PITT | SWANSON ENGINEERING

Laboratory Experimentation on Simultaneous Propagation of Multiple Hydraulic Fractures

Effect of Stress Shadowing

Delal Gunaydin, Cheng Cheng, Wei Fu, and Andrew Bunger
Dept of Civil and Environmental Engineering
Dept of Chemical and Petroleum Engineering
University of Pittsburgh, Pittsburgh, PA, USA
bunger@pitt.edu

Anthony Peirce
Dept of Mathematics
The University of British Columbia
Vancouver, BC, Canada

ARMA HF Workshop, New York, June 27, 2019

Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 25, No. 3, pp. 99–106, 1988
Printed in Great Britain

Towards a Methodology for Rock Mechanics Modelling

A. M. STARFIELD*
P. A. CUNDALL*

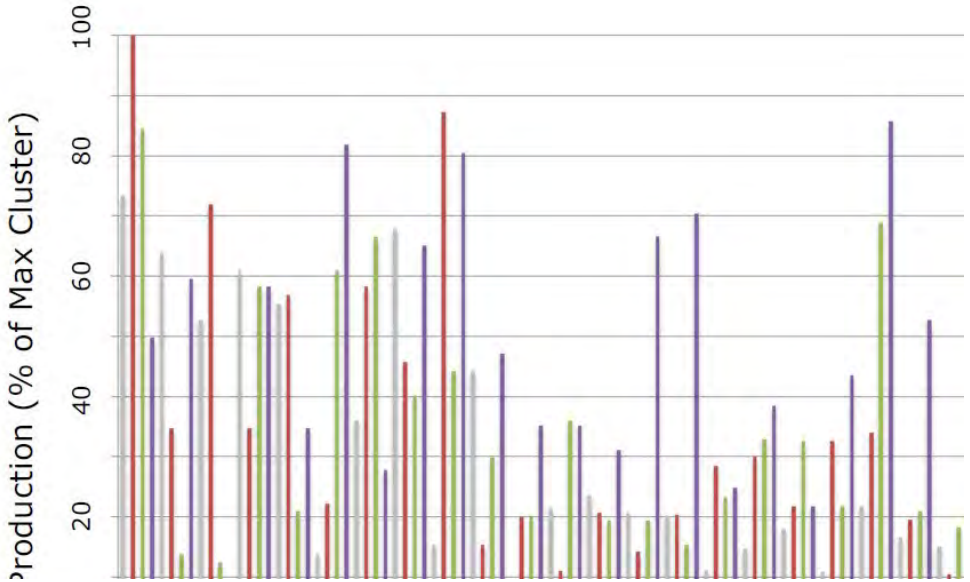
The lack of geologic detail was a major stumbling block to early acceptance of modelling in rock mechanics; models appeared to be such gross oversimplifications of the geology that few stopped to ask whether they might nevertheless be useful. The ability to include more detail is welcome, but only up to a point. As a carryover from the past we still seem to have an implicit credo that more detail implies a better model. It is an addictive credo: the modeller becomes hooked on bigger and "better" models and these in turn need more data, leading to more field and laboratory measurements. At best these efforts are a waste of time and resources; at worst they are counter-productive, concealing the wood for the trees. After all, we build models because the real world is too complex for our understanding; it does not help if we build models that are also too complex. The art of modelling lies in determining what aspects of the geology are essential for the model. The challenge is to turn that art into a methodology.

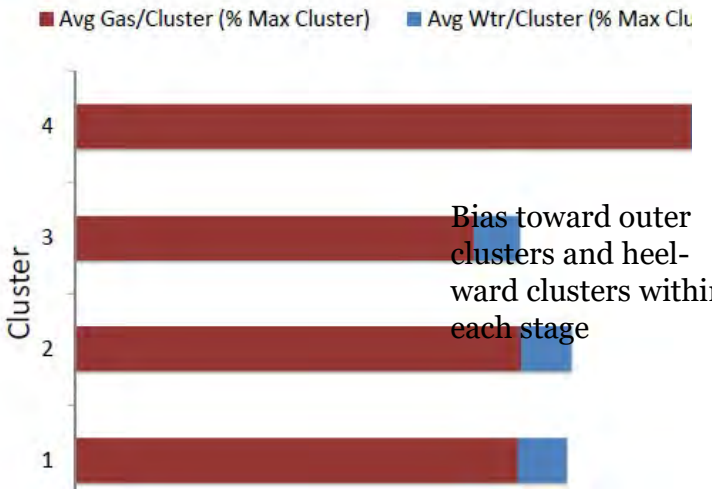
Finally, the success of modelling in other engineering fields has been a spur to modellers in rock mechanics, but we must be wary of emulation because the differences between rock mechanics and, for example, aerospace or even structural mechanics, may be more important than the similarities. Modelling techniques and approaches, as well as expectations of what modelling can achieve, that are appropriate to the one may not be appropriate to the other. The challenge to modellers in rock mechanics is to recognize these differences and to develop a distinctive modelling methodology that is both purposeful and effective. In this paper we will try to identify some of the distinctive features of rock mechanics and to suggest useful approaches and perspectives.

Production Non-Uniformity

Combined effect of:

- Hydraulic heterogeneity (i.e. permeability)
- Mechanical heterogeneity (i.e. in situ stress, elastic moduli, rock strength/toughness)
- Stress interaction among fractures (within stage and previous stage and other wells)

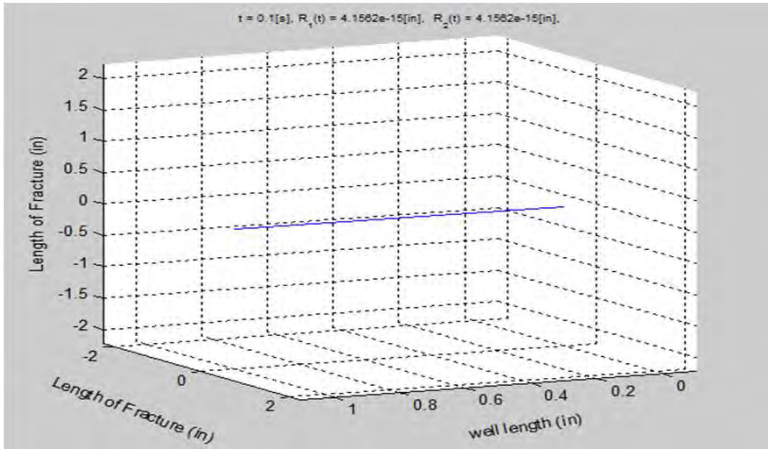


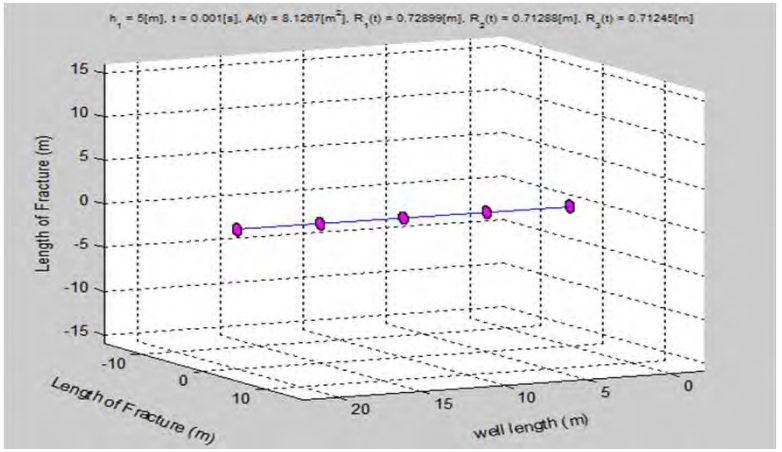


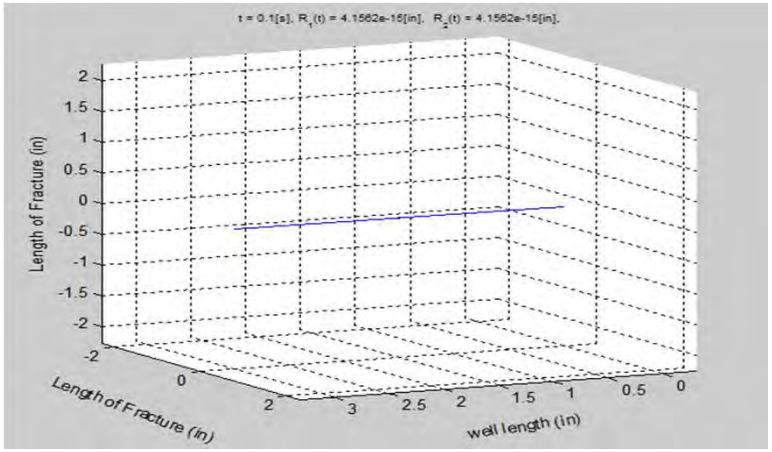
Bias toward outer clusters and heel-ward clusters within each stage

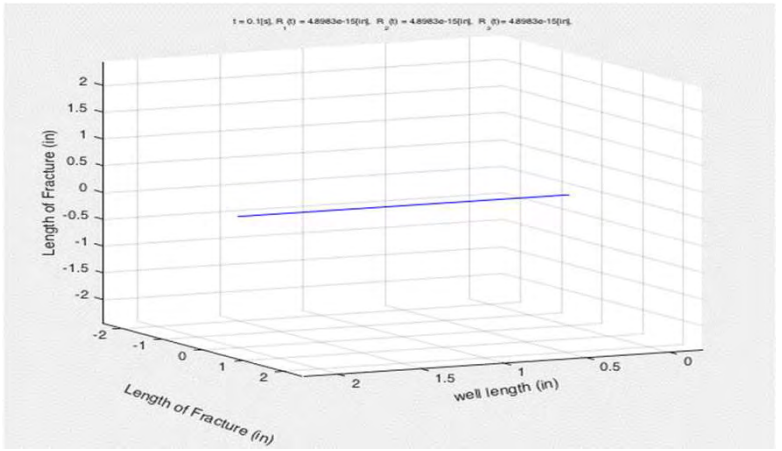
Bunger, A. P., & Cardella, D. J. (2015). Journal of Petroleum Science and Engineering, 133, 162-166.

Stress Shadowing in Numerical Models









Cheng C, Bunger AP. 2016. Int J Numer Analytic Math Geomechanics, 71:281-282

Why Study Stress Shadow?

Arguments to ignore it:

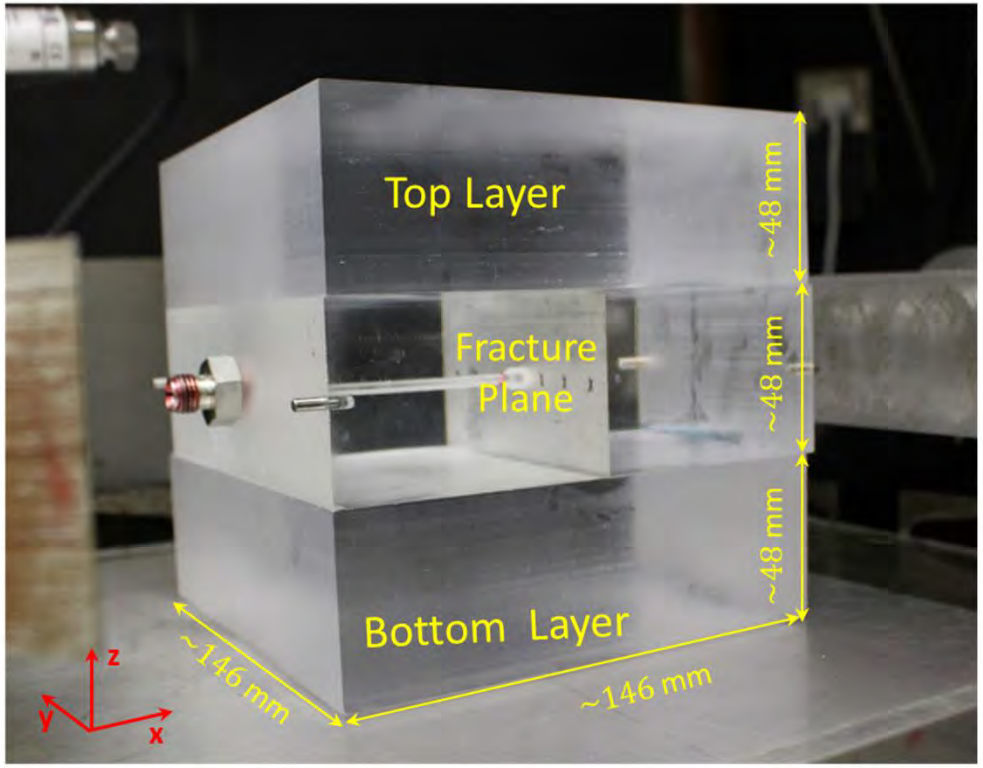
- Large limited entry often "solves" it, practically speaking
- Large in situ stress variability could also overwhelm it
- …So it only looks "ideal" when fluid net pressure is larger than other relevant stress variables

However, simulators need to capture the correct behavior in this limit:

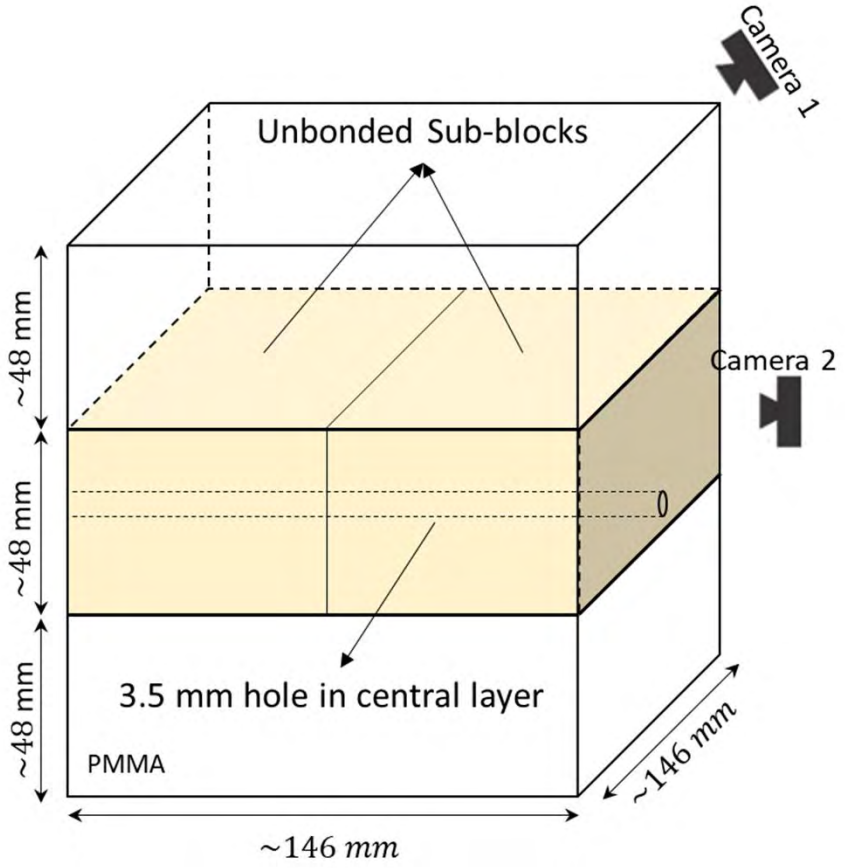
- Observed tendency for production dominated by heel cluster and/or outer clusters
- Sometimes limited entry not possible due to high breakdown/treating pressures
- Design minimum required limited entry
- When to locate clusters according to interpreted stress logs

Laboratory Experiments – Visualization Through PMMA

Single fracture case

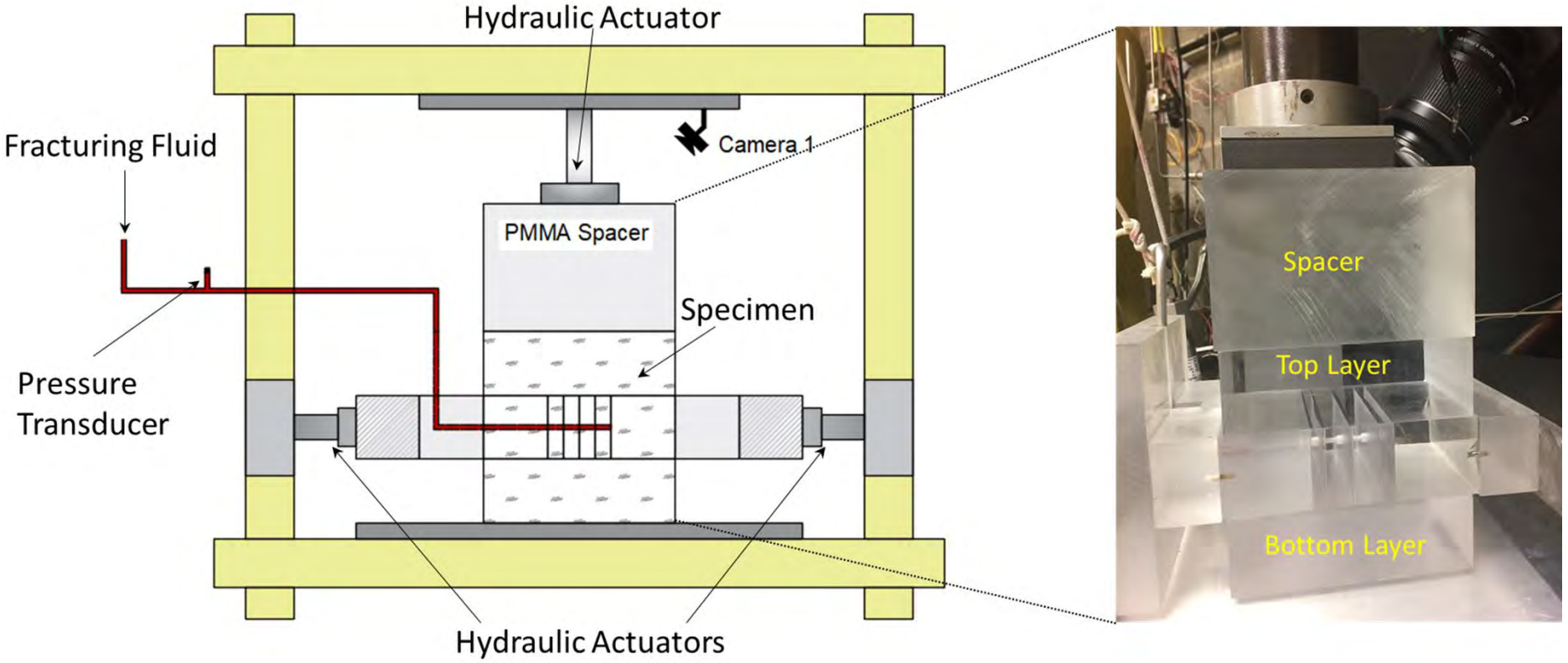


(a)



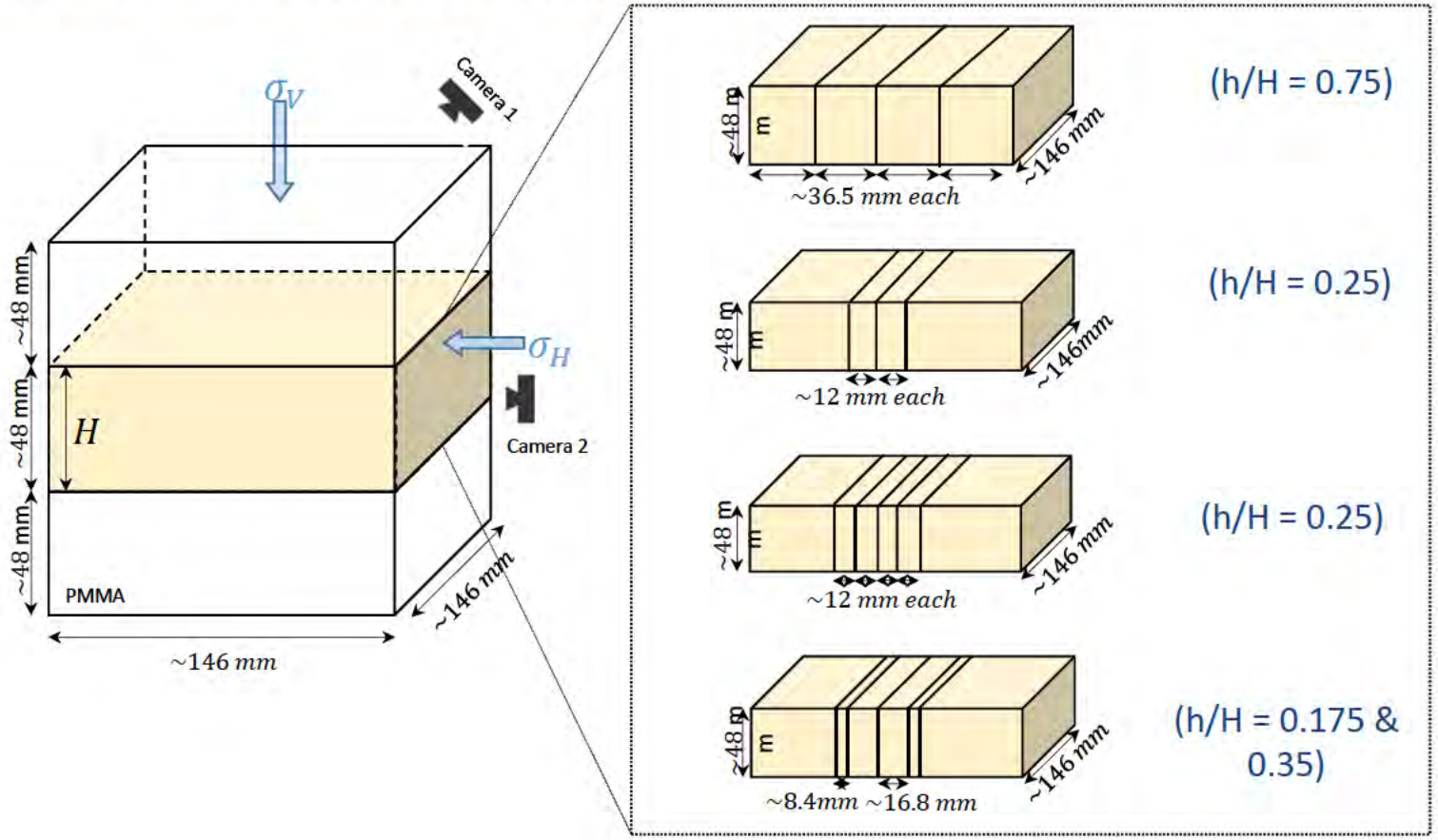
(b)

Laboratory Setup

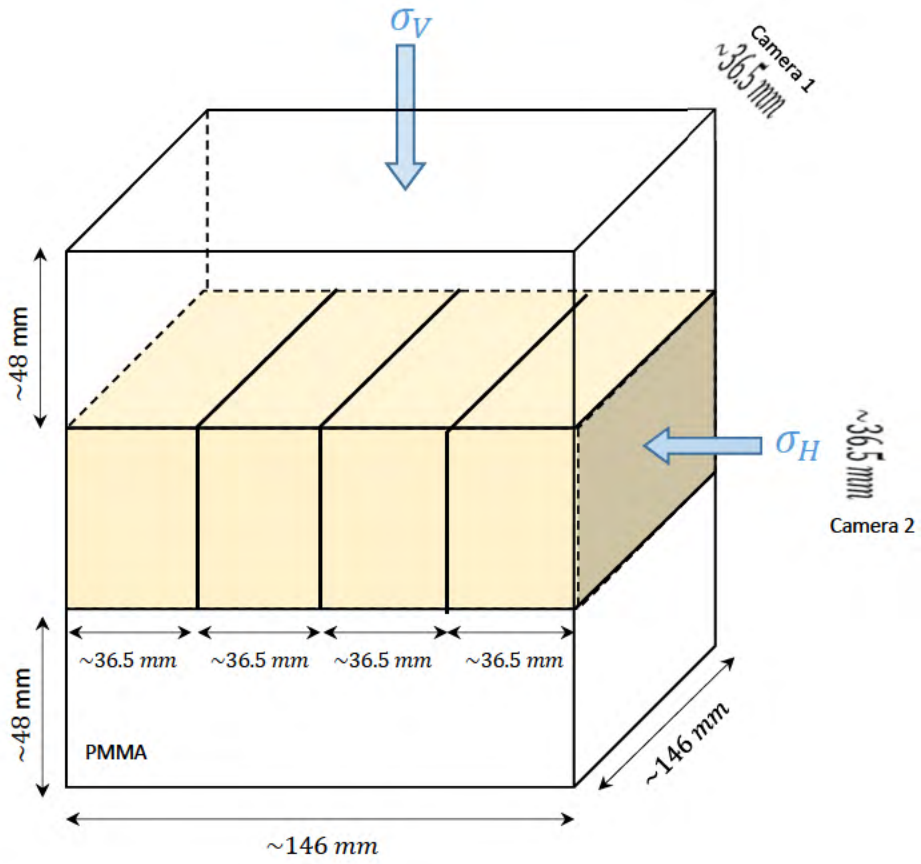


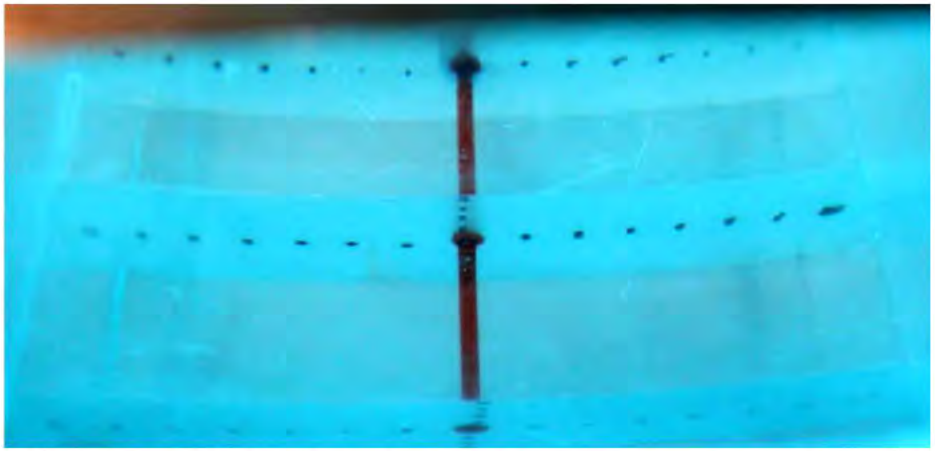
Test Cases

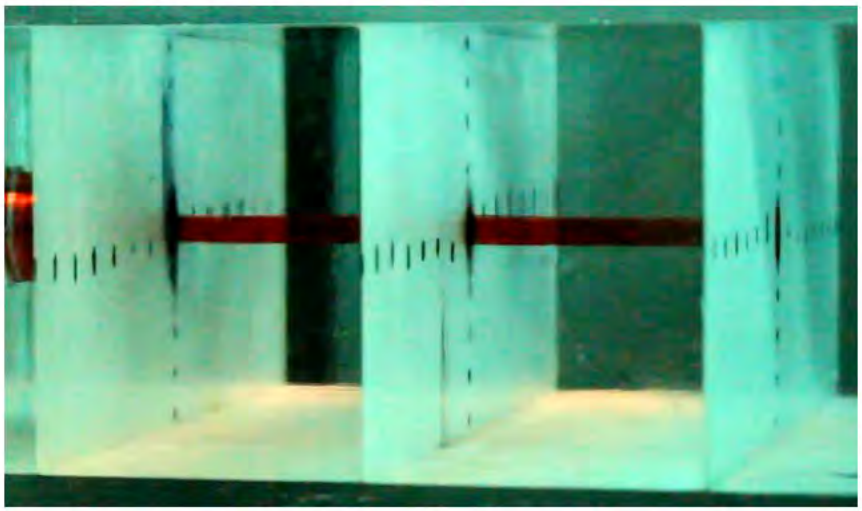
- In each case studied, the number of sub-blocks and the spacing between their interfaces vary



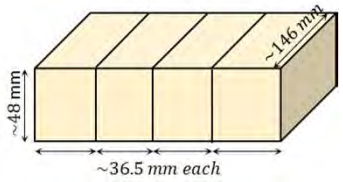
3 Uniform Wide Fractures (h/H = 0.75)

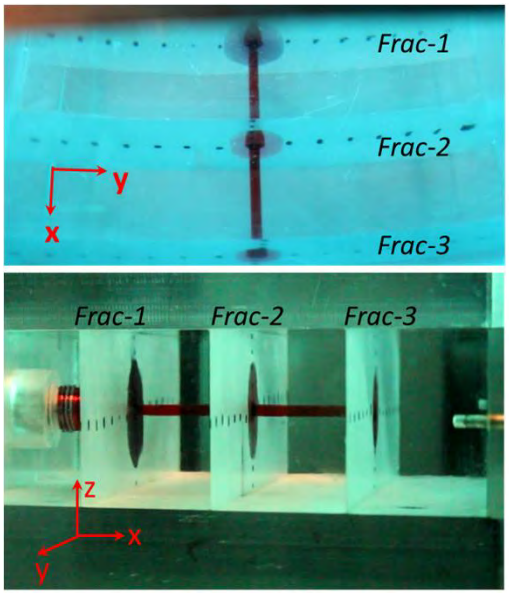




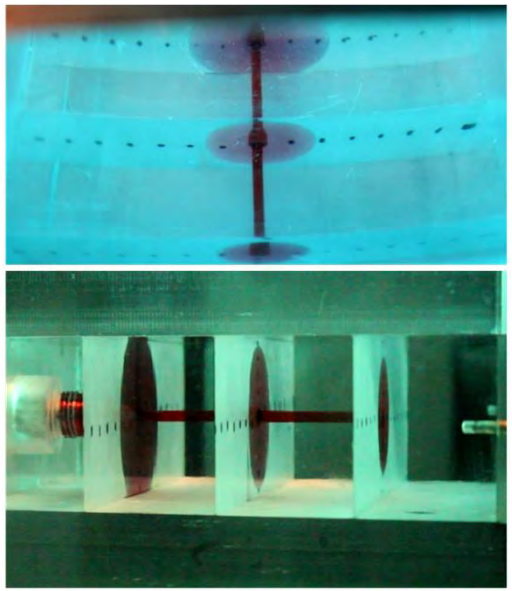


3 Uniform Wide Fractures (h/H = 0.75)

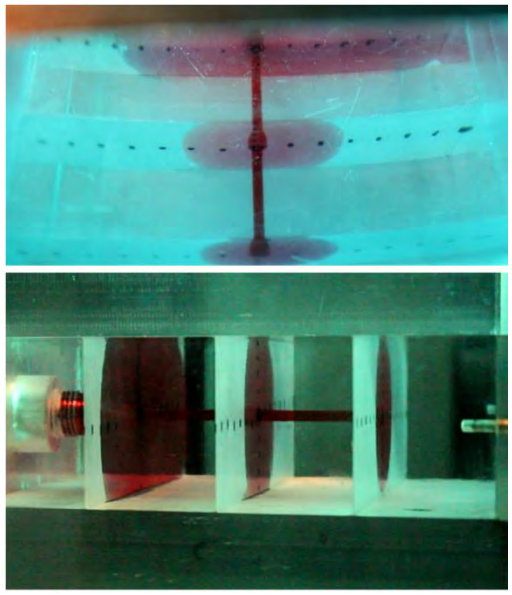




@ 45 seconds



@ 55 seconds

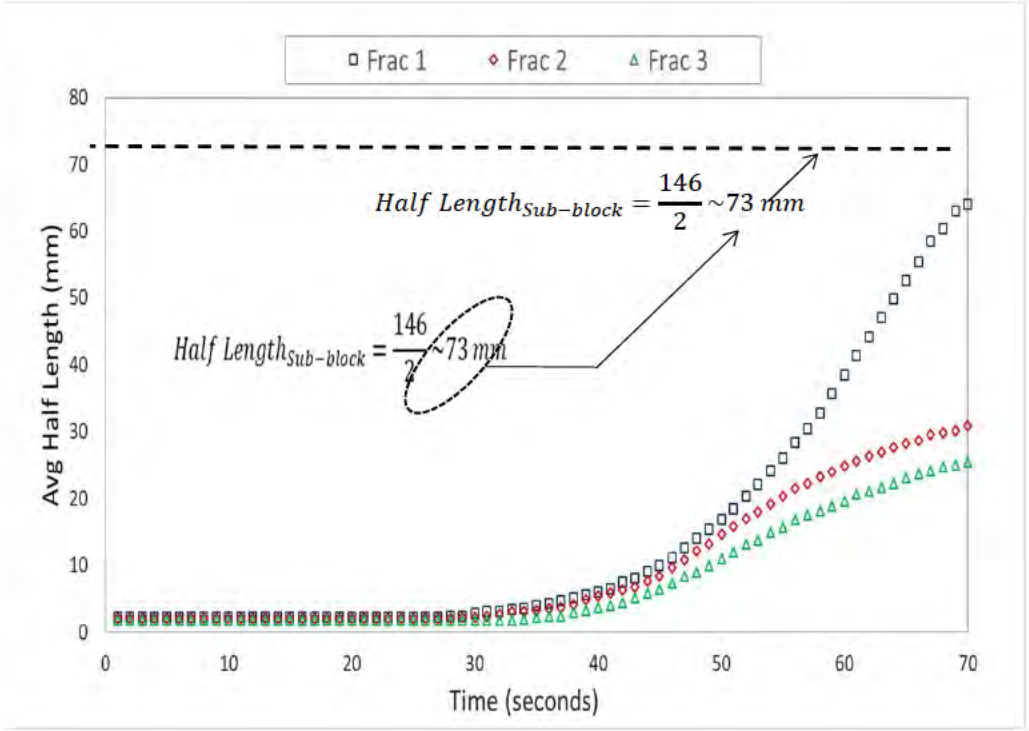


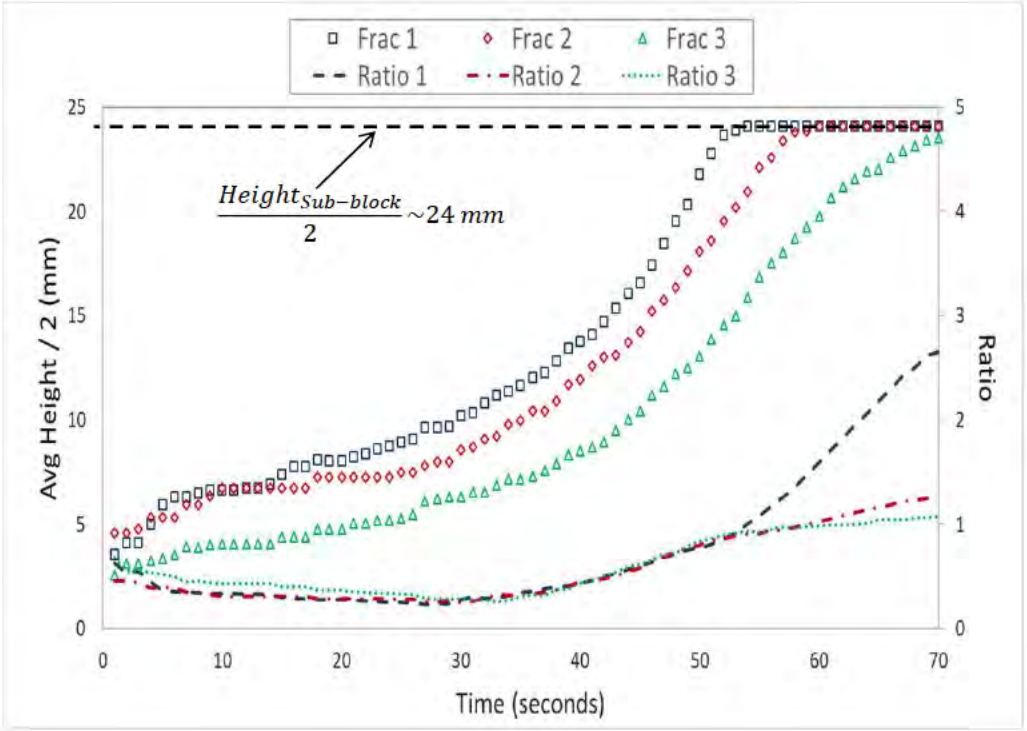
@ 70 seconds

⇦ Camera 1

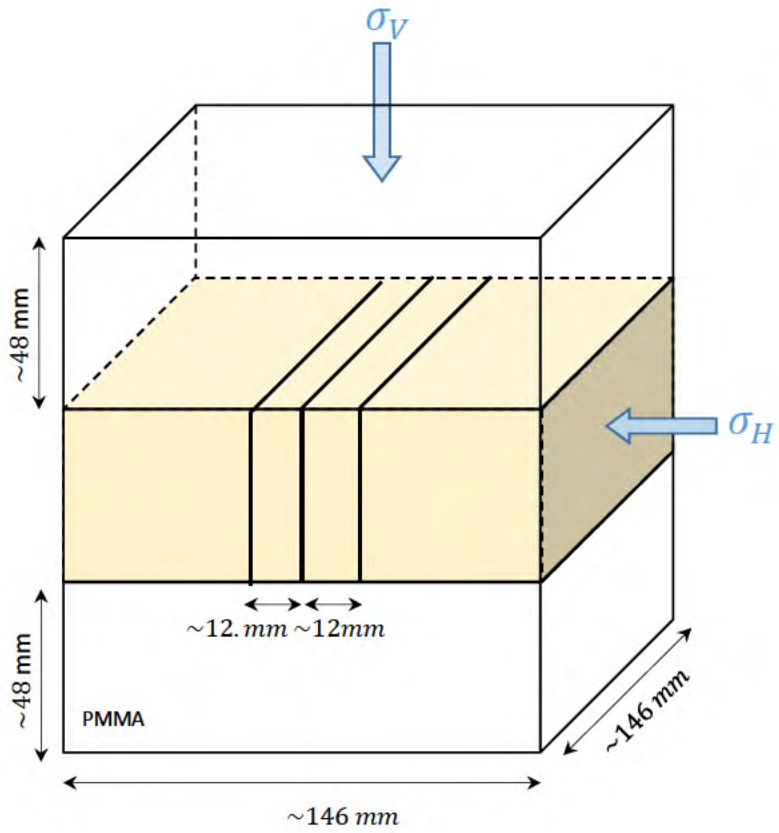
⇦ Camera 2

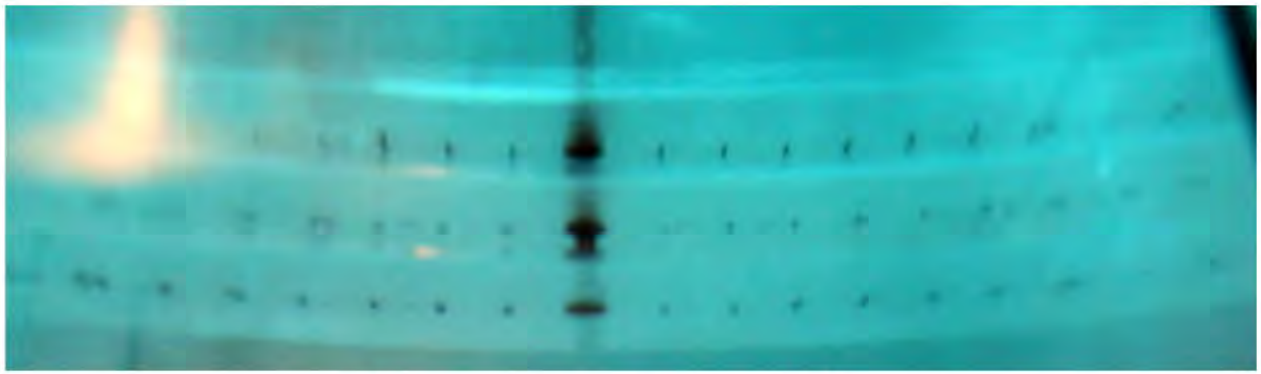
3 Uniform Wide Fractures (h/H = 0.75)

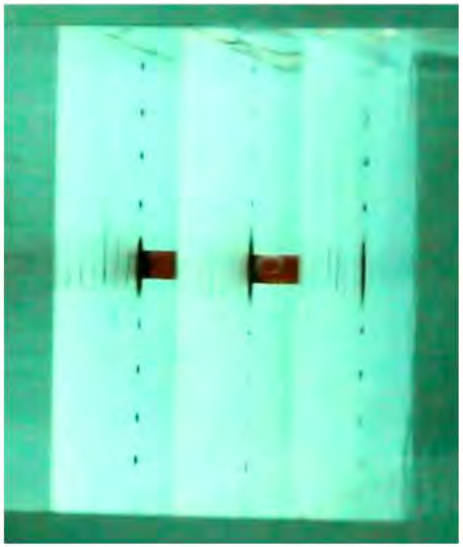




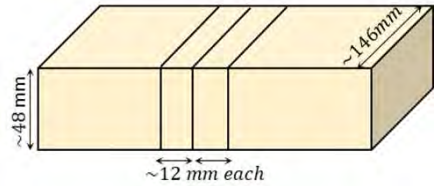
3 Uniform Narrow Fractures (h/H = 0.25)

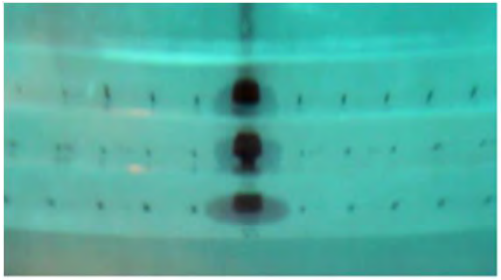
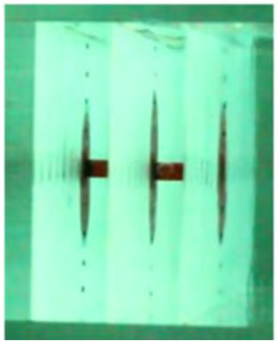




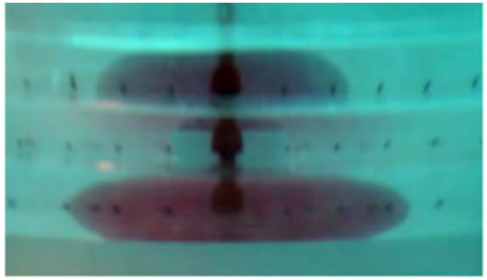
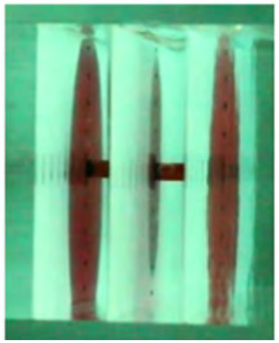


3 Uniform Narrow Fractures (h/H = 0.25)

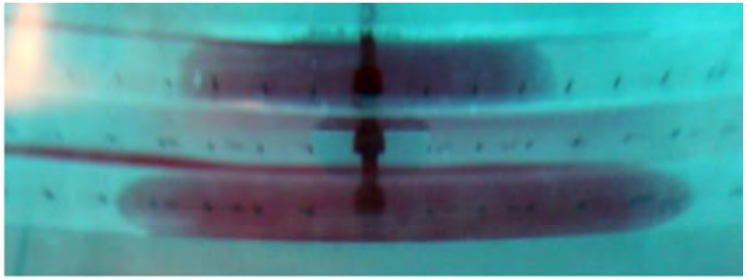
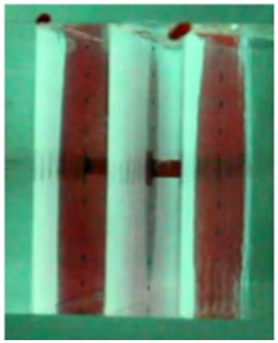


@ 75 seconds

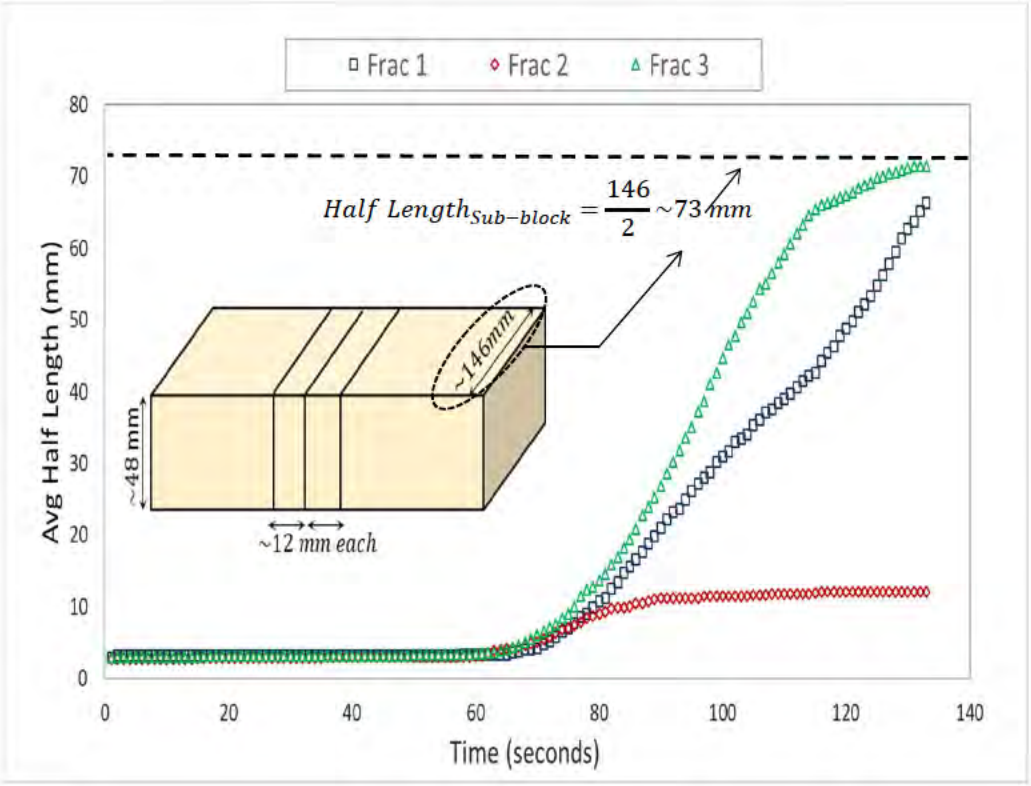



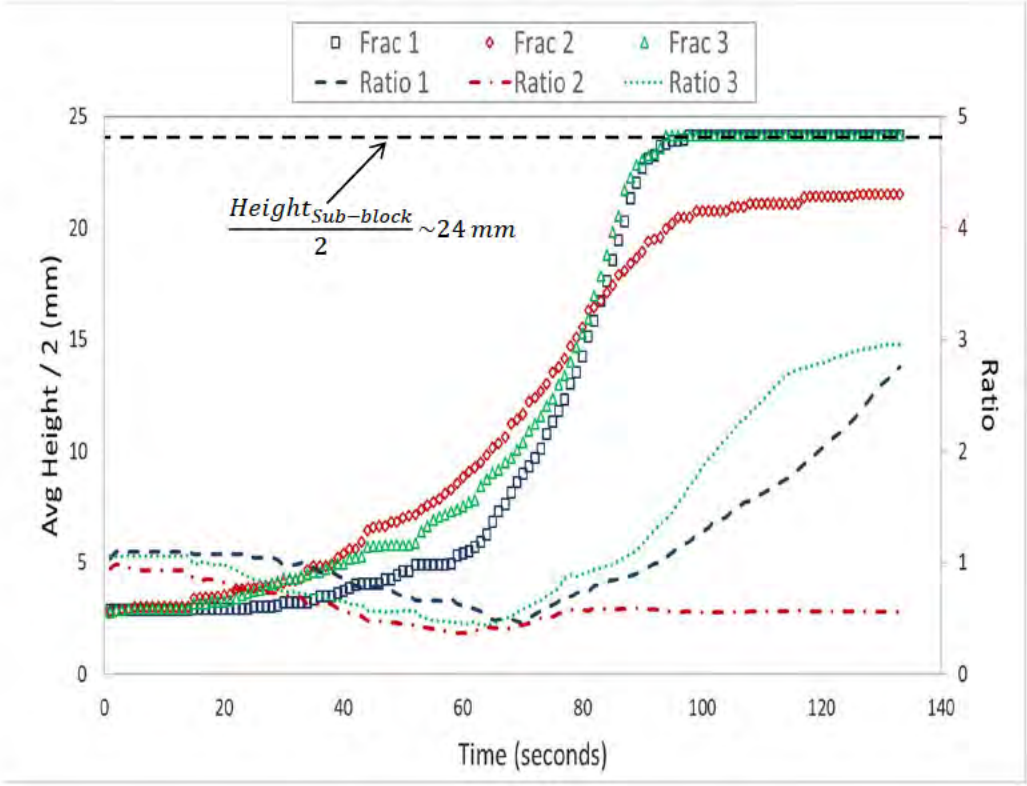
@ 95 seconds

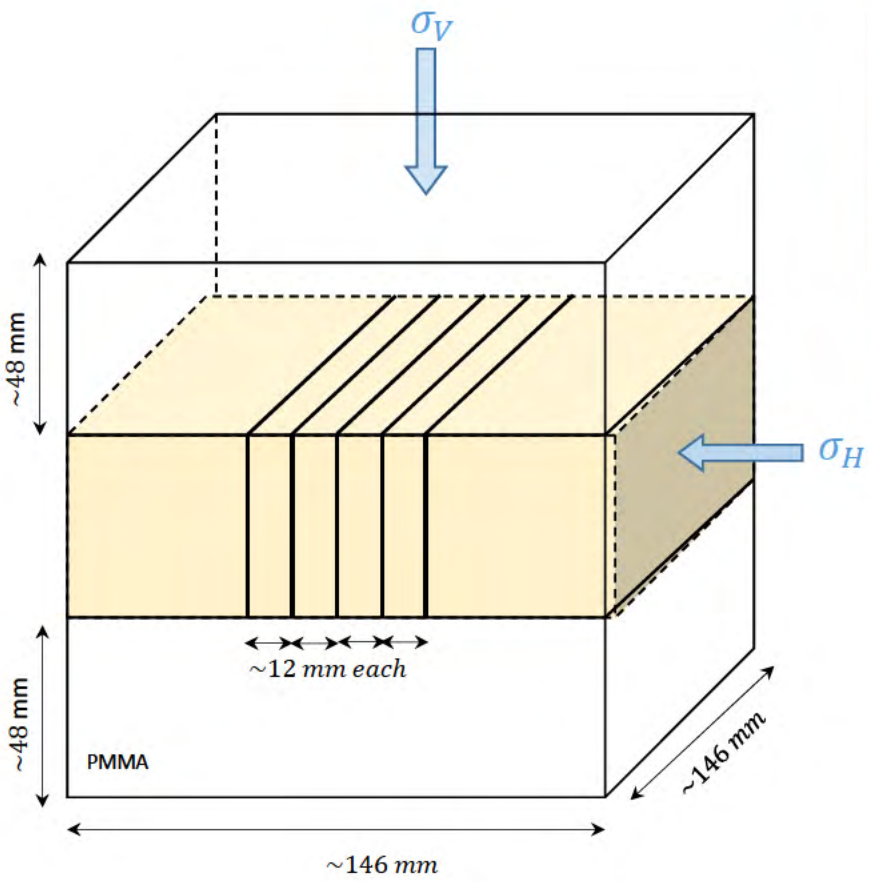
@ 110 second

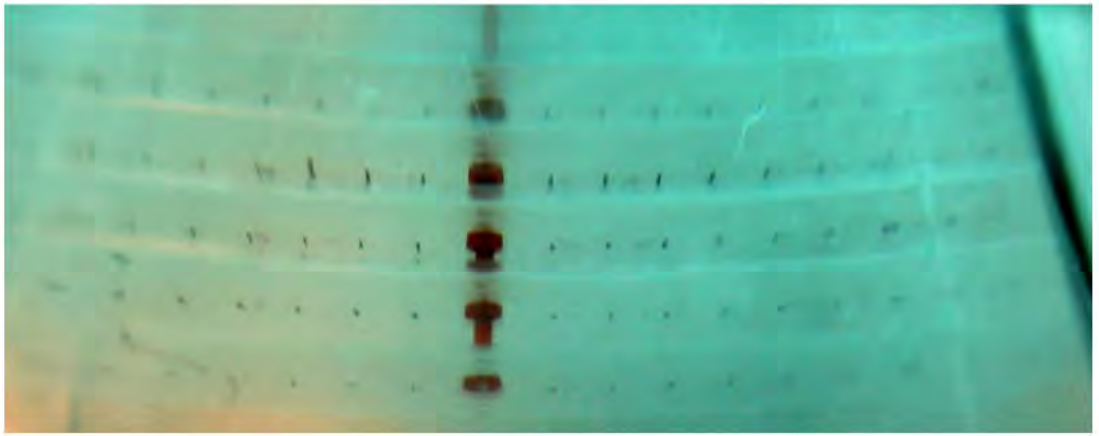
3 Uniform Narrow Fractures (h/H = 0.25)

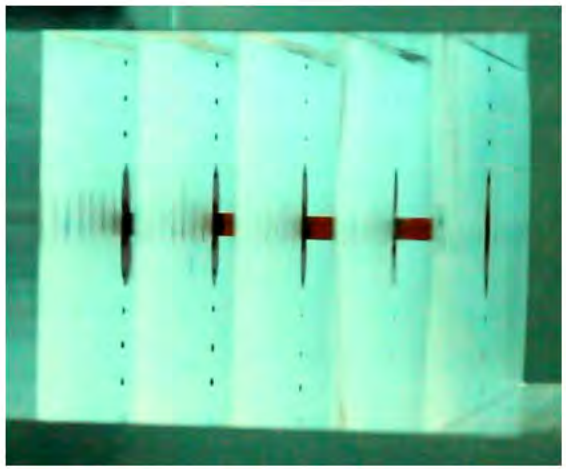




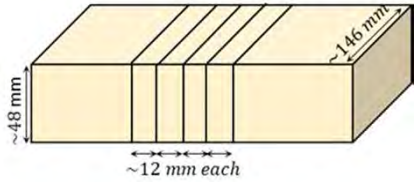
5 Uniform Narrow Fractures (h/H = 0.25)

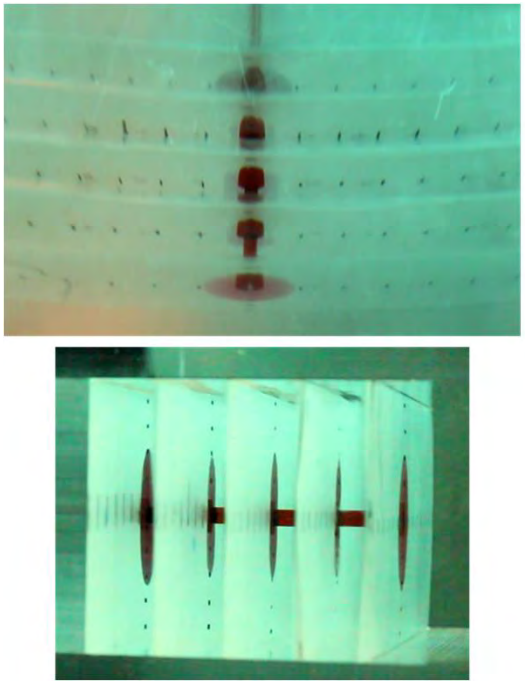




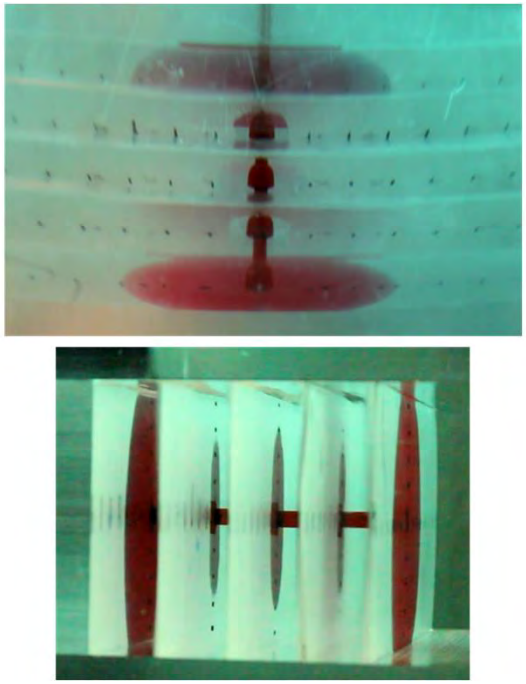


5 Uniform Narrow Fractures (h/H = 0.25)

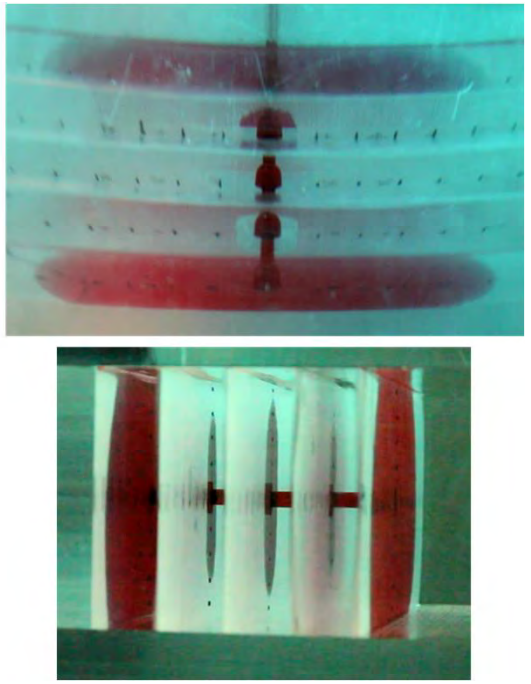




@ 70 seconds

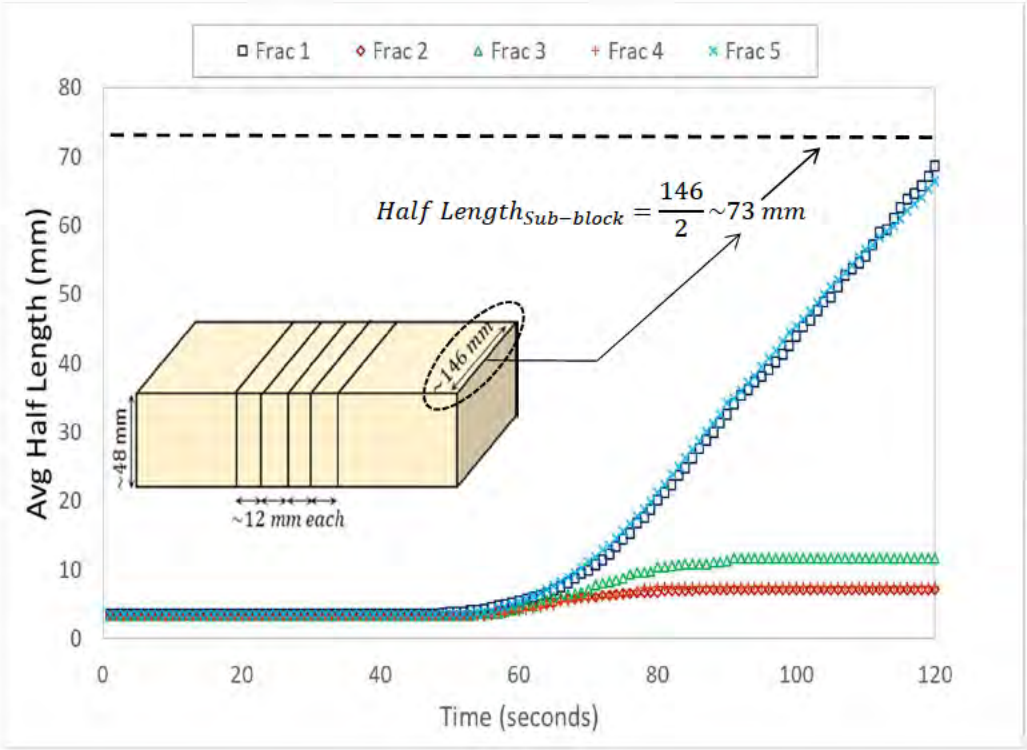


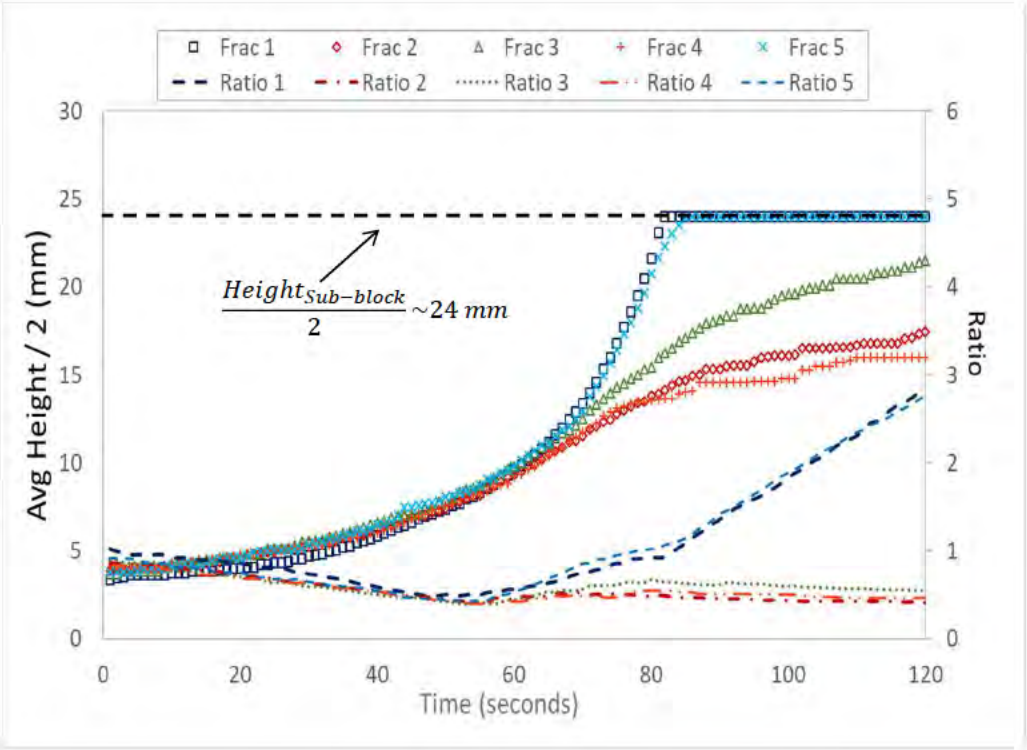
@ 85 seconds



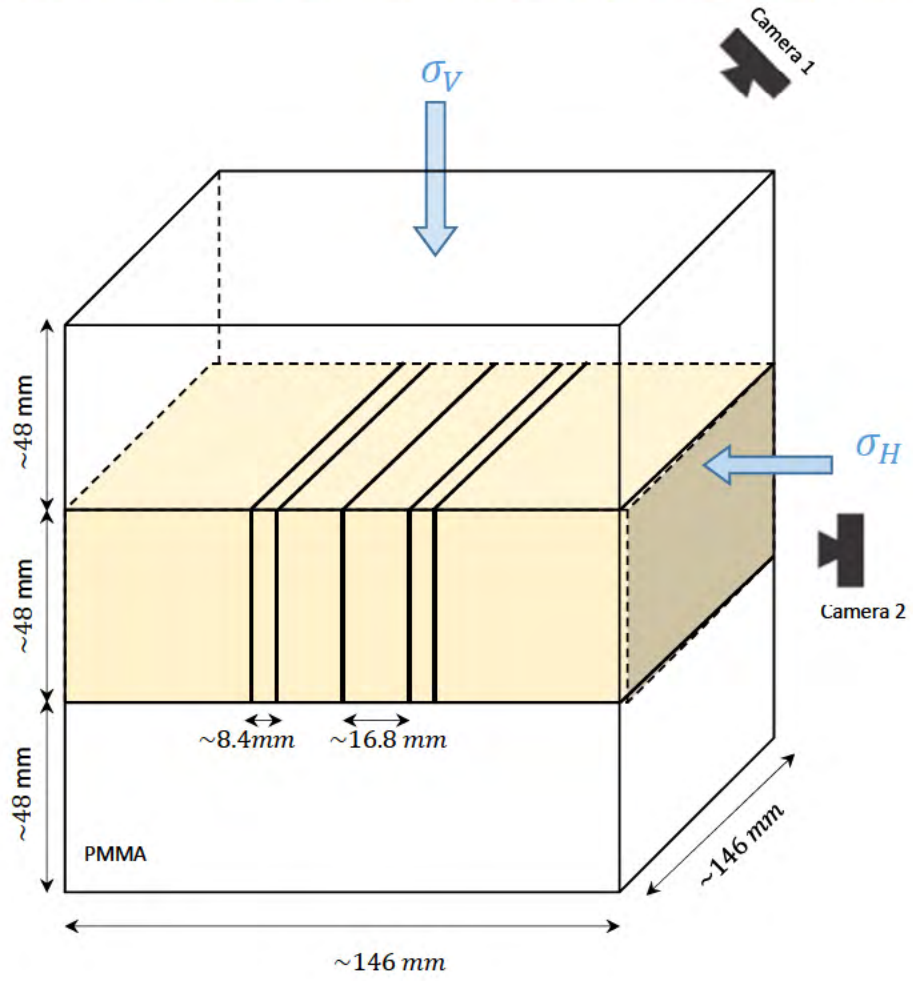
@ 110 second

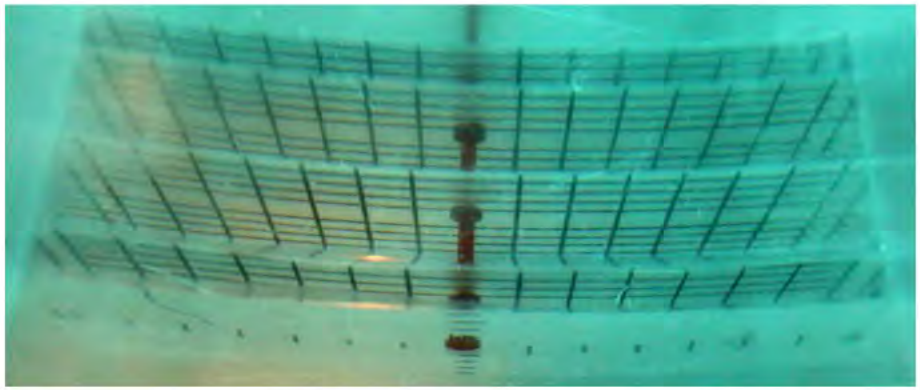
5 Uniform Narrow Fractures (h/H = 0.25)

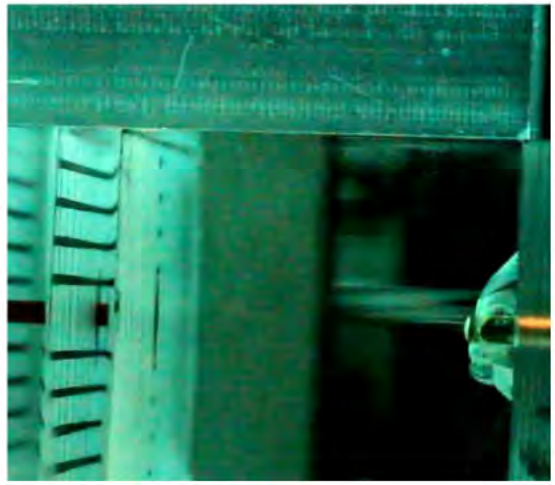




5 Non-Uniform Fractures (h/H = 0.175 & 0.35)







Qualitative Comparisons to Numerical Models

- Fully coupled, parallel-planar 3D HF model (PL3D)

  Peirce, A., & Detournay, E. (2008). An implicit level set method for modeling hydraulically driven fractures. Computer Methods in Applied Mechanics and Engineering, 197(33-40), 2858-2885.

- Distinct element model based on lattice method (DEM)

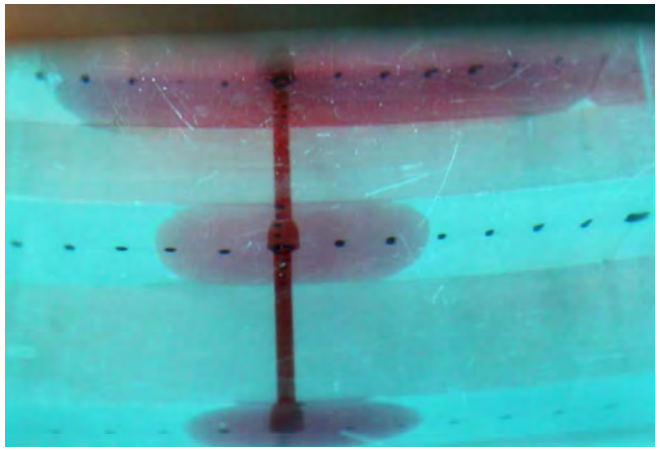
  Damjanac, B., & Cundall, P. (2016). Application of distinct element methods to simulation of hydraulic fracturing in naturally fractured reservoirs. Computers and Geotechnics, 71, 283-294.

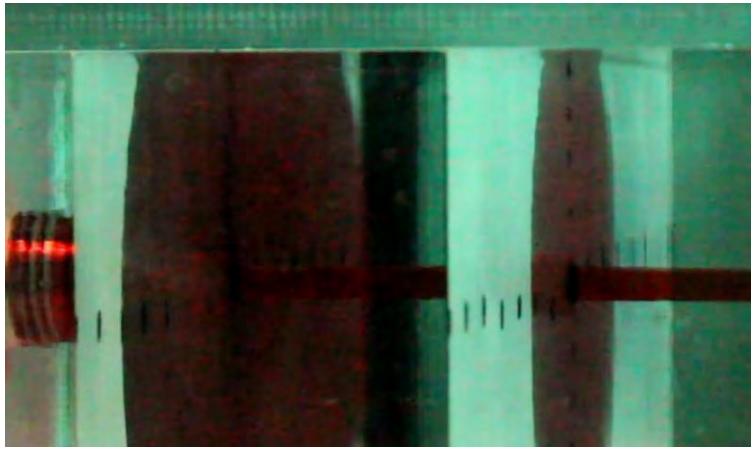
- Mesh free energy based approximate simulator (ROM)

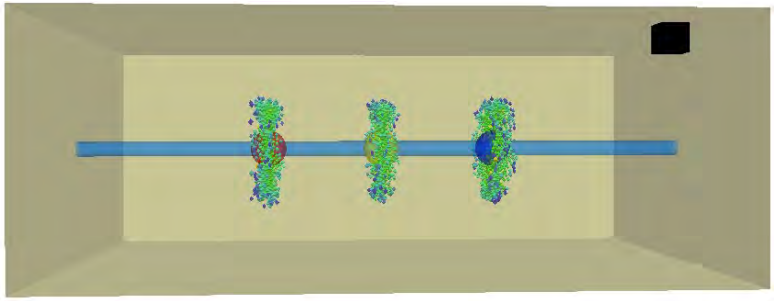
  Cheng, C., & Bunger, A. P. (2019). Reduced order model for simultaneous growth of multiple closely-spaced radial hydraulic fractures. Journal of Computational Physics, 376, 228-248.

Comparison of Experiments to DEM & ROM

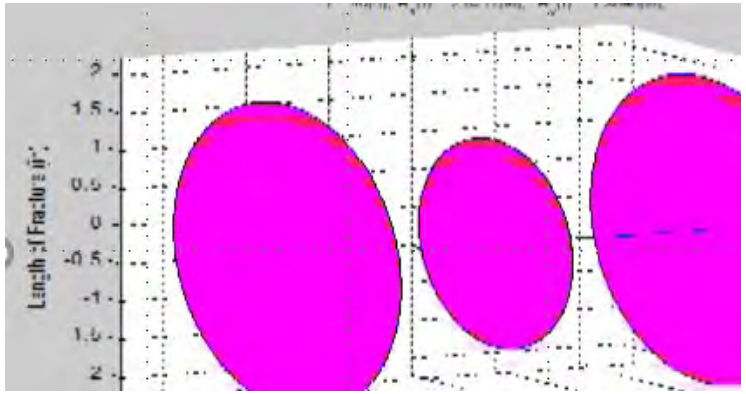
3 Uniform Wide Fractures – h/H=0.75







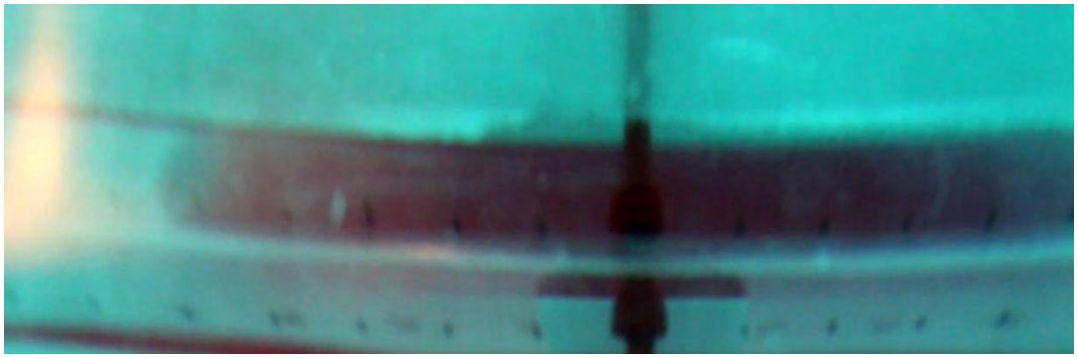
DEM (Fu et al 2019, ARMA 19-0045)

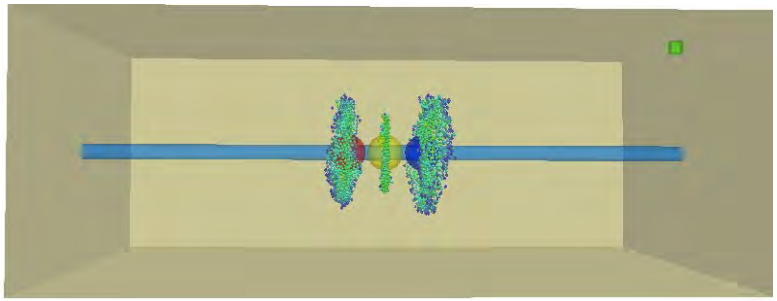


ROM (Cheng and Bunger 2019. Journal of Computational Physics, 376, 228-248)

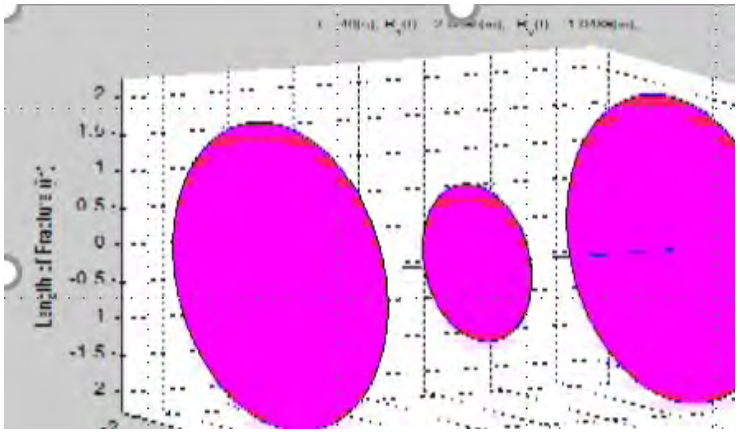
Comparison of Experiments to DEM & ROM

3 Uniform Narrow Fractures – h/H=0.25





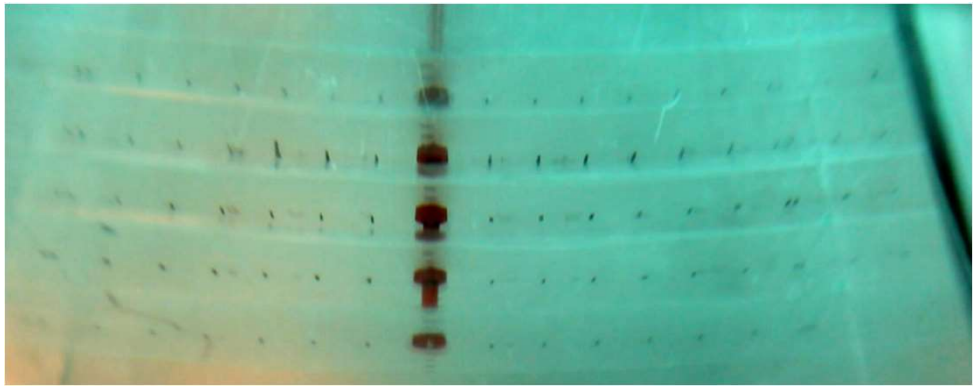
DEM (Fu et al 2019, ARMA 19-0045)

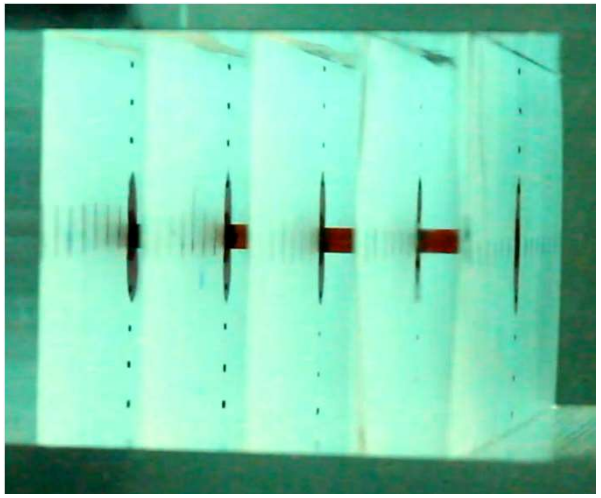


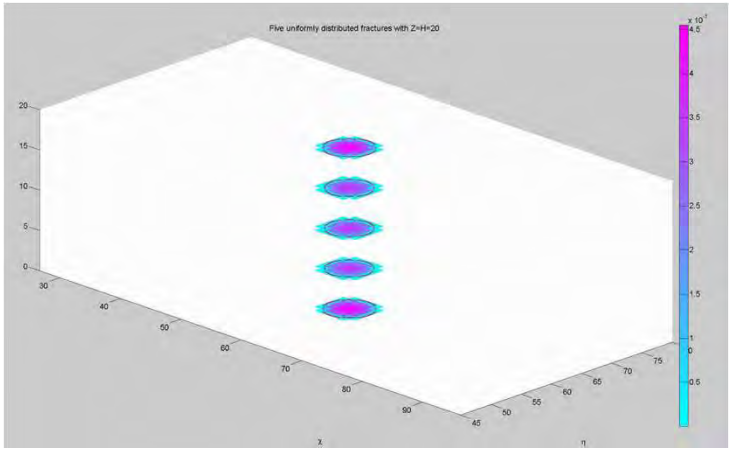
ROM (Cheng and Bunger 2019. Journal of Computational Physics, 376, 228-248)

Comparisons Cont'd

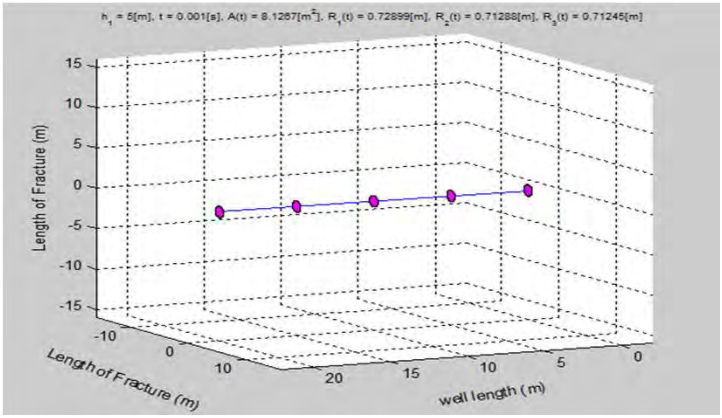
5 Uniform Fractures – h/H=0.25







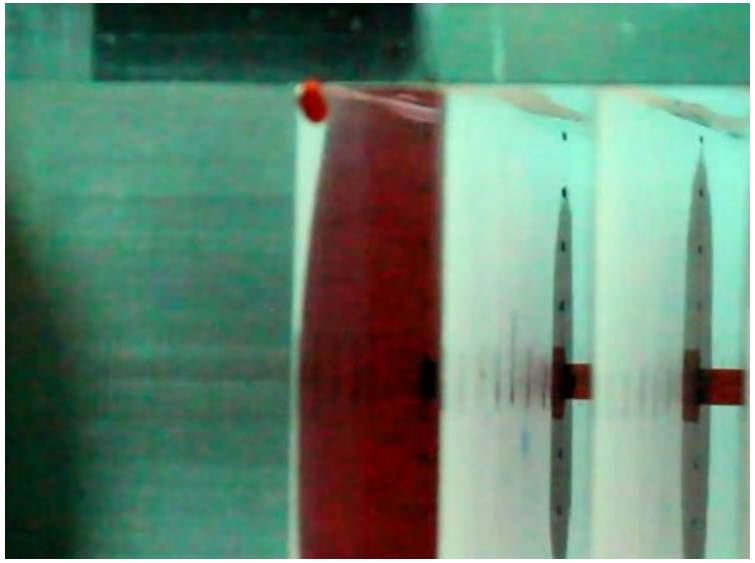
PL3D (Peirce and Bunger 2015. SPE Journal, 20(2): 384-395)



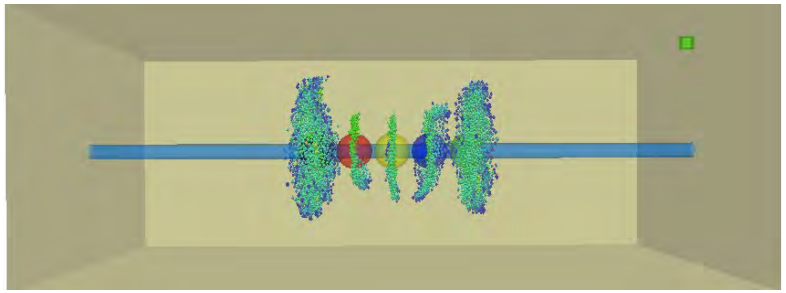
ROM (Cheng and Bunger 2019. Journal of Computational Physics, 376, 228-248)

Comparisons Cont'd

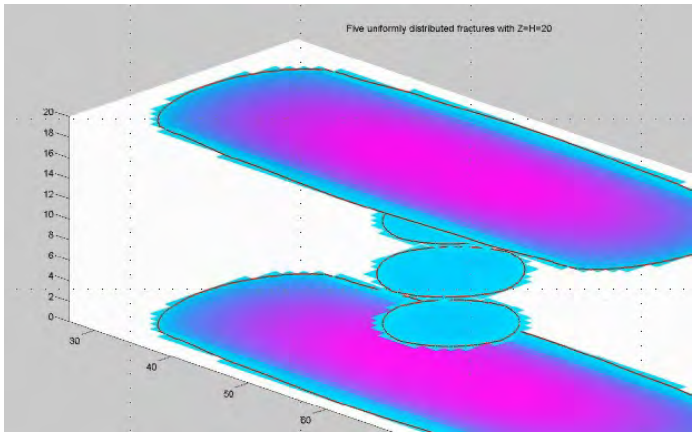
5 Uniform fractures – h/H=0.25



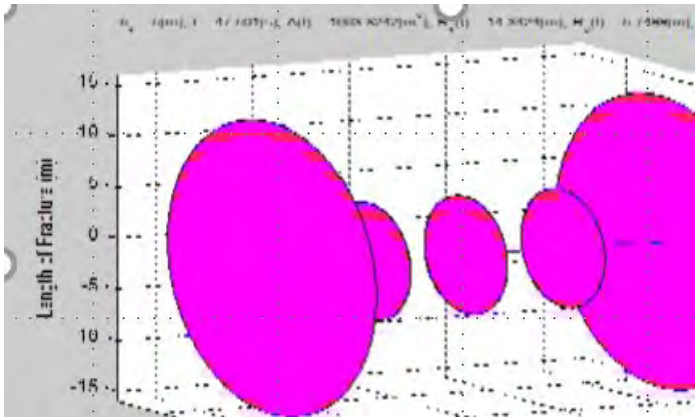
Experiments @ University of Pittsburgh



DEM (Fu et al 2019, ARMA 19-0045)



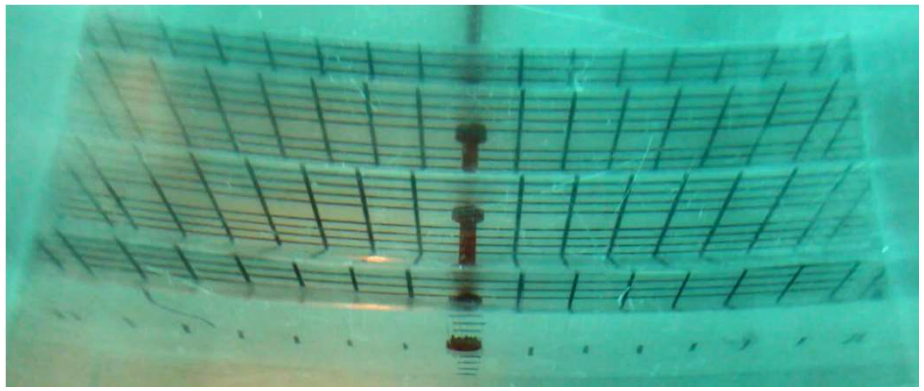
PL3D (Peirce and Bunger 2015. SPE Journal, 20(2): 384-395)

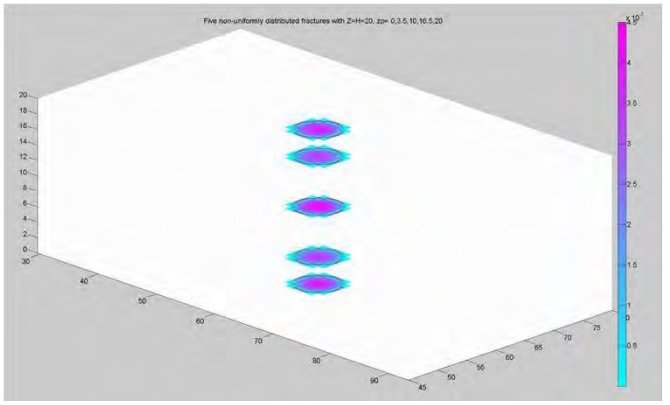


ROM (Cheng and Bunger 2019. Journal of Computational Physics, 376, 228-248)

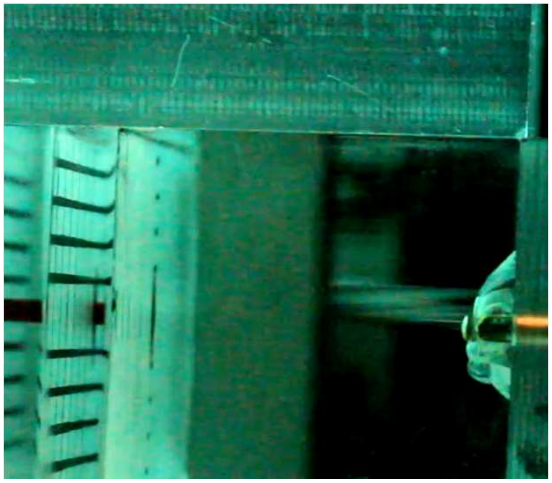
Comparisons Cont'd

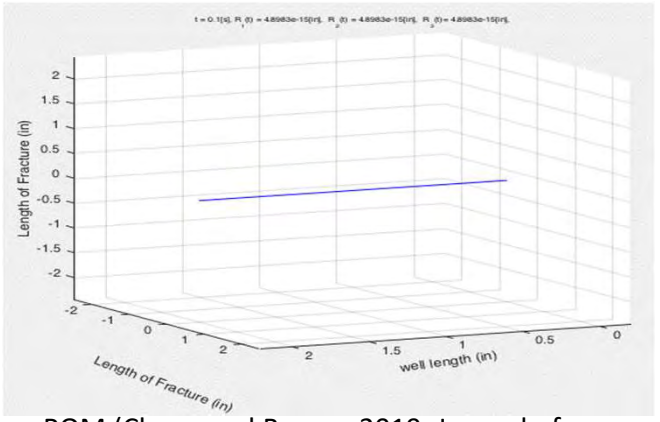
5 Nonuniform Fractures – h/H=0.175 and h/H=0.375





PL3D (Peirce and Bunger 2015. SPE Journal, 20(2): 384-395)

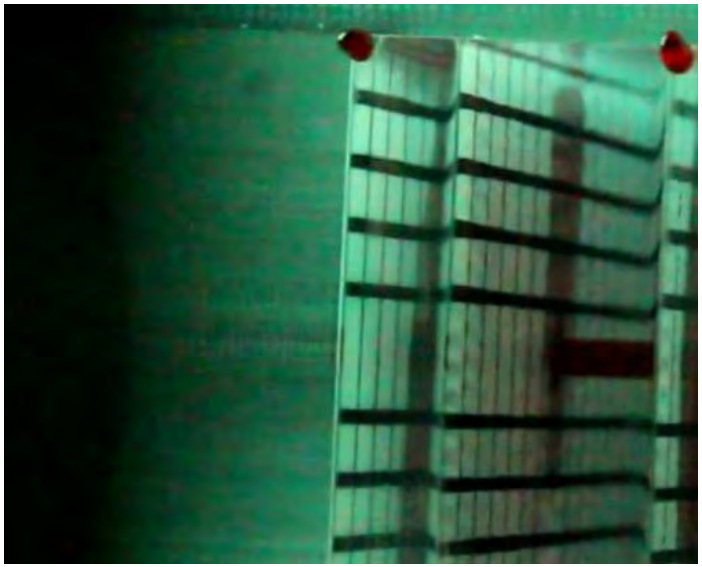




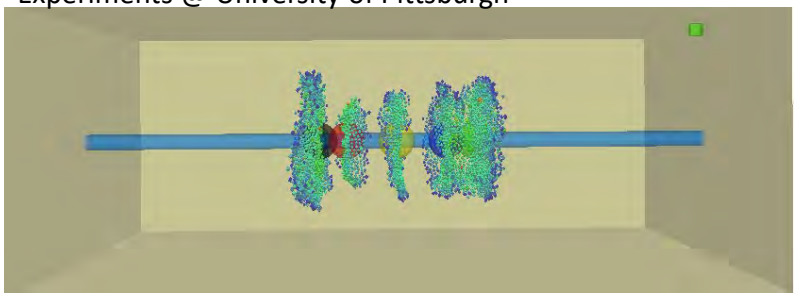
ROM (Cheng and Bunger 2019. Journal of Computational Physics, 376, 228-248)

Comparisons Cont'd

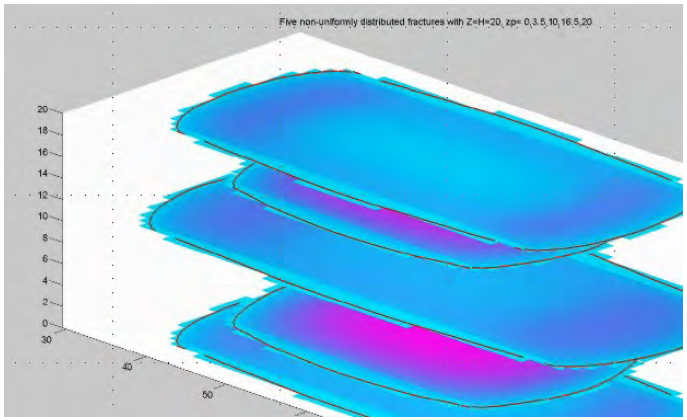
5 Nonuniform fractures – h/H=0.175 and 0.375



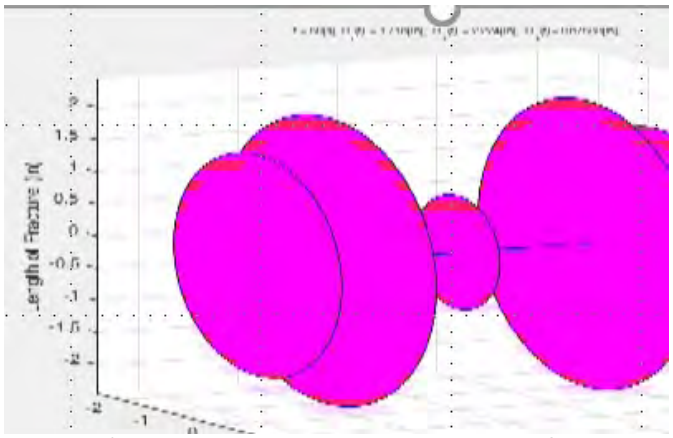
Experiments @ University of Pittsburgh



DEM (Fu et al 2019, ARMA 19-0045)



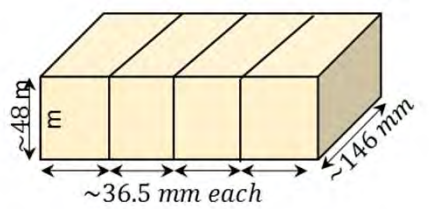
PL3D (Peirce and Bunger 2015. SPE Journal, 20(2): 384-395)



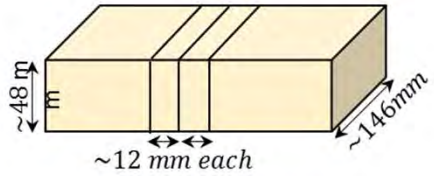
ROM (Cheng and Bunger 2019. Journal of Computational Physics, 376, 228-248)

Summary of Observations

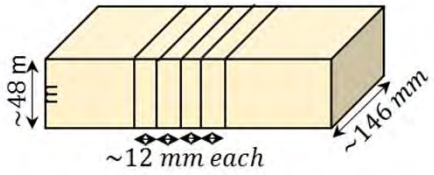
- Distribution of flow in widely separated fractures dominated by wellbore fluid friction and unavoidable stress variability
- Suppression of central fractures is robustly observed for narrow uniform spacing
- Dominance of 3, 1, and 5 observed for non-uniform spacing…but not 2, 4 dominance (yet)
- Simulations broadly similar but quantitative details (and 2,4) dominance difficult to match



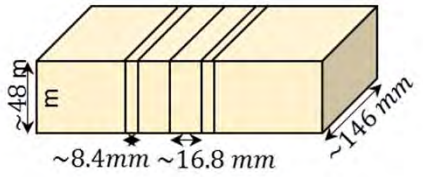
(h/H = 0.75)



(h/H = 0.25)



(h/H = 0.25)



(h/H = 0.175 & 0.35)

Remarks

- Takes precise methods to get distribution as in simulations – “noise” in stress, entry pressure, can wipe out the predicted phenomenon, even qualitatively
- We need to listen to what this is telling us…future efforts focus on
  - Uncertainty
  - Variability
- …Without forgetting that mechanical models need to have the right limiting behaviors even if those limits are not strictly achieved in practical settings.

Acknowledgements

- Ph.D. Students: Cheng Cheng, Delal Gunaydin
- Wei Fu (former Ph.D. student, now with Lawrence Livermore National Laboratory)
- Collaborators: Anthony Peirce (U British Columbia)
- Technical Support: Charles (Scooter) Hager
- Funding: NSF (dyke swarms)

PITT | SWANSON ENGINEERING

NSF

Support provided by:
National Science Foundation Grant No. 1645246.