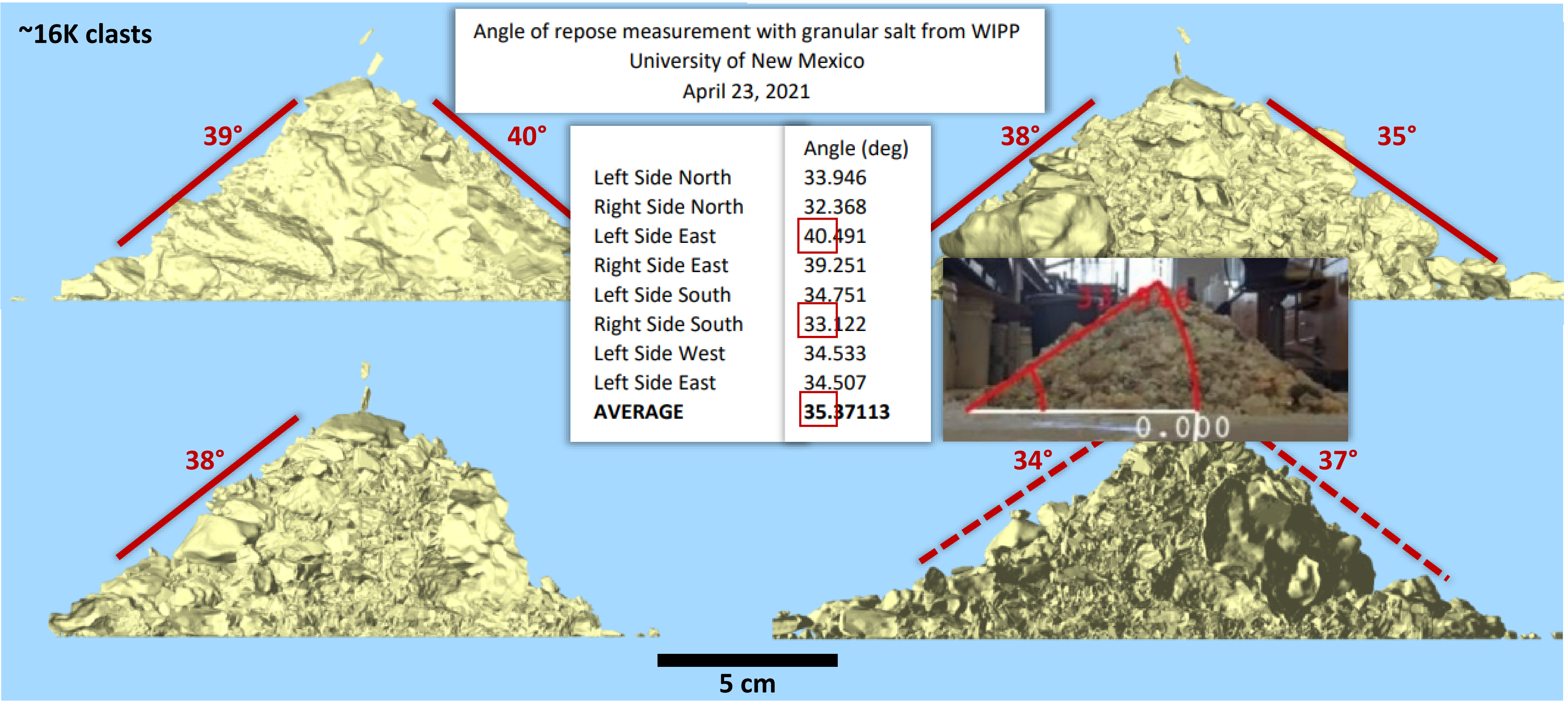
Research Plan

1. Generate synthetic rubble pile realizations
    1. Verify approach using monodisperse spherical packs
    2. Vary clast shapes and size distributions
2. Simulate compaction with various levels of sophistication
3. Use CFD to compute permeability
    1. Explicitly represent macroflow channels and implicitly represent microflow channels
4. Validate against crushed salt or small-scale rubble compaction experiments
    1. Vary the grain size distribution, temperature, and compaction pressure

Synthetic Rubble Pile



Angle of Repose

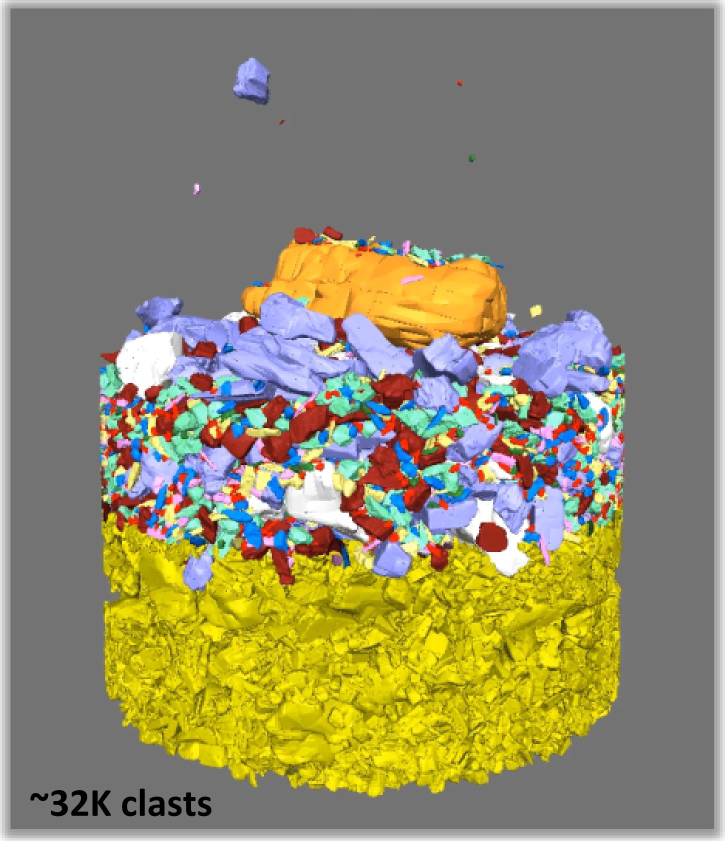


	Angle (deg)
Left Side North	33.946
Right Side North	32.368
Left Side East	40.491
Right Side East	39.251
Left Side South	34.751
Right Side South	33.122
Left Side West	34.533
Left Side East	34.507
AVERAGE	**35.37113**

Effect of Rubble Deposition Mode

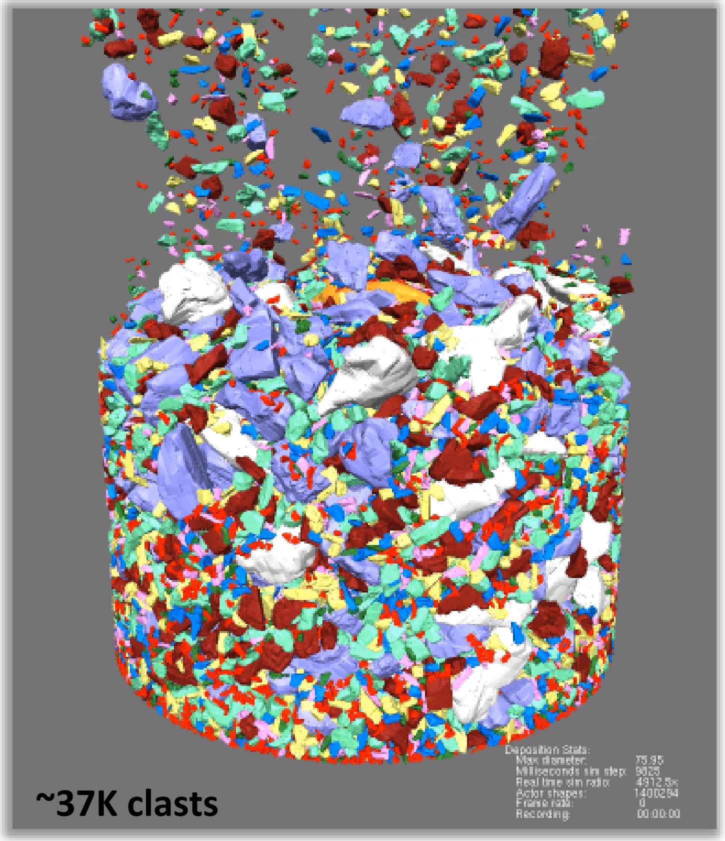
Gentle Deposition

ϕ = 37.4 %



Mass Dump Deposition

ϕ = 37.0 %

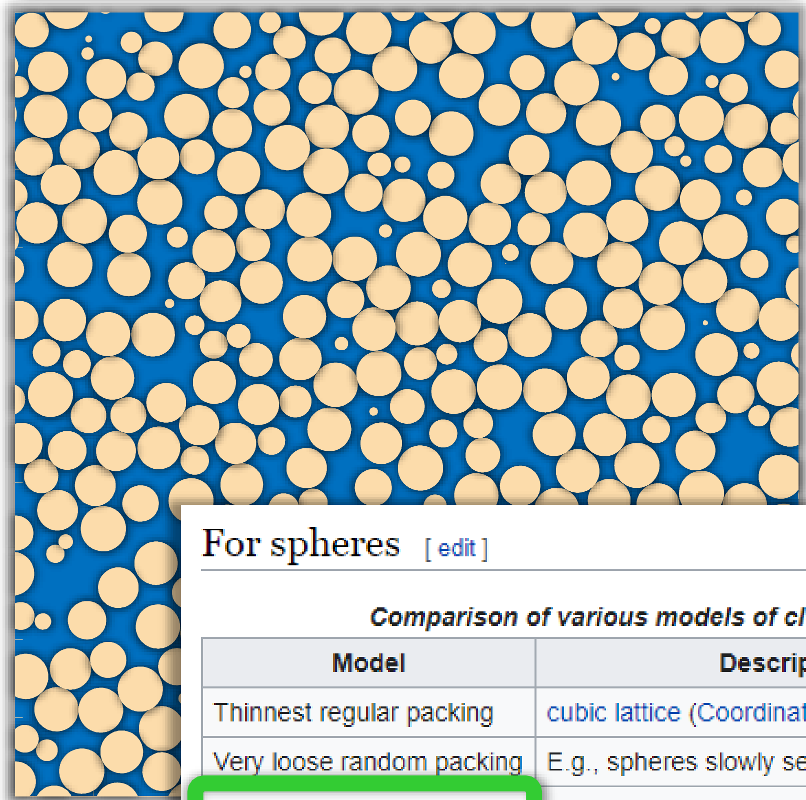


	Opening, mm		
	Min	Max	Color
Sieve A	38.1	57.2	
Sieve B	19.1	28.6	
Sieve C	9.5	14.3	
Sieve 4	4.7	7.1	
Sieve 6	3.4	4.1	
Sieve 8	2.4	2.9	
Sieve 10	2.0	2.2	
Sieve 12	1.7	1.8	
Sieve 14	1.4	1.5	
Sieve 16	1.2	1.3	
Sieve 18	1.0	1.1	

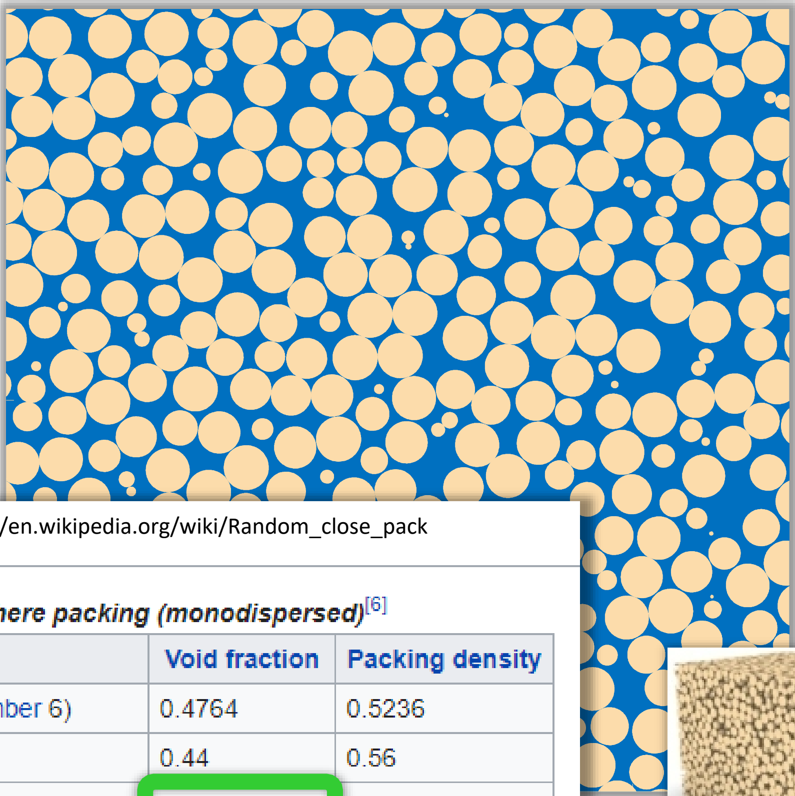
Container Diameter 12 cm

Loose vs. Close Packing of Monodisperse Spherical Clasts

Deposited
ϕ = 40.4 %



Deposited and Shaken
ϕ = 36.4 %

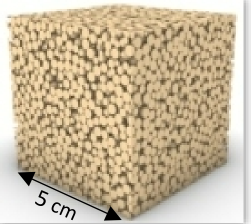


For spheres [edit]

https://en.wikipedia.org/wiki/Random_close_pack

Comparison of various models of close sphere packing (monodispersed)[6]

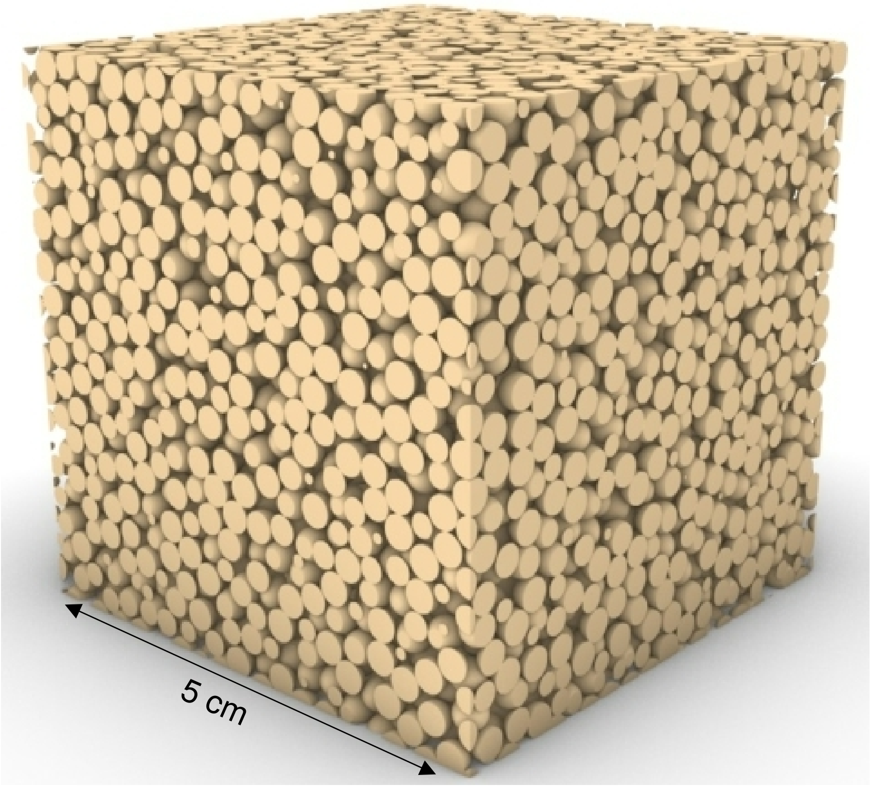
Model	Description	Void fraction	Packing density
Thinnest regular packing	cubic lattice (Coordination number 6)	0.4764	0.5236
Very loose random packing	E.g., spheres slowly settled	0.44	0.56
Loose random packing	E.g., dropped into bed or packed by hand	0.40 to 0.41	0.59 to 0.60
Poured random packing	Spheres poured into bed	0.375 to 0.391	0.609 to 0.625
Close random packing	E.g., the bed vibrated	0.359 to 0.375	0.625 to 0.641
Densest regular packing	fcc or hcp lattice (Coordination number 12)	0.2595	0.7405



Impact of Clast Shape: Monodisperse Size Distribution

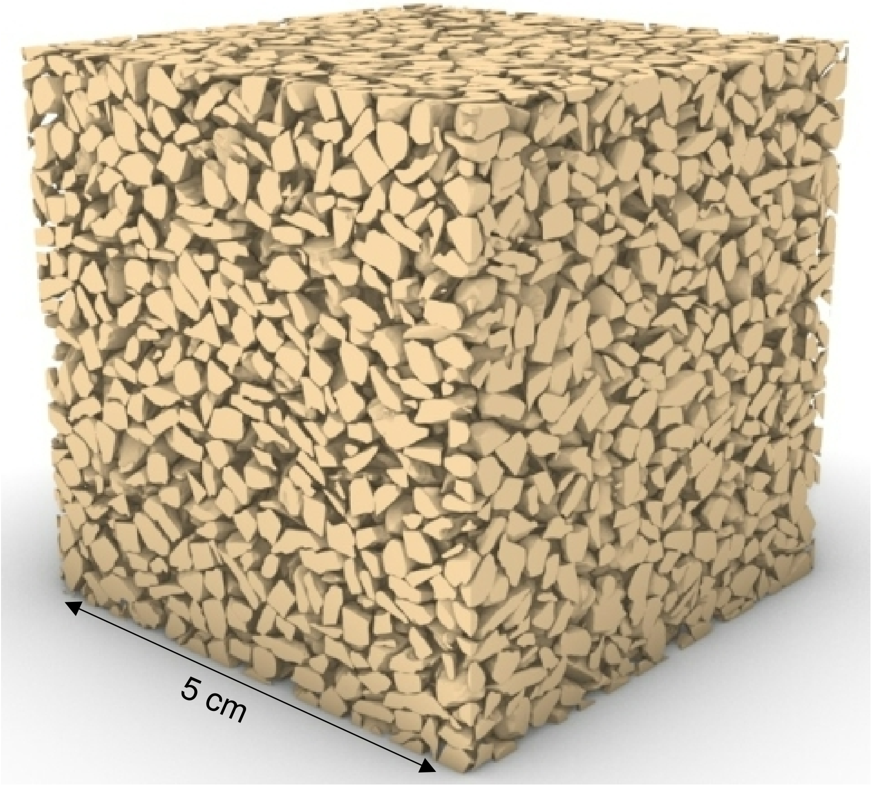
Spherical Clasts

ϕ = 40.4 %



Actual Clasts

ϕ = 47.7 %

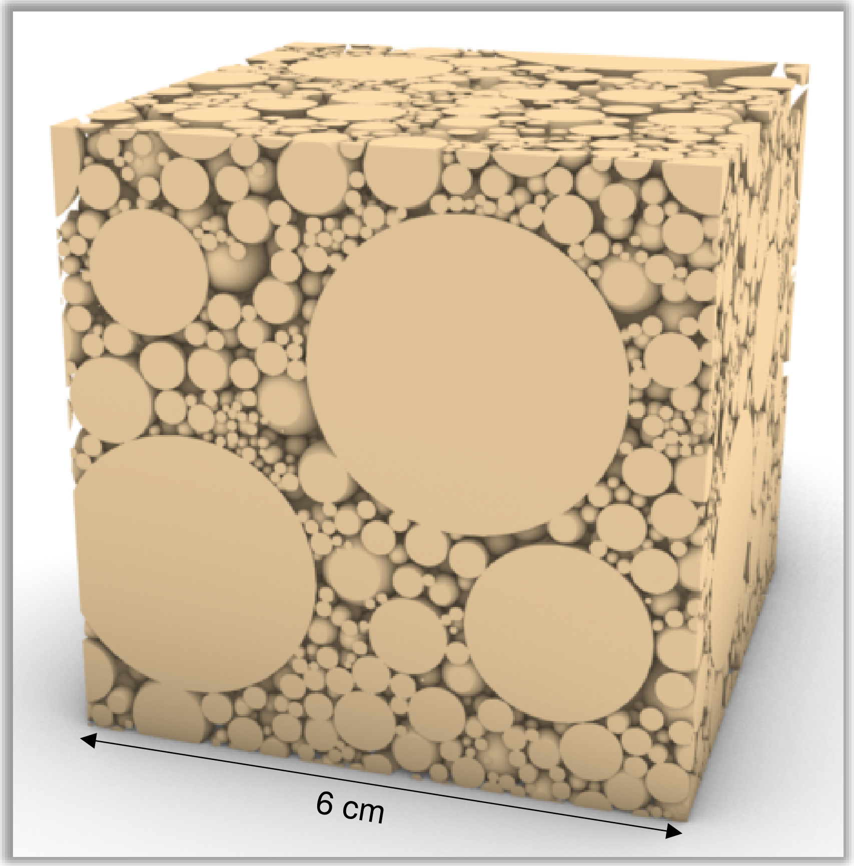


Sieve 8, μ = 0.77

Impact of Clast Shape: Polydisperse Size Distribution

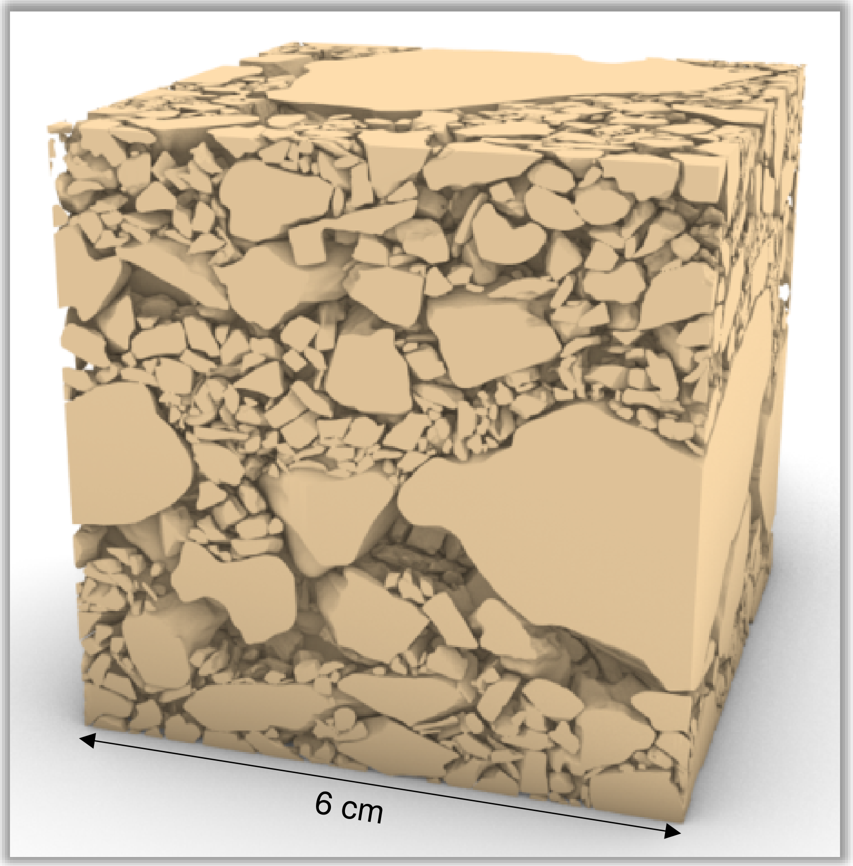
Spherical Clasts

ϕ = 25.7 %



Actual Clasts

ϕ = 37.0 %

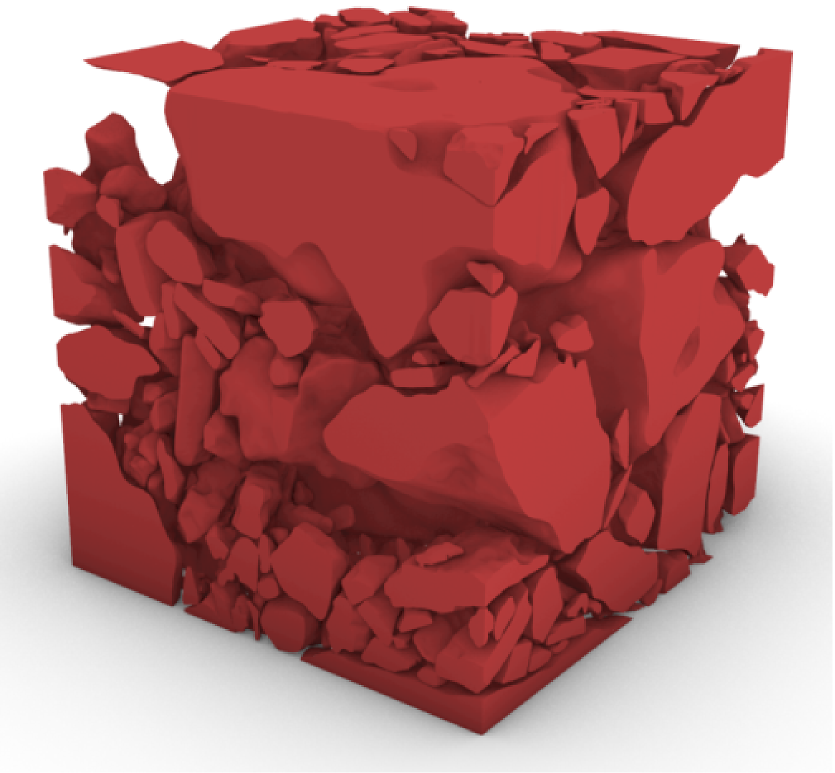


μ = 0.77

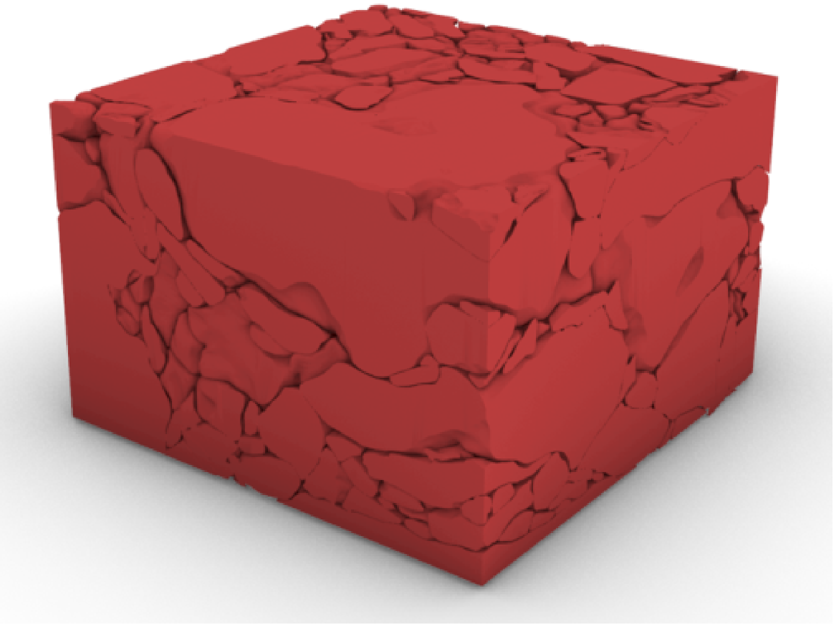
Compaction Simulation

1. Salt Clast Behavior
   1. Elasticity
   2. Pressure solution creep
   3. Dislocation creep
   4. No damage or fracturing
2. Frictional Contact
   1. $\mu = 0.77$
3. Uniaxial Strain
   1. Piston on top
   2. Other boundaries rigid

Initial State: 0 MPa
ϕ = 37 %

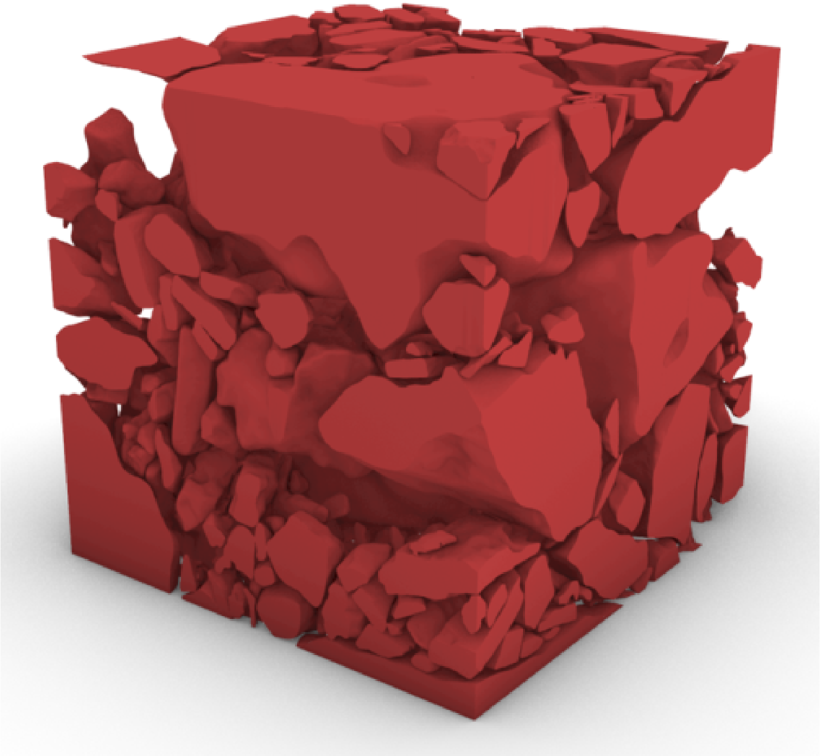


Final State: 15 MPa
ϕ = 6 %

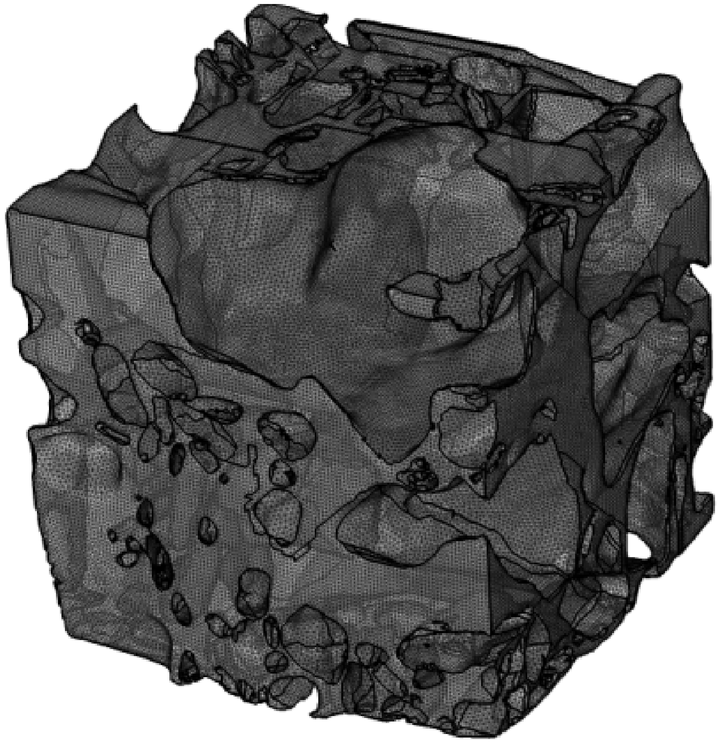


Steady-State CFD Simulation of Air Flow

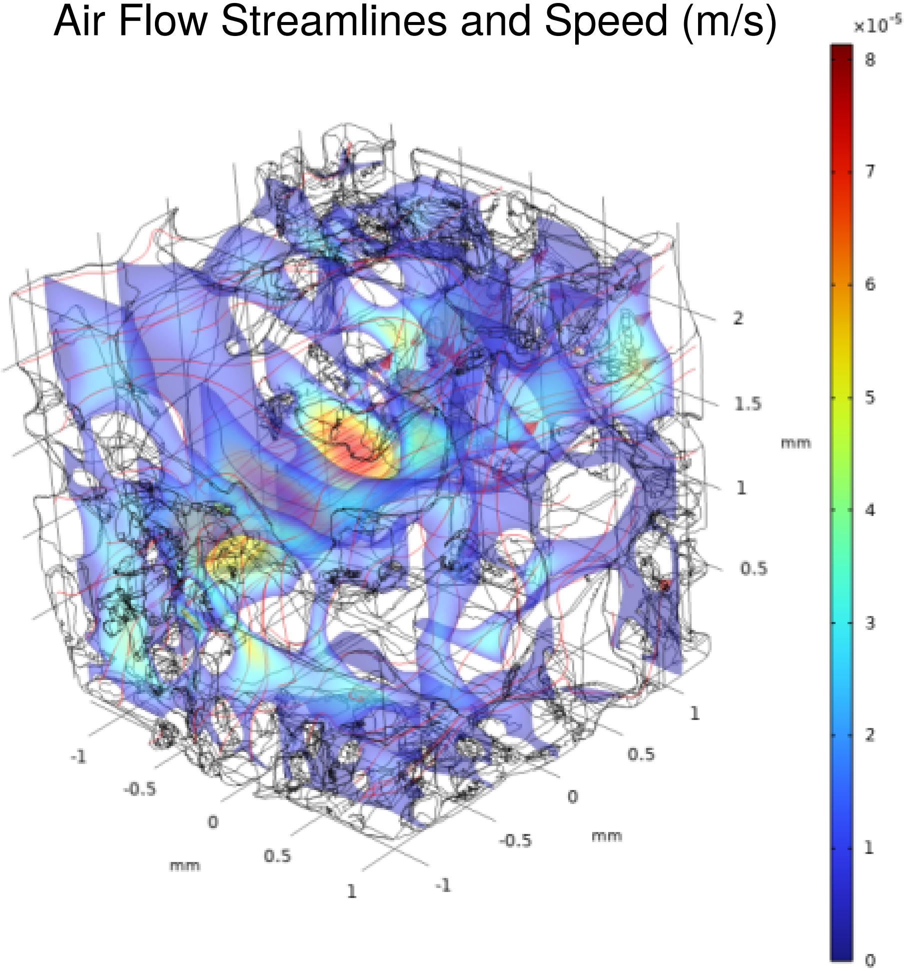
Clasts



Pore Space

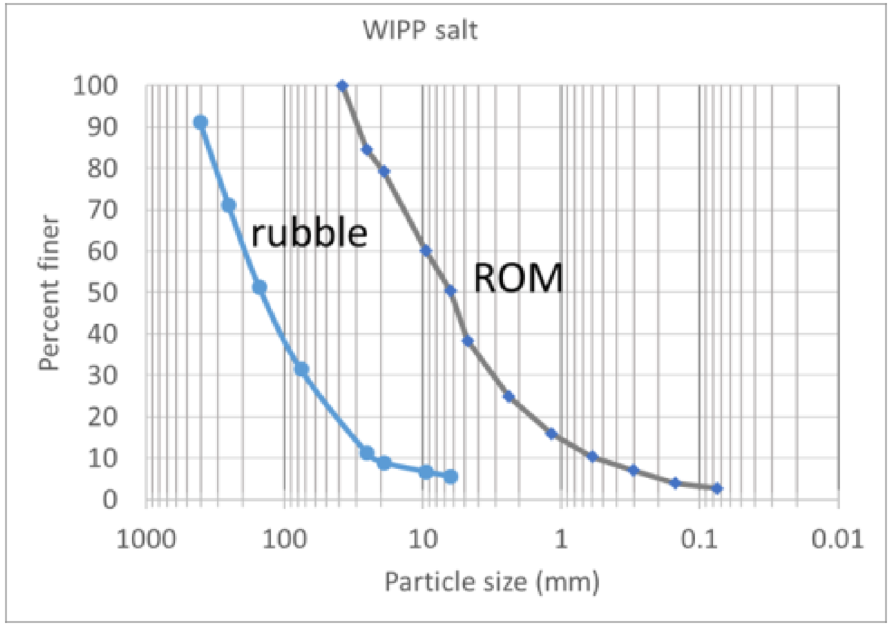


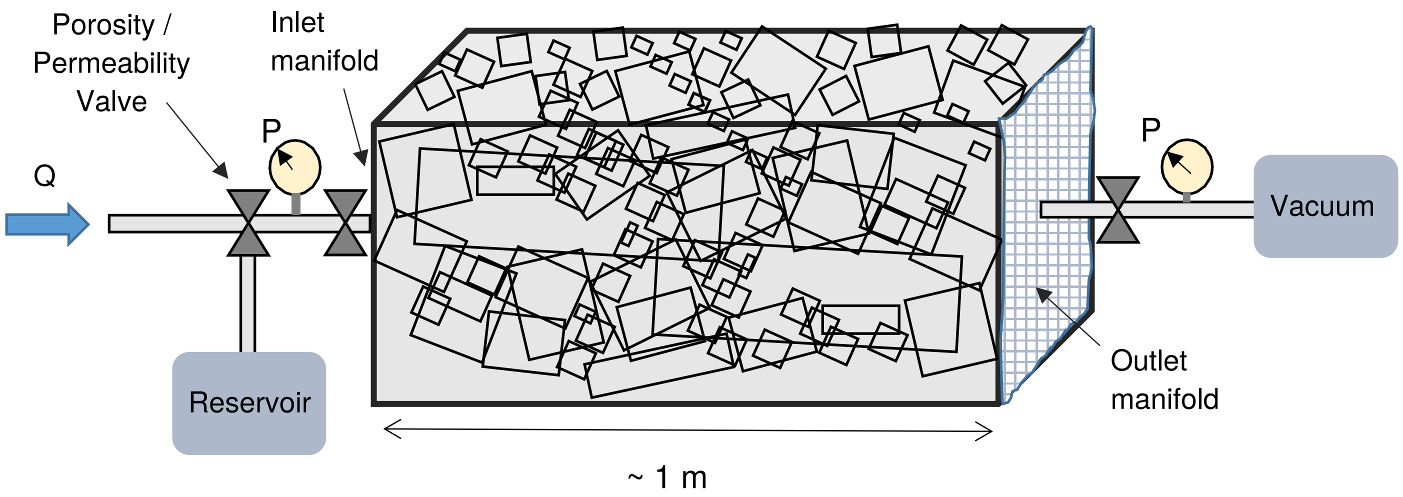
Air Flow Streamlines and Speed (m/s)



1/10th Scale Porosity and Permeability Measurements

Experimental Setup





Preliminary Results

	k (m^2)	ϕ (%)
ROM	$5x10^{-9}$	37
Rubble	$3x10^{-8}$	39

Summary and Future Work

Summary

1. Large-scale Room Collapse and Reconsolidation
   1. Identified mechanisms that will slow down room closure compared to gradual room closure.
   2. Successfully simulated severe deformations, fracture, contact, and rubble pile rearrangement in 2D.
   3. Identified a mechanism that speeds up room closure: roof falls increase room size without changing void space, and larger rooms close faster.

2. Small-Scale Rubble Pile Reconsolidation
   1. Calibrated the friction coefficient against the angle of repose.
   2. Verified deposition simulations against established / measured porosities
   3. Demonstrated the ability to:
      1. Study the effects of clast shape and size distribution on porosity
      2. Simulate rubble pile compaction.
      3. Compute flow through an uncompacted rubble pile.
      4. Measure the porosity and permeability of a 1/10th scale rubble pile

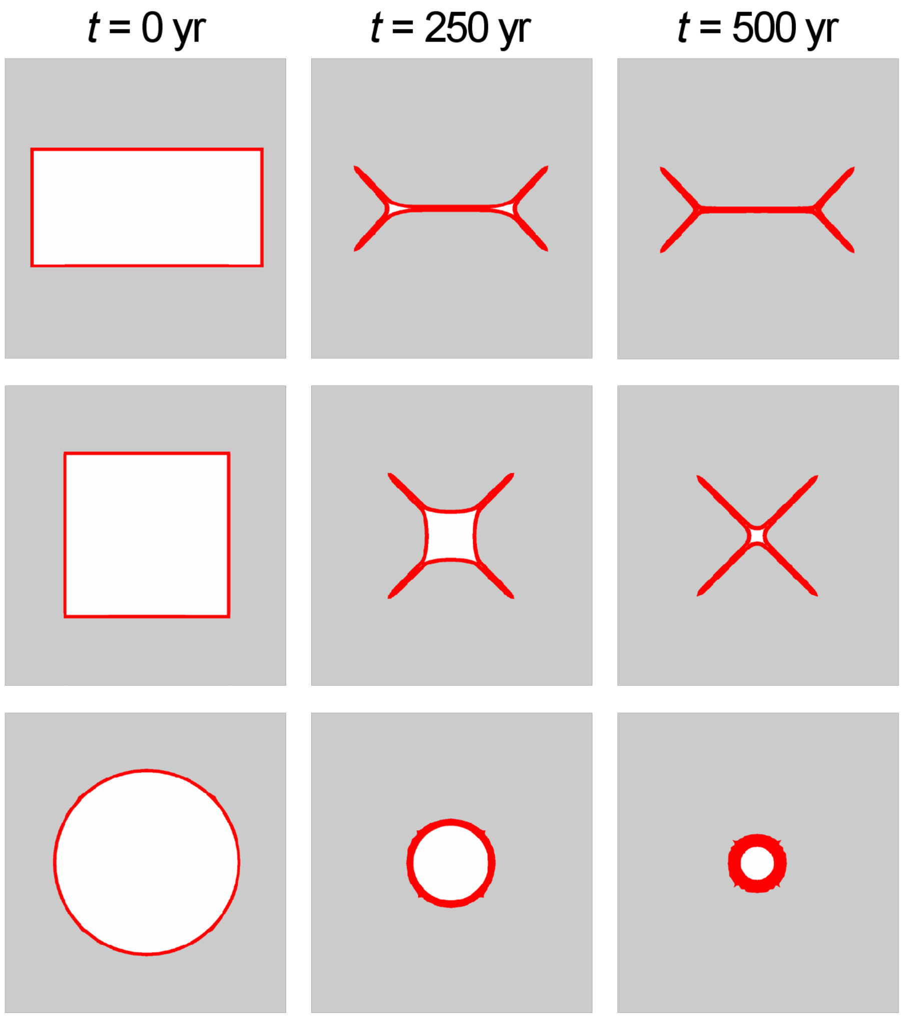
Future Work

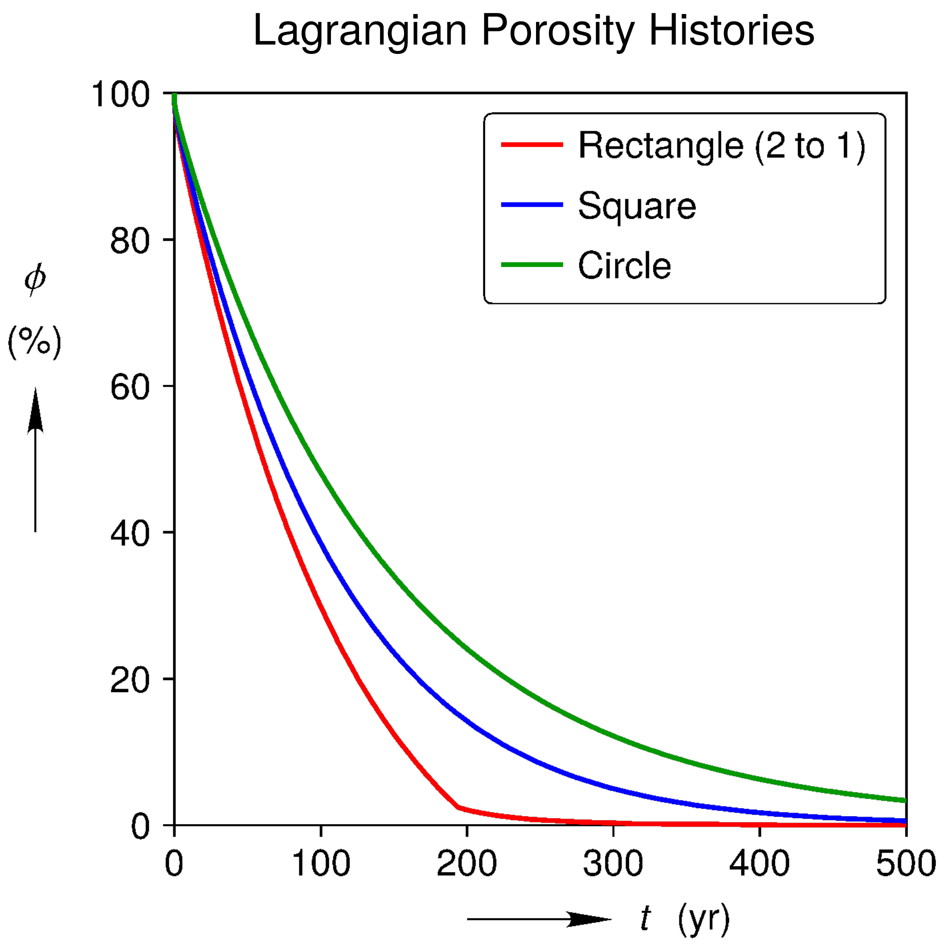
1. Recreate 2D room collapse simulations in Sierra/SolidMechanics and attempt 3D room collapse simulations.
2. Improve salt constitutive model
3. “Consolidate” room collapse, reconsolidation, and permeability simulations into a single work flow.
4. Perform further sensitivity studies
5. Validate simulations against underground observations and laboratory measurements

Thank you for your attention!

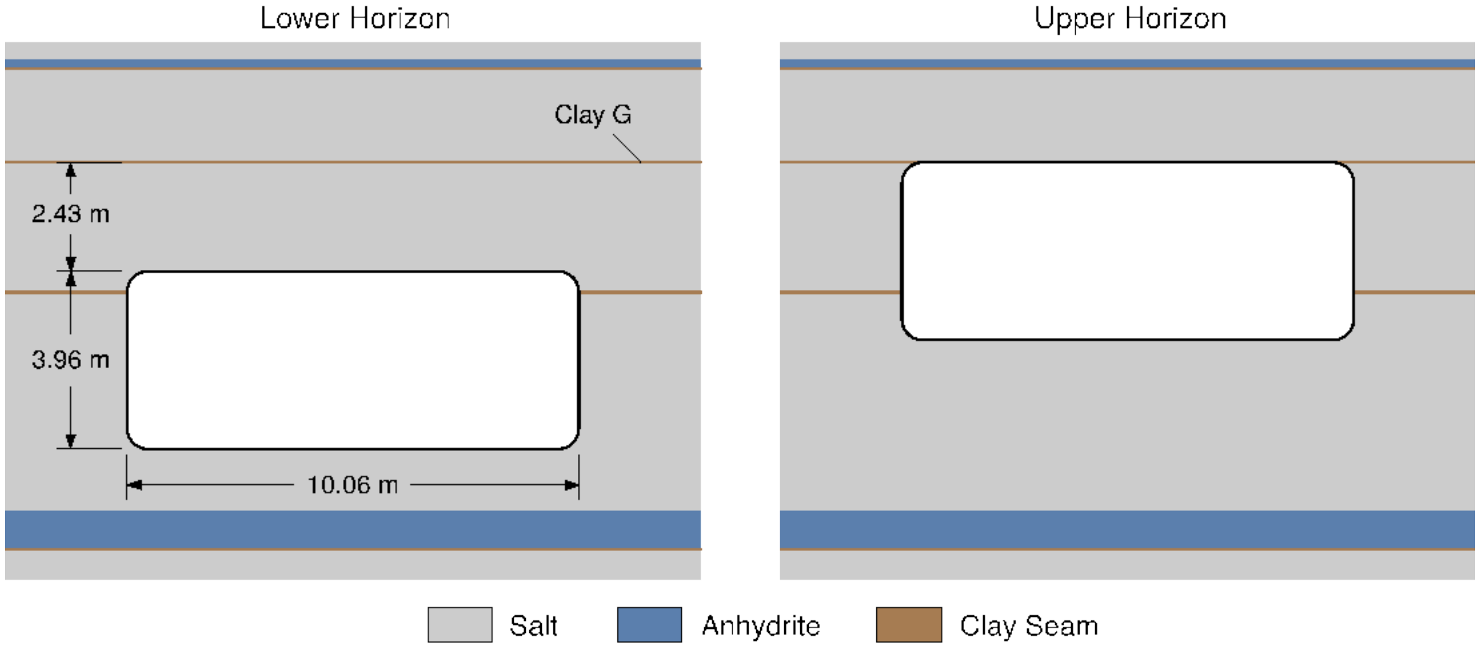
Backup Slides

Roof Falls Change Room Shape

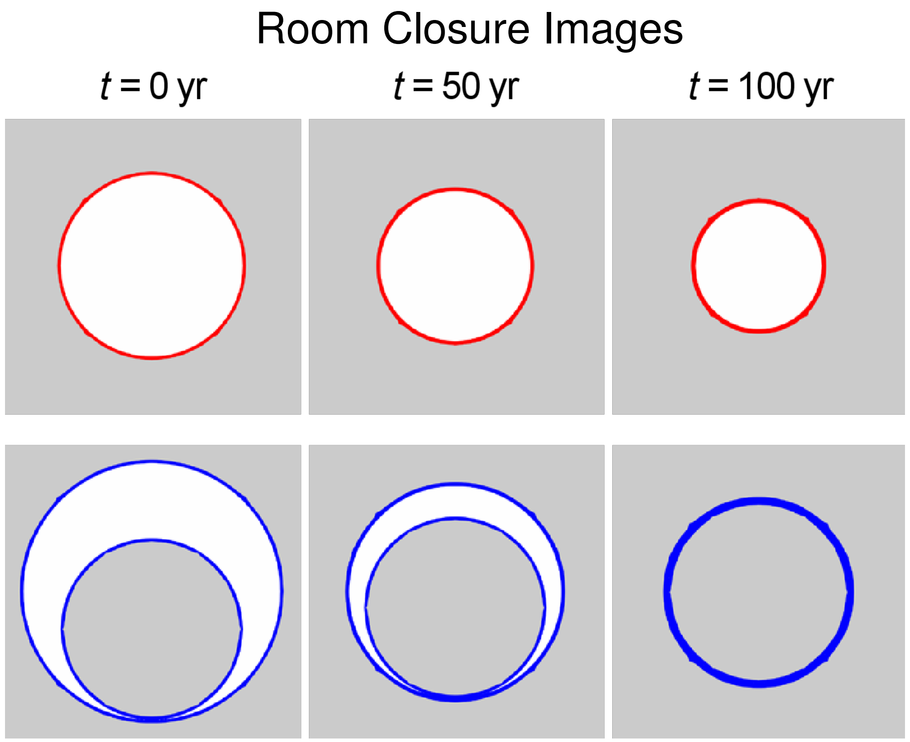


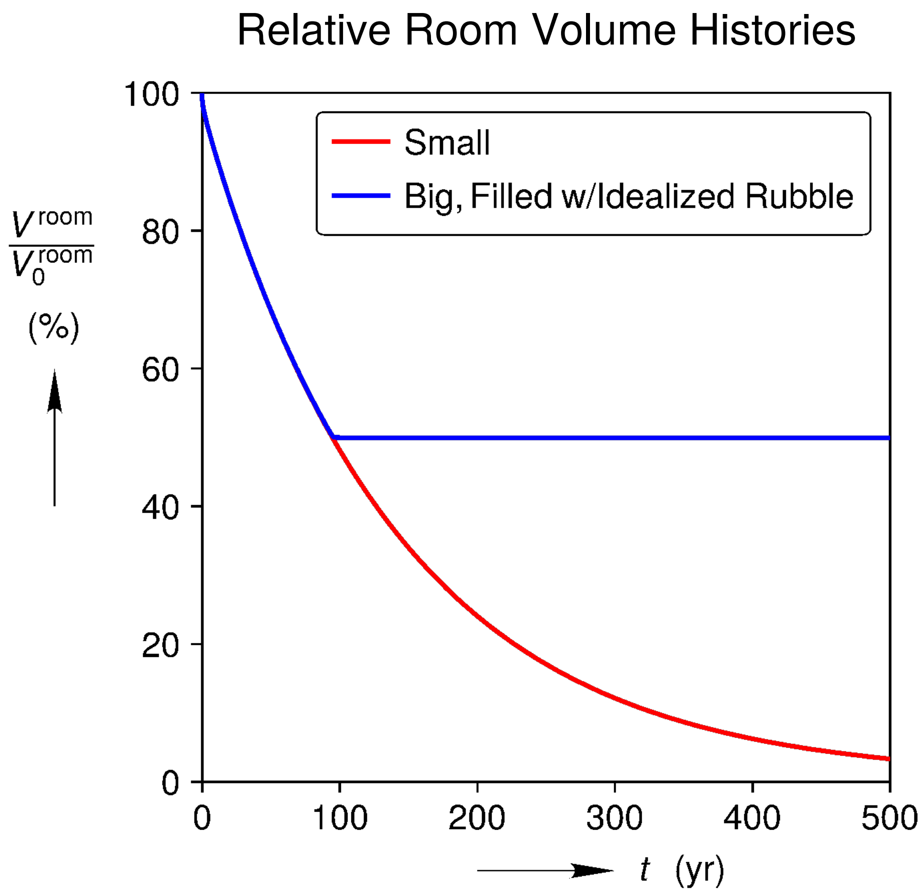


Stratigraphy Can Control Roof Fall Character and Size



A Mechanism That Speeds Up Closure?





Abandoned Drift at Teutschenthal Mine

1. Ventilation drifts originally mined through carnallitite potash in 1962. Nearby collapse in 1996 accelerated closure. Remined perpendicular to drift in 2016.
2. Strength and permeability tests exhibited similar behavior to intact carnallitite potash.

Main access drift 2. level between the cavities 345/445; View to the East {originally mined: 10/1962}.

Popp, T., Minkley, W., Fillinger, E., and Boettge, V. (2018). "Closure of the Teutschenthal backfill mine – About the challenge to elaborate a geomechanical safety concept in salt formations". In: *The Mechanical Behavior of Salt IX*. Ed. by S. Fahland, J. Hammer, F. D. Hansen, S. Heusermann, K.-H. Lux, and W. M. Minkley, pp. 84–99. isbn: 978-3-9814108-6-0.