

RAPID ASSESSMENT PROTOCOL

Rapid Assessment of Remedial Effectiveness and Rebound in
Fractured Bedrock

ESTCP Project ER-201330

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Charles Schaefer, Ph.D.
CDM Smith

David Lippincott, P.G.
CB&I Federal Services

Kirk Hatfield, Ph.D.
Harald Klammler, Ph.D.
University of Florida

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RAPID ASSESSMENT PROTOCOL

The following protocol is intended to serve as a general guidance for designing, implementing, and evaluating the rapid assessment (RA) technique developed as part of ESTCP Project ER-201330.

1. Overall Approach and Testing Location

The RA protocol is intended to assess chlorinated solvent rebound (particularly chlorinated ethane), the potential of naturally occurring dechlorination reactions in low permeability zones, and remedial effectiveness using a pair of closely spaced bedrock wells. This protocol is designed to assess the remedial effectiveness of *in situ* technologies such as bioaugmentation and chemical oxidation that target and biotically or abiotically degrade contaminants in hydraulically conductive fracture zones. The RA technique involves identifying hydraulically conductive fracture zones, flushing contaminant from the fracture zones using water, then evaluating contaminant rebound within this zone while hydraulically isolating the zone from the surrounding contaminated aquifer. The rate, composition, and isotopic signature of contaminant rebound is then used to evaluate the limits of remedial effectiveness, identify the local source/cause of any observed rebound, and provide improvement to the site conceptual model.

The protocol described herein will describe the general methodology for one location (i.e., one well pair). However, depending on the site characteristics, multiple well locations/well pairs may be needed. For example, if the areal extent being considered for remediation consists of multiple geologic units, or if both a source area (with potential DNAPL sources) and the downgradient plume are being considered for *in situ* treatment, then multiple locations should be considered.

For the RA testing, a pair of open borehole wells spaced 5 to 15 ft apart is recommended. The boreholes should be isolated from overburden materials. One borehole will serve as the injection well, and the other borehole will serve as the monitoring well. Following the characterization described in Section 2, up to 3 chlorinated solvent impacted fracture zones (maximum) should be targeted and isolated using either packers or other borehole tools to isolate specific fracture intervals; isolated intervals should not exceed 10 ft. For sites where treatment in multiple hydraulically conductive fracture zones with multiple (>3) geologic layers, multiple sets of RA test well pairs may be considered.

2. Initial Characterization

Information regarding the fracture flow field, contaminant distribution, and rock matrix properties are needed to perform the RA testing. Specifically, this information is needed to determine which interval(s) to isolate for the RA test, and to provide information needed to interpret the rebound data via matrix back-diffusion simulations. Much of this information may be readily available based on site information attained from previous testing and investigations; however, additional testing may be required to properly design, implement, and interpret RA test results. The initial characterization information discussed below is required for each fracture zone of each well targeted for potential treatment.

Fracture Identification

Identification of potentially conductive fractures or fracture zones serves as one of the initial steps of the RA approach. Numerous borehole geophysical tools are available for this identification, as

well as visual core logging; a detailed discussion of these tools are beyond the scope of this protocol. It is noted that identifying the number of fracture planes within a targeted test interval is useful for estimating the potential contribution from the rock matrix during rebound (see Section 5).

Rock Matrix

A measure of the rock matrix porosity is needed to estimate the effective aqueous phase diffusion coefficient through the rock matrix, via use of readily applied correlations (e.g., Boving and Grathwohl, 2001). More complex models and/or experimental approaches also can be employed in anisotropic matrices that contain bedding planes (Schaefer et al., 2012). Rock containing ferrous minerals may also facilitate abiotic dechlorination of chlorinated ethenes; bench-scale batch testing methods have been developed to quantify these dechlorination reactions (Schaefer et al., 2015). Together, this information can be used in a screening-level matrix back-diffusion model (e.g., CRAFLUSH model [Sudicky and Frind, 1982; Davis and Johnston, 1984; Sudicky and Frind, 1984]) to interpret RA testing results.

Contaminant Characterization

Baseline concentrations of chlorinated solvents in each of the identified hydraulically conductive fracture zones need to be determined. These baseline concentrations should initially be made both prior to the hydraulic and tracer testing (described in the section below) to facilitate identification of the relevant fracture zones for testing, and then just prior to the rapid flushing phase (described in Section 3). This characterization should be performed using discrete interval sampling (e.g., packers) with the target fracture zone(s) isolated. The contaminant characterization performed immediately prior to the rapid flushing also should consist of compound specific isotope analysis (CSIA) for carbon, as carbon isotopic shifts during rebound can provide insight into the rebound mechanism (discussed in greater detail in Section 5).

Hydraulic and Tracer Testing

Using the isolated fracture intervals, hydraulic testing should be performed for each target interval. Short term pump or drawdown testing should be used to estimate the hydraulic conductivity within each interval, and to confirm a hydraulic connection between the injection and monitoring well intervals. A borehole dilution test is needed in the injection well across the entire injection interval. The injection interval of the injection well can be a single zone extending across the multiple discrete intervals of the monitoring well, or multiple injection intervals corresponding to fracture zones in the monitoring well (see Figure 1). This information is used to determine the ambient flow into the injection well, and ultimately the injection rate needed to provide the hydraulic control needed during the slow injection (rebound) phase of the RA testing (Section 4). Borehole sampling should be performed to limit the volume of water removed from the borehole via strategies such as in-well recirculation of fluids.

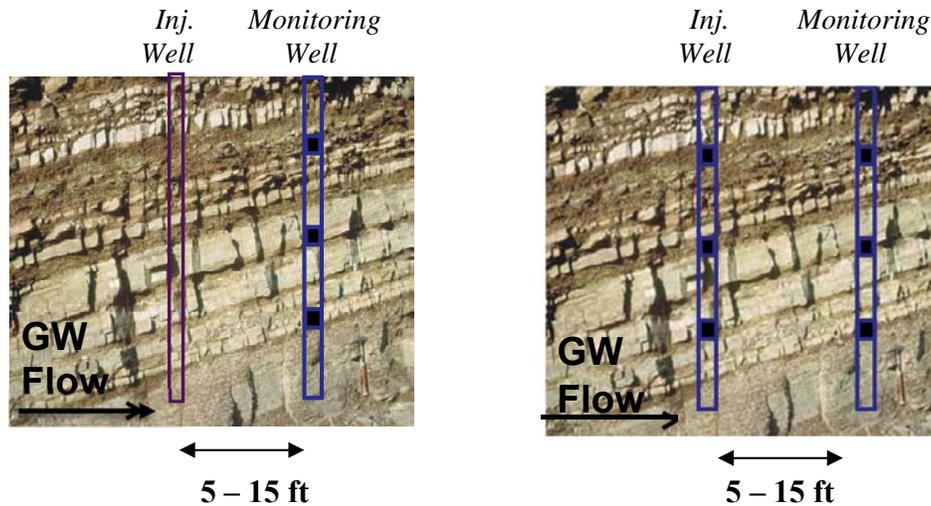


Figure 1. The injection well can be configured such that the open borehole injection interval spans the interval of the multi-level monitoring well (left), or the injection well can be configure as a multi-level injection well (right).

If the option on the right is selected, borehole dilution and tracer testing should be performed for each of the injection well intervals. The shaded zones in the wells represent packers.

To confirm the fracture flowpath and estimate the effective fracture porosity and aperture (via a radial plug flow along identified fractures), a tracer test is required. The tracer injection should be performed in the same interval(s) used for the injection well borehole dilution testing, and monitored in each of the target intervals in the monitoring well. Sampling in the monitoring well locations during the tracer testing should be performed in a way that limits the volume of water removed, thereby limiting any induced hydraulic gradients during the ambient flow tracer test.

3. Rapid Flushing

After completion of the testing described in Section 2, and immediately after the final baseline sampling and CSIA analysis, the rapid flushing phase of the RA testing should commence. The objective of the rapid flushing is to remove contaminants (a minimum of 99% removal) from hydraulically conductive fractures in the test intervals by injecting “clean” (i.e., non-contaminated) water into the injection well, thereby simulating the effects of *in situ* treatment. A period of 1 to 3 months is recommended for the rapid flushing. Periodic monitoring of both the injection well and monitoring well intervals should be performed to determine the extent to which the target contaminants have been flushed from the system. The injection flow will be dependent upon the capacity of the injection well, as well as how quickly the monitoring well intervals are being flushed. If needed, direct injection into the monitoring well intervals can be performed to enhance the flushing of contaminants from the test zone. Fast flushing should continue (at least) until dissolved contaminant concentrations decrease to less than 1% of baseline levels.

A minimum of 1 month of flushing is recommended so that rebound can be more effectively evaluated. During rapid flushing, care should be taken to ensure the borehole intervals are sufficiently mixed so that stagnant zones do not impede flushing. If continued flushing and direct

flushing into the monitoring well do not result in concentrations decreasing by 99%, DNAPL may be present within or adjacent to the boreholes.

4. Slow Flushing / Rebound

Immediately following the rapid flushing, the slow flushing (rebound) phase of the testing will commence. The objective of the slow flushing phase of the RA testing is to observe and quantify the rate of any contaminant rebound following the rapid flushing while controlling the flow field between the injection well and monitoring well so that chlorinated solvent-impacted groundwater from upgradient does not impact the monitoring well. Thus, any increases in contaminant concentrations observed at the monitoring well during the slow flushing phase are attributable to contaminant mass along the flow path between the injection and monitoring well, and not from contaminants migrating into the “treatment zone” from upgradient.

Clean water used for the slow injection phase should be delivered into the injection well using the same configuration (i.e., Figure 1) used during the rapid flushing phase. The injection rate during the slow flushing will be based upon the Darcy flow into the injection well (or, injection well interval) measured as part of the testing described in Section 2.

The injection rate used during the rebound phase is intended to limit excessive dilution, while at the same time prevent upgradient impacts to the monitoring well from fractures intersecting the well pair. Using the calculated Darcy flow (Section 2), the total ambient groundwater flow rate passing through the cross-section area defined by the injection well depth interval and the radial distance r from the injection well (where r is the distance between the injection and monitoring wells) is calculated. The injection well flow rate during the slow flushing phase should be approximately twice this ambient rate, thereby providing a reasonable level of confidence that groundwater flow from upgradient is not entering the targeted intervals of the monitoring well.

Periodic monitoring for target contaminants should be performed at monitoring well locations during the rebound period. The rebound period should last a minimum of 3 months, or until either a clear trend or stability has been attained. Sampling for CSIA (carbon) should be performed on all target contaminants; this sampling should be (at least) performed at the final rebound sampling event.

5. Data Evaluation

Both the rate and extent of rebound, as well as the CSIA data, can be used to provide insight into the contaminant mass distribution and the extent to which *in situ* treatment may be effective. If the CSIA carbon data show isotopic enrichment at the end of baseline, then the source of the rebound is likely due to enhanced dechlorination reactions occurring in either the rock matrix or lower transmissivity fractures zones (rebound from DNAPL is unlikely to exhibit isotopic enrichment). As discussed in Section 2, bench scale testing using rock core can also be used to determine if dechlorination reactions are occurring within the rock matrix.

Using a matrix back-diffusion model such as CRAFLUSH, along with parameters determined during the testing described in Section 2 (effective diffusion coefficient through the rock, number of fractures, fracture aperture, travel time through the fractures, dechlorination rate constant within the rock matrix), the expected rebound during the slow flushing phase of the RA testing (Section 4) can be predicted. Comparison of the model rebound data to the model prediction should be used

to assess whether or not the observed rebound is reasonably explained by matrix back-diffusion. For the case where matrix back diffusion is identified as the mechanism for the observed rebound, a model such as CRAFLUSH can be used to scale results to the intended treatment zone, which would likely extend beyond the 5 to 15 feet that separate the injection and monitoring well for most site applications. What is key is that the results of the rebound testing provide the critical mass transfer parameters needed to assess the impacts of the rock matrix, and any dechlorination reactions therein, on groundwater quality. If matrix back diffusion is not responsible (based on comparison of the model) for the observed rebound, DNAPL sources and/or contaminant mass in lower transmissivity fractures would be the suspected cause of the rebound. Additional tracer testing, as described in Schaefer et al. (2016) would need to be implemented to provide additional characterization.

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