Hydraulic Tomography Using Fiber Bragg Grating Multilevel Well

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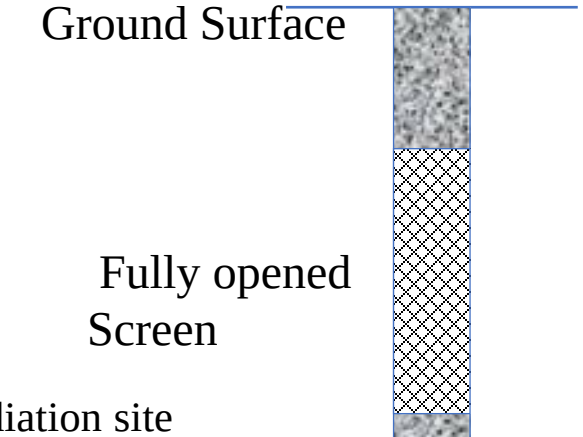
Outline

- Introduction
- Theory-Fiber Bragg Grating Sensor
- Theory-Hydraulic tomography
- Field study
- Conclusion

Introduction

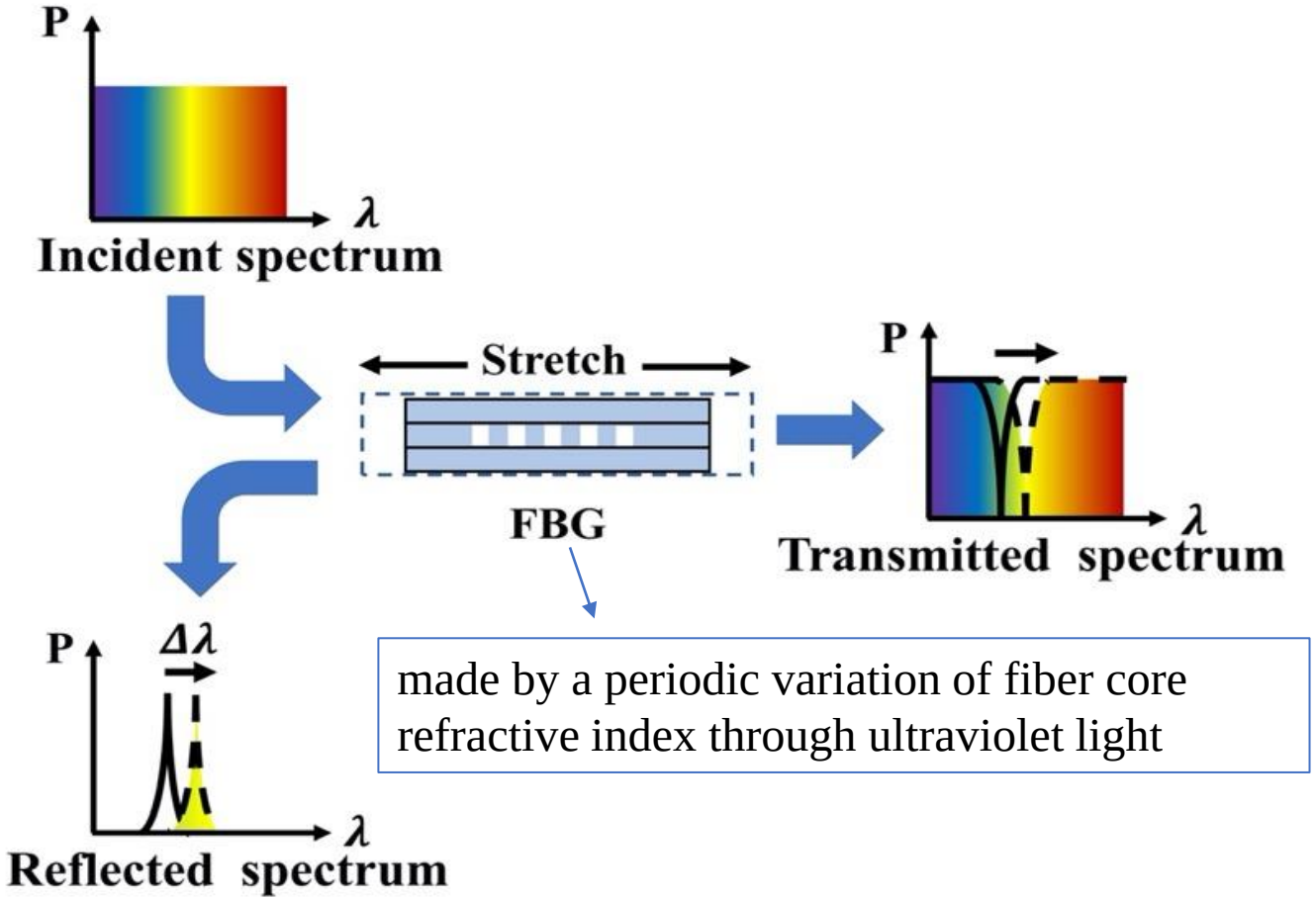
- Target of our EPA project
  - Soil and groundwater remediation
  - Delineating a three dimensional hydrogeological parameter fields using head observations
  - Predict the flow paths of plume and remediation agent
- Limitations need to be overcome
  - Well diameter is 2-in
  - Fully penetrating
  - Depth-discrete measurements
    - Packer installation
    - Electronic sensor: Cable diameter ∝ measurement length



Traditional well in the remediation site

Fiber optical sensors - Theory

- Fiber Bragg grating (FBG) sensor



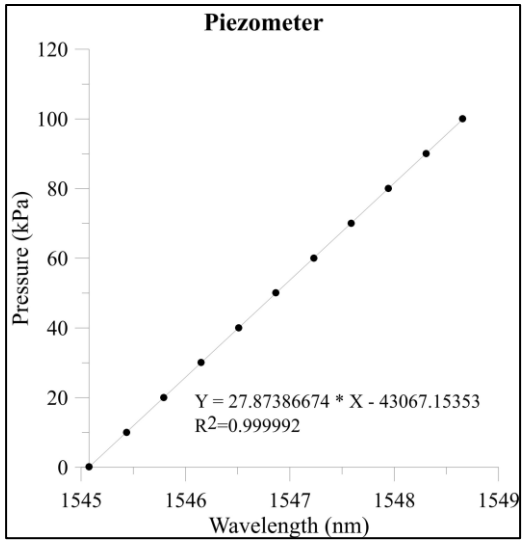
made by a periodic variation of fiber core refractive index through ultraviolet light

$$e = \frac{Dl}{l} = \frac{D\lambda_B}{\lambda_B}$$

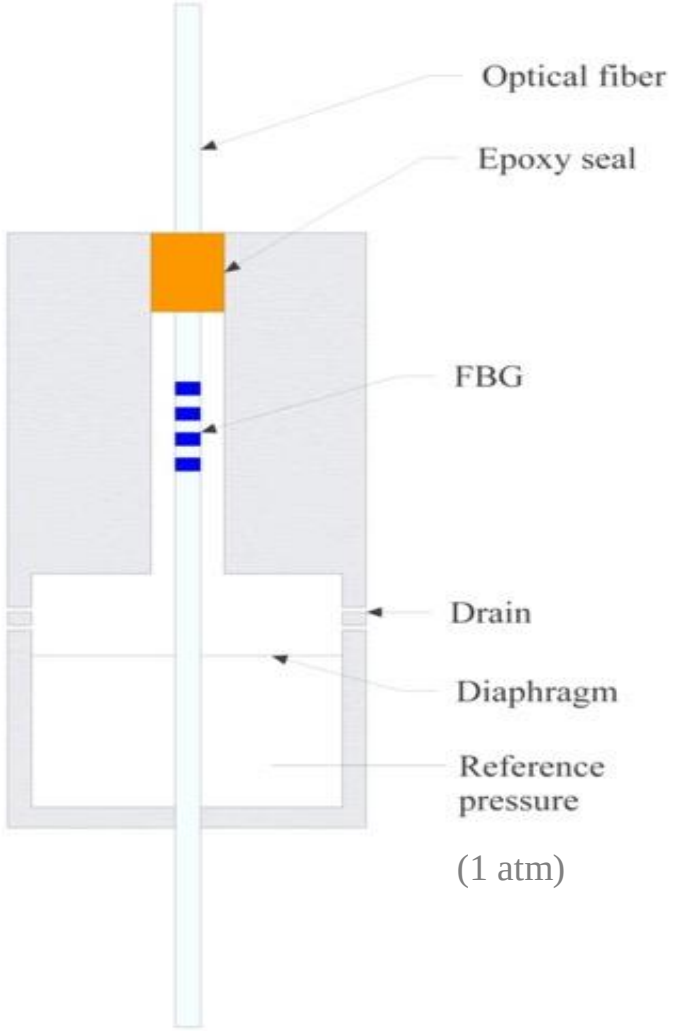
e : strain

λ_B : wavelength

Huang, An-Bin, et al. "Stability monitoring of rainfall-induced deep landslides through pore pressure profile measurements." Soils and Foundations 52.4 (2012): 737-747.

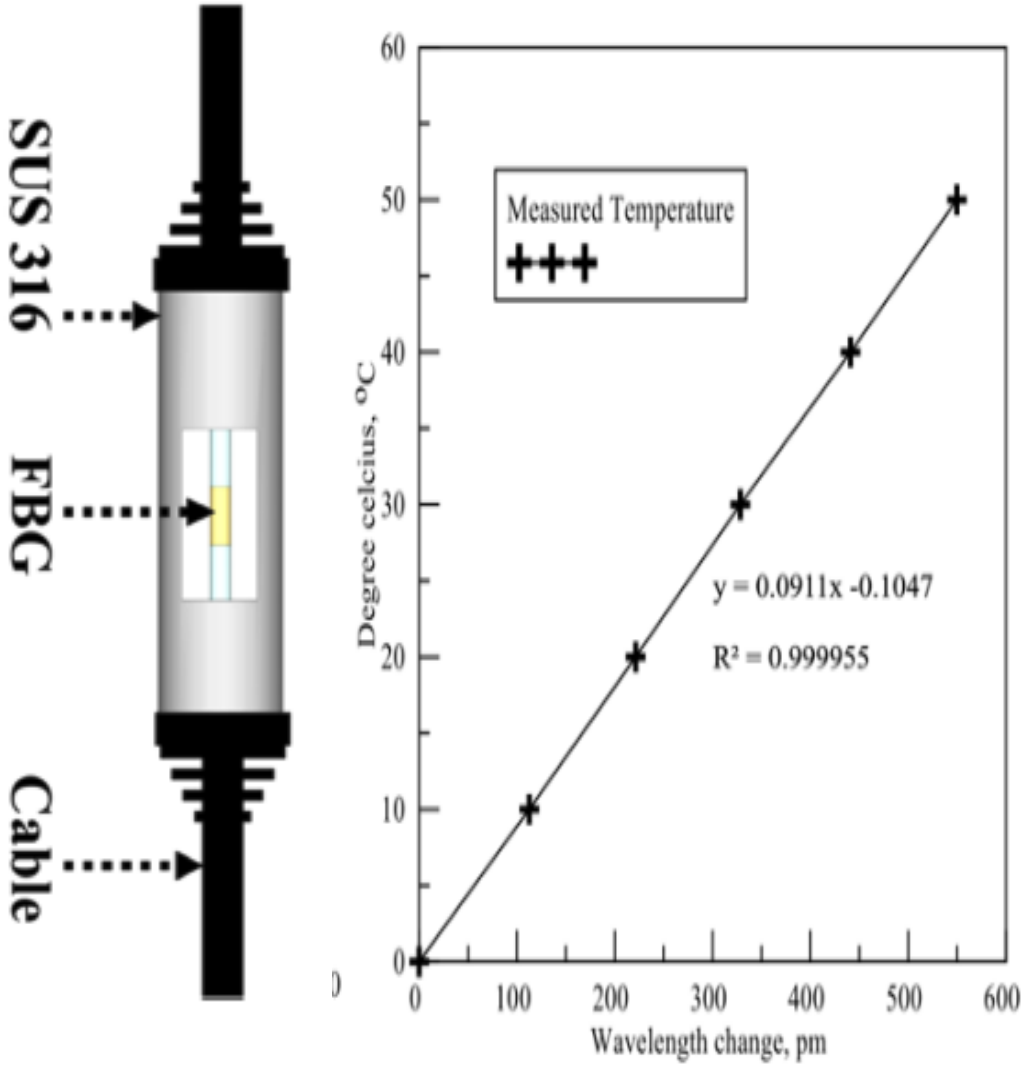


Laboratory test - FBG piezometer



- Measurement ranges: 0 – 400 kPa (40.8 mH_2O)
- Diameter: 36 mm
- Wight: 500-600 g
- Resolution : 0.1 kP a
- Accuracy : 0.2% FS
- Wavelength range: 1520-1570 nm
- Manufactured by Citpo Tech

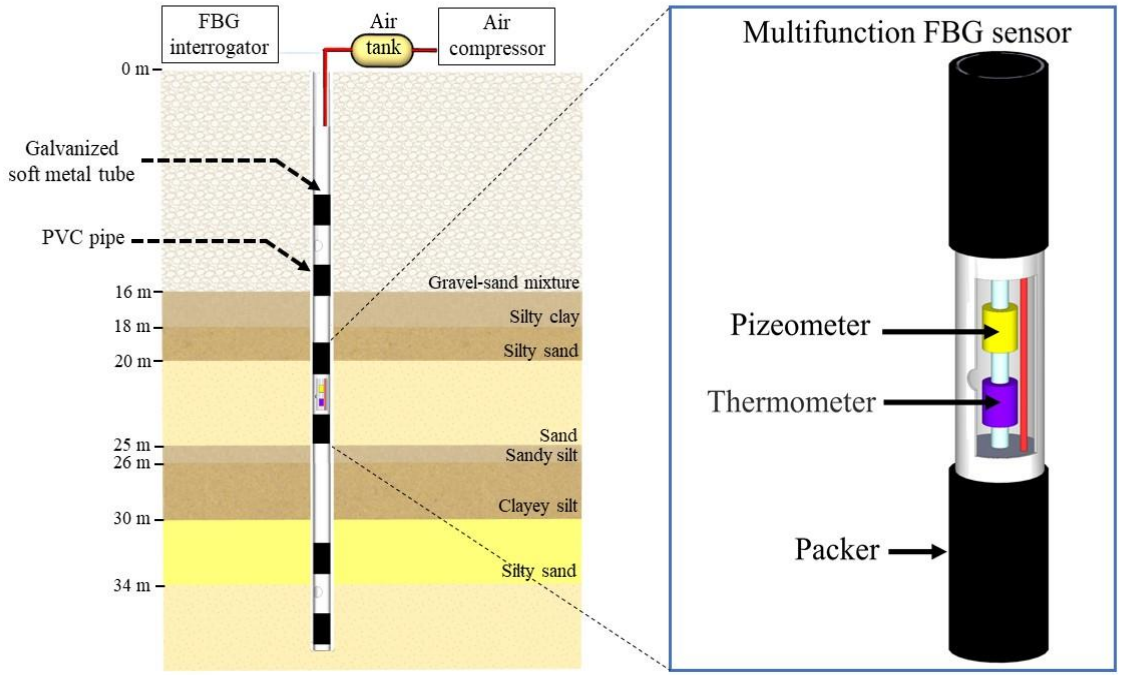
Laboratory test - FBG thermometer



- Measurement ranges: 0–50℃
- Length: 50-60 mm
- Wight: 10-20 g
- Resolution : 0.1 ℃
- Accuracy : 0.4% FS
- Wavelength range: 1520-1570 nm
- Manufactured by Citpo Tech

Development of multilevel well using FBG

- FBG multilevel well



Custom designed by Cipto tech., Taiwan

- Multifunction FBG sensor

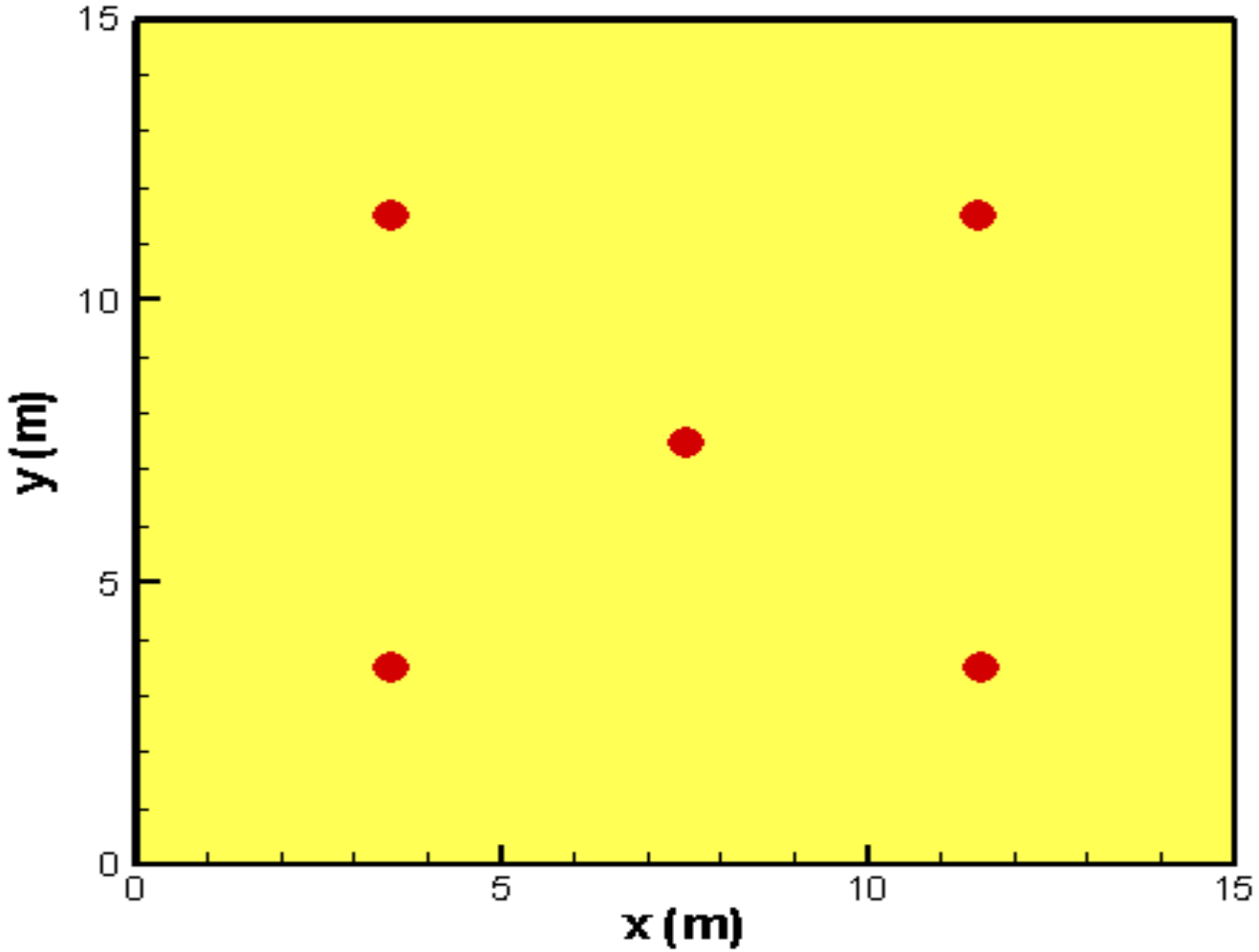
Assemble the multifunction FBG sensors in the study site

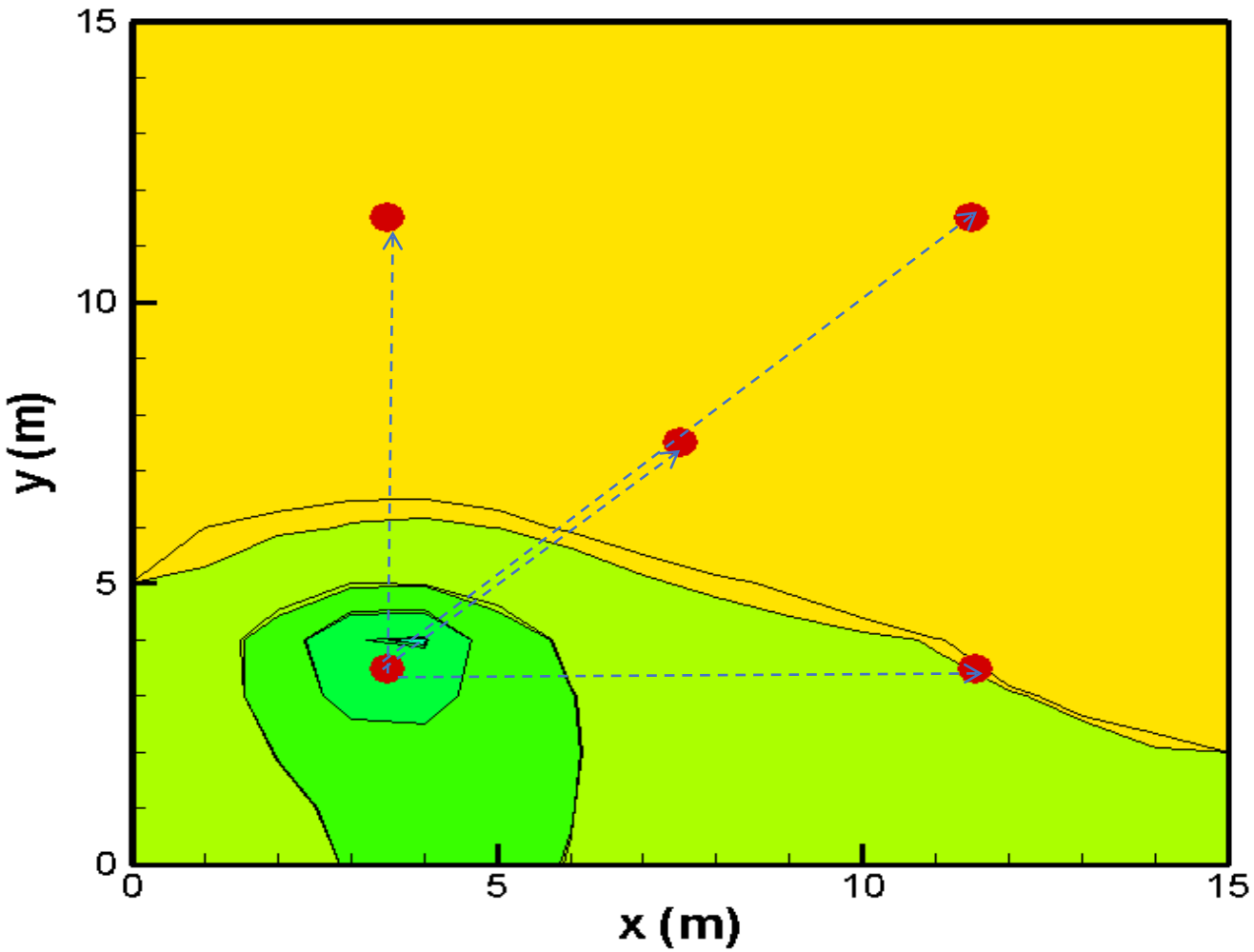
Hydraulic tomography (HT)

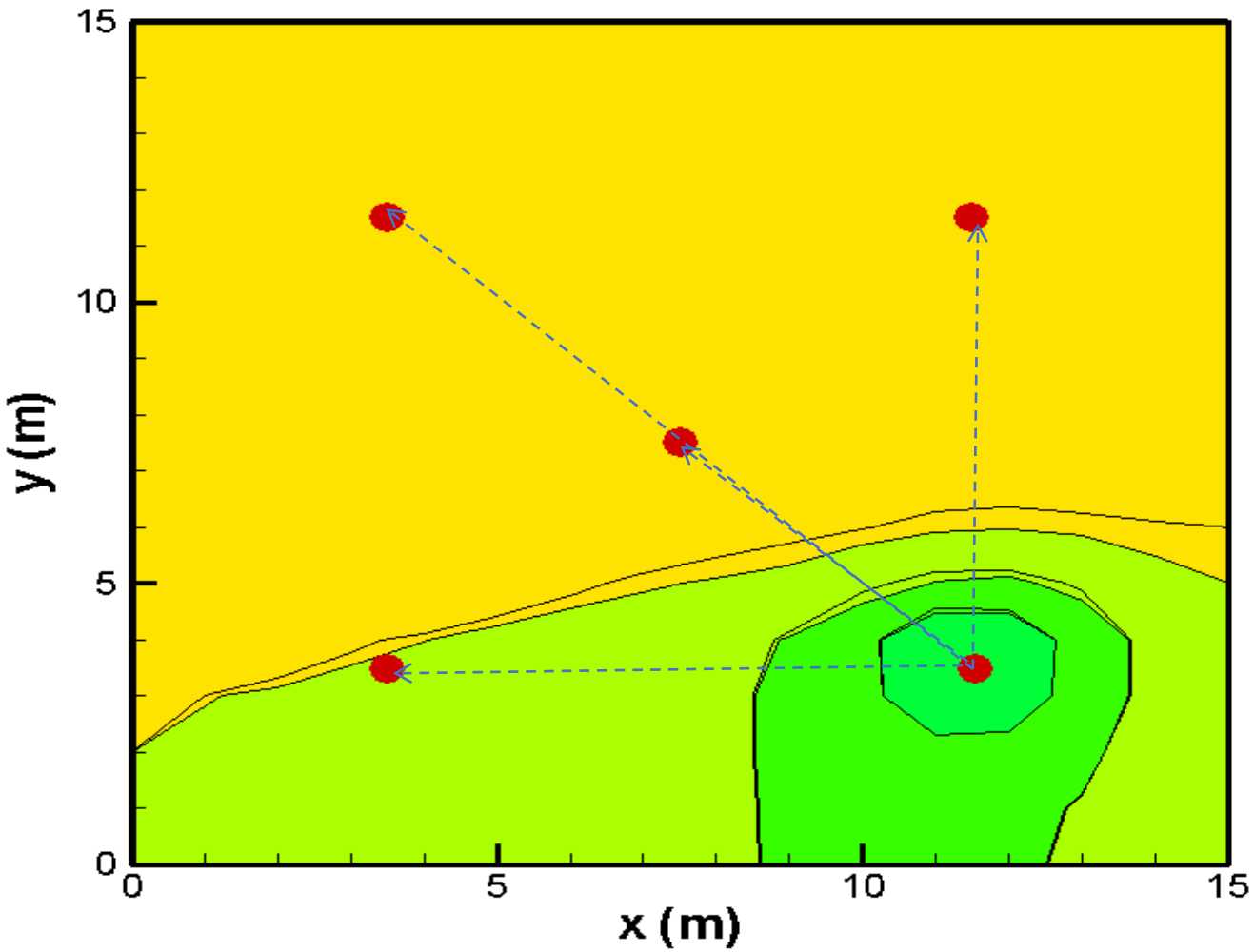
- Hydraulic tomography (HT) is a type of data collection strategy
- The collected head data sets are converted to aquifer parameter filed through successfully linear estimator (SLE), which is developed by Prof. T.-C. Jim Yeh in 1996

A simple example

2-D horizontal aquifer




15
10
5
0
y (m)
0
5
10
15
x (m)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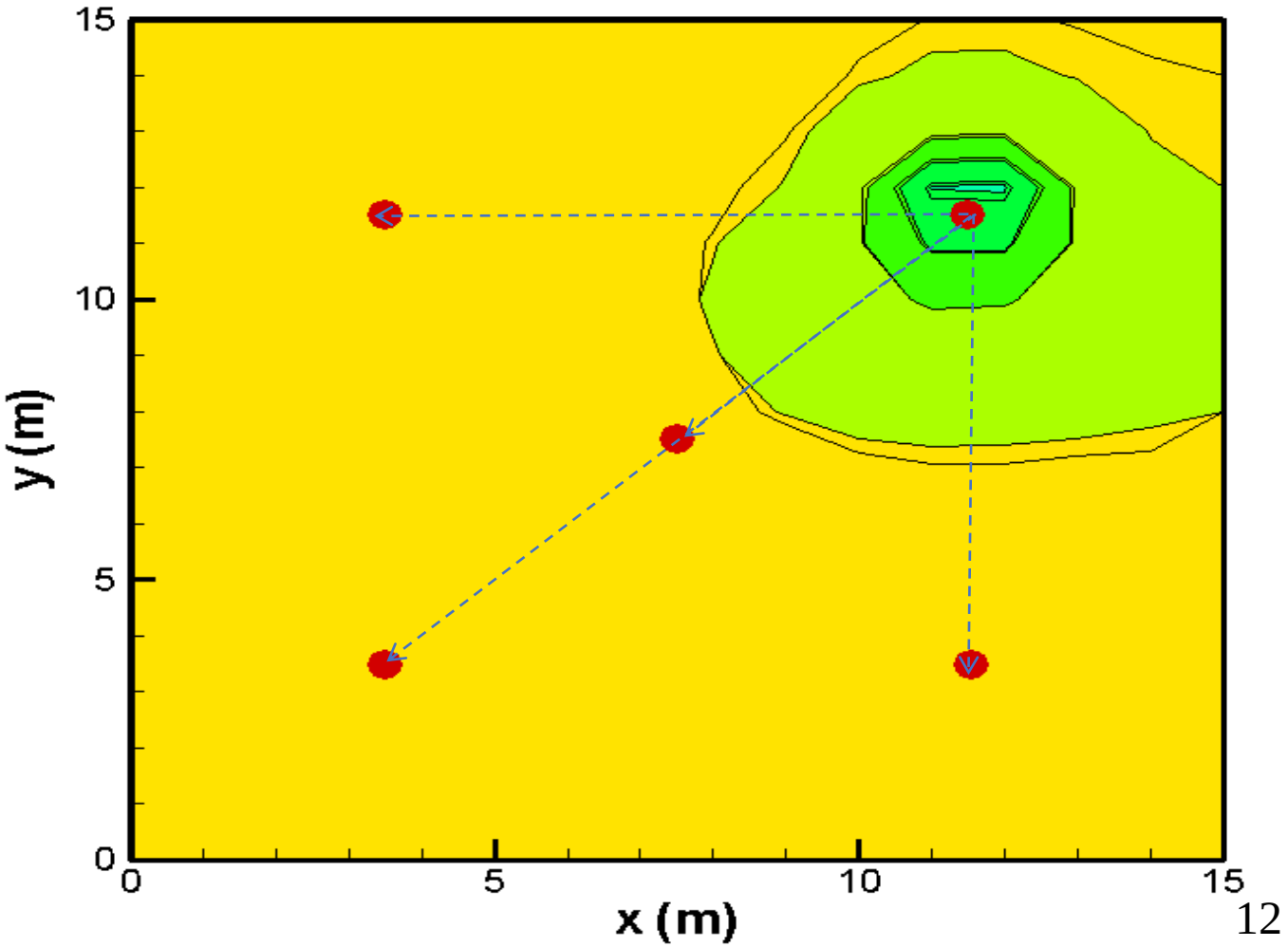

15
10
5
0
y (m)
0
5
10
15
x (m)

Successive Linear Estimator (SLE)

Objective: conditional expectation of a stochastic field
given sampled observations **h** collected in hydraulic tomographic survey

- Successive linear approximation of the nonlinear relationship between **h** and **Y**

$$\hat{\mathbf{Y}}_c^{(r+1)} = \hat{\mathbf{Y}}_c^{(r)} + w^{\mathrm{T}} \left(h^* - h^{(r)} \right)$$

➢ Weights depend on spatial correlation function of Y and sensitivity of h to Y

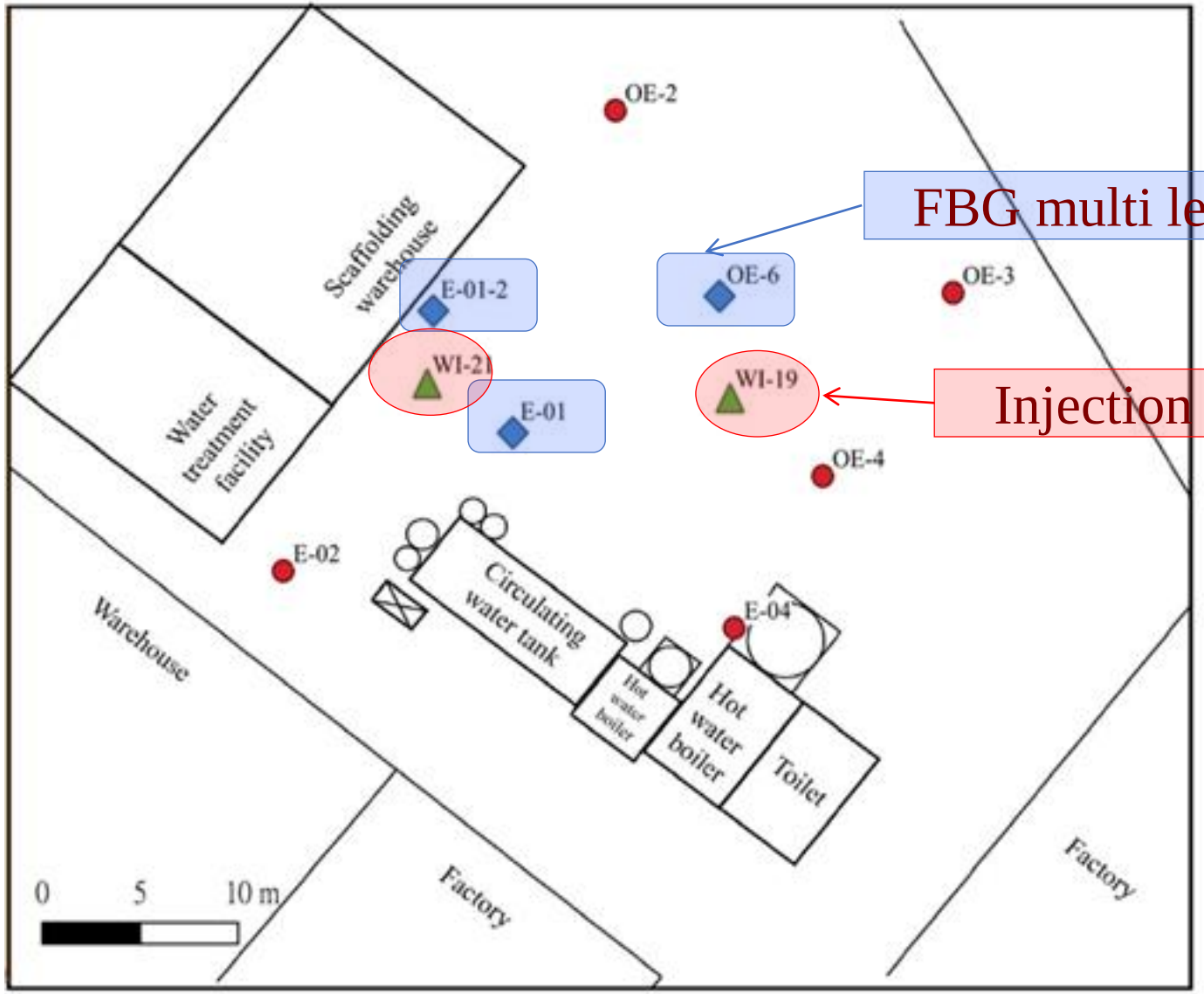
- Update residual covariance (uncertainty) and cross-covariance to obtain new weights

$$\boldsymbol{\varepsilon}_{yy}^{(r+1)} = \boldsymbol{\varepsilon}_{yy}^{(r)} - \boldsymbol{\omega}^{\mathrm{T}} \boldsymbol{\varepsilon}_{dy}$$

➢ Start iteration with unconditional covariance function of **Y** (a prior information)
➢ Stop iteration when no improvement

(Yeh et al., 1996)

Experimental configurations



FBG multi level well system

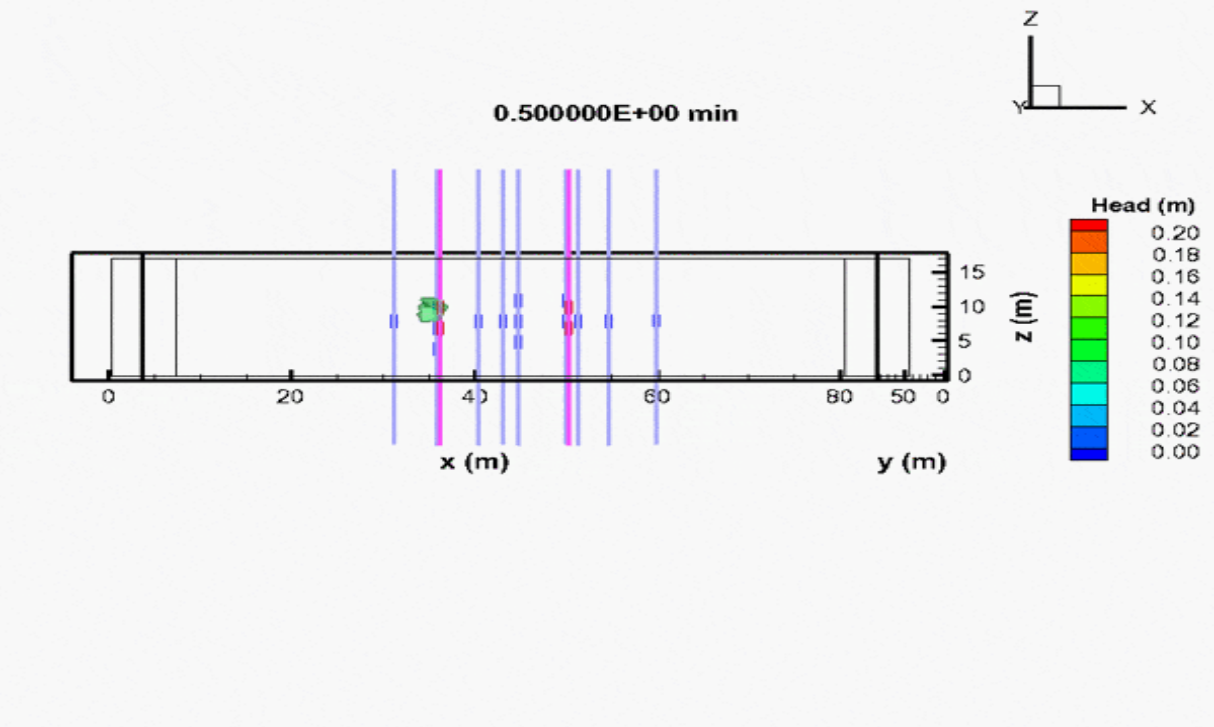
Injection well

Table 1 Arrangement for the **four injection events**

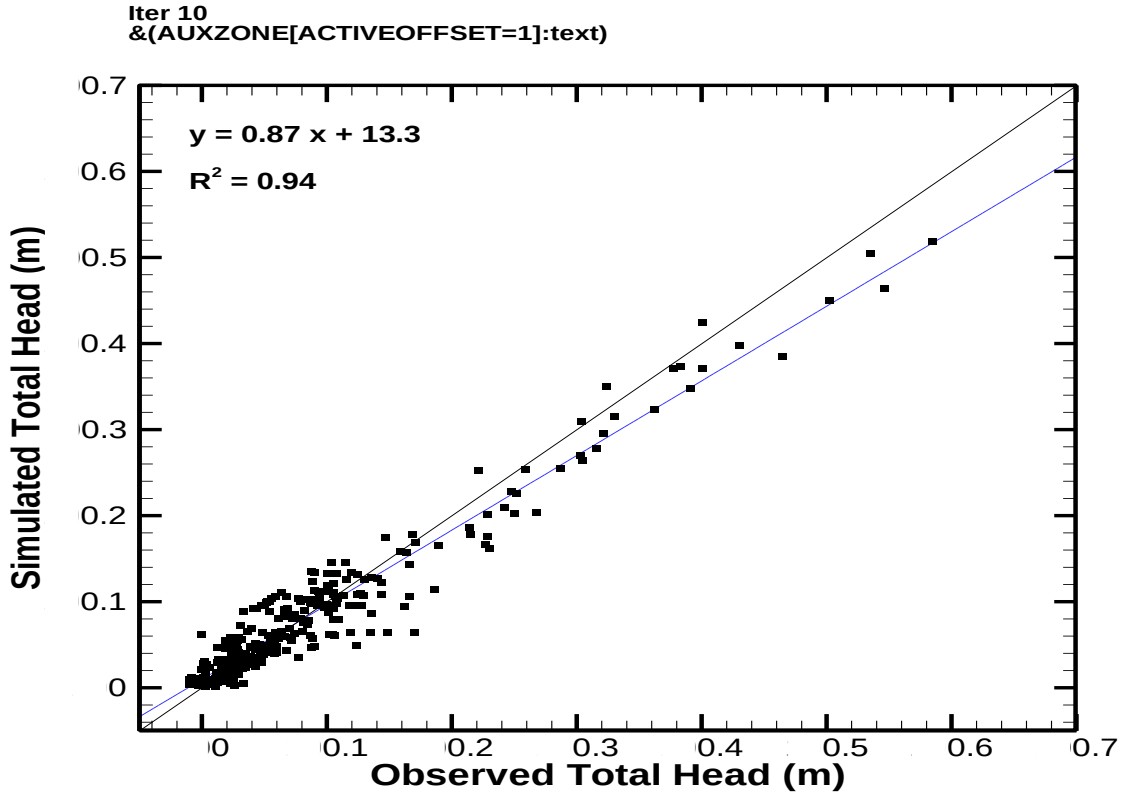
Date: 22th Oct., 2018, PM15:00-17:00			
Name of the Observation well	The depth of the FBG sensors in the MLMS from ground surface		
E-01-2	7m, 10m, and 13m		
E-01-1	5.5m, 8.5m, and11.5m		
OE-6	6m and 9m		
Name of the injection well	Depth of the injection hole from the ground surface	Injection schedule	Injection rate of the remediation agent
WI-19	7 m	15:08-15:28	10L/min
	10m	15:40-16:00	10L/min
WI-21	7 m	16:08-16:28	10L/min
	10m	16:48-17:08	10L/min

Hydraulic tomography

- Head variations during the four injection events

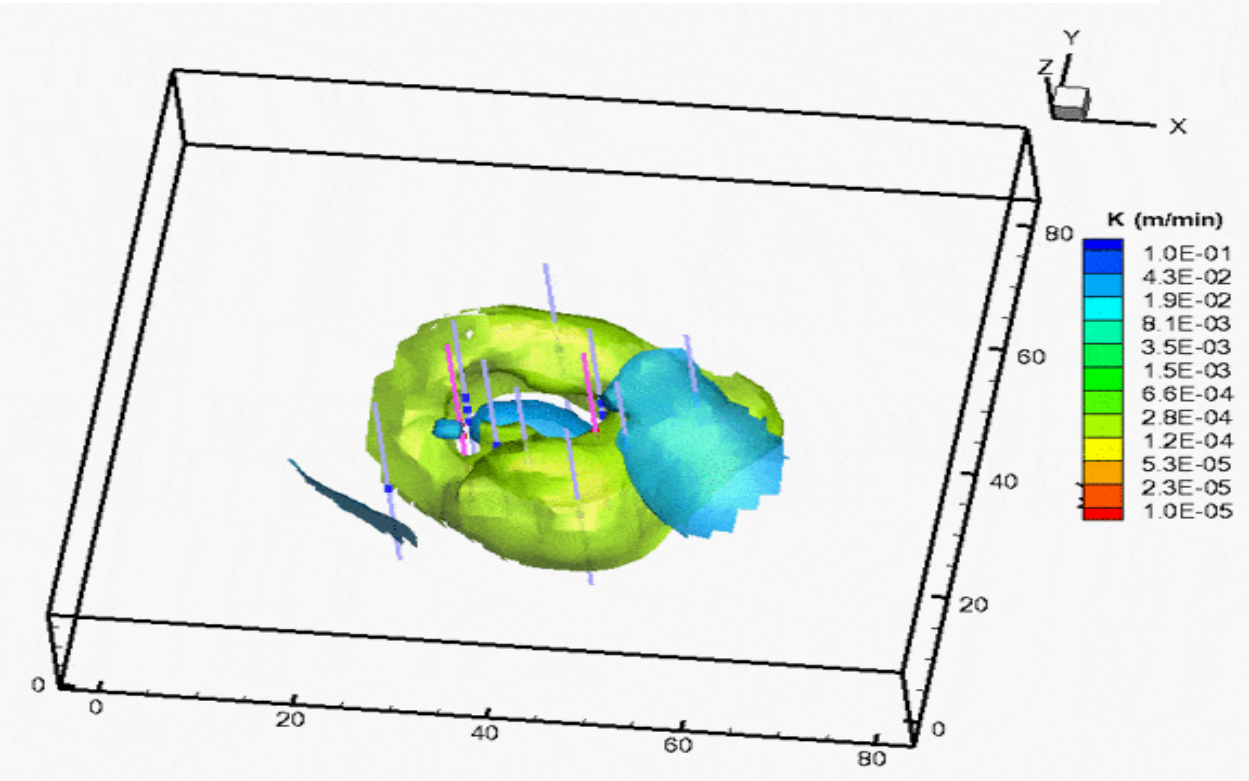


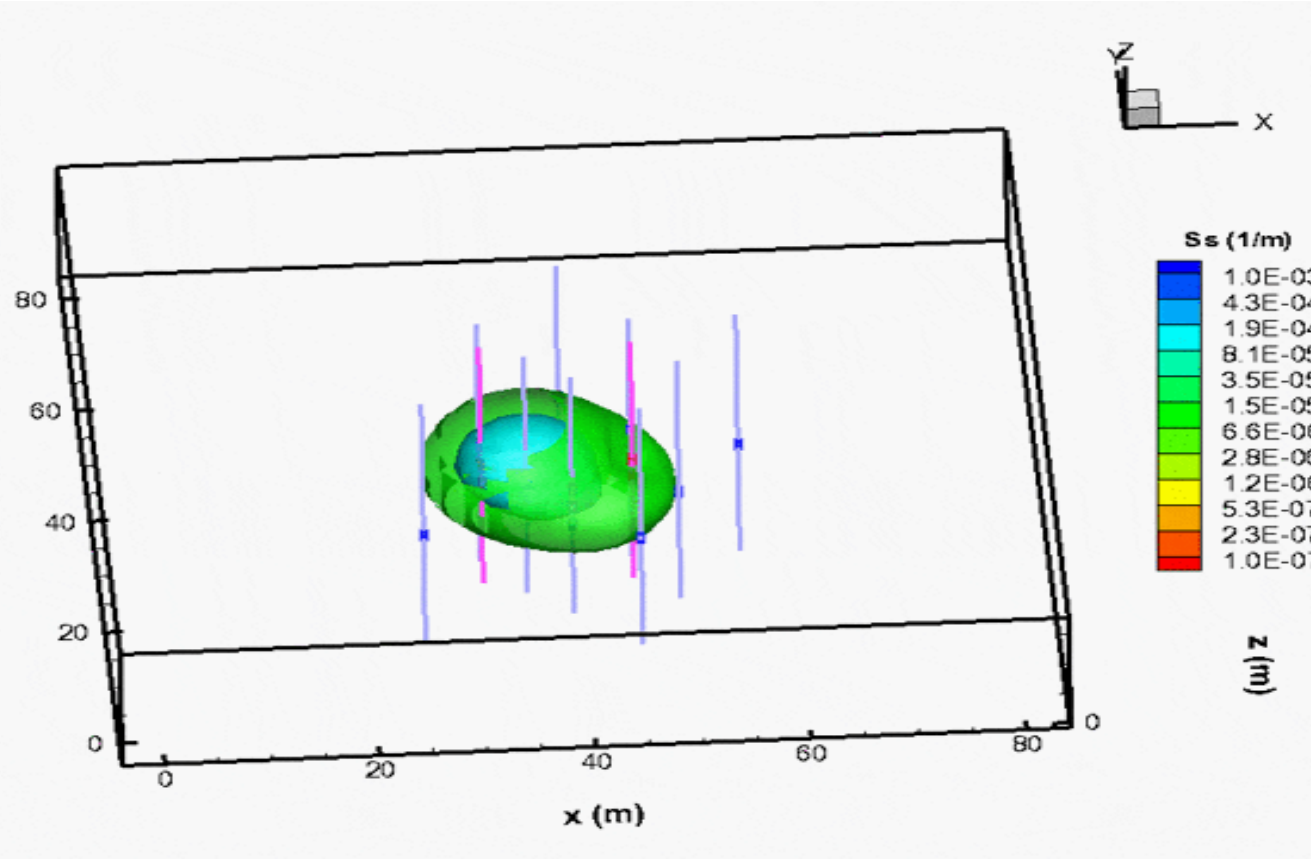
- Scatter plot of simulated and observed groundwater levels



Hydraulic tomography using FBG data

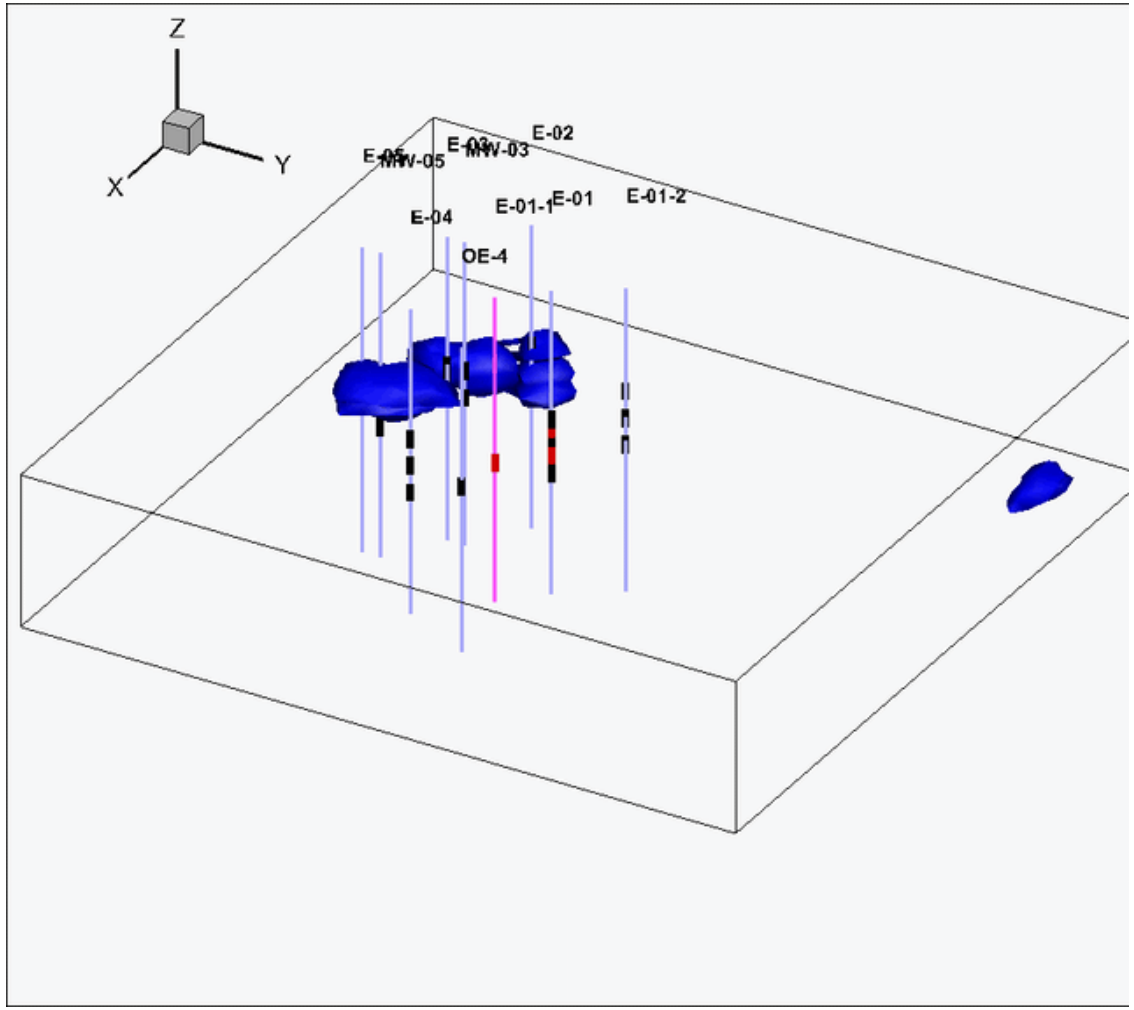
- Estimated K field
- S_s estimate





Predicting the flow paths of remediation agent

- Predict the spatiotemporal distribution of remediation agent based on the groundwater model with the estimated parameter fields.
- Facilitate the planning of contaminated site remediation.



Conclusion

- This study successfully employed FBG technology to develop a multilevel monitoring system (MLMS) to monitor the spatiotemporal groundwater pressure and temperature in the subsurface environment.
- The groundwater levels in response to the four injections from different levels in 2-in wells are monitored precisely.
- The multi-depth groundwater level measurements are successfully used to delineate the 3-D K and Ss fields for the study site.
- FBG MLMS is testing in several sites in Taiwan.

Thanks for your listening!

Q&A

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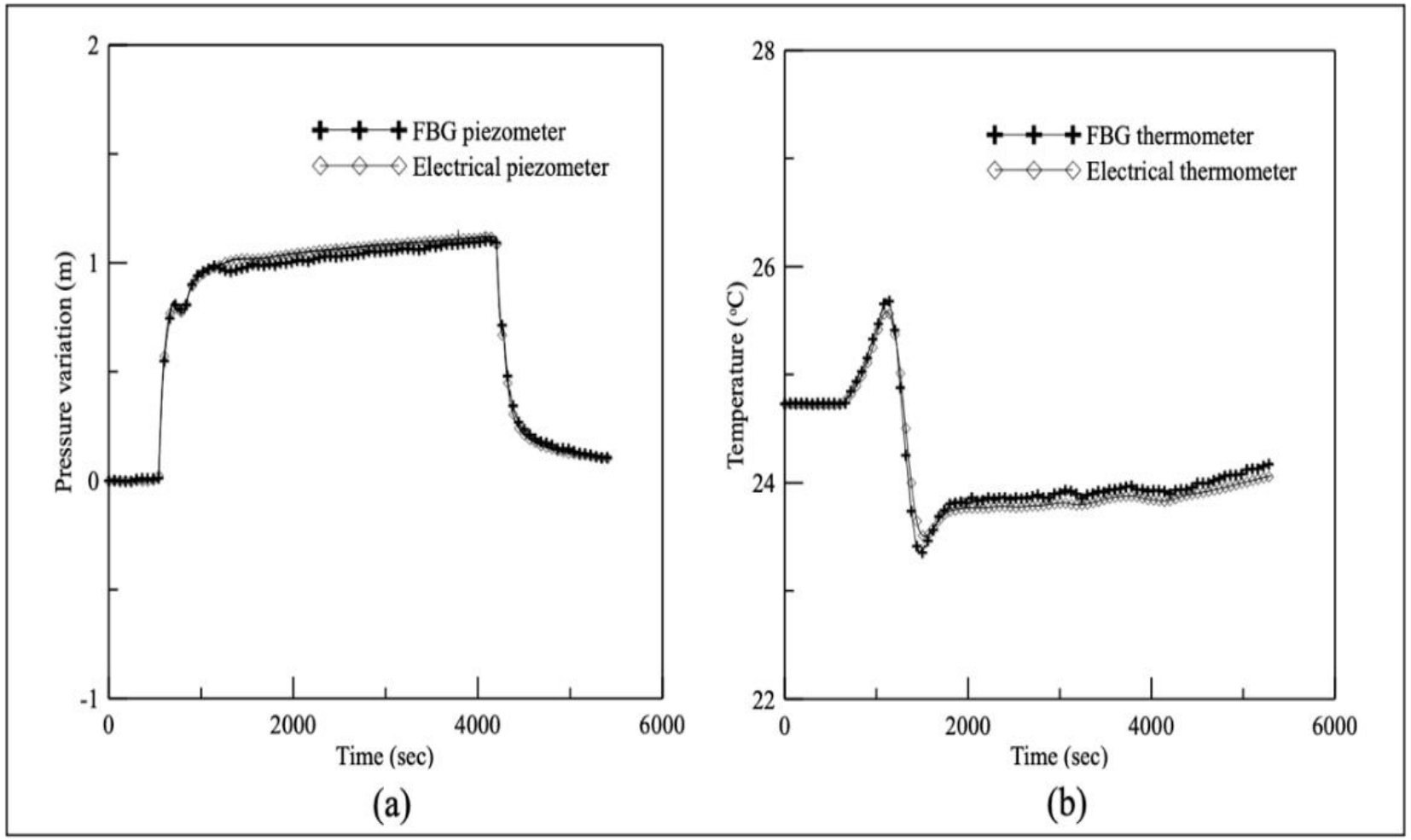
Comparisons of the measurements between FBG and electronic sensors



- Solinst Levelogger Model 3001
  - range = 100 m
  - accuracy of 0.05% FS in pressure
  - 0.05℃ in temperature
- Maximum difference
  - 5 cm H_2O in pressure
  - 0.27 ℃ in temperature
- Difference may source from different sensor accuracy and response time

Validation of Estimated K filed

Electrical resistivity profile images

K profile images