INTEGRATED FIELD RESEARCH CHALLENGE SITE
Hanford 300 Area

U.S. Department of Energy Office of Science

Environmental Remediation Sciences Program

Environmental Remediation Sciences

Integrating Scale-Dependent Hydrogeological Data Using a Bayesian Geostatistical Framework

Haruko Murakami[1], Xingyuan Chen[2], Hang Bai[2], Mark Rockhold[3], Yoram Rubin[2]
[1]Department of Nuclear Engineering, University of California, Berkeley, CA
[2]Department of Civil and Environmental Engineering, University of California, Berkeley, CA
[3]Pacific Northwest National Laboratory, Richland, WA

Pacific Northwest

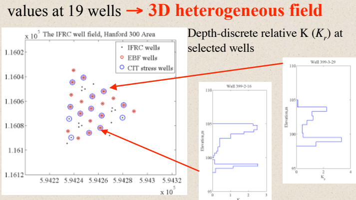
Office of Science

1. Objective

Estimate a heterogeneous hydraulic conductivity field (K field) at the IFRC site.

- Electromagnetic Borehole Flowmeter (EBF) data

→ Point-scale depth-discrete "relative" conductivity values at 19 wells → **3D heterogeneous field**



Depth-discrete relative K (K_r) at selected wells

- It requires point-scale transmissivities (T) at the EBF wells as relative-to-absolute-value ratios

→ Short-duration (~20 min) Constant-rate Injection Tests (CIT) are conducted at 14 wells

2. Challenge

High permeability of the Hanford formation

Zone-of-influence in the CIT expands rapidly

→ Conventional type-curve analyses can yield only large-scale effective conductivity regardless of well distances. [Sánchez-Vila *et al.*,1999]

→ Artificially smooth out variability of the field

3. Our Proposal

Use the temporal moments of drawdown in the CIT to estimate point-scale T at the EBF wells through geostatistical inversion techniques

4. CIT Analysis Model in 2D: Theory

* Although the aquifer is unconfined, the flow converged to the 2D radial flow in less than 30 seconds during CIT, due to coarse-grained and highly permeable mature of the formation.

4.1. 2D Geostatistical Model:Method of Anchor Distribution (MAD)

Assumption: Log-transmissivity is multivariate Gaussian: log-$T \sim MVN(\boldsymbol{\mu}_c, \boldsymbol{C}_c)$

- $\boldsymbol{\mu}_c$, $\boldsymbol{C}_c$: mean vector and covariance matrix conditioned on anchors

Parameters

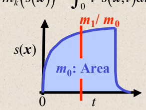
- Structural parameters: $\boldsymbol{\theta} = \{\text{mean, variance, scale}\}$
- Anchors: $\psi = \{\psi_1, \psi_2, ..., \psi_p\}$

- Anchors serve as conditioning points of the field
- CIT data is transferred to anchor values through inversion

4.2. Temporal moments of drawdown in the CIT [Zhu and Yeh, 2005]

m_k: k-th moment of drawdown, $s(\boldsymbol{x})$, in the observation well at $\boldsymbol{x}$

$$m_k(s(\boldsymbol{x})) = \int_0^\infty t^k s(\boldsymbol{x},t)dt$$



Moment Equations

$$\nabla \bullet (T\nabla m_k) + \frac{\tau^{k+1}}{k+1} Q\delta(\boldsymbol{x}-\boldsymbol{x}_p) = -Skm_{k-1} - St_{end}{}^k H_0(\boldsymbol{x},t)$$

T: transmissivity, S: storage coefficient Q : injection rate

τ : injection duration, t_{end} : end time of recovery

H_0: ambient head, $\boldsymbol{x}_p$: pumping well location

with B.C. $m_k = 0$, at $\Gamma_{Dri} \forall t$,

$\mathbf{n} \bullet T\nabla m_k = 0$, at $\Gamma_{Neu} \forall t$.

Advantage

- Reduction of data dimensions from an entire time series of the drawdowns
- Flexibility to include complex ambient head fluctuation (river fluctuation)

4.3. Bayesian Geostatistical Inversion

Obtain the posterior distribution of parameters conditioned on the temporal moments

$$p(\boldsymbol{\theta},\psi \mid m_0, m_1, m_2.....) \propto p(m_0, m_1, m_2..... \mid \boldsymbol{\theta}, \psi)\, p(\boldsymbol{\theta},\psi)$$

← prior

Likelihood: estimated using MC simulations of moments

***T* field**

5. Conversion of EBF Data to Absolute K

- K_{rij}: Measured "relative" conductivity at Interval i of Well j in EBF
- T_j: Estimated T at Well j from CIT data and geostatistical inversion
- b_j: Aquifer thickness at Well j during CIT

$$K_{ij} = \frac{T_j}{b_j} K_{r,ij}, \quad i = 1,2,..., \; j = 1,2,....$$

→ Point-scale conductivity at interval i of well j and :K_{ij} → **3D K field**

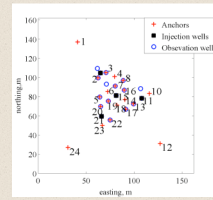
6. Domain for the CIT Analysis

6.1. Data and Experiment Setting

- 4 out of 14 CIT with 8-9 observation wells per test *
- No direct K measurements
- Linear interpolation to remove the river fluctuation effect

6.2. Inversion Setting

- 24 anchors (labeled): 20 at the EBF wells
- Only zeroth moments as data for inversion *
- MCMC algorithm to obtain the posterior distribution
- Multivariate Gaussian approximation for the likelihood estimation * Due to computational limitation

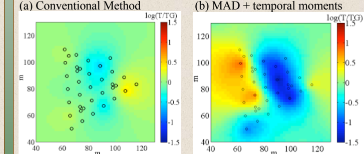


7. Results

* Conventional method: type-curve analysis at each injection well for T estimation

7.1. Estimated 2D Mean T Field

(a) Conventional Method (b) MAD + temporal moments

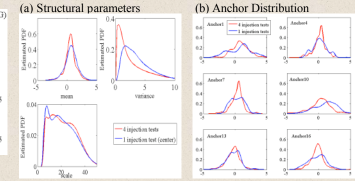


- Our method can resolve local heterogeneity, while the conventional method smoothes it out.

7.2. Impact of Multiple Injection Tests

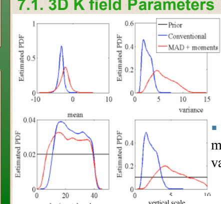
- Compare the results from 1 (center) and 4 injection tests

(a) Structural parameters (b) Anchor Distribution



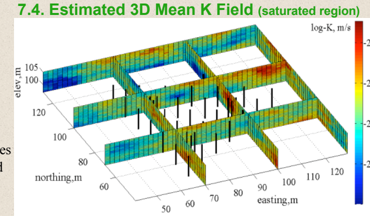
More data = sharper distribution, uncertainty reduced

7.1. 3D K field Parameters



- The conventional method underestimates variability of the field

7.4. Estimated 3D Mean K Field (saturated region)



8. Summary

- Demonstrated methodology for combining EBF and CIT, in order to characterize the local-scale heterogeneity of hydraulic conductivity in a high permeable formation.
- Geostatistical inversion with MAD and temporal moments of drawdowns is used to estimate the local-scale transmissivities, to convert the EBF data to point-scale conductivities..
- Applications to IFRC experimental data: estimates of geostatistical parameters indicate larger variability than conventional approach.
- Obtained 3D heterogeneous conductivity field.

9. Future Work

- Optimize the number of anchors and their locations
- Utilize all the pumping tests
- Estimate the heterogeneous storage coefficient
- Implement a 3D geostatistical model with 3D temporal moment equations for combining EBF/CIT: computational efficiency needs to be improved

References

- Sánchez-Vila X, PM Meier, and J Carrera, 1999, "Pumping tests in heterogeneous aquifers: An analytical study of what can be obtained from their interpretation using Jacob's method", *Water Resources Research*, 35(4): 943:952
- Zhang Z. and Y. Rubin, "Inverse modeling of Spatial Random Fields Using Anchors", under review in water resources research
- Zhu, J., and T.-C. J. Yeh (2006), Analysis of hydraulic tomography using temporal moments of drawdown recovery data, *Water Resour. Res.*, 42.

Acknowledgment

This work is supported by U.S. Department of Energy under contract DE-AC05-76RL01830.

We thank the IFRC field experiment team for providing us the excellent experiment data, and Wolfgang Nowak for providing us the FFT-based random field generation code.