Session: Parallel Session 2: MS18 Abstract ID: 350

Estimation of aquifer permeability using aquifer testing with fiber-optic Distributed Strain Sensing

- Yi Zhang (zhangyi@rite.or.jp), Tsutomu Hashimoto, Ziqiu Xue

a) Geological Carbon dioxide Storage Technology Research Association, Kyoto, Japan

b) Research Institute of Innovative Technology for the Earth (RITE), Kyoto, Japan

Acknowledgment：
This presentation is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization(NEDO) and the Ministry of Economy, Trade and Industry(METI) of Japan (grant no. JPNP18006). This research is partially supported by Initiative on Promotion of Supercomputing for Young or Women Researchers, Supercomputing Division, Information Technology Center, The University of Tokyo.

Introduction

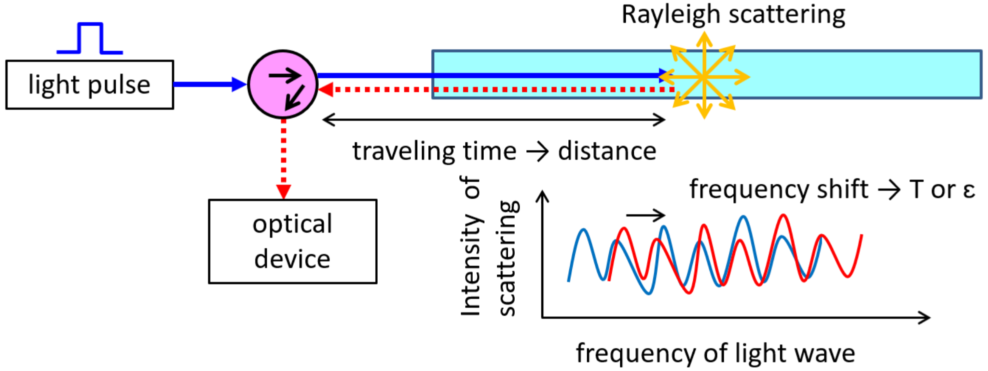
- **Permeability & compressibility** (or hydraulic conductivity & specific storage) structures are critical for predicting fluid flow behavior as well as utilizing and managing subsurface fluid resources (e.g., groundwater, oil & gas, and CO_2 storage).

- A better characterization of spatial hydraulic parameters can facilitate more manageable and optimized operations for these utilizations through numerical modeling.

- Hydrogeologists have long pursued a better understanding of the spatial structure of hydraulic parameters in aquifer formation.

- However, due to the difficulties in equipment and sensor placement, in conventional aquifer testing methods, it is difficult to obtain fine-scale permeability structure in the vertical direction.
    - Double packer testing is difficult to operate and not suitable for cased holes.

- **We are trying to use fiber-optic Distributed Strain Sensing (DSS) technique for solving the problem.**



$$\Delta f = A\Delta\varepsilon + B\Delta T$$

- Each distributed point (a short portion; e.g., 5 cm) can be taken as a sensing element along the entire length (e.g. 5 km) of an optical fiber
- High accuracy: 0.5 με (less than 0.000 001)

A brief introduction to fiber-optic DSS

- Optical fiber sensors work with the principle that the environmental effects (e.g., strain and temperature) can alter the phase, frequency, spectral content, and power of backscattered light propagated through an optical fiber.

- There are three types of scattering mechanisms – Raman, Brillouin, and Rayleigh scattering – used for measuring temperature or strain changes.

- Rayleigh backscattering occurs when light propagates due to the existence of small random optical defects or impurities in the fiber core. Rayleigh backscatter spectrum of a point in an optical fiber can be considered as a fingerprint of the fiber.

- From the frequency shift between the reference Rayleigh-scattering power spectrum (RSPS) and a target RSPS using the cross-correlation method, the strain or temperature change at the point can be calculated.

Can the technique be used for aquifer testing?

The original purpose of DSS technique is for geomechanical or geotechnical engineering monitoring.

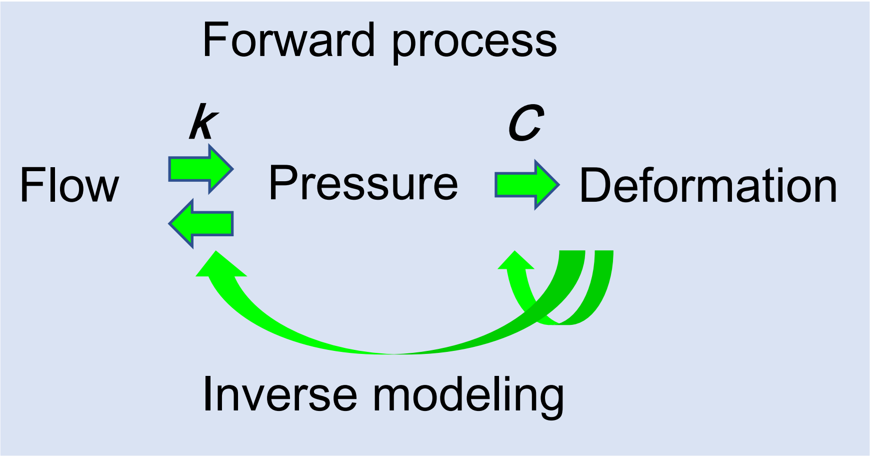
Physics:

Quasi-static linear poroelasticity theory (Biot 1941)

- Coupled flow and geomechanical model

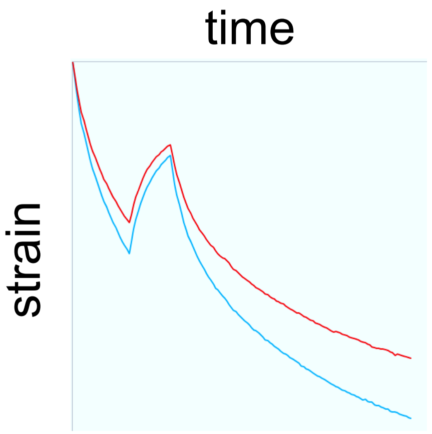
$$\rho S \frac{\partial p}{\partial t} + \nabla \cdot (\rho q) = Q - \rho \alpha \frac{\varepsilon_{kk}}{\partial t}$$

$$\sigma_{ij} = 2G\varepsilon_{ij} + 2G\frac{\upsilon}{1-2\upsilon}\varepsilon_{kk}\delta_{ij} + \alpha p \delta_{ij}$$



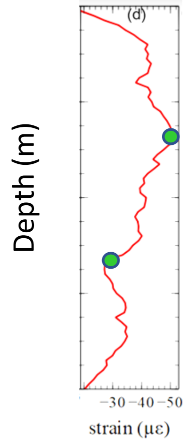
k: permeability

C: compressibility

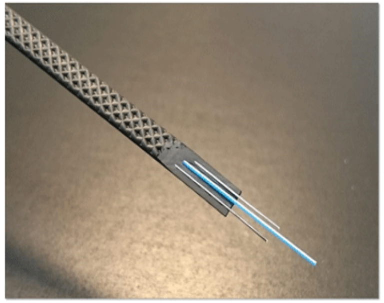


Depth with different ***k*** or ***C*** has different shape of strain curve

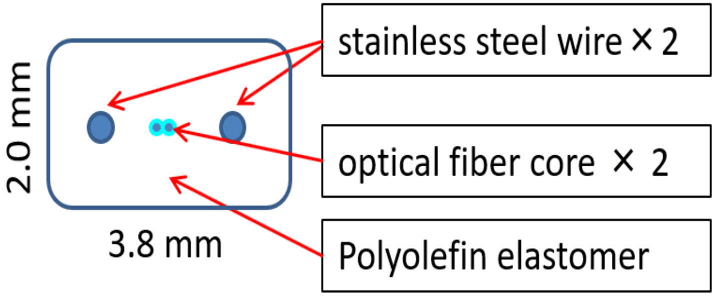
Strain changes bring the information of ***k*** and ***C***



Field deployment



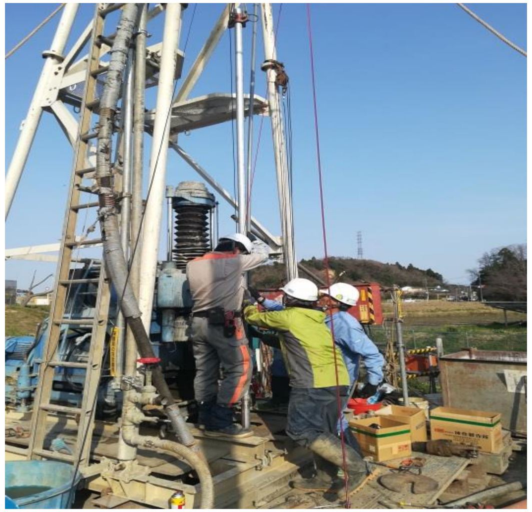
(a)



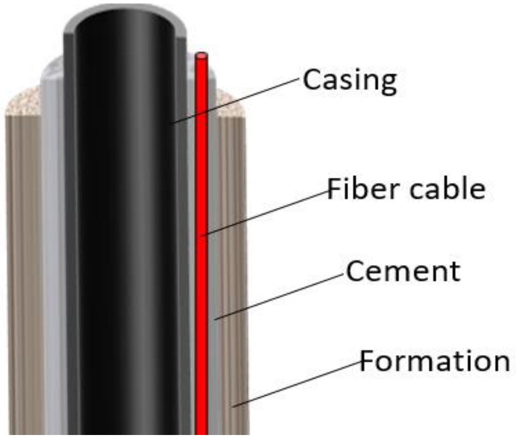
(b)

Fabricated fiber cable

Fabricated fiber cable using extrinsic reinforced jackets for protecting the central fiber core and practically installing the fiber in underground wellbores



Carefully placing casing with fiber cable



Well section with cemented fiber cable

Cementing

Cementing operations with injection of cement slurry were undertaken to further fix the fiber cable and seal the annulus after the siting of the casing

Cementing ensures tight coupling between formation-casing, making strain can well transfer to fiber cable

Great longevity

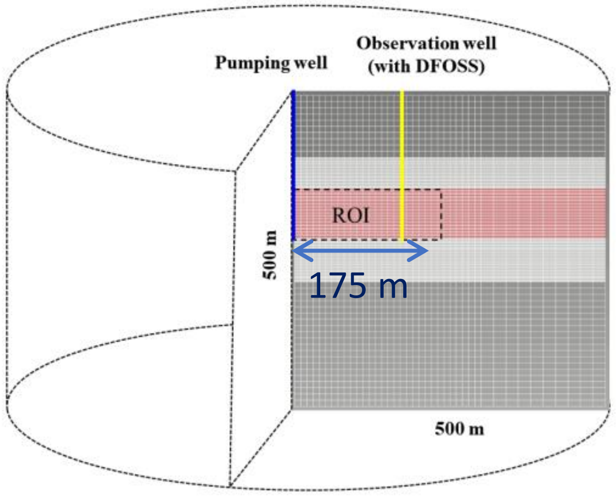
Once installation, long term use (>20 years)

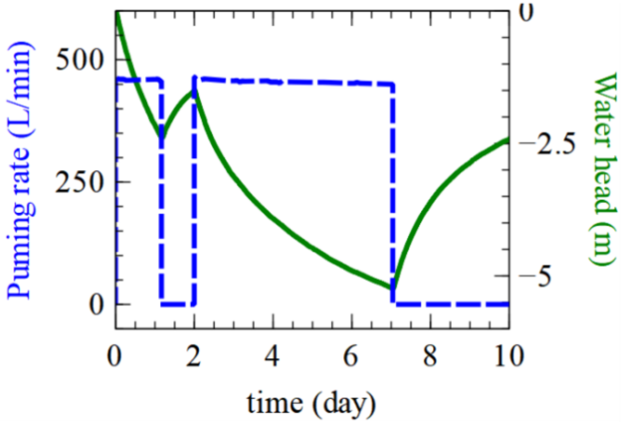
Aquifer cross-well pumping test (@Mobara, Japan)

EMI

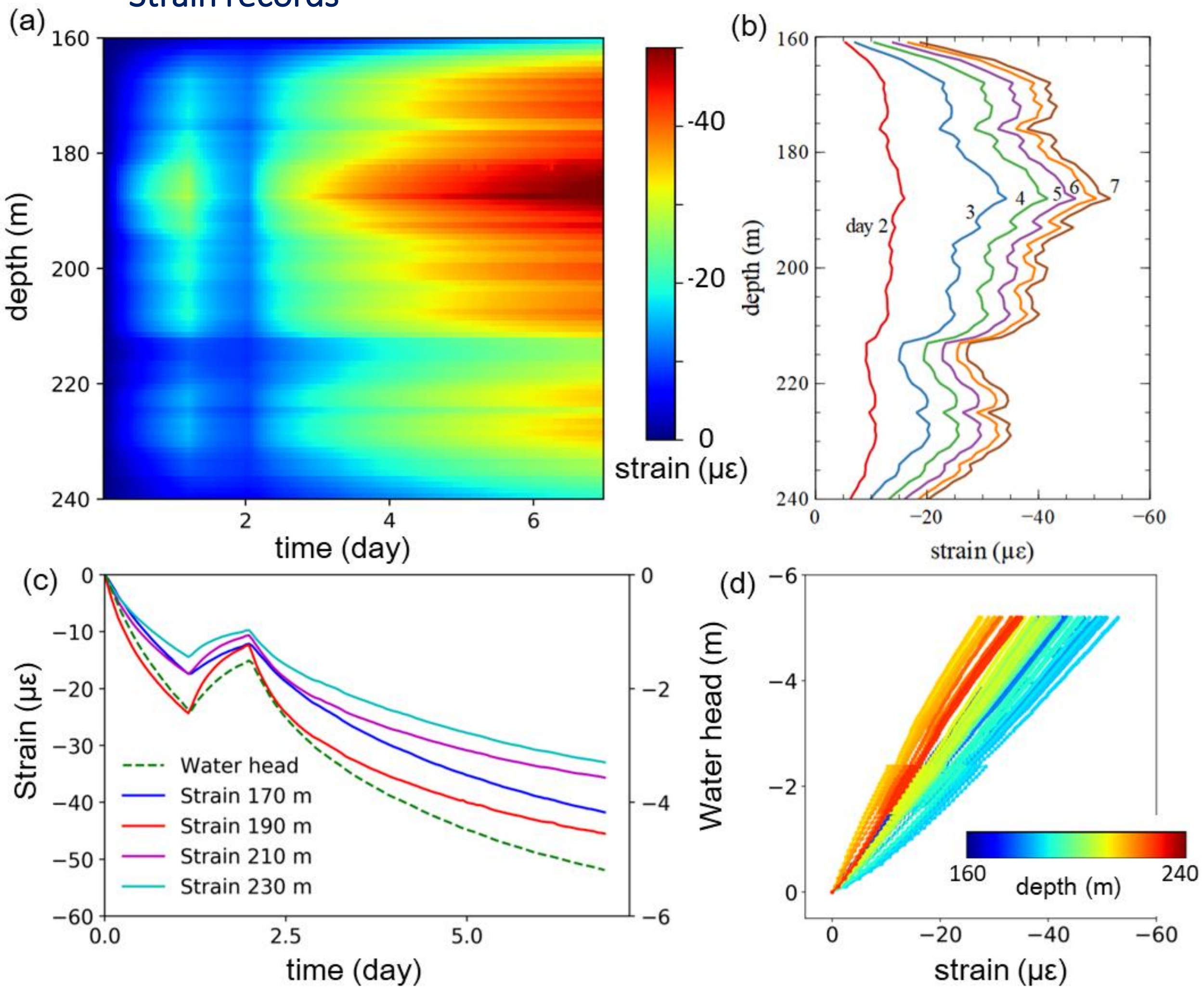
vertically heterogeneous

Simplified model





Strain records

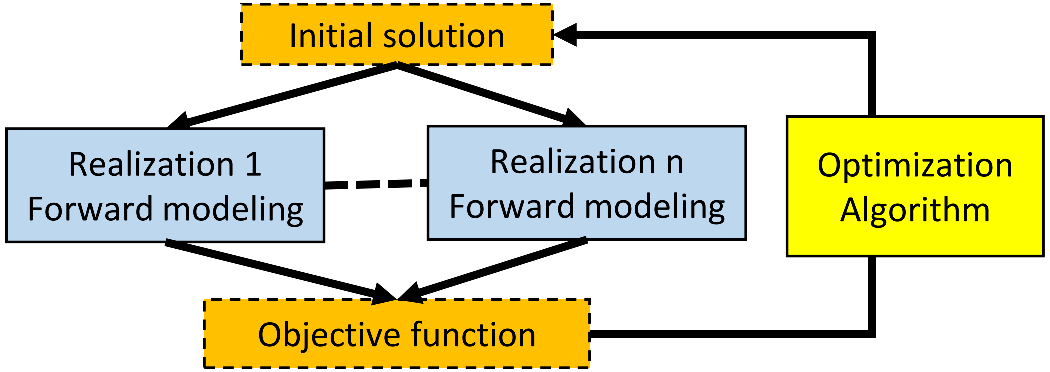


Near elastic

Inverse estimation of hydraulic parameters by history matching

- Search the minimum residual of strain difference
- High-dimensional problem (e.g., 160 unknowns)
- Gradient-based algorithm (with trust region method)

  - The forward run was slow.
  - We used a supercomputer system (Oakbridge-CX Supercomputer System, University of Tokyo) to accelerate the Jacobian computation in parallel
  - We used the Tikhonov regularization method to condition the problem (e.g. by minimizing the sum of parameter gradient) and stabilize the estimation



Coupled flow and geomechanical model

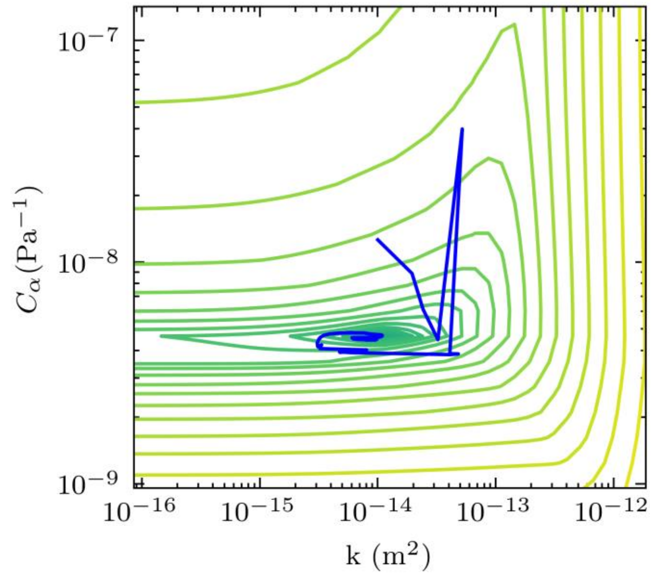
$$\sigma_{ij} = 2G\varepsilon_{ij} + 2G\frac{v}{1-2v}\varepsilon_{kk}\delta_{ij} + \alpha p\delta_{ij}$$

$$\rho S\frac{\partial p}{\partial t} + \nabla\cdot(\rho q) = Q - \rho\alpha\frac{\varepsilon_{kk}}{\partial t}$$

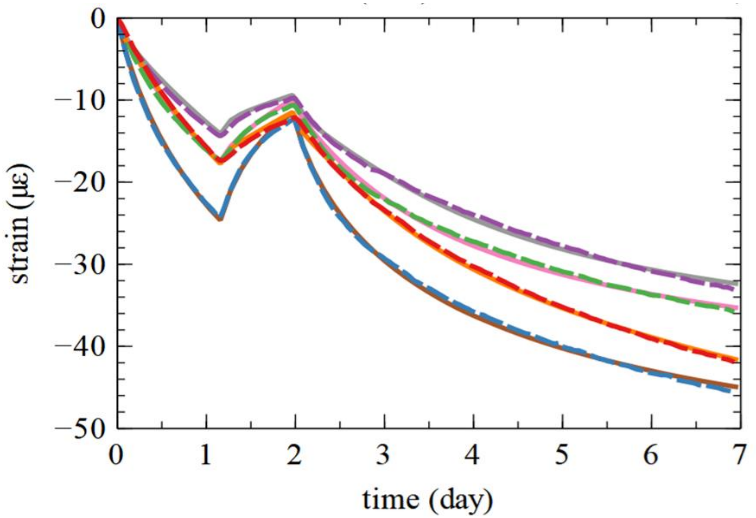
Forward model solved using FEM method (MOOSE Framework)

Inversion results

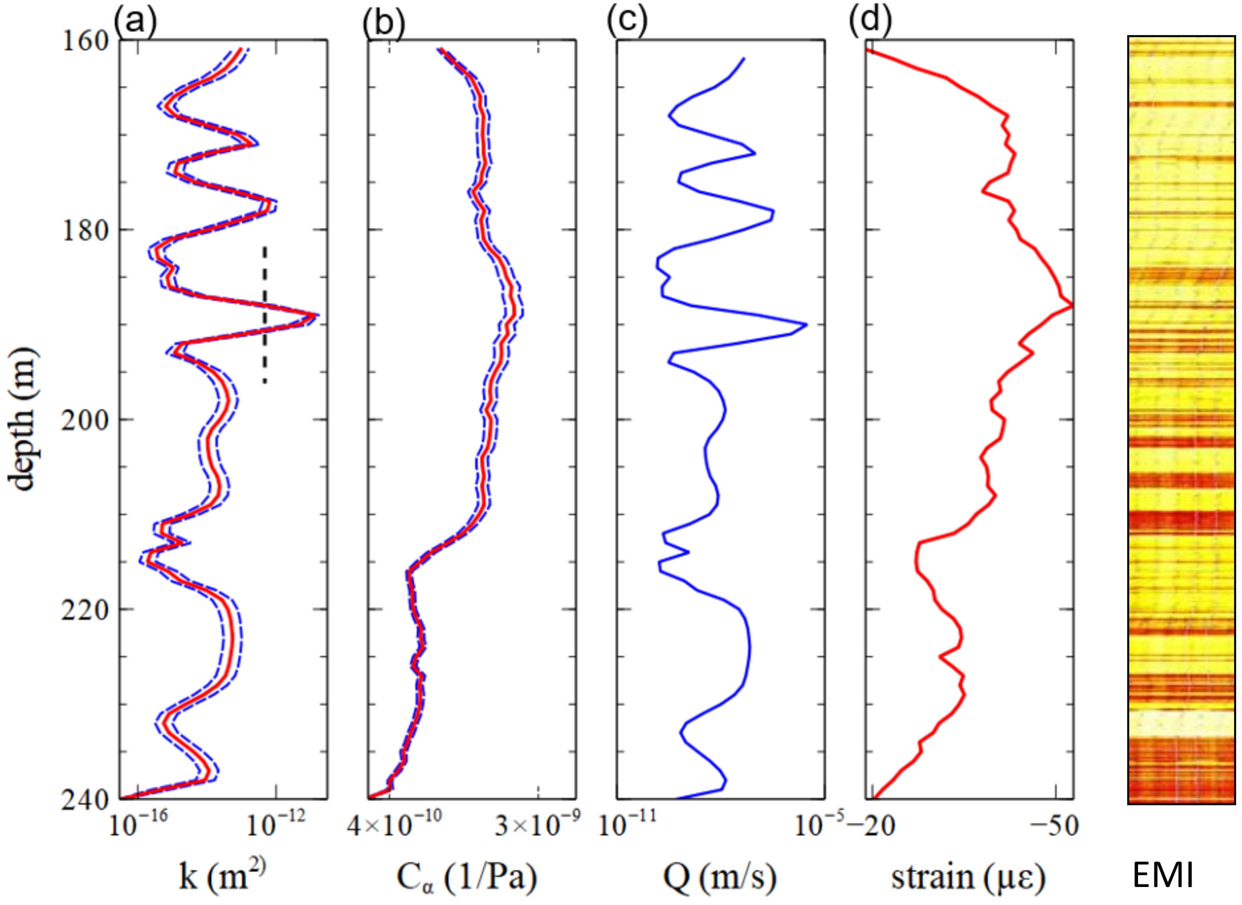
Find the minimum residual in *k* and *C* space



Matched strain curves



Permeability Compressibility Flow rate Strain



For more details (e.g. synthetic test, sensitivity study, the trade off between parameters and limitations), please see

Zhang, Lei, Hashimoto, & Xue. (2021). Towards retrieving distributed aquifer hydraulic parameters from distributed strain sensing. *Journal of Geophysical Research: Solid Earth*.

Conclusions

- In this study, based on the results of a field aquifer test, we show that fiber-optic Distributed Strain Sensing can provide high-resolution aquifer formation characterization at fine scales.
- The strain changes indicate the spatial distribution of fluid pressure migration. The strain changes, like the pressure changes, contain the information of formation permeability & compressibility.
- We further apply an inversion algorithm to estimate the fine-scale vertical permeability & compressibility profiles from field DSS records.
- Our study gives a new aquifer characterization method using DSS in aquifer testing.

Thank you!

References

[1] Zhang, Yi., Lei, X., Hashimoto, T., & Xue, Z. (2021). Toward retrieving distributed aquifer hydraulic parameters from distributed strain sensing. Journal of Geophysical Research: Solid Earth, 126(1), e2020JB020056.

[2] Zhang, Yi., Xue, Z., Park, H., Shi, J. Q., Kiyama, T., Lei, X., … & Liang, Y. (2019). Tracking CO2 plumes in clay-rich rock by distributed fiber optic strain sensing (DFOSS): A laboratory demonstration. Water Resources Research, 55(1), 856-867.

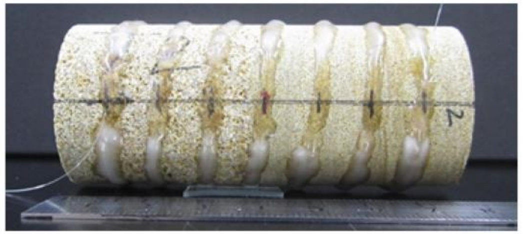
[3] Zhang, Yi, & Xue, Z. (2019). Deformation-based monitoring of water migration in rocks using distributed fiber optic strain sensing: A laboratory study. Water Resources Research 55(11) , 8368-8383.

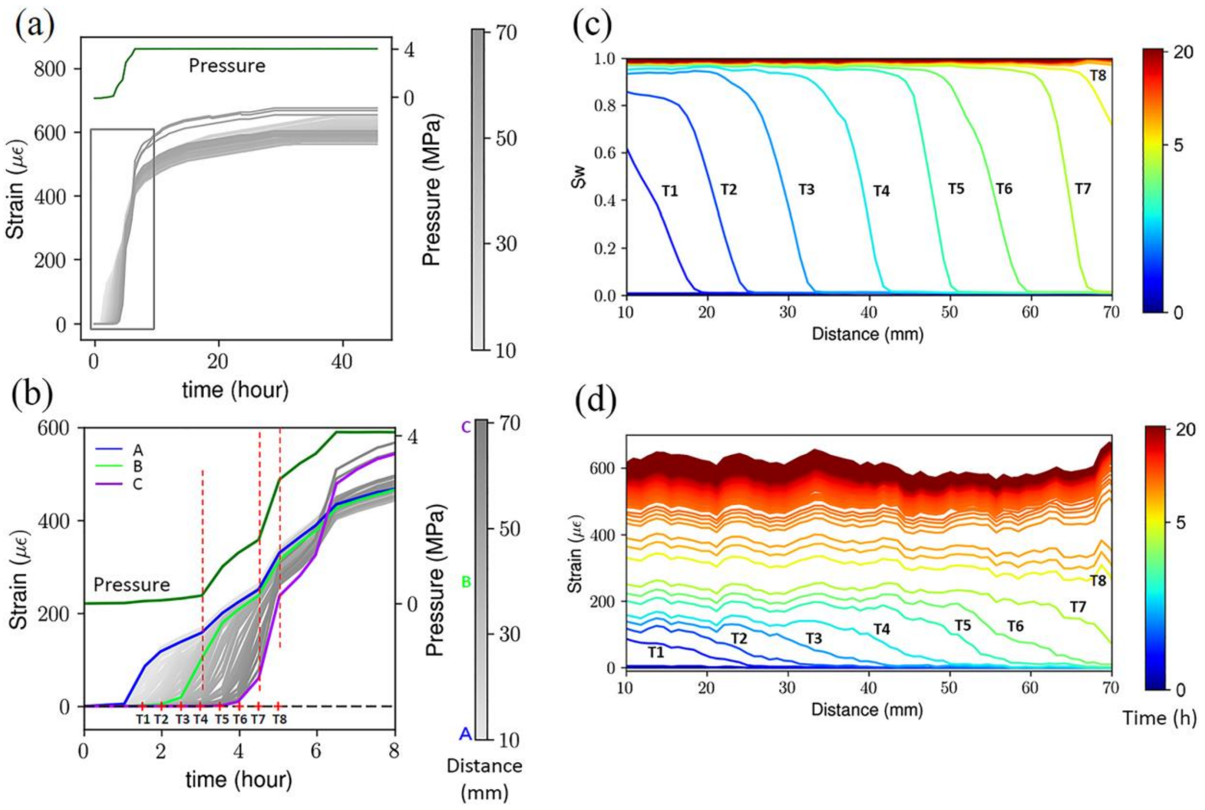
[4] Zhang, Yi., Lei, X., Hashimoto, T., & Xue, Z. (2020). In situ hydromechanical responses during well drilling recorded by fiber-optic distributed strain sensing. Solid Earth, 11(6), 2487-2497.

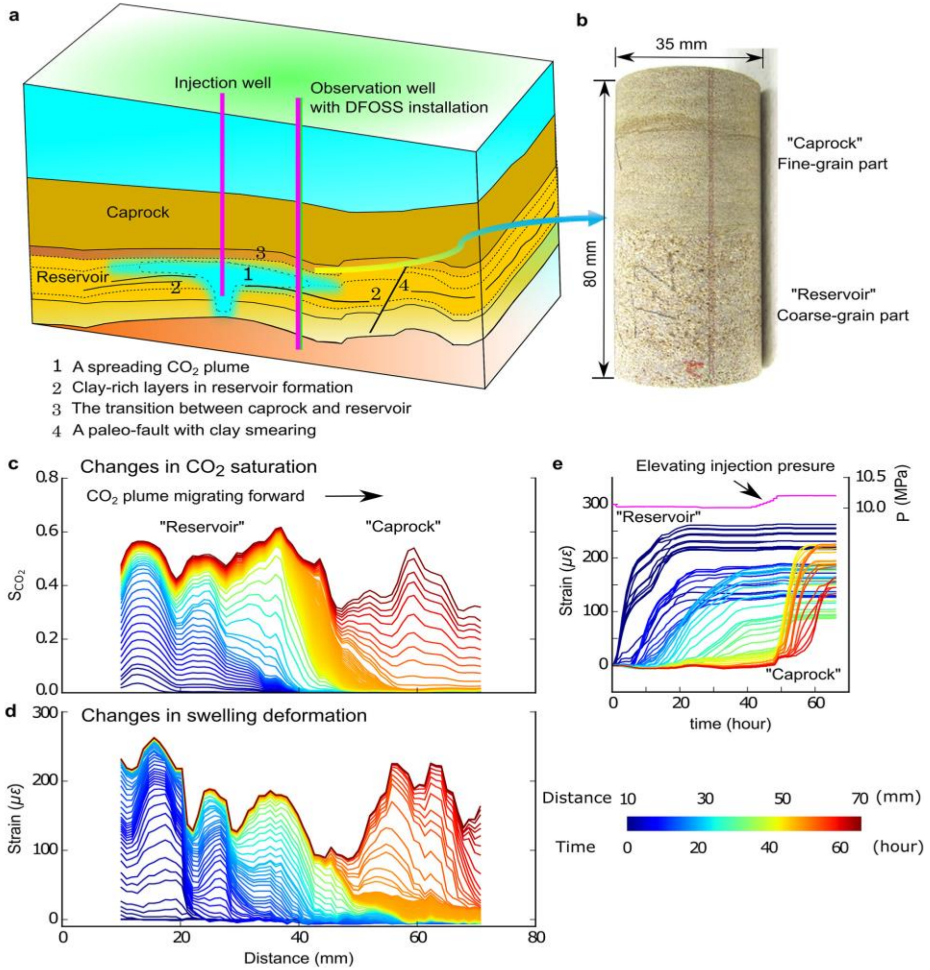
Contact: Yi Zhang, zhangyi@rite.or.jp

Lab tests (Water wetting and supercritical CO2/brine displacement)

(a)







Zhang et al. Water Resources Research, Volume: 55, Issue: 11, Pages: 8368-8383, 2019

Zhang et al. Water Resources Research, Volume: 55, Issue: 1, Pages: 856-867, 2018