MIT EARTH RESOURCES LABORATORY
ANNUAL FOUNDING MEMBERS MEETING 2018

Earth Resources Laboratory

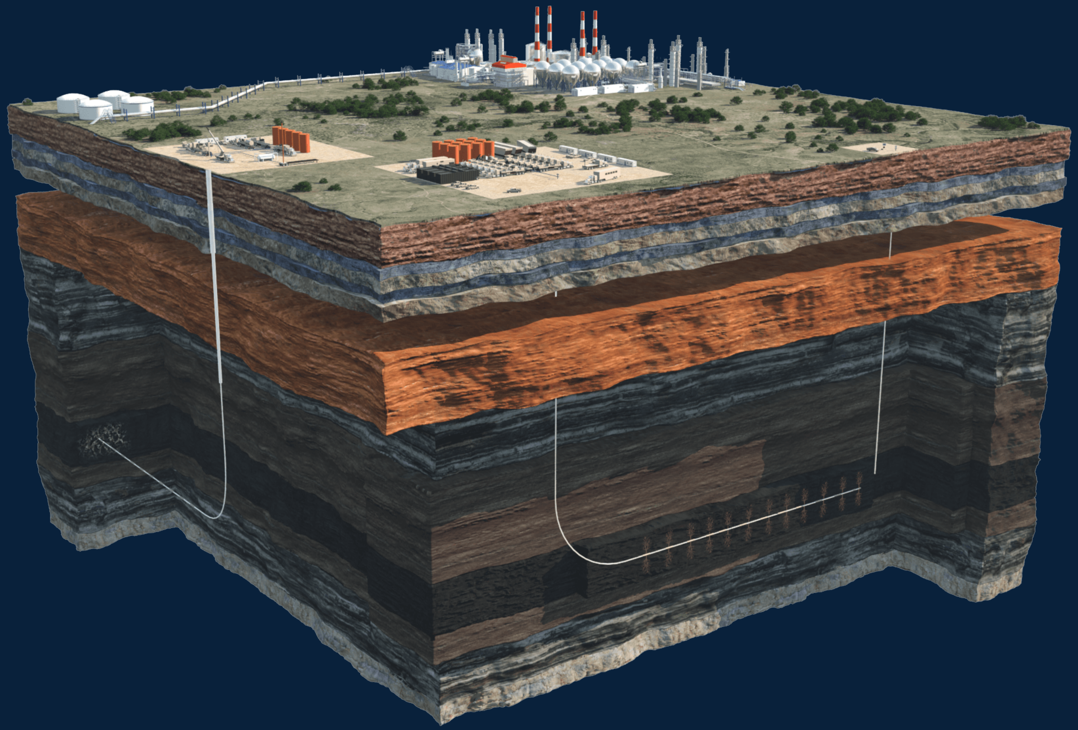
Experimental Study of Rock Matrix Dissolution and Wormhole Formation

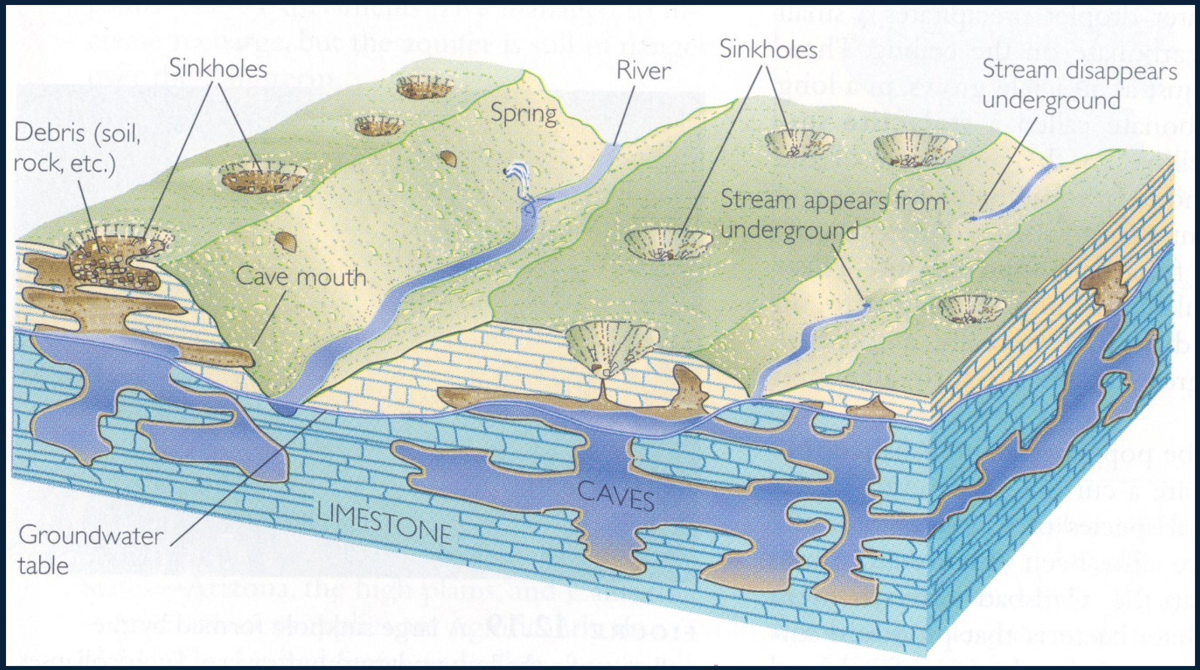
Wei Li
PHD CANDIDATE [DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING]

In collaboration with Professor Herbert H. Einstein

Background

- Rock dissolution and wormhole formation
  - Oil reservoir acid stimulation
  - Carbon dioxide storage
  - Limestone dissolution
  - Gypsum dissolution



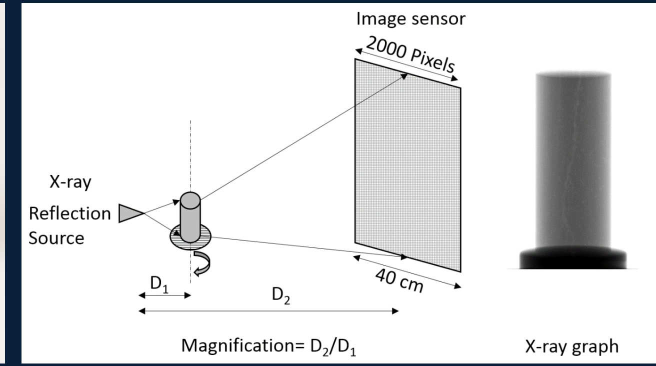


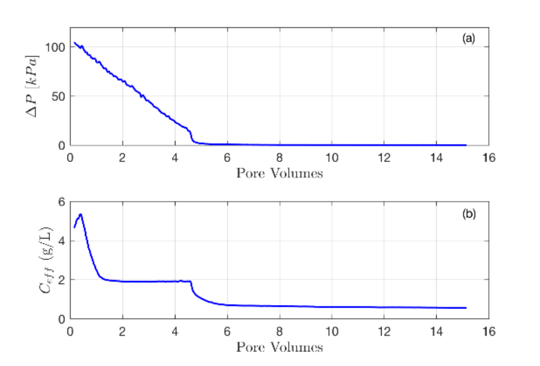
Key points

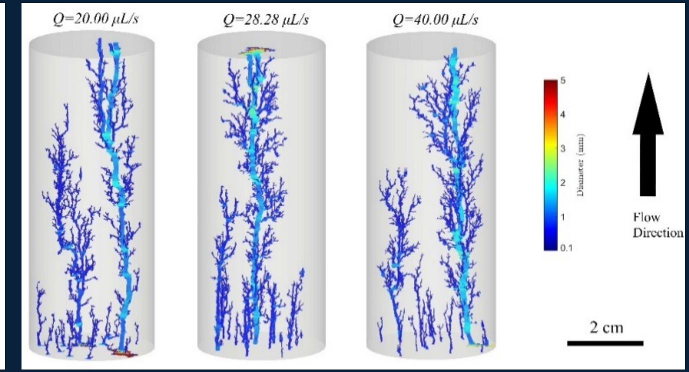
- Studied the reaction kinetics based on the continuous effluent concentration measurement.
- Studied the effect of flow rate on wormhole formations based on the X-ray CT scan quantitative analysis.

Contents

- Introduction
- Experimental setup
  - Triaxial system
  - Effluent chemistry monitoring system
  - Material
  - X-ray computed tomography
- Results
  - *Effluent concentration data*
  - *X-ray CT data 3D reconstruction.*
  - *Current work*
- Conclusion







Introduction

- Wormholes are the long, finger-like channels that form due to the dissolution heterogeneity in the rock matrix.
- Wormholes greatly increase the porosity & permeability of the formation.

Daccord, 1987

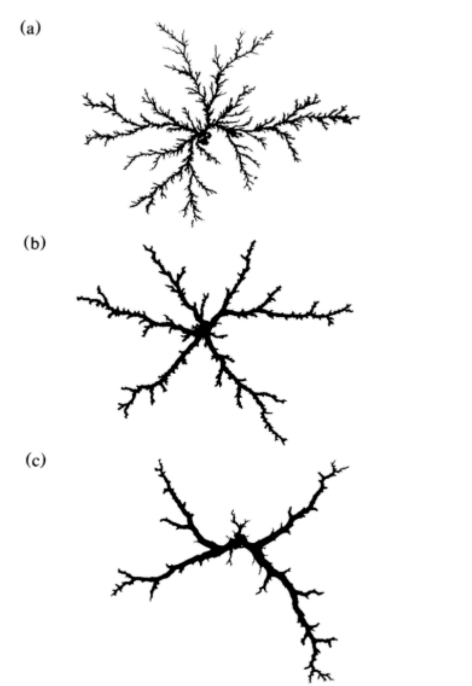
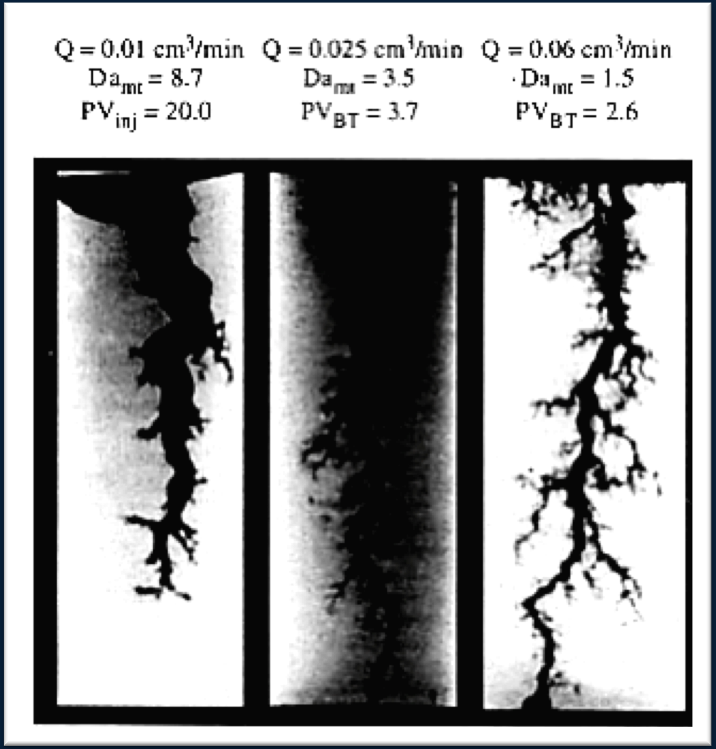
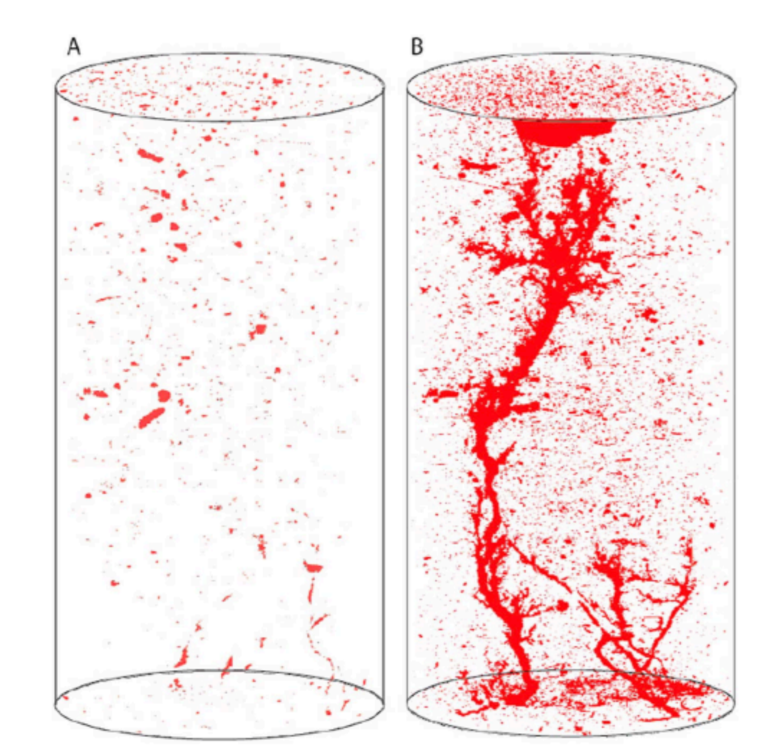


FIG. 1. Photographs of 2D radial experiments stopped after 4 h and performed at different injection rates. (a) 48 cm^3/h. (b) 4 cm^3/h. (c) 2 cm^3/h.

Fredd and Fogler, 1998

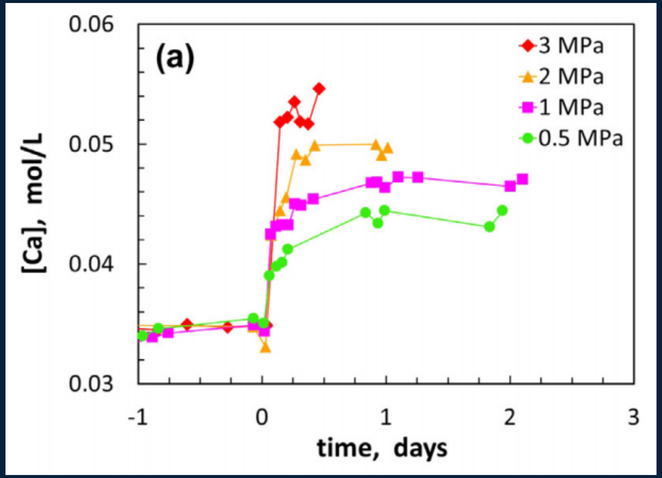


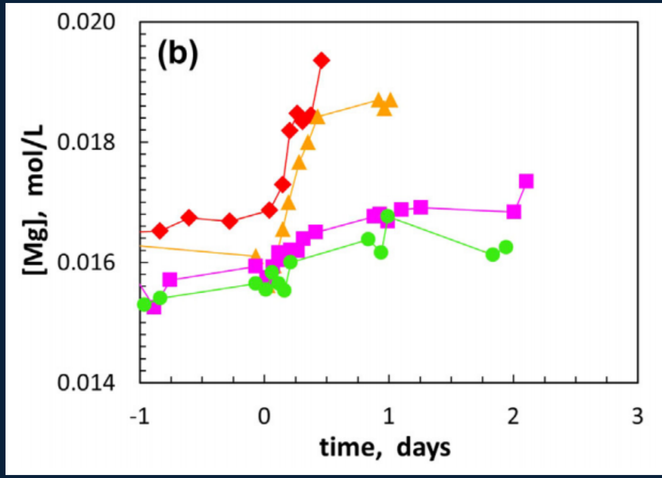
Wang et al., 2016

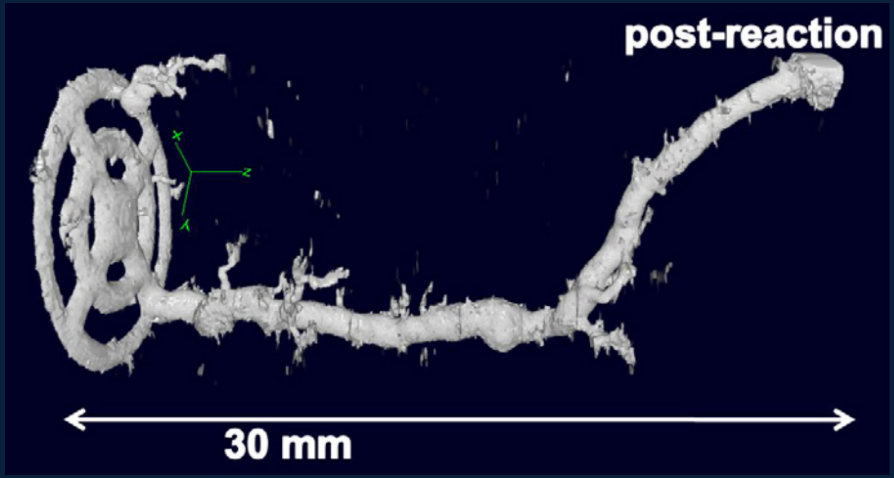


Introduction

- Core flood tests can be used to study the dissolution process, but the current tests have the limitations:
  - Limited discrete effluent concentration data.
  - X-ray CT analysis only qualitative.





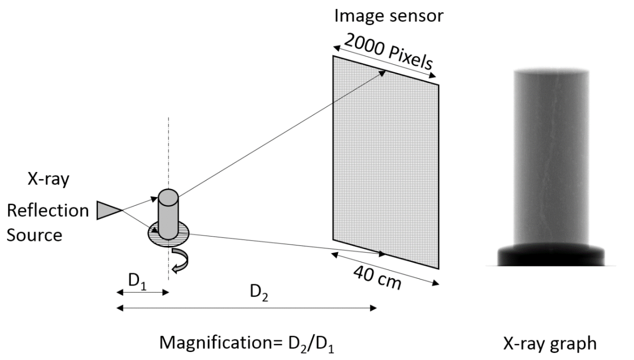


Introduction

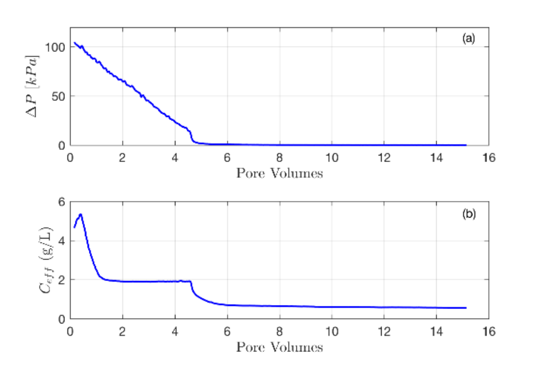
- To overcome these limitations:
  - Effluent chemistry monitoring system integrated in triaxial setup.
  - CT data analysis.
- The improved setup is used to study the effect of flow rate on the rock matrix dissolution and wormhole formation.

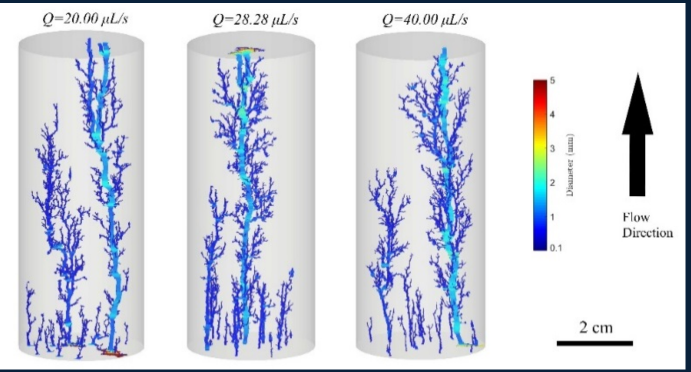
Contents

- Introduction
- Experimental setup
  - Triaxial system
  - Effluent chemistry monitoring system
  - Material
  - X-ray computed tomography



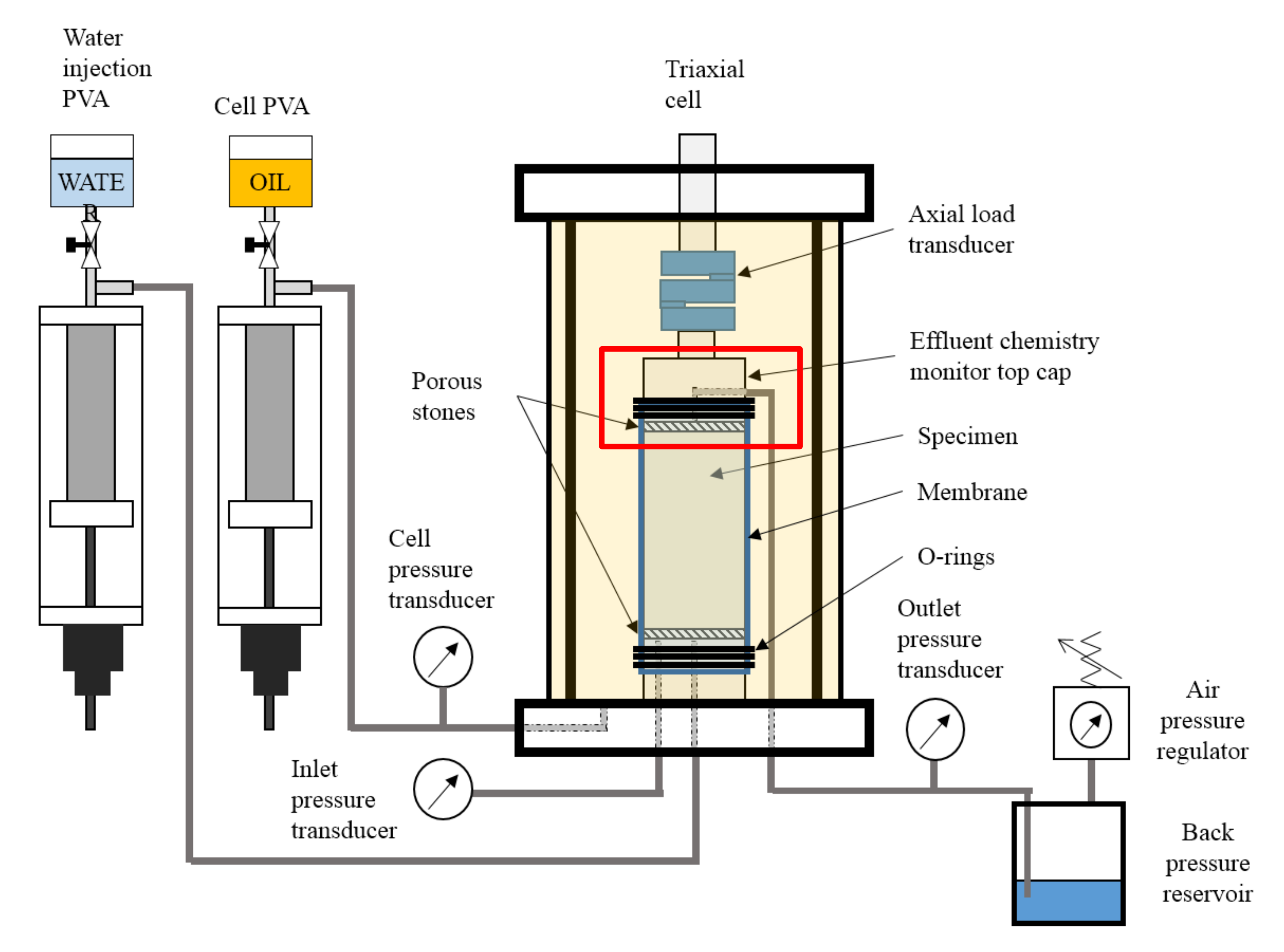
- Results
  - *Effluent concentration data*
  - *X-ray CT data 3D reconstruction.*
  - *Current work*
- Conclusion





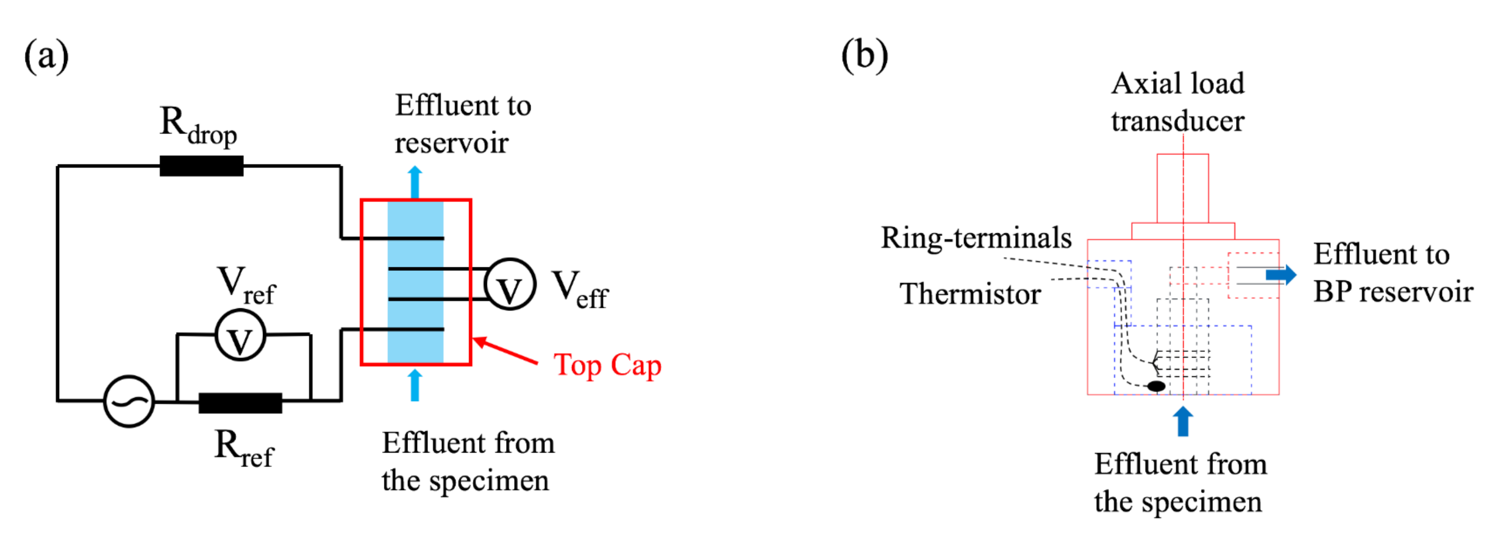
Experimental setup

- Triaxial system
  - Control and monitor
    - *Confining stress*
    - *Axial stress*
    - *Injection rate*
    - *Backpressure*
  - Monitor
    - *Inlet pressure*
    - *Outlet pressure*
    - *Axial displacement*
    - *Effluent concentration*
    - *Effluent temperature*



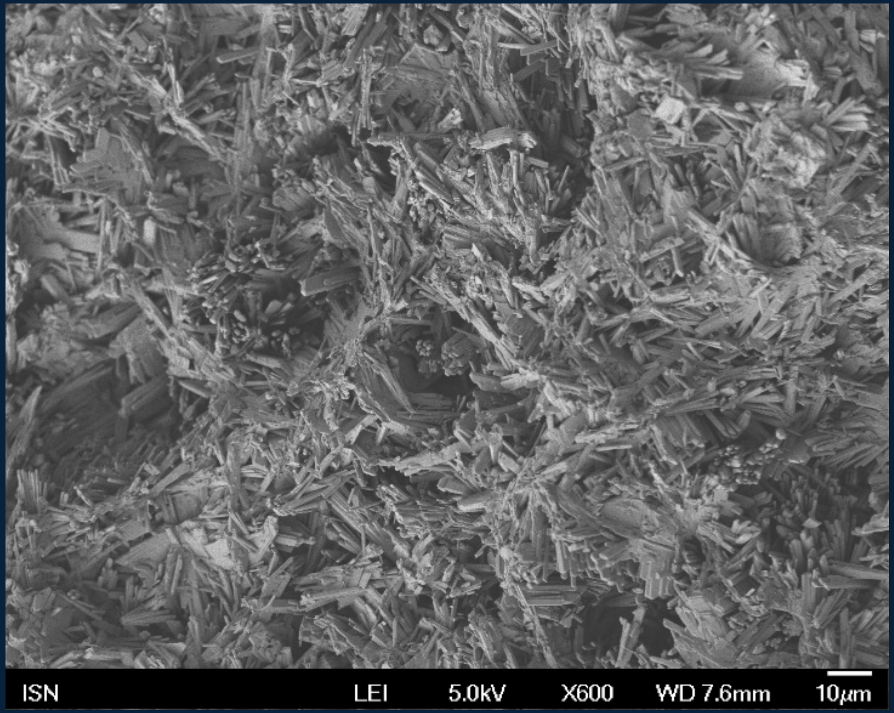
Experimental setup

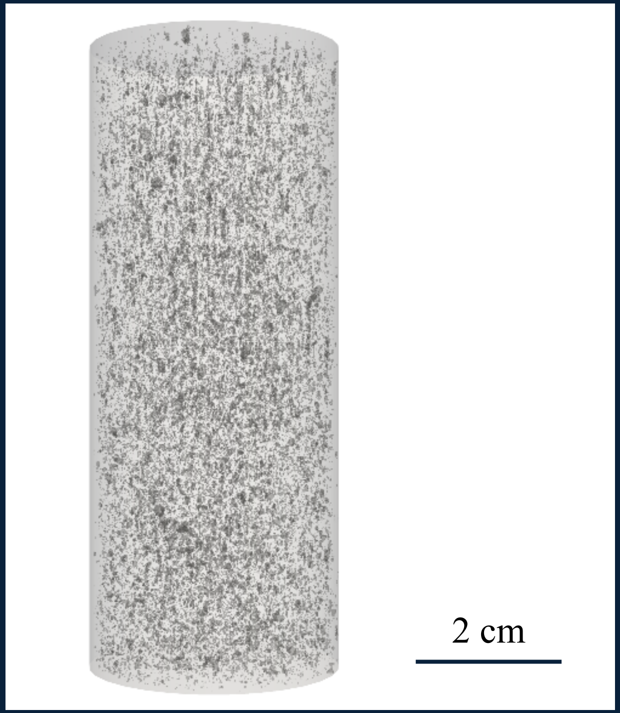
- Effluent chemistry monitoring system.
  1. In-situ effluent chemistry monitoring (back-pressurized).
  2. Small effluent sample is sufficient (<0.2mL).
  3. Long term continuous monitoring (avoid ion plating).
  4. Calibrated for gypsum-water, mortar-water systems.



Experimental setup

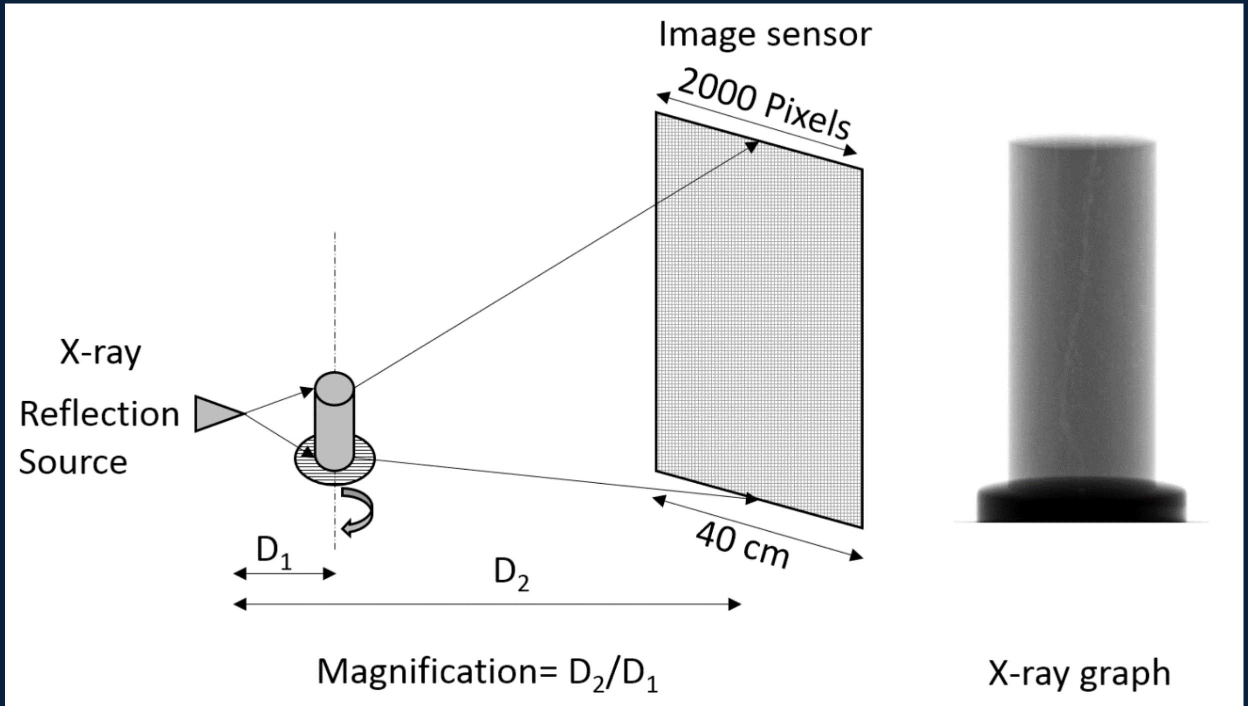
- Material
  - Laboratory cast Plaster of Paris was used to prepare specimens (consistency and workability).





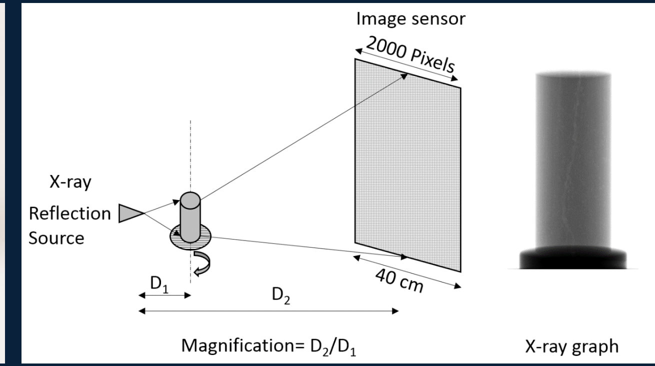
Experimental setup

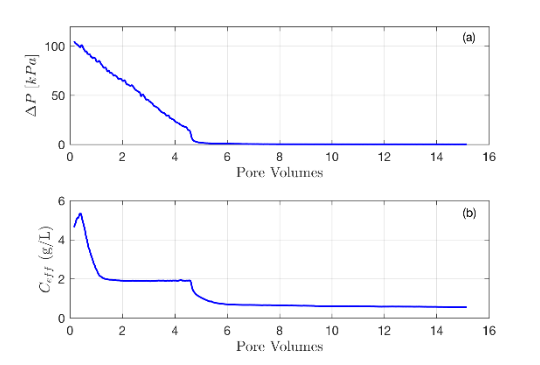
- X-ray computed tomography
  - After the core flood test, the specimen was scanned with 50 μm voxel resolution.

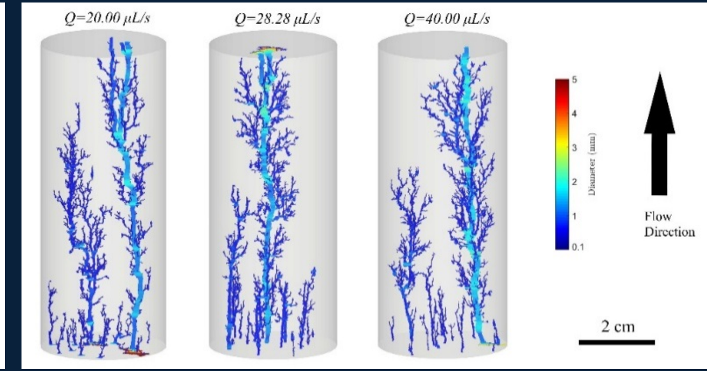


Contents

- Introduction
- Experimental setup
  - Triaxial system
  - Effluent chemistry monitoring system
  - Material
  - X-ray computed tomography
- Results
  - *Effluent concentration data*
  - *X-ray CT data 3D reconstruction.*
  - *Current work*
- Conclusion

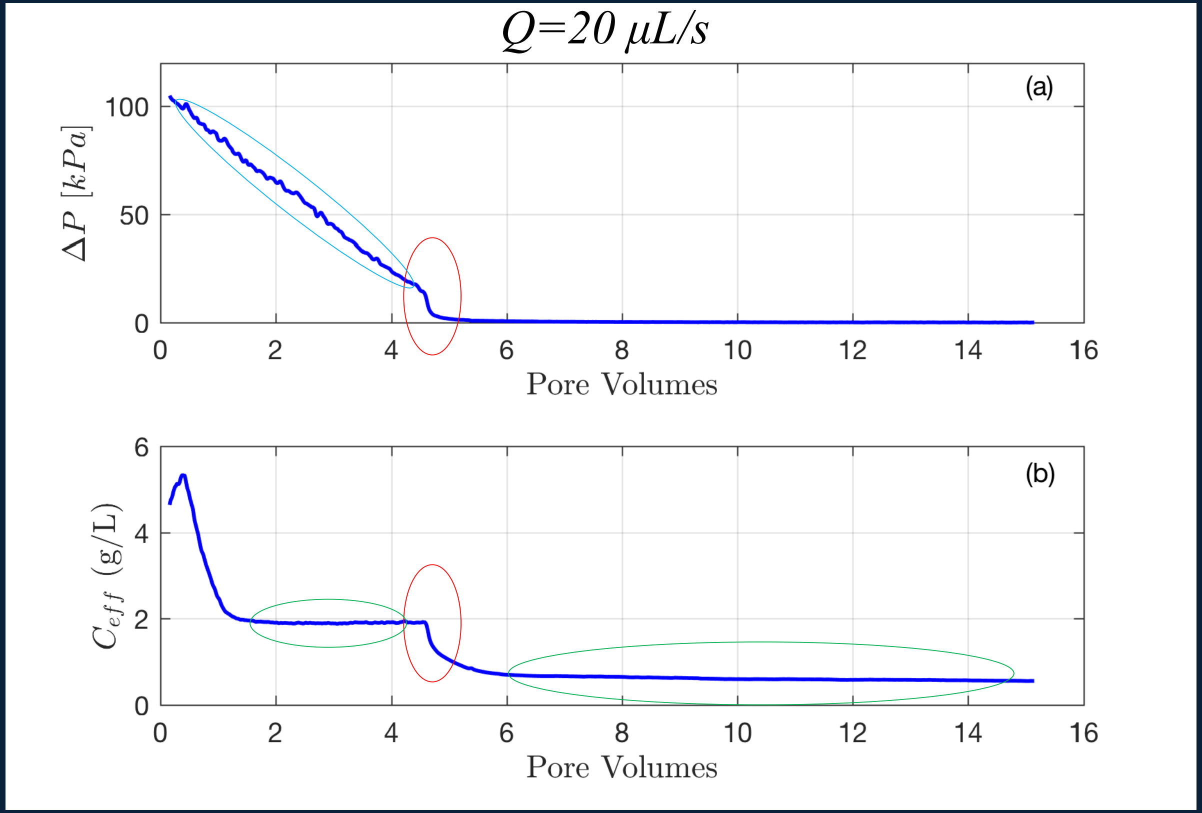






Results

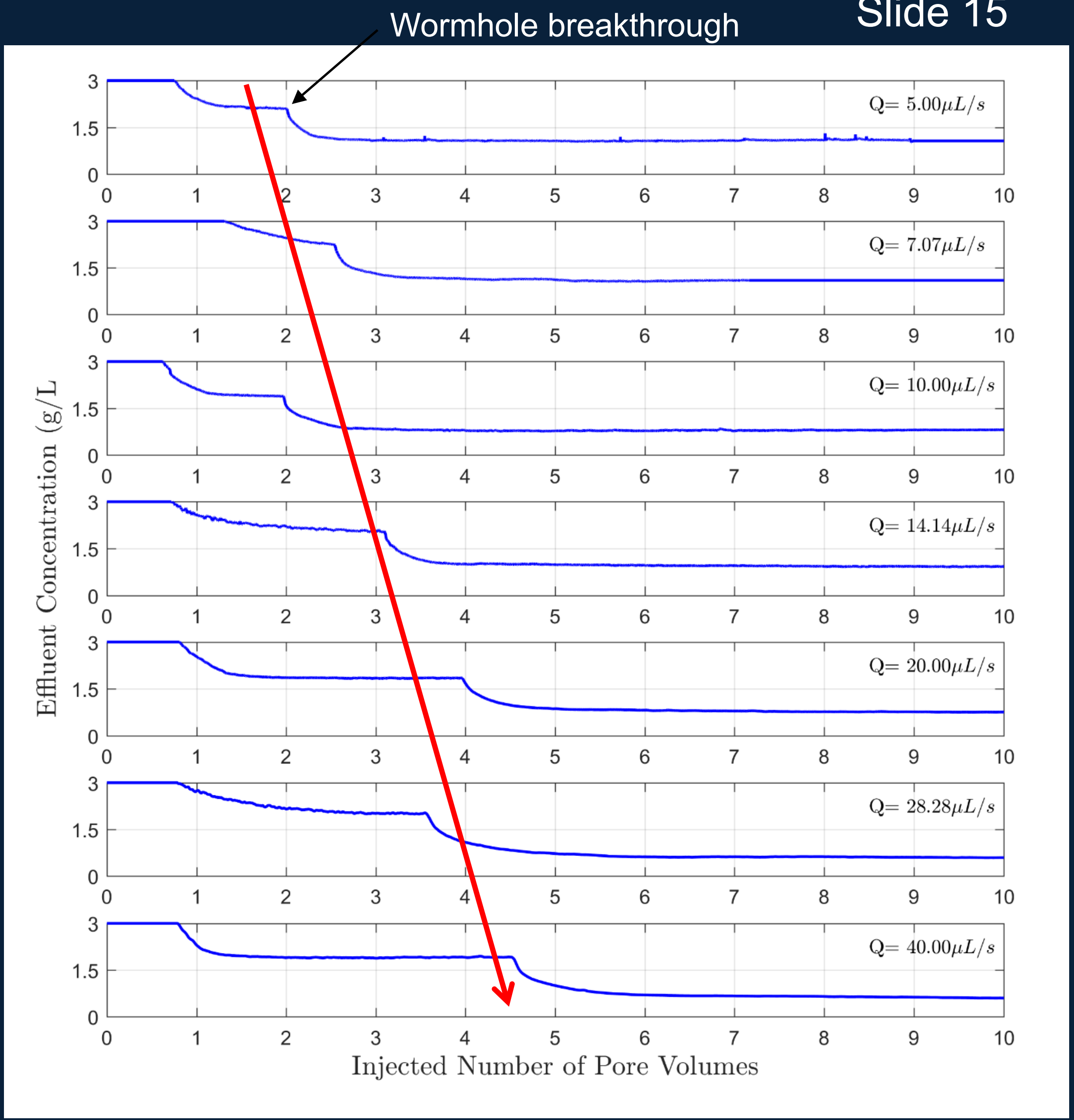
- Seven tests were conducted to study the effect of injection rate on the formation of wormholes.



- The pressure difference decreases linearly with injected volume, which is consistent with the results from the literature (Daccord, 1987).
- The sudden drops in the effluent concentration and pressure difference indicate the breakthrough of wormholes.
- Quasi-steady state dissolution before and after the wormhole breakthrough.

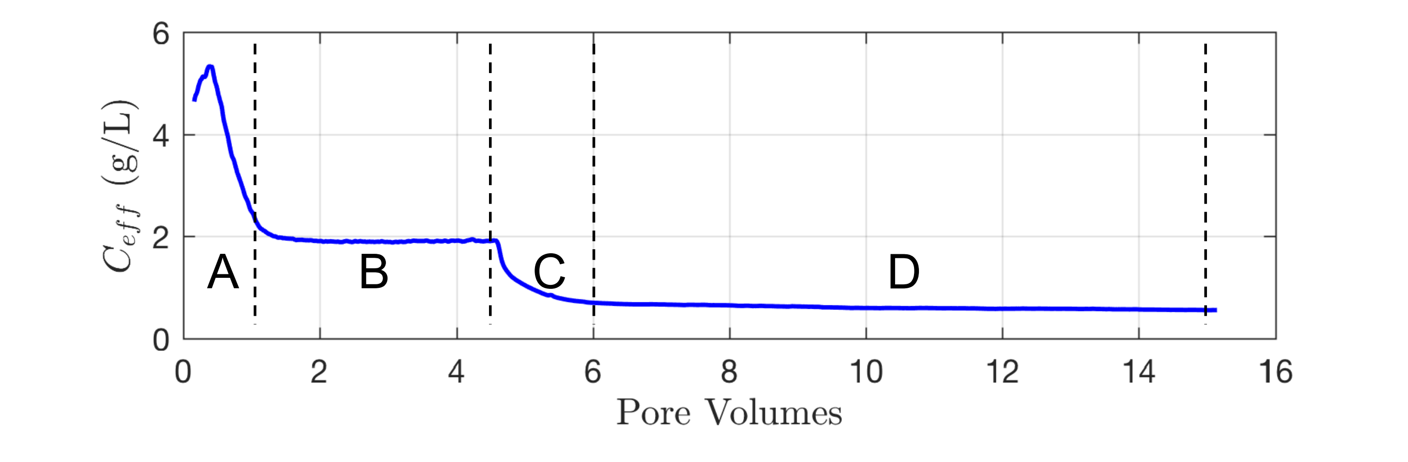
Results

- Effluent concentration analysis
  - The number of injected pore volumes needed for the wormhole to breakthrough increases with higher injection flow rate (Fredd and Fogler, 1998).



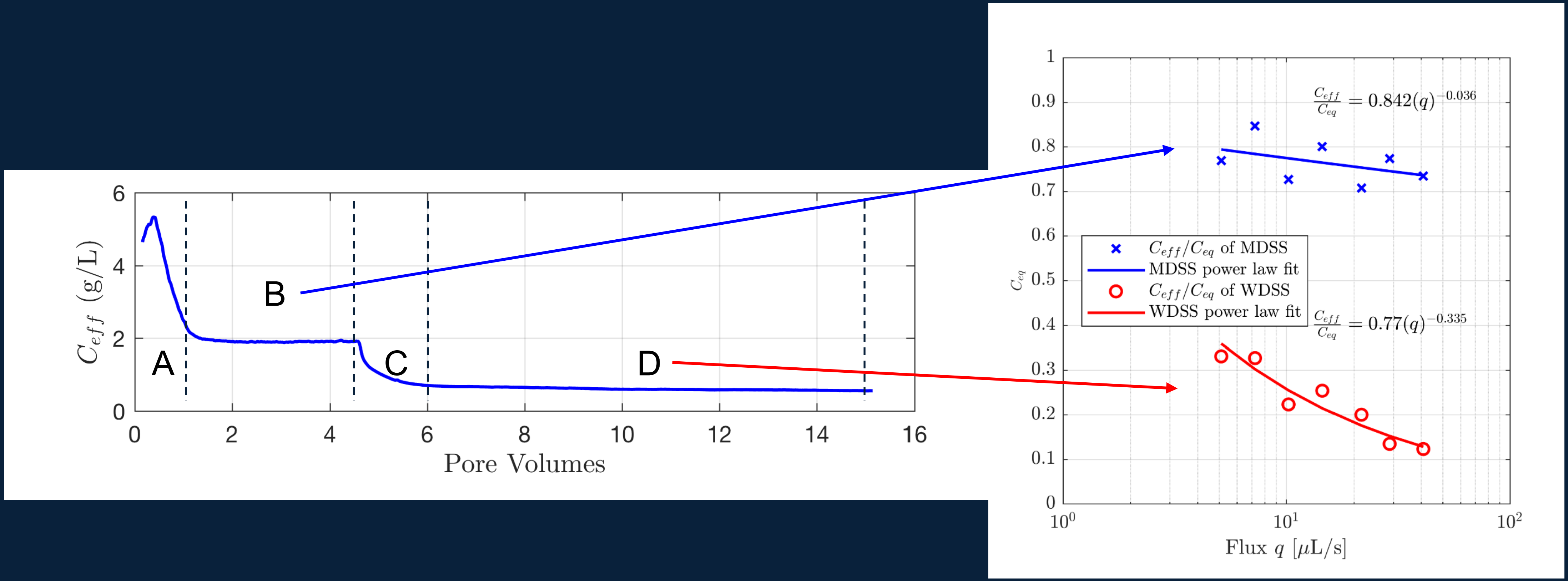
Results

- Effluent concentration analysis
  - Based on the effluent concentration, the core flood tests can be divided into four states:
    A. Initial transient state
    B. Mixed dissolution quasi-steady state
    C. Breakthrough transient state
    D. Wormhole dissolution quasi-steady state



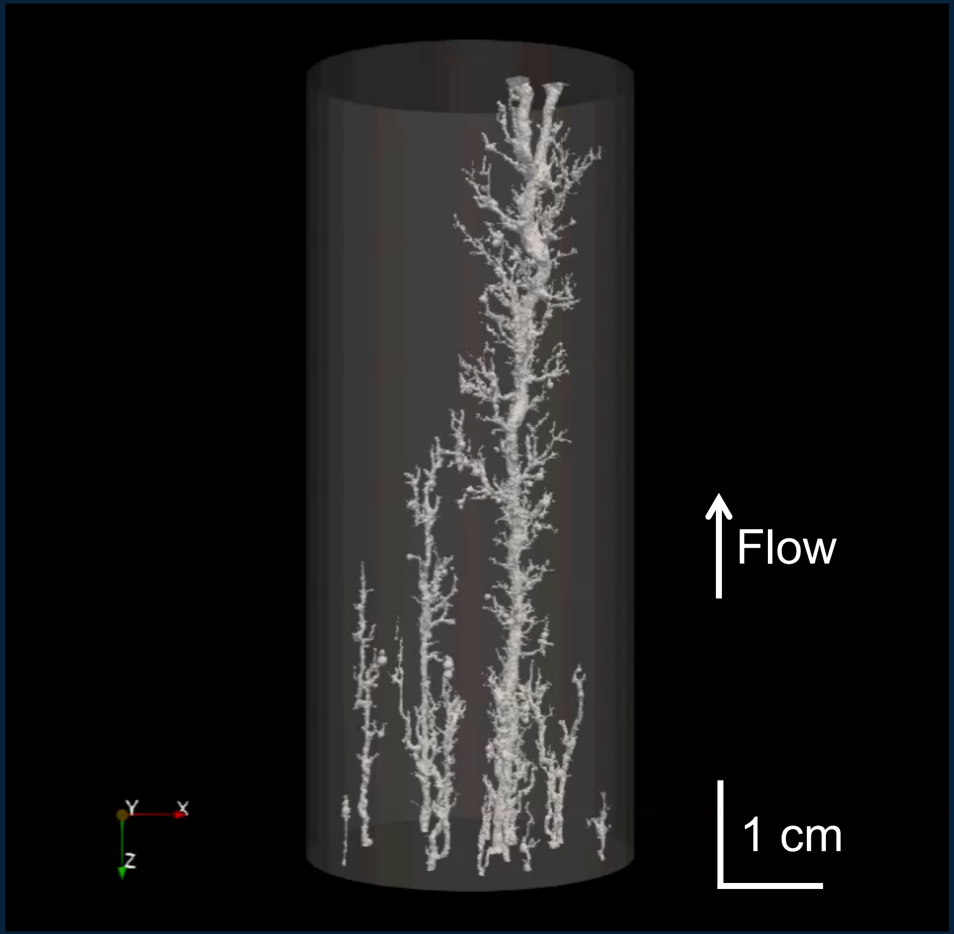
Results

- Effluent concentration analysis
  - The effluent concentration of the two quasi-steady states are summarized and fitted with power law curves.



Results

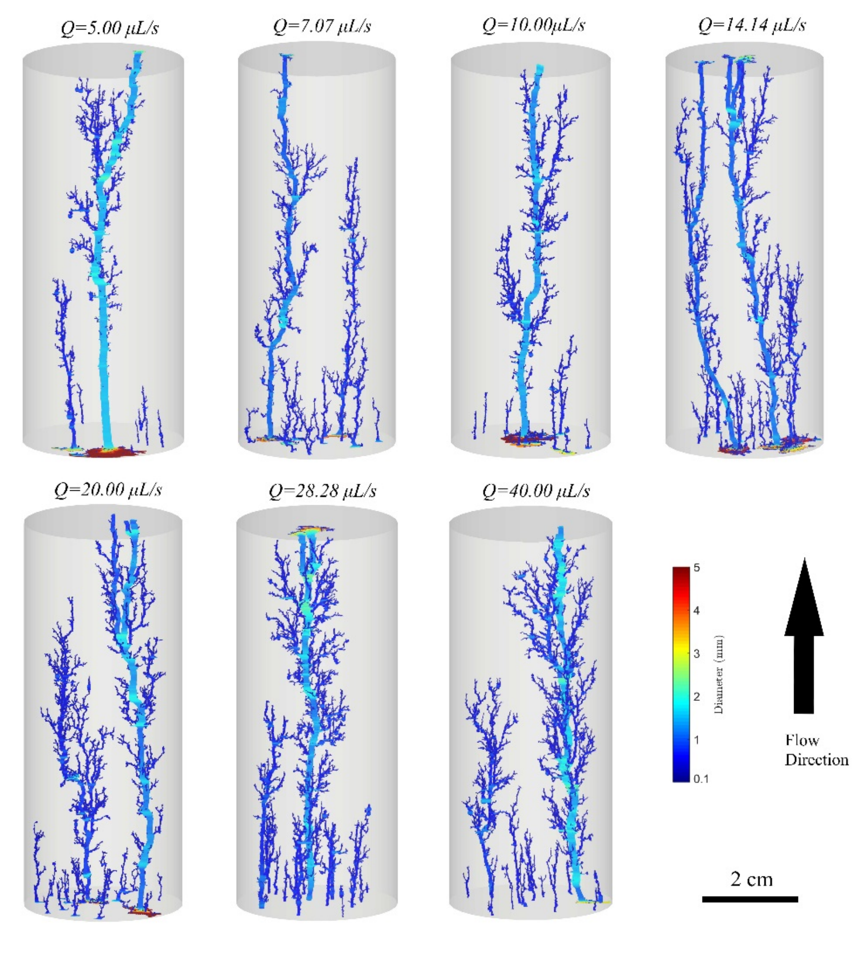
- X-ray CT data 3D reconstruction



- 3D reconstruction based on the X-ray CT scan.
- 3D processing using topographic and morphologic algorithms developed in MATLAB.
    - identify wormholes;
    - filter isolated pores;
    - measure geometries.

Results

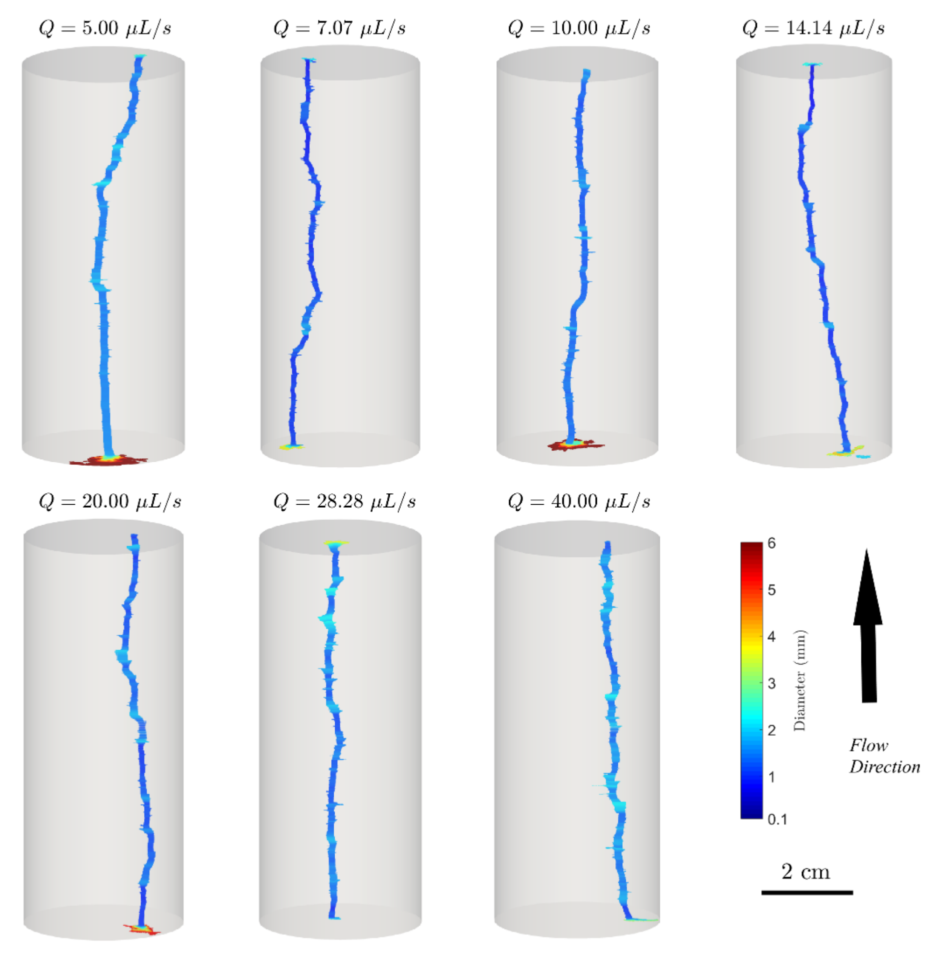
- X-ray CT data 3D reconstruction



- One major wormhole connecting the inlet and outlet.
- Higher flow rate results in more secondary wormholes and more branches.

Results

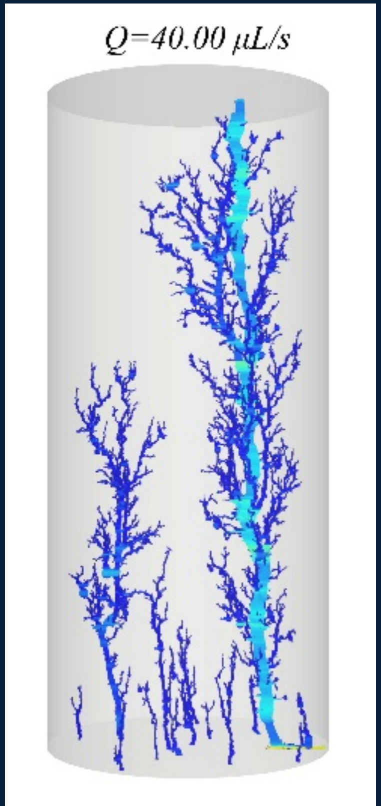
- X-ray CT data 3D reconstruction

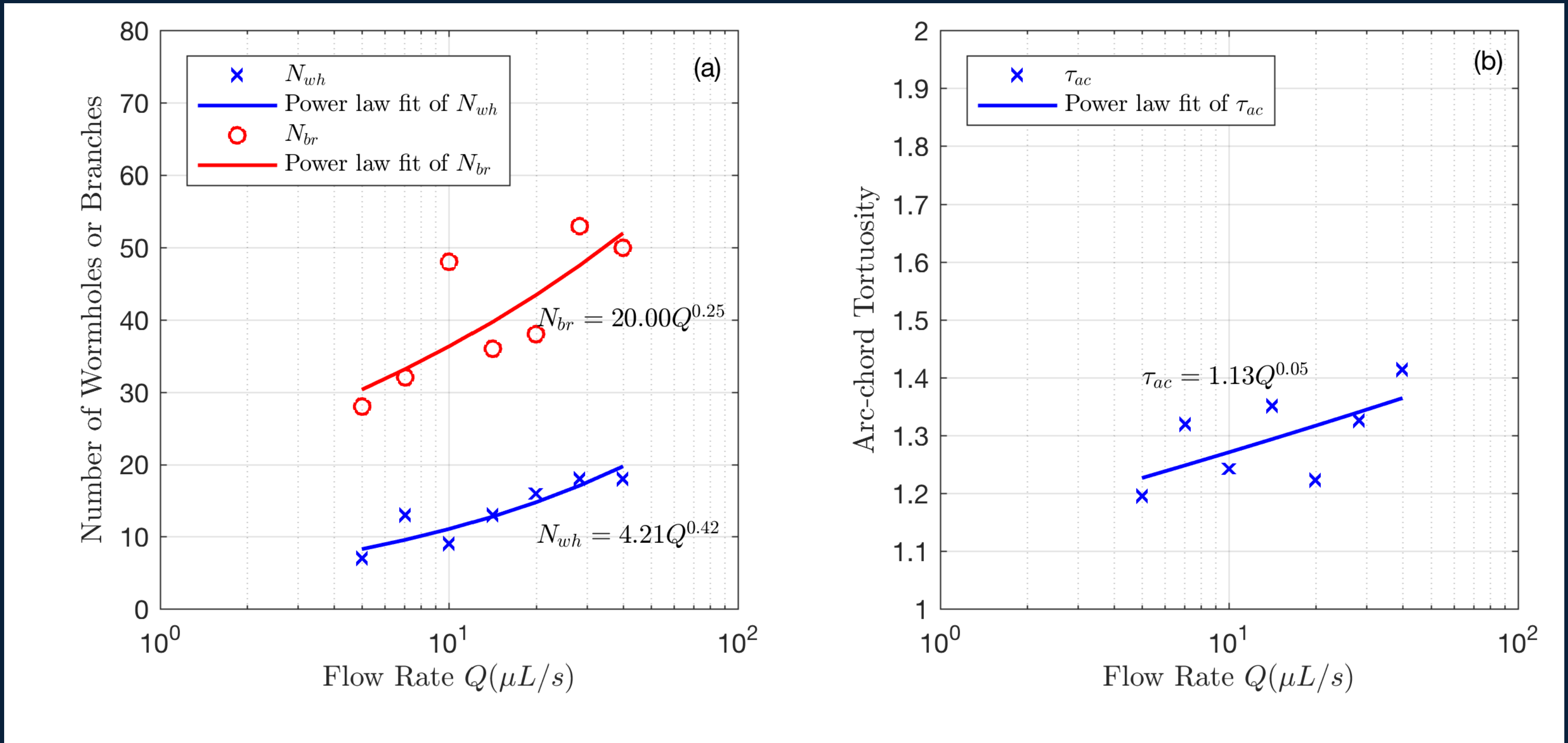


- The major wormholes have an enlarged inlet due to the entrance effect. (Li and Einstein, 2017)

Results

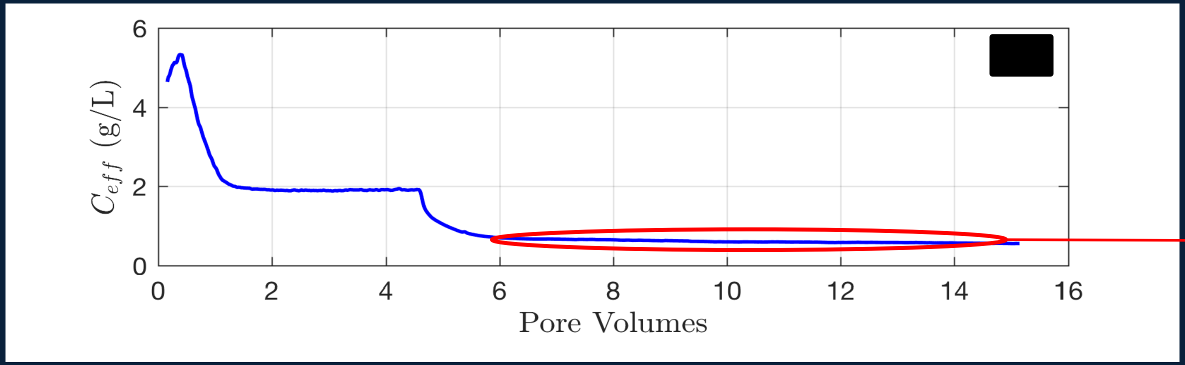
- X-ray CT data 3D reconstruction
  - Morphologic algorithms were developed to identify the wormholes and branches.
  - The arc-chord tortuosity can also be calculated for the major wormhole.

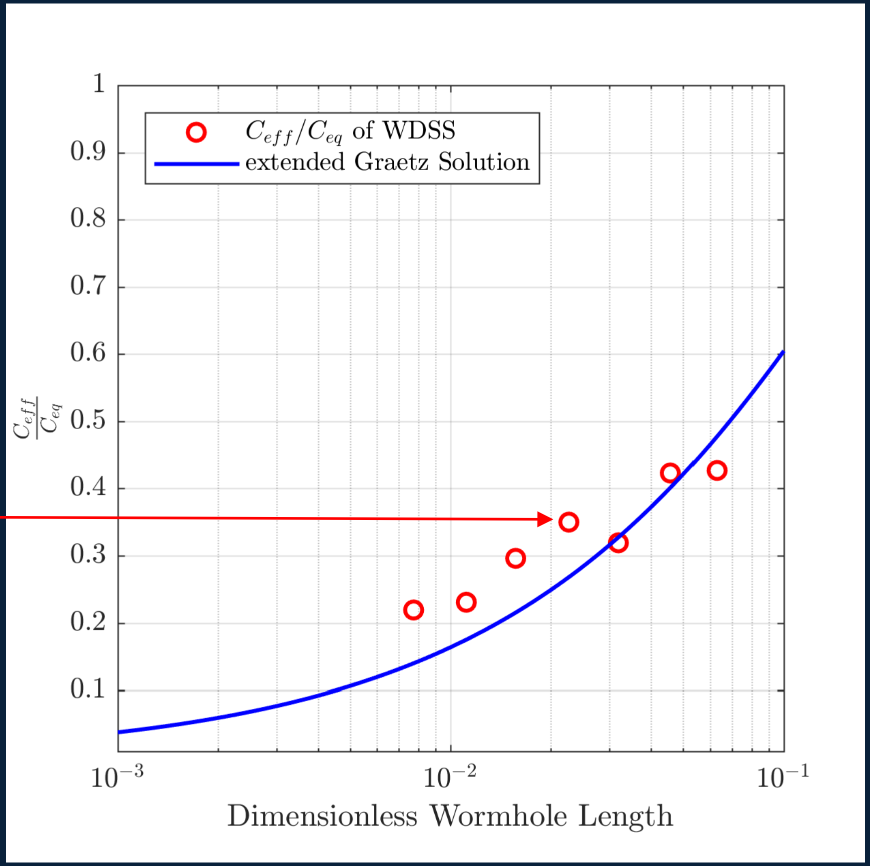




Current work

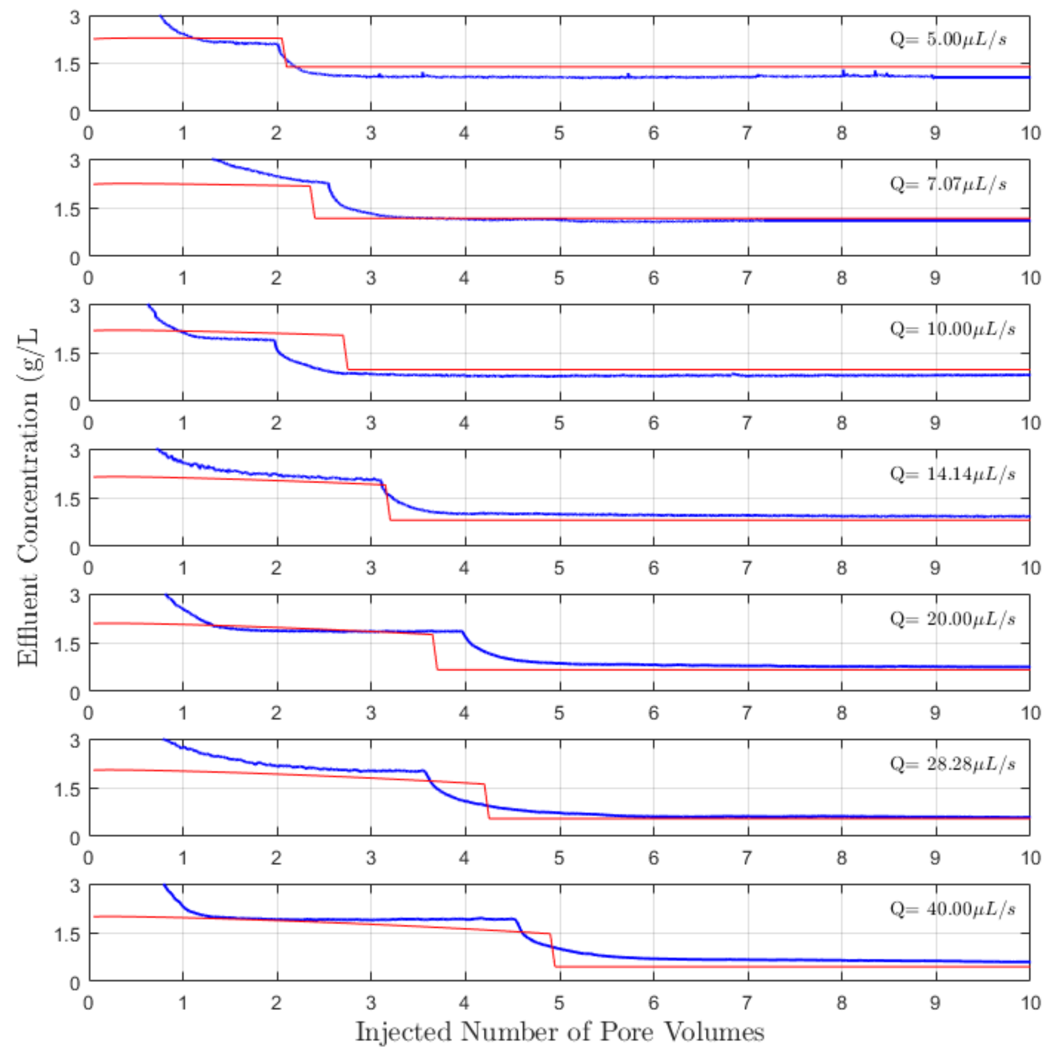
- Model the wormhole dissolution quasi-steady state using the extended Graetz solution (Li and Einstein, 2017).





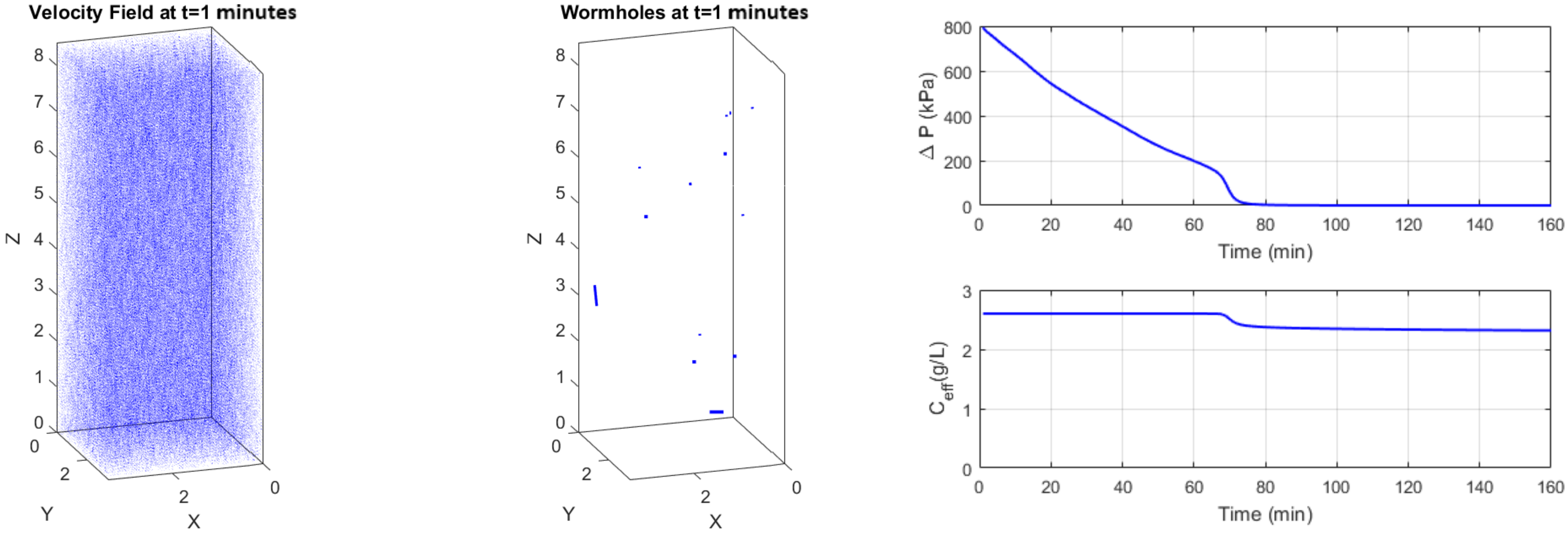
Current work

- Semi-empirical model



Current work

- Pipe network model



Conclusion

- Gypsum core flood tests have been conducted and the results are consistent with the literature.
- The effluent chemistry monitoring system shows that the overall dissolution rate has different dependence on the flow rate before and after the wormhole breakthrough.
- The new CT data processing algorithm quantitatively showed that the high flow rates results in more complicated wormholes in terms of number of wormholes and tortuosity.
- Analytical and numerical models are developed to study the dissolution kinetics and the evolution of wormholes.

Acknowledgement

- Sponsors:
  - Masdar Institute of Science and Technology
  - ADNOC

Questions

WEI LI (WEILI08@MIT.EDU)

Backup Slides

Experimental setup

- Effluent chemistry monitoring system
  - The system measures the electric conductivity of the effluent.
  - The system is calibrated with gypsum solutions. So the electric conductivity measurement can be converted to gypsum concentration.