

FACT SHEET

Geoelectrical Characterization of Mobile/Immobile Exchange: New Technologies for Field Testing and Data Analysis



Introduction

The classical advective-dispersive transport model inadequately describes the migration of contaminants or other chemicals in groundwater in many geologic settings, particularly in heterogeneous aquifers and fractured rock. Alternative models, including the mobile/immobile model, are necessary to explain contaminant rebound at the end of pump-and-treat operations, extremely slow rates of contaminant removal, and other phenomena attributed to “back diffusion.” In the mobile/immobile model, the geologic medium comprises dual overlapping domains (Figure 1), one in which water and chemicals move through advection and dispersion (the mobile domain), and the other in which water is stagnant and chemicals are stored and slowly released (the immobile domain). Contamination trapped in the immobile domain acts as a long-term source, as it slowly diffuses back into the mobile domain where it is measured or observed in groundwater samples. The mobile/immobile model is widely used and supported in popular computer codes for contaminant transport including the U.S. Geological Survey’s MODFLOW 6 (Langevin et al., 2017) and the MT3D family of codes.

Compared to advective-dispersive transport models, the mobile/immobile model requires additional information in the form of two parameters: (1) the ratio of immobile to mobile porosity, β , and (2) the rate coefficient governing mobile/immobile diffusive exchange, α . These parameters are difficult to measure in situ because the immobile domain is inaccessible—effectively invisible—to conventional sampling, which draws fluid preferentially from the mobile domain (Figure 1); thus, contaminant mass residing in the immobile domain is difficult to quantify, and prediction of remedy effectiveness is challenging. Commonly, estimation of mobile/immobile parameters is based on history matching, (i.e., calibration of site-wide transport models, and parameters are assumed to be spatially uniform across a site).

Whereas fluid sampling draws preferentially from the mobile domain, electrical geophysical measurements average over both mobile and immobile domains, as demonstrated in field experiments (Singha et al., 2007; Briggs et al., 2013, 2018; Scruggs et al., 2019) and laboratory experiments (Swanson et al., 2012; Briggs et al., 2014; Swanson et al., 2015). In the presence of immobile porosity, a time-varying (or hysteretic) relationship can develop during push-pull tracer tests using electrically conductive ionic tracers. Analysis of the combined fluid and geophysical data allows for estimation of α and β . The analysis for β involves a simple graphical procedure (Briggs et al., 2014), whereas analysis for α ranges from curve fitting procedures to model calibration (Briggs et al., 2018).

To fully capitalize on the potential of geophysical approaches to understanding immobile porosity, new technologies are needed for (1) field testing, and (2) data analysis. To this end, the Mobile Immobile Porosity Exchange Tool (MI-PET) and Data Analysis and Visualization Tool (DAVT) were developed under the Environmental Security Technology Certification Program (ESTCP) project ER-201732.

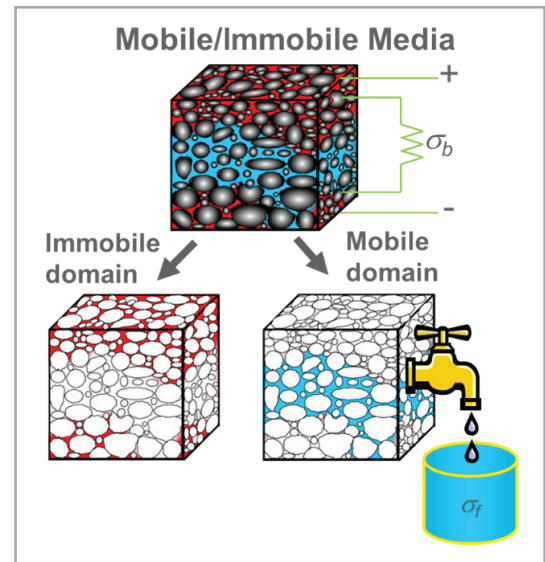


Figure 1. In the mobile/immobile model, the geologic media are conceptualized as comprising two overlapping domains, mobile and immobile. Conventional fluid sampling draws preferentially from the mobile domain, for example providing measurements of pore fluid conductivity (σ_f), whereas electrical geophysical measurements are sensitive to both domains and provide the bulk electrical conductivity of a porous medium (σ_b). (Source: Courtesy of U.S. Geographical Survey [USGS])



Technology Background

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The MI-PET, a borehole field apparatus (Figures 2 and 3) utilizes the following steps (1) inflatable packers for hydraulic isolation of testing zones, (2) electrodes for geophysical measurements, (3) fluid injection/sampling, and (4) measurement of fluid conductivity. The MI-PET is highly customizable. Three-dimensional (3-D) printing technology was used to develop interchangeable packers of different diameter and packer/electrode spacers of varying length. It is important to note that the geophysical measurements require electrical contact with the rock or soil; hence, the borehole intervals for testing must be uncased or screened with polyvinyl chloride (PVC). Fluid sampling also requires open or screened intervals.

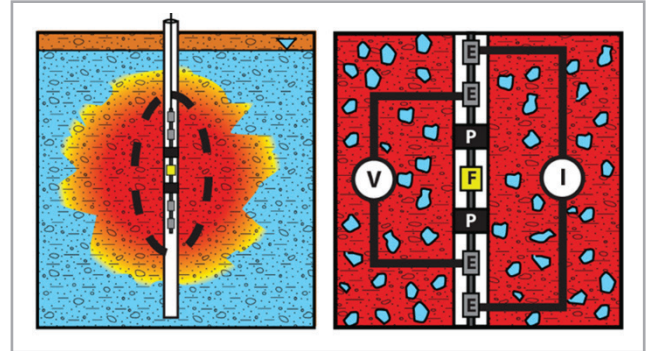


Figure 2. Schematic diagram of the MI-PET. The tool comprises packers (P); electrodes (E); and fluid injection/extraction and measurement of fluid conductivity (F). The tool performs a tracer test and collects geophysical measurements by injecting an electrical current (I) between two electrodes while measuring voltages (V) between two other electrodes (E). (Source: Courtesy of USGS)

The DAVT is a software tool developed in the computer language R. The DAVT is user friendly and platform independent. It reads and plots time series of bulk and fluid electrical conductivity, which are the output of the MI-PET. The DAVT provides an interactive graphical procedure to estimate β and an automated curve-fitting procedure to estimate α . Although designed for analysis of borehole data collected using the MI-PET, the DAVT can also be used to analyze data collected in laboratory experiments (e.g., Swanson et al., 2012; Briggs et al. 2014) or in streambed or lakebed applications (e.g., Scruggs et al., 2019); thus, the hydrogeophysical approach can be applied to data collected across a range of scales and settings.

How Does It Work?

An MI-PET experiment involves placement of the tool downhole; inflation of packers to isolate a borehole interval, possibly centered on a discrete fracture or fracture zone; injection and subsequent extraction of an ionic tracer (e.g., NaCl, NaBr, or KBr); and time-lapse electrical measurements and fluid sampling. Depending on formation properties, experiments may range in duration from hours to days. As the tracer is injected, it migrates through the mobile pore spaces from which it slowly diffuses into immobile pore spaces. During this first period, as the mobile domain loads with tracer, the bulk conductivity (σ_b) and fluid conductivity (σ_f) both increase. Eventually, σ_f in the mobile domain approaches that of the tracer, and thus the sampled σ_f stabilizes. However, the electrically conductive tracer continues to diffuse into and load the immobile domain, and thus σ_b continues to rise during this second period. The relationship between the bulk-conductivity change during the first period and the change during the second period is a function of β . Assuming σ_b is a porosity-weighted average over the mobile and immobile domains (Singha et al., 2007), β is simply the ratio of σ_b rise for the second period compared to the first period. The rate at which σ_b stabilizes during the second period is controlled by α , and thus α can be estimated using a curve fitting procedure.



Figure 3. The MI-PET tool ready for a downhole installation. (Source: Courtesy of Rutgers University)





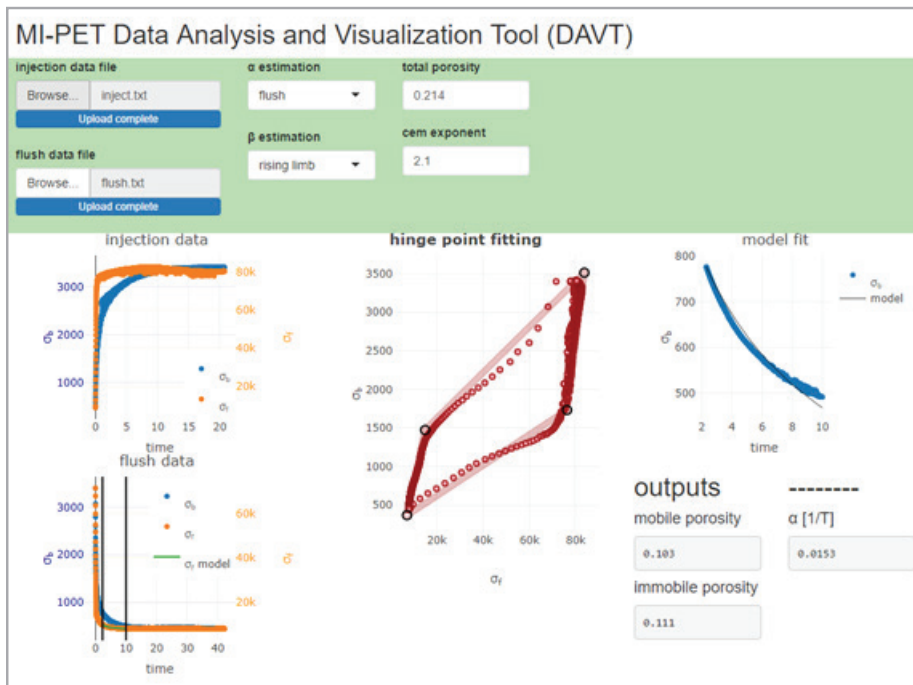
Case Study

Case Study

The MI-PET is currently undergoing field testing and validation. Here, DAVT results are presented (Figure 4) for a case study based on laboratory experimental data collected under the Strategic Environmental Research and Development Program (SERDP) SERDP ER-2421 on cores from a chlorinated solvent contaminated site in Wisconsin (Slater et al., 2020). High-pressure tracer injections and extractions and time-lapse electrical measurements were conducted in laboratory experiments on cores of sandstone and dolostone from a borehole.

For the estimation of β in the DAVT, the user manually adjusts the end points of four connected line segments to match a plot of σ_b vs. σ_f . The change in σ_b needed for estimation of β is calculated for periods during (1) tracer loading of the mobile domain, and (2) tracer loading of the immobile domain. The same procedure can be applied during the tracer flushing phase, i.e., the pull phase during the push-pull experiments, to yield a second estimate of β .

For the estimation of α , the user first identifies a subset of the σ_b and σ_f time series data where σ_f is approaching equilibrium with the injection. For this subset of data, the DAVT uses nonlinear regression to fit a semi-analytical model describing mobile/immobile exchange, thus yielding an estimate of α . It is important to note that the estimated α is specific to the tracer used; however, an α for another solute of interest (e.g., a contaminant) can be easily calculated based on the α for the tracer, the molecular diffusion coefficients for the tracer and the other solute of interest.



How Can It Help?

The MI-PET and DAVT enable:

- In situ testing to estimate mobile/immobile parameters;
- Characterization of spatially variable mobile/immobile parameters; and
- Improved input for transport codes that use the mobile/immobile model to represent back diffusion.

Further, the MI-PET and DAVT can potentially contribute to improving:

- Estimation of contaminant mass stored in immobile pore spaces; and
- Predictions of remedy performance.

Figure 4. Screenshot of the DAVT graphical user interface and analysis of case study data from a chlorinated solvent contaminated site. The user interactively drags hinge points (middle) to fit a quadrilateral to a plot of σ_b vs. σ_f , which yields an estimate of β . The user then identifies a subset of data (left) for which sampled σ_f is approaching the conductivity of injected fluid. The DAVT uses nonlinear regression to fit a semi-analytical model (right) to the data, which yields an estimate of α . (Source: Courtesy of USGS)





Conclusions

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Mobile/immobile models can describe contaminant rebound and other back-diffusion phenomena associated with contaminant storage in low permeability zones; however, the use and predictive power of these models are limited by lack of means to characterize the controlling parameters. Field characterization of immobile porosity and mobile/immobile exchange is problematic because immobile porosity and the fluid it contains are effectively invisible to conventional in situ sampling. The MI-PET represents new technology for in situ testing and characterization of spatially variable immobile porosity and mobile/immobile exchange. The DAVT streamlines rigorous estimation of the parameters needed to represent mobile/immobile exchange in computer codes widely used for contaminant transport (e.g., MODFLOW 6, MT3DMS).

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References

- Briggs, M.A., F.D. Day-Lewis, G.P. Curtis, J.B. Ong, and J.W. Lane Jr. 2013. "Simultaneous estimation of local-scale and flow path-scale dual domain mass transfer parameters using geoelectrical monitoring," *Water Resources Research*, 49, 5615–5630, doi:10.1002/wrcr.20397.
- Briggs, M.A., F.D. Day-Lewis, J.B. Ong, J.W. Harvey, and J.W. Lane Jr. 2014. "Dual-domain mass-transfer parameters from electrical hysteresis: Theory and analytical approach applied to laboratory, synthetic streambed, and groundwater experiments," *Water Resources Research*, 50, 8281–8299, doi:10.1002/2014WR015880.
- Briggs, M.A., F.D. Day-Lewis, F.M.P. Dehkordy, T. Hampton, J. Zarnetske, C.R. Scruggs, K. Singha, J.W. Harvey, and J.W. Lane. 2018. "Direct observations of hydrologic exchange occurring with less-mobile porosity and the development of anoxic microzones in sandy lakebed sediments," *Water Resources Research*, 54, 4714–4729, <https://doi.org/10.1029/2018WR022823>.
- ESTCP Project ER-201732, Demonstration and Validation of New Non-Invasive Technology to Assess Contaminant Storage in Low Permeability Media and Rock Matrix.
- Langevin, C.D., J.D. Hughes, E.R. Banta, R.G. Niswonger, S. Panday, and A.M. Provost. 2017. "Documentation for the MODFLOW 6 Groundwater Flow Model," *Techniques and Methods* 6-A55, doi:10.3133/tm6A55.
- Scruggs, C.R., M. Briggs, F.D. Day-Lewis, D. Werkema, and J.W. Lane. 2019. "The Dual-Domain Porosity Apparatus: Characterizing Dual Porosity at the Sediment/Water Interface," *Groundwater*, doi:10.1111/gwat.12846.
- Singha, K., F.D. Day-Lewis, and J.W. Lane Jr. 2007. "Geoelectrical evidence of bicontinuum transport in groundwater," *Geophysical Research Letters*, 34, L12401, doi:10.1029/2007GL030019.
- Slater, L.D., F.D. Day-Lewis, K. Keating, and B. Parker. 2020. "Investigating the Sensitivity of Emerging Geophysical Technologies to Immobile Porosity and Isolated DNAPL and Dissolved/Sorbed VOC Mass in Fractured Media," SERDP Project ER-2421 Final Report,
- Swanson, R.D., K. Singha, F.D. Day-Lewis, A. Binley, K. Keating, and R. Haggerty. 2012. "Direct geoelectrical evidence of mass transfer at the laboratory scale," *Water Resources Research*, 48, W10543, doi:10.1029/2012WR012431.
- Swanson, R.D., A. Binley, K. Keating, S. France, G. Osterman, F.D. Day-Lewis, and K. Singha. 2015. "Anomalous solute transport in saturated porous media: Relating transport model parameters to electrical and nuclear magnetic resonance properties," *Water Resources Research*, 51, 1264–1283, doi:10.1002/2014WR015284.



REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) 27/12/2021		2. REPORT TYPE ESTCP Fact Sheet		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Geoelectrical Characterization of Mobile/Immobile Exchange: New Technologies for Field Testing and Data Analysis				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Ramona Iery and Steven Hammett: NAVFAC EXWC Neil Terry: USGS Lee Slater: Rutgers University Newark				5d. PROJECT NUMBER ER-201732	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NAVFAC EXWC 1000 23rd Ave. Building 1000 Port Hueneme, CA 93043				8. PERFORMING ORGANIZATION REPORT NUMBER ER-201732	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 16F16 Alexandria, VA 22350-3605				10. SPONSOR/MONITOR'S ACRONYM(S) ESTCP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) ER-201732	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The classical advective-dispersive transport model inadequately describes the migration of contaminants or other chemicals in groundwater in many geologic settings, particularly in heterogeneous aquifers and fractured rock. Alternative models, including the mobile/immobile model, are necessary to explain contaminant rebound at the end of pump-and-treat operations, extremely slow rates of contaminant removal, and other phenomena attributed to "back diffusion." In the mobile/immobile model, the geologic medium comprises dual overlapping domains (Figure 1), one in which water and chemicals move through advection and dispersion (the mobile domain), and the other in which water is stagnant and chemicals are stored and slowly released (the immobile domain). Contamination trapped in the immobile domain acts as a long-term source, as it slowly diffuses back into the mobile domain where it is measured or observed in groundwater samples. The mobile/immobile model is widely used and supported in popular computer codes for contaminant transport including the U.S. Geological Survey's MODFLOW 6 (Langevin et al., 2017) and the MT3D family of codes.					
15. SUBJECT TERMS Geoelectrical Characterization, Mobile/Immobile Exchange, Field Testing, Data Analysis					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON Ramona Iery
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			19b. TELEPHONE NUMBER (Include area code) 614-205-5349