MIT EARTH RESOURCES LABORATORY
ANNUAL FOUNDING MEMBERS MEETING 2018

Earth Resources Laboratory

The simulation of complex rock mechanics problems

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Contents

SIMULATING ROCK MECHANICS

- Understanding Fracture in Rock
- Numerical Simulation of Fracture
- Graphyt – a new simulation engine
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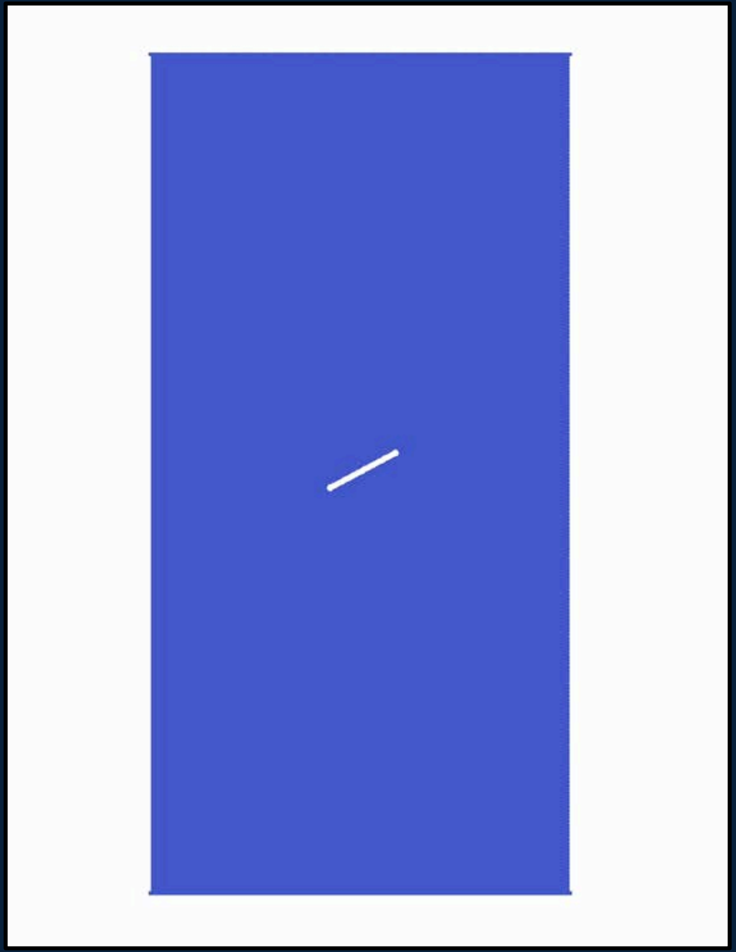
- Looking Ahead



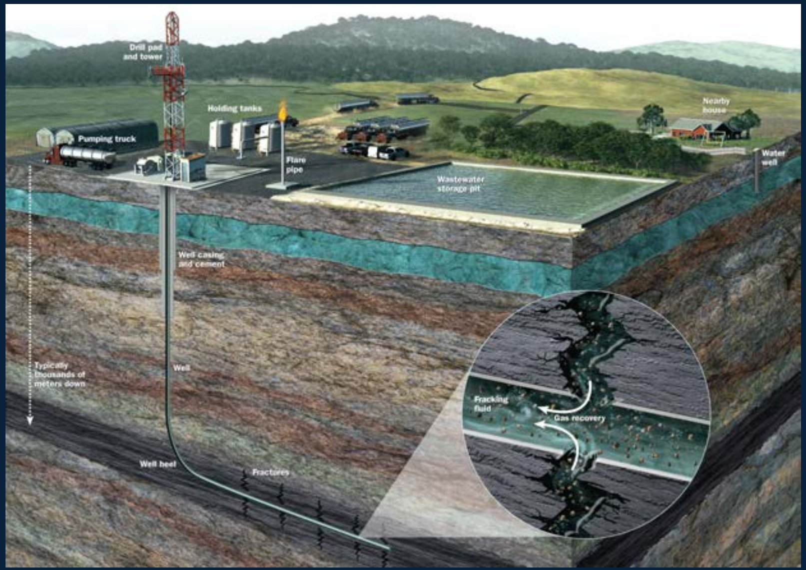
Understanding Fracture in Rock

Understanding Fracture in Rock

WHY DO WE CARE ABOUT FRACTURE IN ROCKS?

SAFETY

RESOURCE EXPLORATION

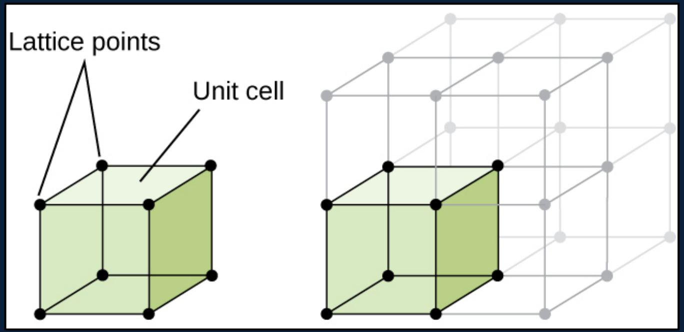


…MEDICAL APPLICATIONS

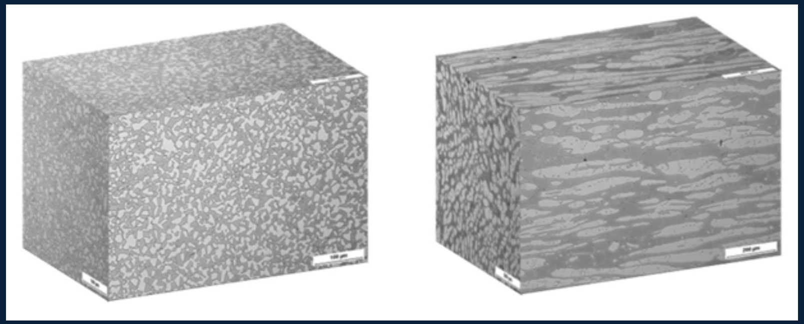
Understanding Fracture in Rock

HOW IS IT DIFFERENT TO OTHER MATERIALS

METALS HAVE AN ORDERED STRUCTURE



ROCKS ARE RANDOM, UNSTRUCTURED, COMPOSITE MATERIALS



Understanding Fracture in Rock

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CHALLENGES IN UNDERSTANDING ROCK FRACTURE

FRACTURES IN ROCK MATERIALS ARE DIFFICULT TO UNDERSTAND…

- FRACTURES GROW VERY FAST
- HARD TO DETECT
- PRODUCED IN EXTREME ENVIRONMENTS

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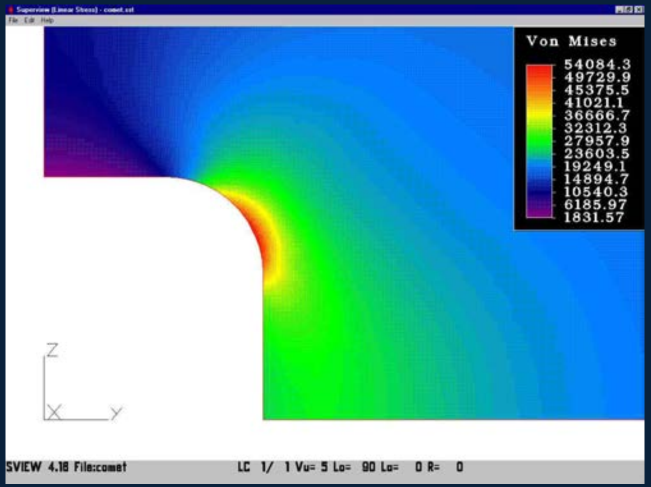
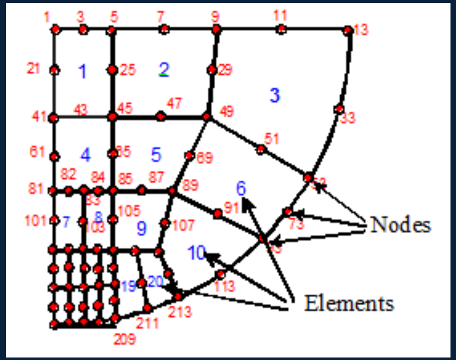
Numerical Simulation of Fracture

Numerical Simulation of Fracture

WHY DO WE NEED NUMERICAL SIMULATIONS

- NUMERICAL SIMULATIONS CAN SHOW US HIDDEN FEATURES
- WE CAN TEST MULTIPLE SAMPLES/PARAMETER TESTING
- TEST DIFFERENT THEORIES OF HOW ROCKS BEHAVE





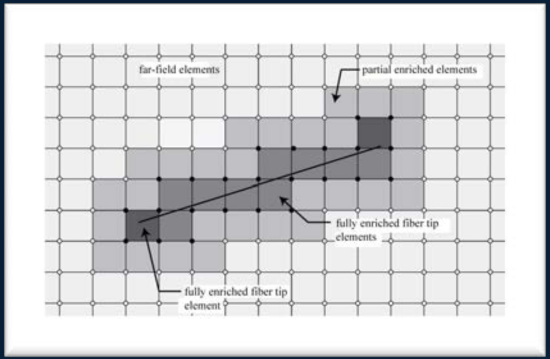
Numerical Simulation of Fracture

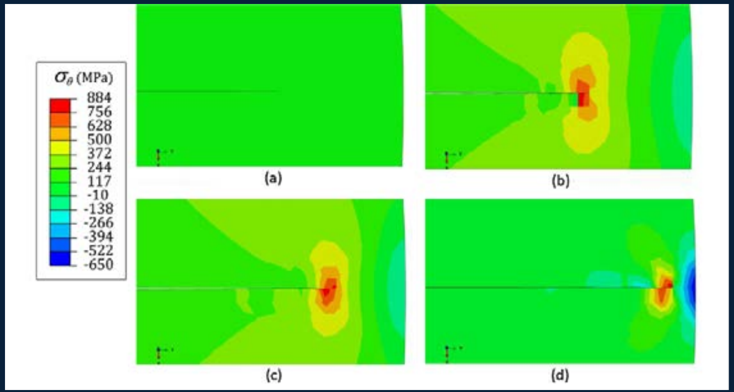
WHAT IS WRONG WITH TRADITIONAL TECHNIQUES

MODERN FINITE ELEMENT USES XFEM

THESE TECHNIQUES STRUGGLE UNDER CERTAIN CONSTRAINTS/SITUATIONS

CAN BE EXPENSIVE AND ERROR PRONE



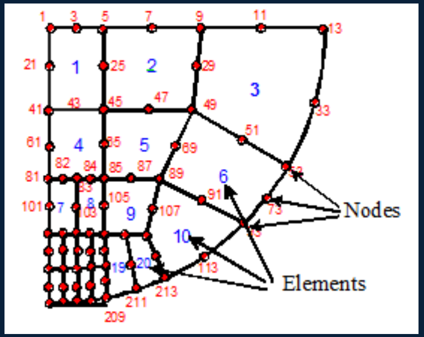


Numerical Simulation of Fracture

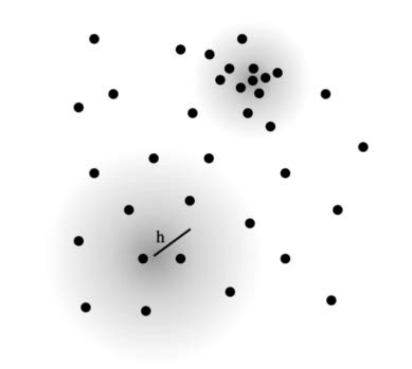
OVERCOMING MESH LIMITATIONS – A MESHLESS ALTERNATIVE

MESHLESS METHODS

- NEW DIRECTION OF SIMULATION INVOLVES NO MESH
- PARTICLES ARE USED TO DEFINE THE MATERIAL
- FRACTURES CAN BE INTRODUCED EASILY AS CAN LARGE DEFORMATION



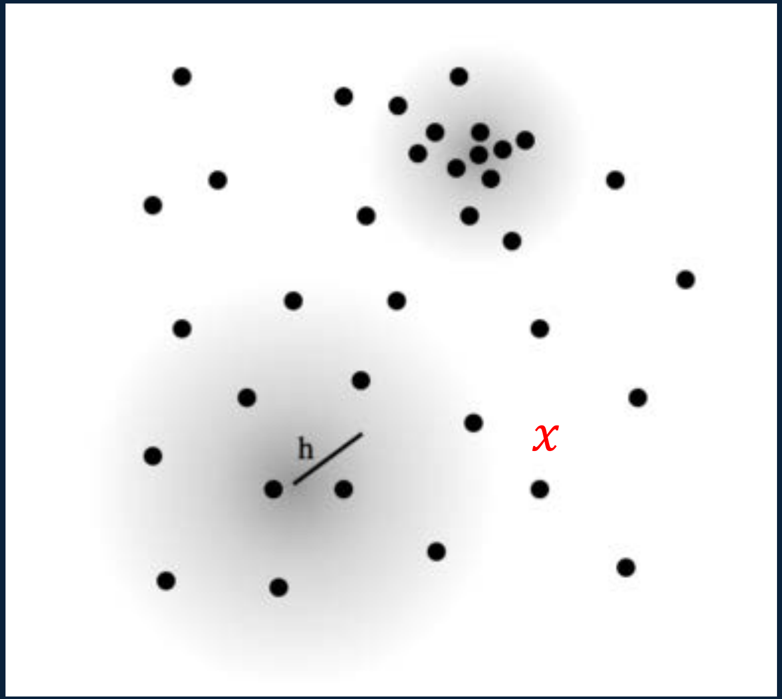
Connections between nodes is severed



Numerical Simulation of Fracture

MESHLESS METHODS – HOW THEY WORK

PARTICLES ARE USED TO CALCULATE VALUES



Particles are used as interpolation points

For example, the mass at point, x, is equal to the weighted sum of the points around that point:

$$Mass_{x} = \sum_{All\ neighbours} Weighted\ Distance\ to\ x \times Mass_{\ Points}$$

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Graphyt – a new simulation engine

Graphyt – a new simulation engine

WHAT IS GRAPHYT?

BASED ON THE MATERIAL POINT METHOD

- PARTICLES ARE USED TO DEFINE GEOMETRY
- INTERNAL FORCES ARE CALCULATED ON A GRID
- UPDATES ARE SENT BACK TO PARTICLES

The MPM algorithm consists, primarily, of 5 steps. With these 5 steps a whole host of simulations can be performed.

First Step : Mass and Momentum are sent to the Grid using linear Interpolation functions

$$M_i = \sum^{N_p} m_p N_{ip} \qquad M_i v_i = \sum^{N_p} m_p v_p N_{ip}$$

Second Step : Internal and External Force vectors are formed on the nodes

$$f_i^{int} = -\sum^{Np} \sigma_p G_{ip} V_p \quad (G_{ip} \equiv \nabla N_{ip}) \qquad f_i^{ext} = \sum^{Np} m_p \mathbf{b} N_{ip}$$

Third Step: Accelerations are solved for on the Grid using Newton's 2nd Law

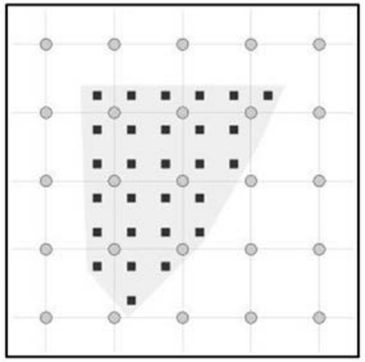
$$M_i a_i = f_i^{int} + f_i^{ext}$$

Fourth Step: Particles are updated with this new acceleration using the same interpolation functions

$$v_p^* = v_p + \sum^{Ni} a_i \Delta t$$

$$x_p^* = x_p + v_p \Delta t$$

Last Step: Grid is reset to avoid any mesh deformation.



Graphyt – a new simulation engine

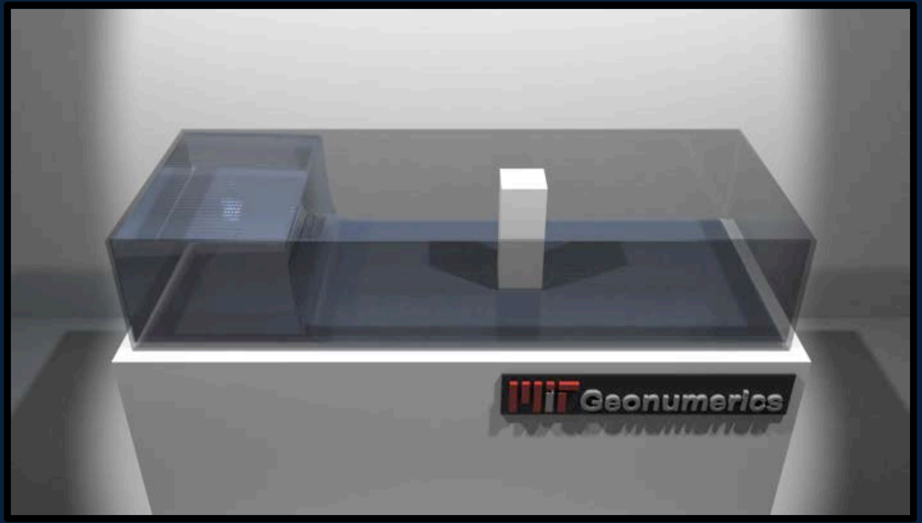
HOW IT WORKS

A parallel MPM code written in C++ for speed

This code is packaged into a python library

```python
# Import the necessary modules
import graphyt
## GEOMETRY ##
# Set the resolution and the pack
cellsize = 0.02
psep = cellsize/2.0
# Background Grid
L = [1.0,1.0,0.0]
nodes = graphyt.Nodes(L, cellsize)
print("+++++ Grid INFO+++++ No. Nodes:", nodes.numNodes)
# Material Points
matpoints = graphyt.MaterialPoints(nodes)
matpoints.psep = psep
# PYCK
# create materials
water = graphyt.MaterialModels()
water.setBulkMod(1e6)
water.setShearMod(0.0)
water.setDensity(1000)
water.setModel(2)
materials = [water]
# create packers and pack
cubic = pyck.CubicPacker(L,psep,[0,0,0])
pack = pyck.StructuredPack(cubic)
# create shapes
liquidLowerLeft = [2.75*cellsize,2.75*cellsize,0.0]
liquidUpperRight = [0.5*L[0],0.75*L[1]-2*cellsize,0.0]
liquid = pyck.Cuboid(1,liquidLowerLeft,liquidUpperRight)
# Add shapes to pack
pack.AddShape(liquid)
pack.Process()
model = pyck.Model(pack)
# Set the objectID's for all objects
objID = model.CreateIntField("objectID",1)
model.SetIntField(objID,1,0)
# Set the material ID for all objects
matID = model.CreateIntField("material",1)
model.SetIntField(matID,1,0)
# Add the geometry from pyck to the matpoints
matIDfield = model.GetIntField(matID)
objIDfield = model.GetIntField(objID)
numParticles = pack.GetNumParticles()
pyckPos = pack.GetPositions()
matpoints.addPyckGeom(pyckPos,numParticles)
matpoints.addPyckIntField(matIDfield)
matpoints.addPyckIntField(objIDfield)
print("+++++ MAT POINT INFO+++++ No. Particles:", matpoints.numParticles)
```

Simulation scripts are written in python for better flexibility and control

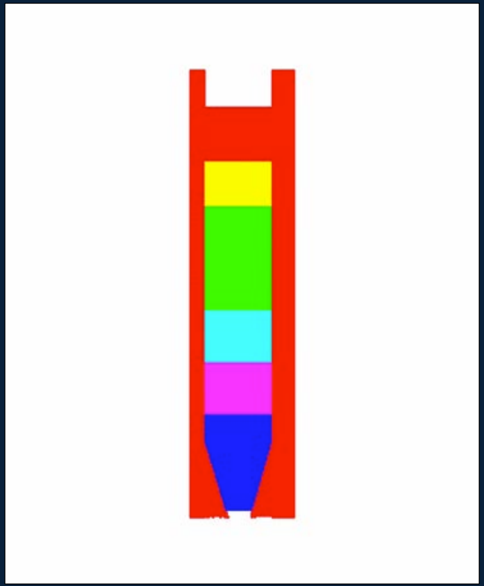


Graphyt – a new simulation engine

CURRENT USES OF GRAPHYT

SOLID MECHANICS

GRAIN MECHANICS



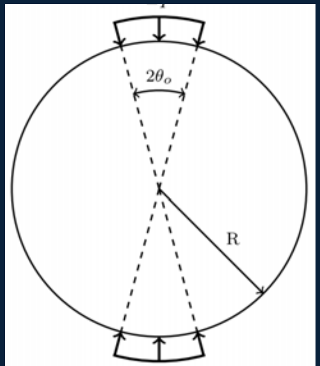
3D PRINTING

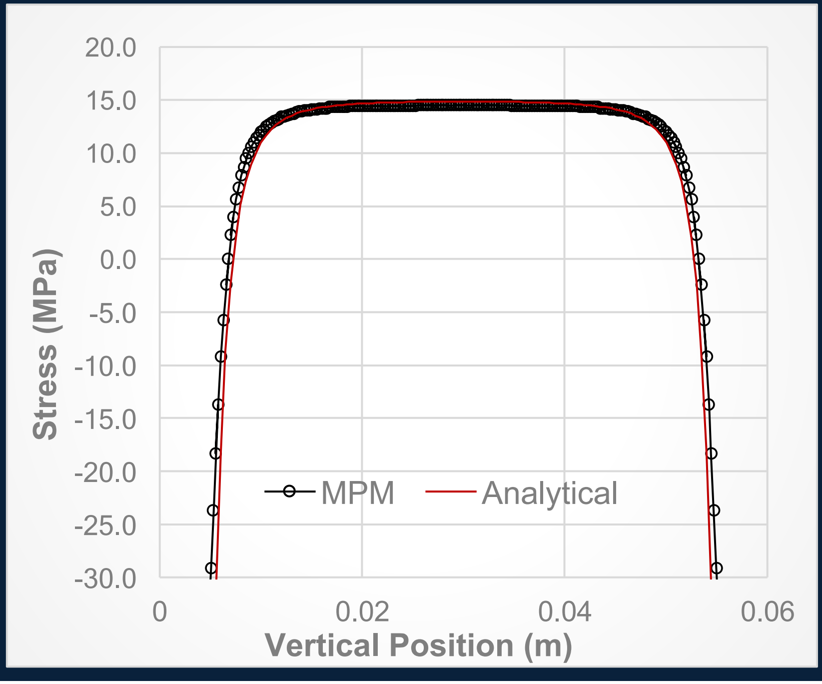
Experimental Validation

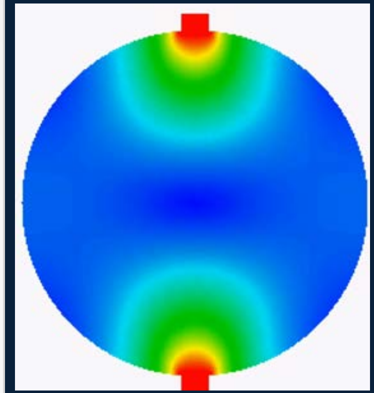
Experimental Validation

BRAZILIAN TEST

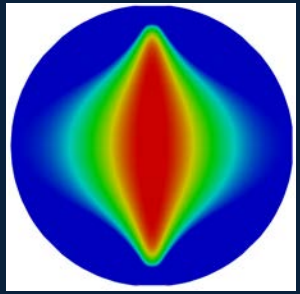
STANDARD TEST OF FRACTURE TOUGHNESS



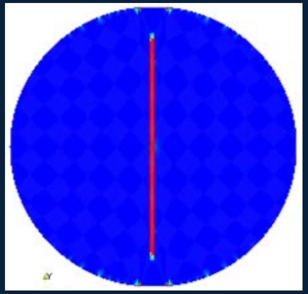




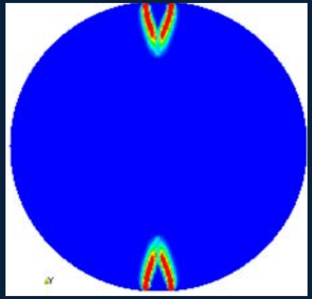
Stress



Damage



Plastic Strain

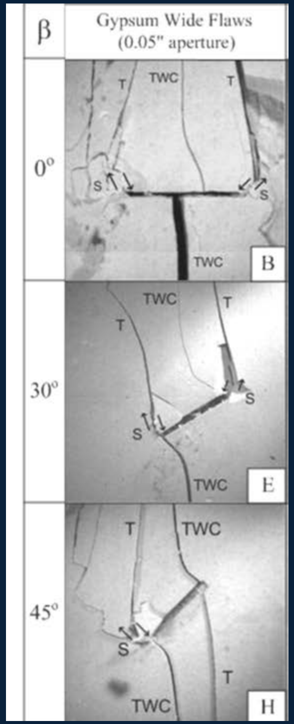


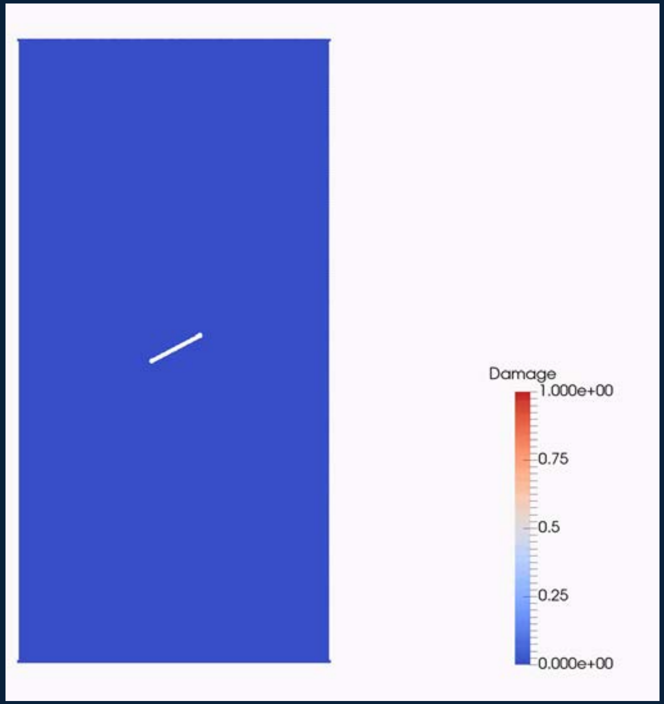
$$\sigma_x(0,y) = \frac{2p}{\pi}\left[\frac{(1-y^2/R^2)\sin 2\theta_o}{1-2y^2/R^2\cos 2\theta_o + y^4/R^4} - \tan^{-1}\left(\frac{1+y^2/R^2}{1-y^2/R^2}\tan\theta_o\right)\right]$$

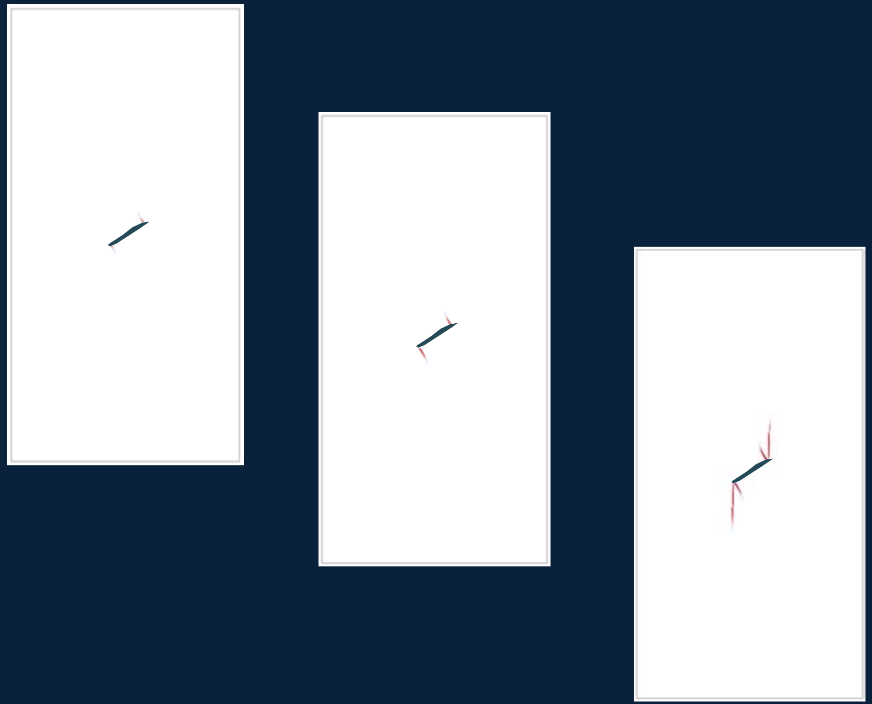
Experimental Validation

SINGLE-FLAW RESULTS

REPRODUCING WORK PERFORMED IN PROF. EINSTEIN'S LAB







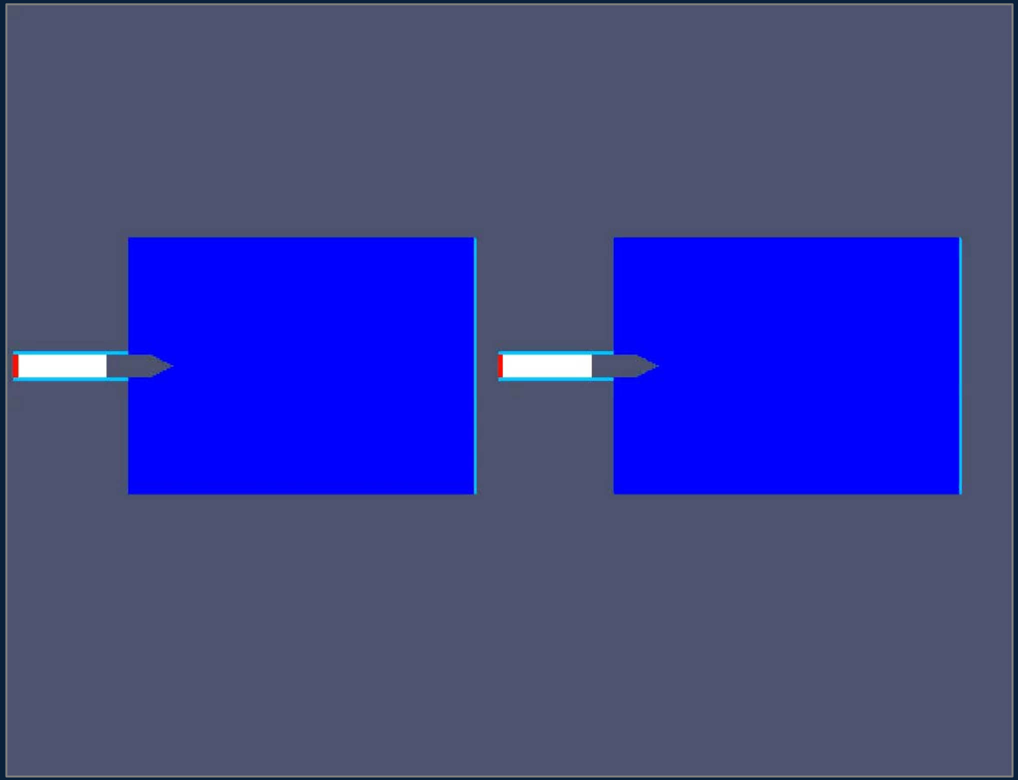
Looking Ahead

Looking Ahead

FLUID/SOLID HYDROFRACTURING

UNDERSTANDING SOLIDS/FLUIDS INTERACTION

- APPLICATIONS TO HYDRAULIC FRACTURING
- FLUIDS INDUCED DAMAGE TO CREATE NEW FRACTURE PATHS
- MEASURING THE FLOW/PLACEMENT OF FLUID

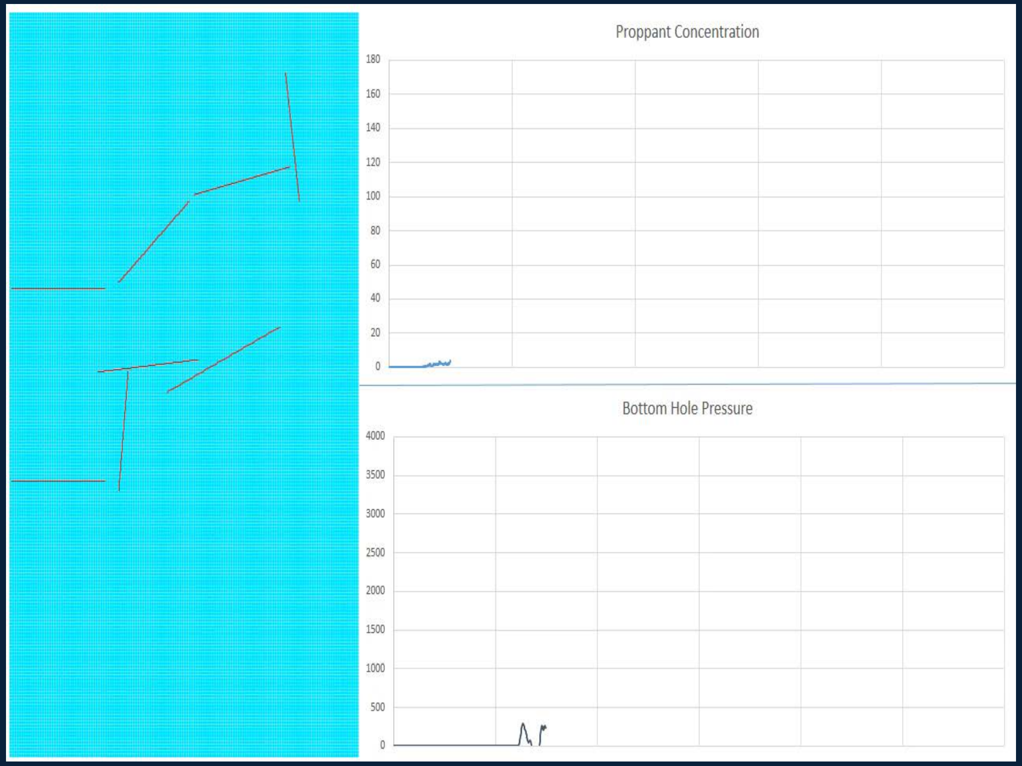


Looking Ahead

MODELING FRACTURE GROWTH WITH NATURAL FRACTURES

INVESTIGATING THE ROLE OF NATURAL FRACTURES

- CONNECTIVITY OF FRACTURE PROPAGATION
- INFLUENCE OF DOMINATE STRESS DIRECTIONS
- ACOUSTIC SIGNATURE OF NATURAL FRACTURES

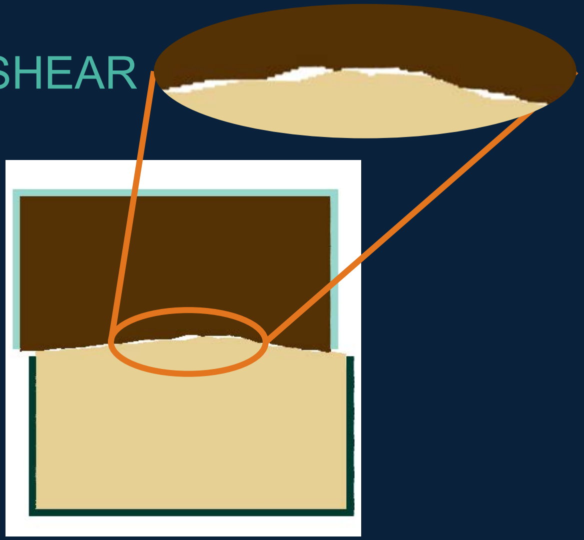


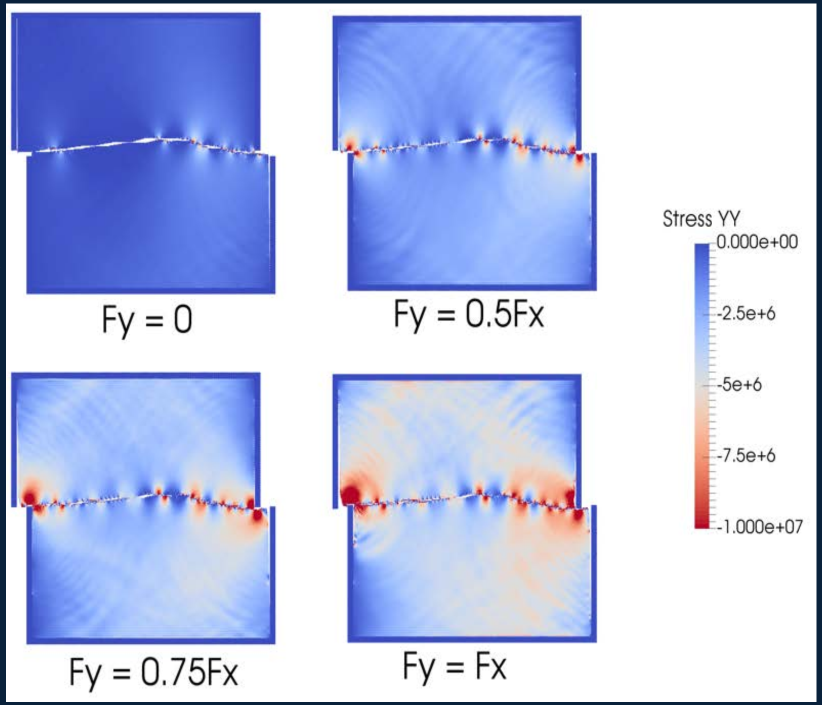
Looking Ahead

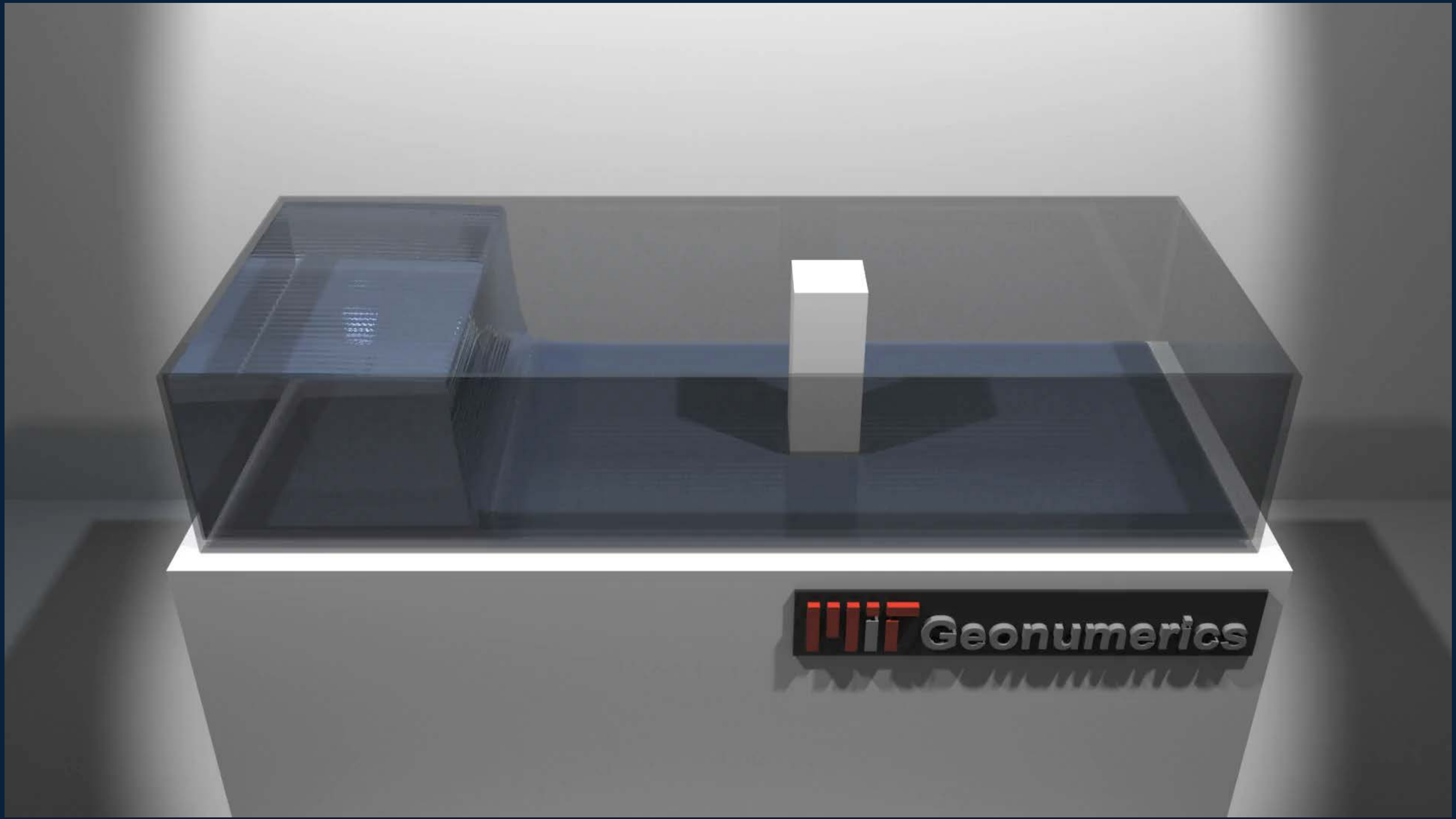
UNDERSTANDING FRACTURE SHEAR - PERMEABILITY

PERMEABILITY RELIANCE ON FRACTURE SHEAR

- EFFECT OF CONFINING FORCES ON FRACTURE DILATION
- PERMEABILITY CHANGES DUE TO SHEAR







Thank you!