***Paper Q-017***, in: Bruce M. Sass (Conference Chair), *Remediation of Chlorinated and Recalcitrant Compounds—2008.* Proceedings of the Sixth International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Monterey, CA; May 2008). ISBN 1-57477-163-9, published by Battelle, Columbus, OH, www.battelle.org/chlorcon.

# Mass Flux Distribution Using the High-Resolution Piezocone and GMS

***Mark Kram*** (mark.kram@navy.mil) (NFESC, Port Hueneme, CA, USA)
Norm Jones (BYU, Provo, Utah, USA)|
Jessica Chau, Gary Robbins, and Amvrossios Bagtzoglou
(University of Connecticut, Storrs, CT, USA)

**ABSTRACT:** Understanding groundwater-flow pathways, gradients, and contaminant mass flux distribution is essential for proper remedial design, risk determination, and evaluation of remediation effectiveness. Conventional long-screened wells are not adequate for determining groundwater and contaminant flow pathways in three dimensions. Therefore, flux distribution estimates resulting from non-discreet well measurements can be flawed. The objective of this project is to demonstrate the use of the high-resolution piezocone direct push sensor probe to determine direction and rate of groundwater flow in three dimensions. Field measured hydraulic conductivity, head, effective porosity and calculated seepage velocity distributions can be estimated through interpolation methods recently incorporated into Groundwater Modeling System. Probe data comprised of soil type and co-located hydraulic information is particularly amenable to innovative data fusion based interpolations available through the modeling platform. Following chemical concentration data collection, these innovative data processing approaches allow for the determination of flux distributions at resolutions and spatial configurations never before available. Field scale data collection, interpolation, and modeling results from deployment at a site in Port Hueneme, California, in 2006 and 2007 will be presented and discussed.

## INTRODUCTION

The Department of Defense (DoD) groundwater assessment and remediation projects require cost-effective methods for determination of the direction and rate of groundwater and contaminant flow. Monitoring wells have typically been used to estimate these parameters. However, detailed three-dimensional groundwater- and contaminant-flow pathways cannot typically be delineated using conventional monitoring well data. Understanding of flow pathways, gradients, and contaminant flux is essential for proper remedial design, risk determination, and evaluation of remediation effectiveness. In particular, contaminant flux can be used to optimize remediation approaches and evaluate remediation system performance (Basu et al., 2007). Since wells are not adequate for determining groundwater- and contaminant-flow pathways in three-dimensions, their use can result in ineffective remediation, faulty monitoring strategies, poor model predictions, and inaccurate risk assessments. Currently available methods capable of providing the required level of resolution to evaluate site conditions in three-dimensions include multi-level piezometer or sampler clusters, high-density soil sampling and laboratory analyses, and tracer tests. These options can be cost-prohibitive, especially at sites where contamination may be spatially extensive or the site has complex hydrogeologic conditions. It is likely that decades and tens of billions of dollars will be required to cleanup DoD sites using standard hydrogeologic assessment methods.

This project employs the use of an innovative direct push sensor probe (the high-resolution piezocone) deployed using a standard cone penetrometer system to determine direction and rate of groundwater flow in three dimensions. The key to determining direction and rate of flow is to understand the spatial distribution of groundwater head, hydraulic gradient, soil effective porosity, and soil hydraulic conductivity. When flow rates are coupled to contaminant concentration, contaminant flux distribution can be derived.

Saturated flow velocity, or *seepage velocity* ($\nu$), is estimated using the following form of Darcy's Law:

$$\nu = \frac{Ki}{\rho} \text{ (length/time)}$$

where: **K** = hydraulic conductivity
**i** = hydraulic gradient
$\rho$ = effective porosity

Contaminant *flux* (**F**) is estimated using the following relationship:

$$F = \nu\,[X]$$
(mass/length$^2$-time; mg/m$^2$-s)

where: $\nu$ = seepage velocity (length/time; m/s)
**[X]** = concentration of solute (mass/volume; mg/m$^3$)

A piezocone (ASTM D5778 and D6067) is a direct push sensor probe consisting of a porous element connected to a customized transducer that converts pore pressure to water level. A high-resolution piezocone (U.S. Patents 6,208,940 and 6,236,941) is a recently developed sensor probe capable of generating highly resolved hydraulic head values (plus or minus one inch of water level) while simultaneously collecting critical soil type information. Direct measurements of hydraulic head, hydraulic conductivity, and estimates of seepage velocity can be derived through deployment of the high-resolution piezocone. Calculation of contaminant flux requires measurement of concentration, which can be accomplished using other innovative direct push technologies such as the membrane interface probe (MIP) or by more conventional approaches (e.g., samples recovered from short screened wells).

The DoD Site Characterization and Analysis Penetrometer System (SCAPS) is a direct-push platform used for advancing hydrological and chemical sensor probes and samplers into the subsurface. Probe data are managed through an integrated system of data acquisition and processing software. Through this effort, high-resolution piezocone data acquisition functions are streamlined for rapid data processing. The sensor probe data is exported to the Groundwater Modeling System (GMS) for conceptualization, statistical rendering and graphical representations of the three-dimensional distribution of seepage velocity. Furthermore, this highly resolved conceptual hydrogeologic model becomes available for fate and transport modeling, risk assessment, and remediation design and optimization applications through simulation and predictive modules within the GMS platform. When concentration data is available, recent upgrades to GMS also allow for estimation of 3D contaminant flux distributions.

This field demonstration served as a comparison of the high-resolution piezocone approach to a more conventional approach using clusters of short screen piezometers to characterize a small test site at the Naval facility in Port Hueneme, California. Conventional hydraulic measurements were compared to direct push measurements. In addition, simulation of a contaminant release was performed using models based on both conventional and innovative data collection approaches, then comparisons derived to evaluate the predictive capabilities of concentration and flux models derived using the high-resolution piezocone.

## MATERIALS AND METHODS

A piezocone is a direct push sensor probe consisting of a porous element connected to a customized transducer that converts pore pressure to water level. The porous element is filled with viscous glycerin oil that is in contact with a transducer located inside the probe housing. As the probe is advanced through the soil, water pressures are transferred through the oil filled porous element directly to the transducer. The signal is recorded and converted to hydraulic head estimates. The piezocone is also capable of generating soil type estimates based on measurements of vertical resistance to force and sleeve friction, or based on pore pressure and vertical resistance to force. A high-resolution piezocone (U.S. Patents 6,208,940 and 6,236,941) is capable of generating highly-resolved hydraulic head values (plus or minus one inch of water level) while simultaneously collecting critical soil type classification information as well as hydraulic conductivity and estimates of effective porosity. Conventional piezocones are only capable of yielding head resolution on the order of one to two feet of water level, which is not adequate for determining 3D gradient or flow direction at small sites.

Project team members performed several pre-demonstration activities to prepare and evaluate the demonstration test site, which consisted of direct push well clusters set at specific depths and constructed with careful design constraints to allow for a comprehensive comparison with probe push data. These activities included advancing three cone penetrometer pushes around and within the footprint of the test facility to determine general lithologic characteristics in accordance with ASTM D3441, D5778, and D6067, and specific well design criteria following the Kram and Farrar Method (U.S. Patent Number 6,317,694). Three monitoring wells (designed based on the penetrometer push soil classifications) were installed around the perimeter of the proposed well cluster test cell in accordance with ASTM D5521, D6724, and D6725. The final orientation of the centerline of the well clusters was determined based on a preliminary potentiometric assessment (i.e., interpolation of water levels in the three perimeter wells) as well as a $CaCl_2$ tracer released from the upgradient well and time lapsed resistivity efforts. Fifty (50) gallons of a $CaCl_2$ solution at a concentration of approximately 215,000 mg/l were released in the most upgradient well at the test site. Time-lapse resistivity observations were used to track the migration of the tracer over a period of about 1.5 months. The geophysical data was then used to orient the configuration of subsequent test facility piezometers and pushes, with the primary goal of establishing a demonstration cell consisting of multi-level monitoring points and probe pushes parallel to the localized gradient. Thirty-nine piezometers (3/4-inch diameter PVC with six-inch prepacked screens) were installed in thirteen clusters. The test site configuration was based on preliminary SCAPS soil classification pushes, whereby soil types for depths of interest were converted to well design specifications based on the Well Design Specification package devised by Kram and Farrar. At each cluster location, piezometers were screened from approximately 8.0 to 8.5 feet bgs (100 sand with 0.006 inch slot prepack), 10.5 to

11.0 feet bgs (20/40 sand with 0.010 inch slot prepack), and 13.5 to 14.0 feet bgs (20/40 sand with 0.010 inch slot prepack). The piezometer depths were chosen to screen three levels within a shallow sandy confined aquifer. Pneumatic slug-out and water slug-in tests were performed on each piezometer cluster in triplicate using a Geoprobe Pneumatic Slug Test Kit to characterize the spatial distribution of hydraulic conductivity, which would serve as the control data set.

The GMS software required modification to allow for the development of a gradient builder, seepage velocity field, flux distribution, and three-dimensional visualizations of the probe-derived hydraulic parameters. To generate three-dimensional hydraulic gradient vector values from scalar head value distributions, a finite difference solution was derived. The seepage velocity was then derived from interpolated hydraulic conductivity, hydraulic gradient, and effective porosity values. This velocity was then used in MODFLOW to establish groundwater and contaminant transport simulations. Once the solute concentration distribution was determined, a mass flux calculator was used to multiply the steady state seepage velocity distribution data set by the concentration distribution data set to create mass flux distributions for each time step analyzed.

## RESULTS AND DISCUSSION

Detailed results are presented in Kram et al., 2008. Figure 1 displays the hydraulic assessment test site configuration. Each numbered dot represents a three piezometer cluster. These were installed approximately every five feet within the test cell domain. Penetrometer probe pushes were advanced adjacent to each cluster for comparison.

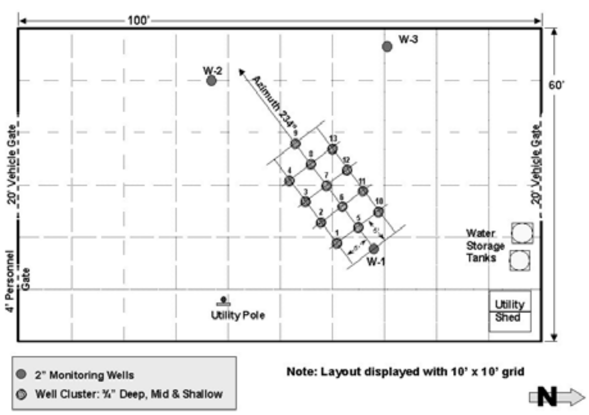


**FIGURE 1. Test site configuration. Numbered dots represent the well and push clusters. W-1, W-2 and W-3 represent perimeter monitoring wells.**

Figure 2 displays high-resolution piezocone output, which consists of logs of soil type, hydraulic conductivity versus depth (based on Robertson and Campanella [1989] soil type conversion), hydraulic conductivity versus depth (based on Parez and Fauriel [1988] relationships), effective porosity, pressure dissipation tests for specific depths, and head versus depth. Dissipation tests are used to determine K and head values for specific test depths. Each of the hydraulic attributes (K, head, and effective porosity) are interpolated and used to calculate seepage velocity distribution within GMS. Before doing so, head values are converted to gradient using the gradient builder function within GMS.

Once this has been completed, and K and porosity values are used to convert the probe data to seepage velocity distributions, chemical concentrations can be incorporated (using other probes or analytical methods) to generate three-dimensional distributions of chemical flux (representing seepage velocity times concentration).

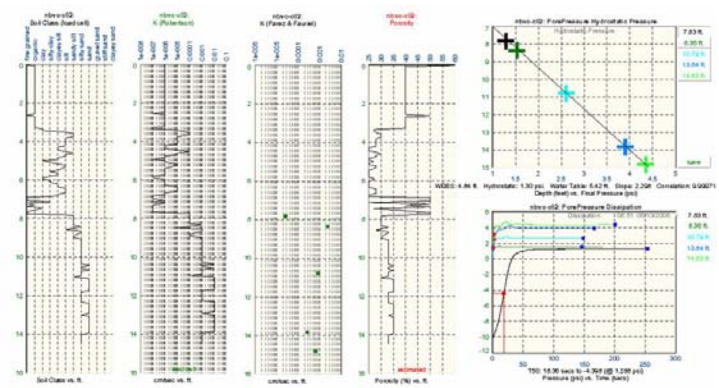

**FIGURE 2. Piezocone test output example for a single push.**

High-resolution piezocone derived K values are classified as $K_{mean,}$ $K_{min}$, $K_{max}$, $K_{form}$ and $K_{lc}$, where mean, minimum and maximum K values are derived through graphical Parez and Fariel relationships, where a Parez and Fariel formula is applied to the dissipation results, and where soil type is converted to K using a lookup chart embedded within the data processing platform. These are compared to K values derived from aquifer tests performed on the wells ($K_{well}$). It was found that the high-resolution piezocone derived hydraulic conductivity values were on average similar to those obtained from monitoring wells. Comparison of geometric mean values (Figure 3) shows that on average the Kmean and Klc values are within about a factor of 2 of the $K_{well}$ values. On average the $K_{min}$, $K_{max}$ and $K_{form}$ values fall within a factor of 5 or better of the $K_{well}$ values. K values derived from piezocone pushes ranged more widely than those derived from slug tests conducted in the adjacent monitoring wells. These differences may be attributed to averaging of the hydraulic conductivity values over the well screen versus more depth discrete determinations from the piezocone, which is more sensitive to vertical heterogeneities. While subtle differences can be seen, the overall agreement appears to be very good.

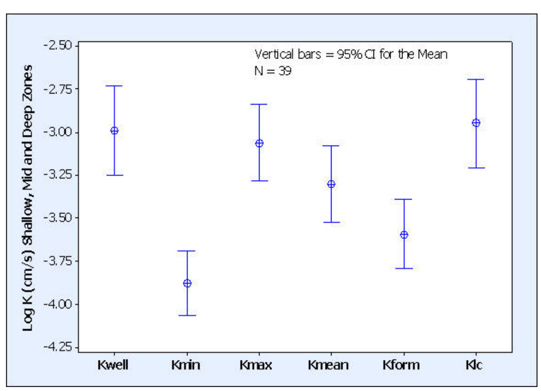


**FIGURE 3. Comparison of all K values, log transformed.
Circles are the geometric mean values.**

Hydraulic head distributions resulting from both the well clusters and the high-resolution piezocone results span only .08 feet for both distributions throughout the 25 foot by 10 foot test cell domain (Kram et al., 2008). While there are some directional nuances associated with each data set, the general gradients and head distributions display similarities. This is critical, as the probe will typically be deployed with much larger push spacing. Therefore, it is anticipated that by meeting these challenging field conditions, the high-resolution piezocone will be able to readily meet most field application requirements for relatively small sites (e.g., drycleaner, UST releases, etc.). Furthermore, the level of detail afforded by the high-resolution piezocone is unprecedented.

Gradient determination (critical for modeling efforts) required development of a gradient field based on recent GMS upgrades, which enabled users to convert scalar head values to gradient distributions. Finite difference calculations were used to transform adjacent grid node head values to gradient in three dimensions. When coupled with hydraulic conductivity and effective porosity distributions, the critical gradient builder step allowed for determination of seepage velocity distributions through the GMS velocity builder. Seepage velocity distributions derived from well hydraulic data and piezocone hydraulic data compared favorably (Kram et al., 2008). Provided concentration distributions are known, and a velocity distribution has been generated using the high-resolution piezocone data, GMS allowed for the determination of flux distributions in three dimensions. To develop concentration distribution predictions, boundary conditions were established through extrapolation of gradient values (derived from head value observations), and then a Modflow transport model was generated to develop realizations of tracer concentration distributions. These concentration distributions were then coupled with seepage velocity distributions to determine flux distributions for specific time steps using the new GMS flux builder tool.

Figure 4 shows predicted tracer flux distributions for Scenarios 1 (conventional well data) and 2a (piezocone data with $K_{mean}$) for 14, 49 and 84 days. The isosurfaces were generated at fluxes of 30 $\mu g/ft^2/day$, which is equivalent to a concentration of 35 ppb moving at the average groundwater velocity at the site (0.03 ft/day). Flow directions for both scenarios were within approximately 30º of the centerline of the piezometer cluster orientation (234º), but the well heads predict flow slightly to the west of the cluster centerline (Scenario 1), while piezocone heads predict flow slightly to the south (Scenario 2a). In considering the predicted flow directions, it is important to note that the zone of influence of the well measurements is distributed or averaged over a 6-inch screen, while the piezocone dissipation test is essentially a point measurement. In our opinion, the fact that there exists a fairly consistent main flow direction demonstrates that the two methods are in good agreement. Furthermore, predicted breakthrough times and concentrations were within an order of magnitude (Kram et al., 2008).

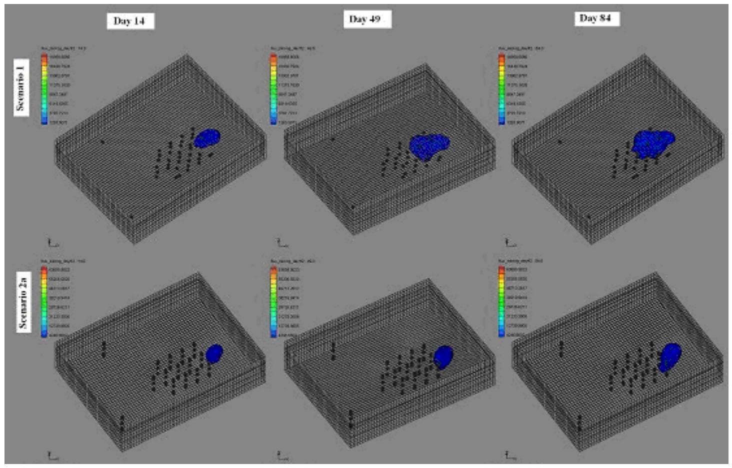


**FIGURE 4. Predicted flux distributions for models based on conventional and piezocone data.**

## CONCLUSIONS

The following conclusions can be derived:

1. High resolution piezocone allows for measurement of head, K, and effective porosity with high precision;
2. Using probe data and GMS, one can render 3D visualizations of seepage velocity, concentration, and flux distribution;
3. Once an initial model is established, well networks can be installed and monitored to track changes in dynamic flux components (e.g., hydraulic head and concentration);
4. Use of the high-resolution piezocone and associated flux models can save significant amounts of time (82 to 89 percent) and cost (62 to 81 percent) per application when compared to conventional flux characterization approaches (Kram et al., 2008).

This technology will be extremely useful during the remedial action optimization (RAO) and long-term monitoring (LTM) phases of a project. For instance, using this approach to determine the contaminant flux distribution will enable RPMs to prioritize and target areas of removal, remediation, and containment. The models generated through implementation of this technology can be used to evaluate competing remedial action designs. For LTM applications, understanding direction of flow, rate of flow, flux distribution, soil type distribution, and plume configuration are critical for establishing a monitoring network and for generating time series analyses appropriate for demonstrating plume attenuation. This technology will allow for generation of a high-resolution conceptual model, proper placement and design of monitoring wells, and for generation of input to models for projecting time of remediation and exposure point concentration near potential receptors.

## ACKNOWLEDGMENTS

The authors would like to express their gratitude to the members of the ESTCP review committees, and current and past team members from the Army, Navy, University of Wyoming and University of Connecticut. In particular, we would like to thank Dale Lorenzana of General Dynamics, Tim Shields (R. Brady and Associates), Kenda Neal (NFESC), Dr. Renduo Zhang (U. Wyoming), Meredith Metcalf (U. Conn.), and Lanbo Liu (U.Conn.), as their efforts proved critical to the success of this project. We would also like to acknowledge the efforts provided by ASTM, ITRC, and other intergovernmental, academic, and private sector participants serving on our Technical Advisory Committee. Their support has been instrumental in helping achieve national recognition and acceptance for the cost-effective technologies demonstrated under the aegis of this ESTCP project.

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