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Determination of Bedrock Hydraulic Conductivity and Hydrochemistry Using a Wellbore Fluid Logging Method

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ABSTRACT

One of the most challenging tasks faced by environmental engineers is cost effective hydraulic and hydrochemical characterization of a fractured bedrock aquifer by means of exploratory wellbores. To address this problem, a new borehole fluid logging method for rapidly and efficiently determining the vertical distribution of hydraulic conductivity in fractured bedrock aquifers has been developed. This new technique was recently applied near two active landfills in southern New England. The technique involves replacing the standing column of water in a borehole with a uniformly deionized fluid, and then profiling the changes in fluid electrical conductivity in the borehole. These changes occur when the contrasting formation water is drawn back into the borehole by continuous low flow rate pumping or by slug testing. A downhole wireline water-quality tool, which simultaneously measures fluid electrical conductivity, temperature, pH and oxidation-reduction potential (Eh), was employed to profile the physical/chemical changes of the "emplaced" fluid. The numerical code BORE, previously verified by Tsang et al. (1990), was employed to determine the inflow parameters and fracture-specific fluid electrical conductivity for the hydraulically conductive fractures. Straddle packer testing at 10-foot intervals was conducted to confirm the slug testing results. Some discrepancies were encountered which can be explained by accounting for the volume of formation affected by each method.

Based on the data presented herein, this new borehole technique can determine the fracture specific inflow parameters (hydraulic conductivity as a function of depth) and estimate hydrochemical parameters (fluid electrical conductivity, temperature, pH and Eh) for the associated formation water flowing through fractured bedrock aquifers.

INTRODUCTION

This paper presents field application and validation of a new borehole technique for rapidly and efficiently determining the location and hydraulic conductivity of discrete fractures and fractured zones in crystalline bedrock aquifers. The technique employs wellbore fluid logging to record induced changes in fluid electrical conductivity (FEC), temperature, pH and oxidation-reduction potential (Eh) as a function of depth in a borehole. Prior to logging, the wellbore fluid is replaced by a uniformly deionized fluid. Either continuous pumping or slug testing is then used to induce the now contrasting formation water back into the wellbore at specific depths corresponding to individual conductive fractures or fractured zones. The variation in fluid electrical conductivity is then used to determine the hydraulic conductivity versus depth profile.

The technique based on continuous pumping with time sequential fluid logging, and its analysis, was previously developed by Tsang and co-workers (Tsang 1987, Tsang and Hufschmied 1988, Hale and Tsang, 1988, Tsang, et. al. 1990). Field validation of this method was described by Tsang et. al. (1990) for the Leuggern well which is a deep borehole (2700m) drilled through granite and biotite gneiss in Switzerland for research related to nuclear waste isolation. The slug testing based technique was described by Pedler and Urish (1988) for the shallow geohydrological environment. This method was field validated in multiple boreholes up to 125 feet deep at an active landfill in Southeastern Massachusetts (Pedler et. al. 1989). As presented below, the continuous pumping/time sequential logging technique has
been recently applied to the shallow environment in a 200 foot deep wellbore near an active landfill in Rhode Island. The parameters of fluid electrical conductivity (FEC), temperature, pH and oxidation-reduction potential (Eh) were logged at this site to evaluate the fracture specific hydrochemistry as well as determine the variation of hydraulic conductivity with depth.

The application of this technique in the shallow hydrologic environment is emphasized in this paper in as much as this regime encompasses most hazardous waste investigatory work performed in the Northeastern United States. Data obtained for the shallow environment using both slug testing (Pedler et al. 1989) and continuous pumping techniques are presented.

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**GEONHYDROLOGIC SETTING**

Wellbore fluid logging after slug testing was conducted at an active landfill in southeastern Massachusetts. The two boreholes tested are proximate to a thrust fault controlled contact between the metamorphics of the Pennsylvanian Narraganset Basin Series Wampsutta formation and faulted Precambrian Dedham granite (Figure 1a). The second study area, where the data was developed by fluid logging during continuous pumping, was located near an active landfill in Rhode Island (Figure 1b). This landfill, located on fractured Scituate Granite/Granodiorite, has been the subject of extensive geohydrological and geophysical investigations. Surficial overburden deposits at both sites consist of glacial derived sediments.

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**Figure No. 1a.** Massachusetts landfill site/exploration plan for wellbore fluid logging after slug testing.
FIGURE No. 1b. Rhode Island landfill site/exploration location plan for wellbore fluid logging during continuous pumping.

METHODOLOGY

The technique can be summarized as comprising the following steps. First, a solid riser is deployed to the bottom of the wellbore to emplace the uniformly deionized fluid during simultaneous evacuation of the borehole water near the free water surface. The deionized fluid consists of either formation water or potable water with dissolved ionic species removed. Unlike many fluids commonly used for tracer studies, deionized water is completely safe from environmental and health and safety standpoints. Logging of the baseline conditions is performed immediately after emplacement of the deionized fluid. Slug or continuous pumping tests are then conducted to induce contrasting formation water into the wellbore. Changes in fluid electrical conductivity of the borehole water occur due to mixing of (and subsequent displacement by) the contrasting formation water with the emplaced column of deionized fluid. Wireline water quality instrumentation is employed to log the wellbore fluid column and record the resulting fluid electrical conductivity (FEC) profile. The FEC logging results are then used in conjunction with the slug test or pumping test data to identify the producing intervals and determine depth specific hydraulic conductivity.
At the Massachusetts landfill (wellbores GZ-14 and GZ-15), slug testing was performed in accordance with procedures developed by Hvorslev (1951). Testing was accomplished by rapid extraction of a small volume of water from the top of the borehole using an extraction riser and pump. A drop in piezometric head of approximately 3 feet was typically employed. The rise in the free water surface was recorded with time and a conventional time lag plot developed. Wellbore fluid logging was conducted after near complete recovery of the piezometric surface. Lastly, analyses were performed to obtain quantitative values for the individual hydraulically conductive zones from the initial slug test results.

At the Rhode Island landfill (borehole PA0-1), time series wellbore fluid logging during continuous pumping was conducted. Procedures were similar to standard pumping tests, with a constant rate of fluid extraction maintained and measurement of the piezometric surface. The changing wellbore fluid conditions were logged as a function of depth at different times during pumping. The resulting time sequential FEC logs and the “short-term” pumping test were then analyzed to determine the hydraulic conductivity of the individual producing intervals. Temperature, pH and Eh logs were contemporaneously obtained to evaluate the hydrochemical conditions of the formation water.

**Results of Wellbore Fluid Logging after Slug Testing**

The location and relative importance of individual fractures or fractured zones are determined by comparison of the initial baseline fluid electrical conductivity (FEC) log and subsequent FEC logs obtained after slug test extraction. These data for borehole No. GZ-15 are presented in Figure 2a. A uniform baseline fluid electrical conductivity of 25 micromho/cm was achieved over the entire 70 feet of open bedrock borehole. Much higher conductivities, consistent with the formation water, remained in the cased interval where the formation water was not removed. FEC logging after extraction of 3.5 feet (5 gallons) of the wellbore water showed one well-defined, discrete zone of increased conductivity at a depth of about 67 feet. A conductivity increase from 25 to 40 micromho/cm was easily discernable as the formation water invaded the borehole and mixed with the deionized fluid. The signature location corresponded to the only hydraulically transmissive zone previously predicted using straddle packer testing. Subsequent extraction of an additional 10 feet (15 gallons) of fluid provided further conductivity contrast (130 versus 25 micromho/cm) at the fractured zone. Even after final extraction, the bottom 40 feet of borehole, below the fractured zone, exhibited no significant change in conductivity. The 10-foot interval above the fracture zone showed a minor change, as expected due to formation water flowing up the borehole and mixing with deionized fluid during successive logging runs.

The ultimate goal of fluid electrical conductivity logging is not only to locate hydraulically transmissive zones, but also to quantify their hydraulic conductivities. The required analysis assumes that the fluid electrical conductivity of the formation water produced during the slug test is constant with time and depth. Therefore an increase in electrical conductivity after fluid extraction is directly proportional to the volume of formation water drawn into the borehole at any given depth, and thus, proportional to the hydraulic conductivity of the associated fracture or fractured interval. Determination of the hydraulic conductivity profile from the FEC log first requires discretization of the total borehole transmissivity measured during the initial slug test. This is accomplished based on the relative areas subtended by anomalies in the post-extraction FEC log, as compared to the baseline FEC log. The individual transmissivities are then converted to hydraulic conductivity values using a 10-foot long interval and assuming a multi-layered porous media model. An interval length of 10 feet was adopted for consistency with the packer testing used to evaluate the accuracy of this new technique. While it is recognized that the interval length selected influences the hydraulic conductivity computed in an inverse linear fashion, and that the medium is fractured instead of porous, the same compromises are present for the packer testing. Figure 2a graphically portrays the hydraulic conductivity derived from this technique in comparison to the associated straddle packer testing data for borehole GZ-15; an excellent correlation is evident.

Similar data are presented for GZ-14, another borehole drilled and tested for bedrock aquifer characterization at this landfill site (Figure 2b). The log for this borehole indicates relatively high electrical conductivities from 70 to 110 feet (generally greater than 65 versus 50 micromho/cm) with particularly high values at 78 and 98 feet (peak conductivities of 85 and 75 micromho/cm, respectively). The FEC log implies that a hydraulically conductive zone is located at these peaks. Review of the packer testing data in conjunction with these FEC logs
and those subsequent logs obtained during very early pumping times. These data for borehole PAO-1 are presented in Figure 3. A relatively uniform baseline FEC log (PAO1223) of 5-10 micromho/cm was achieved over the entire borehole length. The slight increase in fluid electrical conductivity observed over the top 10 meters, as well as small undulations in the FEC values, suggest minor contamination of the deionized fluid by formation water during the fluid emplacement procedure. The slight increase in fluid electrical conductivity at 53m suggests that a small volume of formation water emanating from a corresponding fracture zone also contaminated the deionized wellbore fluid prior to baseline logging.

Due to mechanical difficulties experienced, fluid remained stagnant for approximately 63 minutes. A second logging (log PAO1345) was therefore conducted prior to fluid extraction. This log clearly shows three distinct spikes at 16m, 26m and 53m. It is hypothesized that these spikes identify fracture locations where formation water has infiltrated the deionized borehole column due to hydraulic pressures indigenous to the aquifer.

At the completion of the second logging, pumping was initiated at a constant rate of 1.85 gpm. After approximately 21 minutes, a third logging (log PAO1406) was conducted. This log displays saturation of the interval from 12.5m to 16m with fluid exhibiting an electrical conductivity of 45 micromho/cm. The saturation conductivity reflects a mixture of formation water and deionized water displaced from below, and is therefore less than the conductivity of the formation water produced from the 16m fracture. Mixing occurs at all fractures (except for the deepest fracture) because formation water produced at a given depth is injected into the borehole fluid which is moving upward due to displacement by fluid production at greater depths. Further review of log PAO1406 shows the first indications of a producing fracture zone at 29m. This producing zone was not observed in the previous log (PAO1345).

The next logging (PAO1428) was conducted after 44 minutes of constant pumping (approximately 82 gallons or 0.3 wellbore volumes). The FEC response to the producing fracture zone at 53m displays an increased amplitude; from 52 micromho/cm in log PAO1406 to 90 micromho/cm in log PAO1428. The area subtended by the response curve for this fracture zone has also increased. The leading edge, or front, associated with this response curve has continued to progress up the wellbore while the trailing edge has advanced down the wellbore. The movement of the trailing edge in a direction opposite to that of borehole fluid transport was most probably caused by vertical mixing during logging runs, and to a lesser degree by diffusion.

The continued production of formation water from the fracture zone at 29.5m has advanced the associated front to the point where the "trough" between 25m and 29.5 meters (log PAO1345) is now dramatically reduced as shown in log PAO1428. The front associated with the fracture at 25m has advanced considerably and has "overlapped" the signature associated with the fracture at 16m. The mixing of the advancing front with the formation water produced at 16m has caused an increased fluid electrical conductivity at the 16m location. The fluid electrical conductivity at 16m continued to increase as the front advanced until the interval from 16m to 29.5m was saturated with 120 micromho/cm water (log PAO1623).

The last log was obtained after 2.65 hours of continuous pumping (approximately 295 gallons or one wellbore volume). This log (PAO1623) shows the continued growth of the fluid electrical conductivity response for the fracture zone at 53m and saturation of the interval from 29.5m to 10m. This interval should remain saturated at this value until the deeper advancing front (associated with the fracture zone at 53m) encounters the fracture zone at 29.5m. Complete saturation of the wellbore fluid column occurs after the lowermost front has encountered all the producing intervals and advanced to the pump inlet.

**Results of Time Series Wellbore Fluid Logging During Continuous Pumping**

Time series wellbore fluid logging during continuous pumping was conducted near an active landfill in Rhode Island. Similar to slug testing procedures, the locations of individual fractures and/or fracture zones were determined by comparison of the initial baseline FEC log and those subsequent logs obtained during very early pumping times. These data for borehole PAO-1 are presented in Figure 3. A relatively uniform baseline FEC log (PAO1223) of 5-10 micromho/cm was
To analyze these data, the considerations and formulae from Hale and Tsang (1988) and Tsang, Hufschmied, and Hale (1990) were applied. Three fractures are schematically shown in Figure 4. Note that the flow rates at different parts of the wellbore are different, being equal to the sum of all upstream inflow rates. At each fracture inflow point, the parameters characterizing the flow are: t, the time when the fracture fluid emerges at the wellbore; x, the location of the inflow point; q, the volumetric inflow rate; and q, the solute mass inflow rate, where C is the concentration of ionic solutes in the fracture fluid. It has been assumed that t can generally be different for different fracture inflow points. This could be due to differences in initial values of hydraulic head in these fractures or the specific borehole development and pressure history, with the result that the deionized water enters the fractures to varying degrees during emplacement of the deionized water. Therefore, when the wellbore is pumped at flow rate Q, the deionized water from the fractures first returns to the borehole, thus delaying the arrival of in-situ fracture water.

**Fluid Electrical Conductivity (micromho/cm)**

![Fluid Electrical Conductivity Graph]

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<td>(baseline)</td>
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<tr>
<td></td>
<td>PA01623</td>
<td>(2.65 hrs.)</td>
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FIGURE No. 3. Time series fluid electrical conductivity profiles obtained by fluid logging during continuous pumping of POA 1.
Figure 5 displays schematically the salinity distribution inferred from the fluid electric conductivity distribution in the wellbore for a series of times. Tsang and co-workers developed a computer program called BORE which performed a multi-parameter fit of the FEC logs to determine values of $q$ and $C_1$ for each of the producing fractures. Details may be found in the references.

\[
\begin{align*}
q_1 + q_2 + q_3 + w \\
q_1 + q_2 + w \\
q_1 + w
\end{align*}
\]

**Figure No. 4.** Schematic picture of a wellbore with three inflow points and a background flow rate $w$ from below.

Figure 6 describes the BORE input parameters and the resulting match to the field data obtained for wellbore PAO-1. For the producing fracture zone at 15m, 25m and 29.5m, BORE accurately simulated the field data for both early and late times. The lowermost producing fractures at 53m yields the poorest match between the code generated early time logs and the corresponding field logs. The late time logging (2.65 hrs) provides the best fit for this interval. The suspected cause for the poor match was fluid dispersion by the logging tool.

Once $q$ is determined for each producing interval, the corresponding hydraulic conductivity can be determined from review of the drawdown data recorded during pumping. Assuming steady state conditions, a 2-dimensional radial flow pattern, and an effective radius ($r_e$) of 350 feet, an equation after Hvorslev (1951) for hydraulic conductivity is

\[
K = \frac{Q}{2\pi L \Delta h_w} \ln \frac{r_e}{r_w}
\]

where $Q$ is the steady state flow from each test interval of length $L$, $r_w$ is the borehole radius and $\Delta h_w$ is the head difference between ambient and steady state conditions. $Q$ is equal to $q$ for each of the identified producing intervals. The solution for hydraulic conductivity for each $q$ using $L=10$ feet and $\Delta h_w = 13.15$ is given in Figure 6.

Previous field validation of this analytical method (Tsang et al. 1990) was successfully performed in deep wellbores based on independent straddle packer testing and discrete formation water sampling. Current results for the case of shallower wells will be further validated via independent straddle packer testing which is presently underway. The study will also determine the efficacy and cost versus benefit of this technique in the relatively shallow fractured bedrock aquifer environment.

**Estimation of Fracture-Specific Hydrochemistry**

As described in the previous section, fracture-specific fluid electrical conductivity was determined using the code, BORE. Contemporaneously with the fluid electrical conductivity logging, the hydrochemical parameters of pH and oxidation-reduction potential (Eh) were recorded. Figure 7 presents the logs for these parameters obtained during logging run PAO1623. A review of these logs gives a qualitative estimate of the variability of water types present in the wellbore. A quantitative method for analysis of these results is currently being developed based on the specific fracture zone flux as identified by the fluid electrical conductivity logging analysis described above.

Based on the work to date, it appears that further development of the instrumentation is needed to provide stabilized readings of pH and Eh in formation waters of low ionic strength. It is anticipated that with these forthcoming developments, fracture specific values for pH can be obtained by application of mass balance principles similar to those employed for determining fracture specific fluid electrical conductivity.
A new borehole method, developed for characterization of groundwater flow in fracture bedrock aquifers, has been tested in the crystalline bedrock hydrogeologic regime near two active landfills in southeastern New England. The technique combines standard pumping or slug testing methodologies with fluid logging in wellbores where the water column has been replaced with an environmentally safe deionized fluid. Fluid electrical conductivity logging is used to elucidate zones of contrast between the emplaced fluid and the formation water which invades the borehole under pumping or slug testing procedures. These fluid electrical conductivity logs are then evaluated to determine hydraulic conductivity as a function of depth for the bedrock aquifer.

Data developed using the slug testing indicate that this new, more cost effective investigatory method compares favorably with standard straddle packer testing. Application of the previously verified numerical code, BORE (Tsang 1987, Hale and Tsang 1988, Tsang et al 1990) to the FEC logging data obtained during low flowrate continuous pumping further demonstrates the usefulness and capability of this new technique.

The data appears to support the following conclusions:

- The associated aquifer is subjected to minimal disturbance. In the case of slug testing, hydraulic characterization was achieved after extraction of 20 gallons of wellbore fluids. For the fluid logging during continuous pumping, hydraulic and hydrochemical characterization was achieved with the net removal of only one wellbore volume of fluid.
Employment of time dependent wellbore fluid logging after completion of deionized fluid emplacement, or at the completion of formation water induction, could be employed to observe and quantify vertical flow in the wellbore under ambient pressure conditions.

With continued downhole instrument improvement, this new technique has the potential of estimating specific hydrochemical parameters (temperature, fluid electrical conductivity, pH and oxidation-reduction potential) of fracture-specific formation water. The technique can yield information commonly obtained with injection/extraction packer testing, but in a much shorter time and at a significantly reduced cost. Further validation studies are underway and more complete results will be presented in the near future. However, it already appears that this investigatory tool may be particularly valuable for the hazardous waste engineer involved in projects where an understanding of bedrock contaminant transport mechanisms is critical for site remediation.

**FIGURE No. 7.** Fluid electrical conductivity, temperature, pH and oxidation-reduction potential (Eh) logs for late time logging.
ACKNOWLEDGEMENTS

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