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.

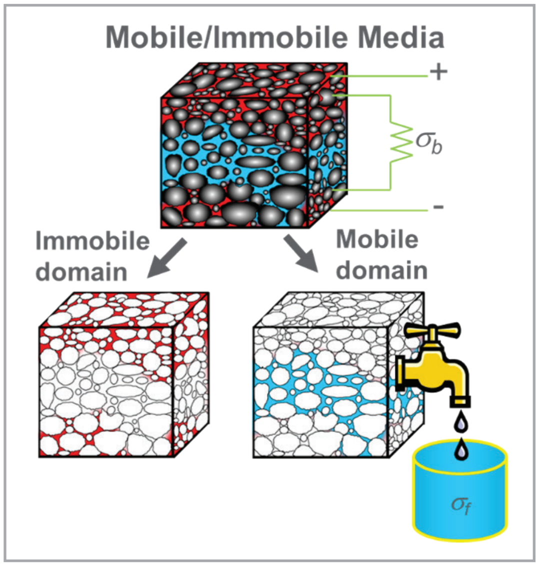


**Figure 1. In the mobile/immobile model, the geologic media are conceptualized as comprising two overlapping domains, mobile and immobile. Conventional fluid sampling draws preferentially from the mobile domain, for example providing measurements of pore fluid conductivity ($\sigma_f$), whereas electrical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

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, $\beta$, and (2) the rate coefficient governing mobile/immobile diffusive exchange, $\alpha$. 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 $\alpha$ and $\beta$. The analysis for $\beta$ involves a simple graphical procedure (Briggs et al., 2014), whereas analysis for $\alpha$ 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.

# 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.

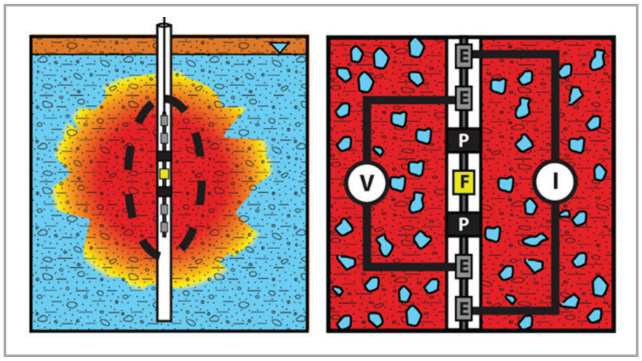


**Figure 2. Schematic diagram of the MI-PET. The tool comprises packers (P); electrodes (E); and fluid injection/extraction and measurement of fluid conductivity (F). The tool performs a tracer test and collects geophysical measurements by injecting an electrical current (I) between two electrodes while 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 $\beta$ and an automated curve-fitting procedure to estimate $\alpha$. 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.

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

## 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 ($\sigma_b$) and fluid conductivity ($\sigma_f$) both increase. Eventually, $\sigma_f$ in the mobile domain approaches that of the tracer, and thus the sampled $\sigma_f$ stabilizes. However, the electrically conductive tracer continues to diffuse into and load the immobile domain, and thus $\sigma_b$ 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 $\beta$. Assuming $\sigma_b$ is a porosity-weighted average over the mobile and immobile domains (Singha et al., 2007), $\beta$ is simply the ratio of $\sigma_b$ rise for the second period compared to the first period. The rate at which $\sigma_b$ stabilizes during the second period is controlled by $\alpha$, and thus $\alpha$ can be estimated using a curve fitting procedure.

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# 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 $\beta$ in the DAVT, the user manually adjusts the end points of four connected line segments to match a plot of $\sigma_b$ vs. $\sigma_f$. The change in $\sigma_b$ needed for estimation of $\beta$ 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 $\beta$.

For the estimation of $\alpha$, the user first identifies a subset of the $\sigma_b$ and $\sigma_f$ time series data where $\sigma_f$ 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 $\alpha$. It is important to note that the estimated $\alpha$ is specific to the tracer used; however, an $\alpha$ for another solute of interest (e.g., a contaminant) can be easily calculated based on the $\alpha$ for the tracer, the molecular diffusion coefficients for the tracer and the other solute of interest.

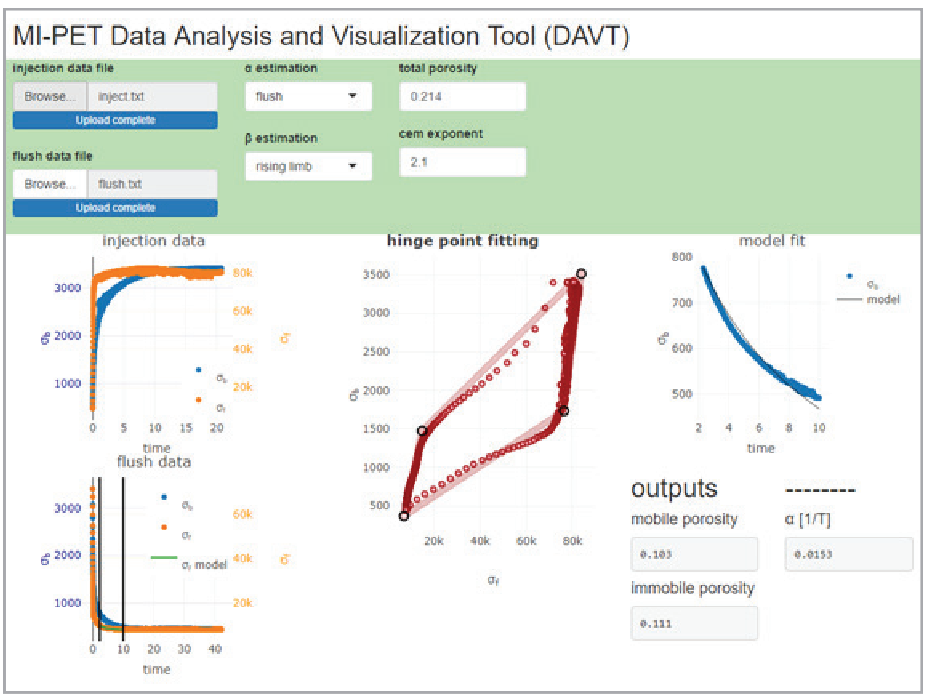


Figure 4. Screenshot of the DAVT graphical user interface and analysis of case study data from a chlorinated solvent contaminated site. The user interactively drags hinge points (middle) to fit a quadrilateral to a plot of $\sigma_b$ vs. $\sigma_f$, which yields an estimate of $\beta$. The user then identifies a subset of data (left) for which sampled $\sigma_f$ 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 $\alpha$. (Source: Courtesy of USGS)

## 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.

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# Conclusions

## Conclusions

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).

## Disclaimer



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