EXECUTIVE SUMMARY

A Rigorous Demonstration of Permeability Enhancement Technology for In Situ Remediation of Low Permeability Media

ESTCP Project ER-201430

JANUARY 2019

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1.0 INTRODUCTION

When reagents that stimulate biological or chemical destruction of contaminants can be mixed uniformly with target contaminants in the subsurface, remediation practitioners can have a high degree of confidence that the treatment will be reasonably effective. While this represents an enormous opportunity for the industry, the formidable challenge remains of ensuring that mixing and/or contact of biological or chemical treatment reagents with target contaminants occurs in a reasonable timeframe in low-permeability or fractured geological settings.

Conventional injection wells are typically adequate for delivering reagents in homogeneous geologic formations with a bulk hydraulic conductivity of 10^{-4} centimeters per second (cm/s) or greater; however, practitioners are well acquainted with the shortcomings of amendment injection using conventional wells in lower permeability settings (United States Department of Energy [DoE] 1996). Another problem with conventional injection wells in low-permeability settings is that a high degree of heterogeneity typically exists even within a 10-foot well screen, often ranging over multiple orders of magnitude of permeability. Given that the volumetric flow rate entering different vertical horizons in the injection well screen is proportional to the hydraulic conductivities of those horizons, the vertical distribution of injected amendment can be highly preferential; that is, 90% or more of the total volume might easily be pushed out into soils adjacent to less than 10% of the well screen interval.

In recent years, several technologies have been developed to address the challenge of achieving a uniform and effective distribution of treatment amendments in low-permeability and fractured media. These advances include hydraulic and pneumatic permeability enhancement technologies, both of which can emplace amendments into low-permeability media. Emplacing treatment amendments using these techniques can help overcome the aforementioned limitations of traditional amendment injection techniques where low-permeability soils can impede delivery. Significant confusion currently exists in the industry as to the differences among hydraulic and pneumatic permeability enhancement technologies and permeation injections. While one technology may be more warranted for a particular application, practitioners often do not have the information required to make good decisions regarding which delivery technique to use. Definitive guidance for selecting the most appropriate technique is needed.

In addition, significant advances have been made in technologies that can provide high-resolution mapping of the subsurface distribution of amendments. However, a rigorous comparison of such methods in different geologies of low hydraulic conductivity has never been made, in part because the high-resolution mapping and data processing tools are proprietary and have not been widely commercialized and implemented. Consequently, no guidance is available for practitioners or site managers to assist in the selection or specification of amendment distribution and monitoring techniques for assessing amendment delivery within low-permeability media.

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2.0 OBJECTIVES

The overall objective of this project is to compare the performance and cost benefits of hydraulic and pneumatic permeability enhancement for *in situ* treatment at low-permeability sites. The technical objectives of this demonstration/validation project are to:

- Demonstrate the amendment distribution capabilities of permeability enhancement techniques in three different geologic settings with low permeability;
- Demonstrate and validate the use of tilt meter monitoring as a novel, high-resolution, and non-invasive mapping technique to aid in evaluating the performance of permeability enhancement technology;
- Collect sufficient performance and cost data to develop a concise guidance document to help remediation project managers and practitioners select and/or specify the optimal *in situ* delivery technique for a given low-permeability site, and the monitoring approach to quickly validate its performance; and
- If possible, compare *in situ* delivery performance results using permeability enhancement techniques to those of more conventional injection approaches.

The technology demonstration was performed at three separate sites with low-permeability lithologies: the Marines Corps Base – Camp Pendleton (MCB-CP) Site 1115 located in Oceanside, California; the Lake City Army Ammunition Plant (LCAAP) Site 17D located in Independence, Missouri; and the Grand Forks Air Force Base (GFAFB) site TU504 located in Grand Forks, North Dakota. The hydraulic approach to permeability enhancement was performed at all three sites. In addition, hybrid pneumatic permeability enhancement was performed at LCAAP to provide a direct comparison between the hydraulic and the hybrid pneumatic approach to permeability enhancement. Advanced geophysics monitoring tools including tilt meter monitoring, electrical conductivity logging (EC logging), and electrical resistivity tomography (ERT) were used to evaluate the vertical and horizontal extent of amendment distribution resulting from permeability enhancement, and conventional soil confirmation and groundwater performance monitoring were used to validate the geophysics monitoring tools.

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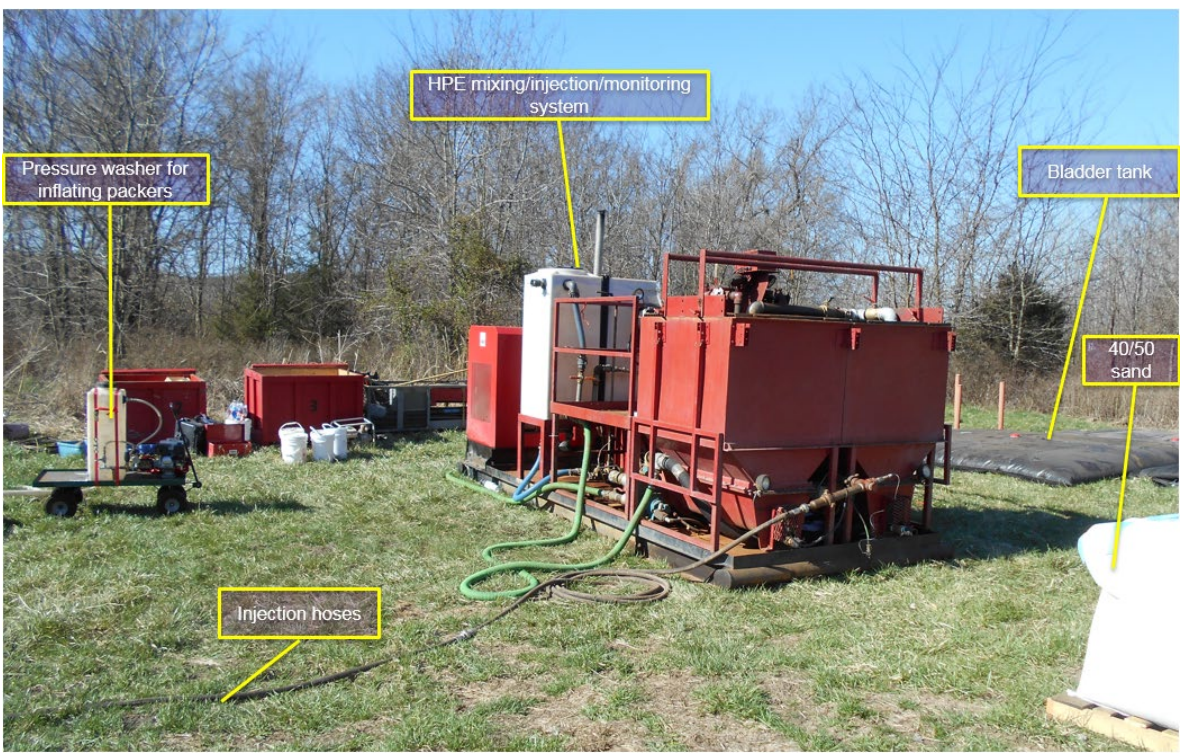
3.0 TECHNOLOGY DESCRIPTION

3.1 HYDRAULIC PERMEABILITY ENHANCEMENT

Invented by the oil and gas industry, permeability enhancement technology was modified to aid remediation of soil and groundwater in the late 1980s (United States Environmental Protection Agency [EPA] 1993 and 1994). The goal of permeability enhancement technology is to increase bulk hydraulic conductivity and amendment delivery radius of influence (ROI) to facilitate enhanced *in situ* remediation in low-permeability formations. A low- or high-viscosity fluid is introduced into a borehole at a rate and pressure high enough to overcome the *in situ* confining stress and the material strength of a geologic formation, resulting in the formation of a fracture. In high-viscosity permeability enhancement applications, sand can be injected simultaneously with a solid amendment such as zero-valent iron (ZVI) to maintain the integrity of the propagated fractures that can otherwise become restricted or collapsed entirely, particularly in plastic geologic materials (U.S. Patent No. 7,179,381). The emplaced fracture network typically results in an increase in hydraulic conductivity by about an order of magnitude and allows for more effective injections or extractions. Hydraulic permeability enhancement can be performed using almost any drilling technique, including direct-push.



3.2 PNEUMATIC PERMEABILITY ENHANCEMENT

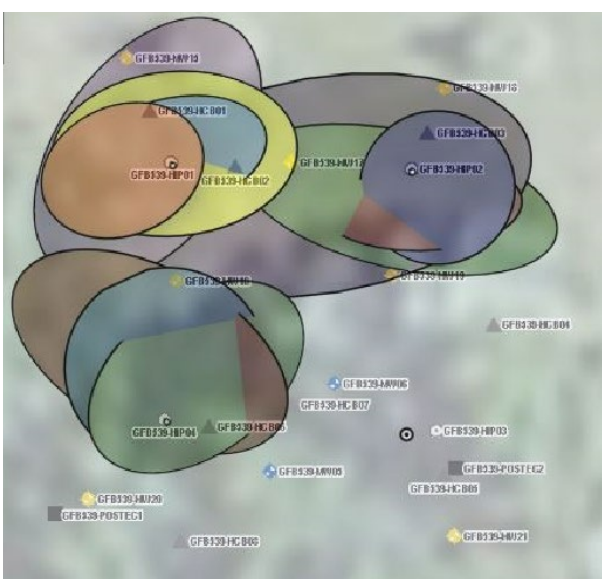
Pneumatic permeability enhancement technology utilizes a gas at flow volumes exceeding the natural permeability of the formation to generate high enough pressures to overcome the *in situ* confining stress and the material strength of a formation such that fractures are formed (EPA 1995). The result is the enhancement of existing fractures and planes of weakness (e.g., bedding planes) and the propagation of a dense fracture network surrounding the *in situ* delivery well. Once a

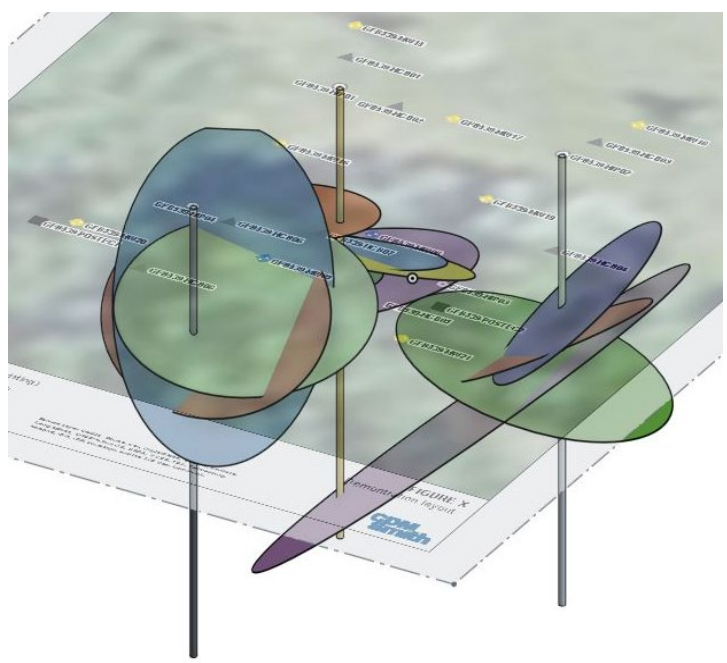
geologic zone has been fractured, the injection of the amendment can be performed in an integrated process. For example, the amendment liquid or slurry can be blended into a nitrogen gas stream above ground and become atomized. Relatively low pressures are required to sustain the flow into the formation. The atomization apparatus is a down-hole injection assembly that consists of an injection nozzle with straddle packers that isolate and focus the injection to the target interval. Using this method, the amendment might be distributed 10 to 25 radial feet depending on site-specific conditions. As with hydraulic permeability enhancement, this fracture network extends the ROI for injection, thus enhancing *in situ* treatment. For this demonstration, a hybrid approach to pneumatic permeability enhancement was applied, where the nitrogen gas stream was used to generate the fracture network, followed by hydraulic delivery of the aqueous amendment.

The nature of permeability enhancement induced by pneumatic techniques is thought to be quite different from hydraulically induced fractures. Conventional wisdom suggests that hydraulic permeability enhancement has the advantage of a larger *in situ* delivery radius and propped fractures that can be used for multiple injections or extractions, while pneumatic permeability enhancement is expected to produce a denser fracture network for the same cost but within a smaller zone. However, no studies have been published comparing and documenting the performance of either of these techniques at multiple low-permeability sites (ESTCP 2014).

3.3 ADVANCED GEOPHYSICS MONITORING TOOLS

Although much more sophisticated, tilt meters operate on the same principle as a carpenter's level (Dunnicliff 1993). Tilt meters contain two tilt sensors (on orthogonal axes) and precision electronics. As the tilt meter tilts, the gas bubble must move to maintain its alignment with the local gravity vector. The movement of the gas bubble within the conductive liquid causes a change in the total resistance between the electrodes. This resistance change is measured with a resistance bridge or voltage divider circuit to precisely detect the amount of tilt. While simple in theory, the instruments are remarkably sensitive. Proper installation and operation of the instruments are required to utilize this resolution. The instruments must be adequately coupled to solid earth and significantly isolated from the large thermal fluctuations of the earth's surface. This is accomplished by setting up ground surface-mounted tilt meters in a concentric array. The changes in resistance created by tilting the bubble sensor are electronically converted to a voltage that is proportional to the tilt of the instrument. The voltage is then recorded either by a local data acquisition unit at each tilt meter site or via cable to a central data acquisition system for the whole tilt meter array. Data collection is most often accomplished with remote data acquisition at each tilt meter site because it removes the need to run cables over the surface area surrounding the wellbore. Real-time monitoring and analysis can still be performed with remote data acquisition units using radio telemetry to send the data to a central computer system for display and analysis. Remote data acquisition units have sufficient storage capabilities to allow periodic data acquisition with a portable computer. Tilt data collected can be processed, analyzed, and converted into a dynamic, 3D graphical output that can be viewed in any perspective in space, and can be manipulated to view individual fracture configurations or the fracture network as a whole. An example 3D visualization of the fracture network generated from the tiltmeter data at GFAFB is shown below.





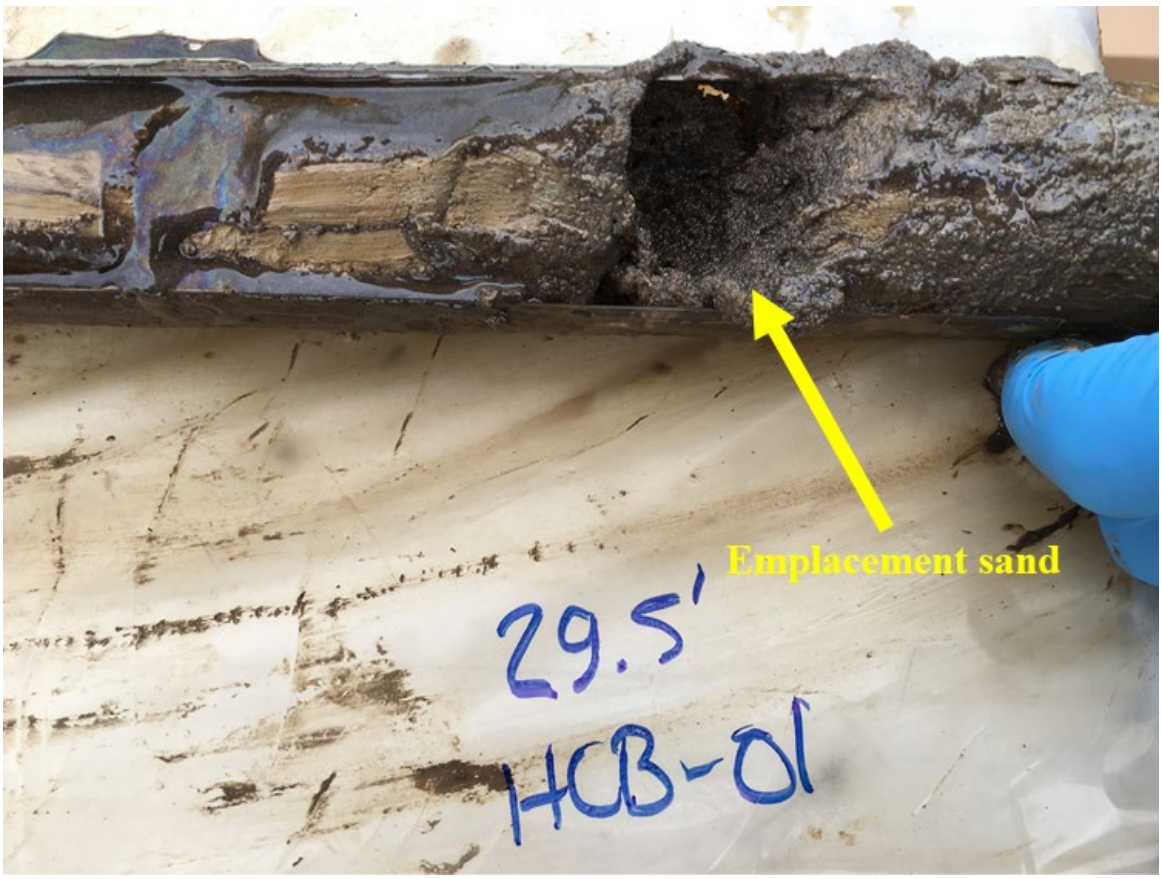
EC logging is utilized for high-resolution characterization of hydrostratigraphic conditions in unconsolidated media (Schulmeister et al. 2007). Direct-push EC probes typically operate using a four-electrode Wenner array, passing current through the outer two electrodes and measuring voltage across the inner two electrodes. The sensors can collect 20 measurements per second and collect data at a vertical resolution of 0.05 foot. Clayey materials tend to have higher electrical conductivity and charge characteristics compared to sandy or gravelly soils. The high vertical resolution of the probe readings allows the user to identify fine-scale features such as low-permeability clay or silt lenses or sand stringers, which are important for transport of injected amendments in the subsurface. The electrical conductivity of the groundwater also affects the conductivity measurements, but the conductivity of groundwater is typically relatively constant over the scale of a shallow, unconsolidated aquifer. By injecting an electrically conductive tracer or amendment solution and measuring electrical conductivity before and after injection activities, intervals impacted by the tracer can be evaluated using the direct-push probes, thereby delineating the vertical distribution of injected amendments.

Electrical resistivity tomography (ERT) is a geophysical visualization technique used to study hydrogeological characteristics of the subsurface. Resistivity, an inherent property of all materials, measures the degree to which a material resists the flow of an electrical current. As resistivity depends on chemical and physical properties such as saturation, concentration, and temperature, ERT can be used to monitor natural and anthropogenic processes responsible for changes in such properties (Daily et al.1992). In the context of environmental engineering, ERT can aid in monitoring active remedial progress and provide insights into material emplacement and deformational processes, both of which are very relevant to *in situ* treatment technologies in general and the permeability enhancement technology in particular (Halihan et al. 2005 and Wilkinson et al. 2008). In the context of this demonstration, ERT has the potential to aid in visualization of the 3D distribution of an injected fluid if the resistivity of that fluid is significantly different from the groundwater.

4.0 PERFORMANCE ASSESSMENT

4.1 QUANTIFYING FRACTURE DISTRIBUTION

Visual observations of fractures and emplaced materials were generally observed during confirmation sampling at all three demonstration sites; an example of such observation is shown in the figure below. In some instances, monitoring wells strategically placed within the target ROI of permeability enhancement were directly impacted by the high-pressure injections. At sites where a solid amendment or permeability enhancement reagents were not used, direct or indirect analyses of the added aqueous treatment reagents (i.e., total organic carbon [TOC], persulfate, or fluorescein) were used to quantify the horizontal and vertical distribution of amendment within the anticipated ROI of permeability enhancement.

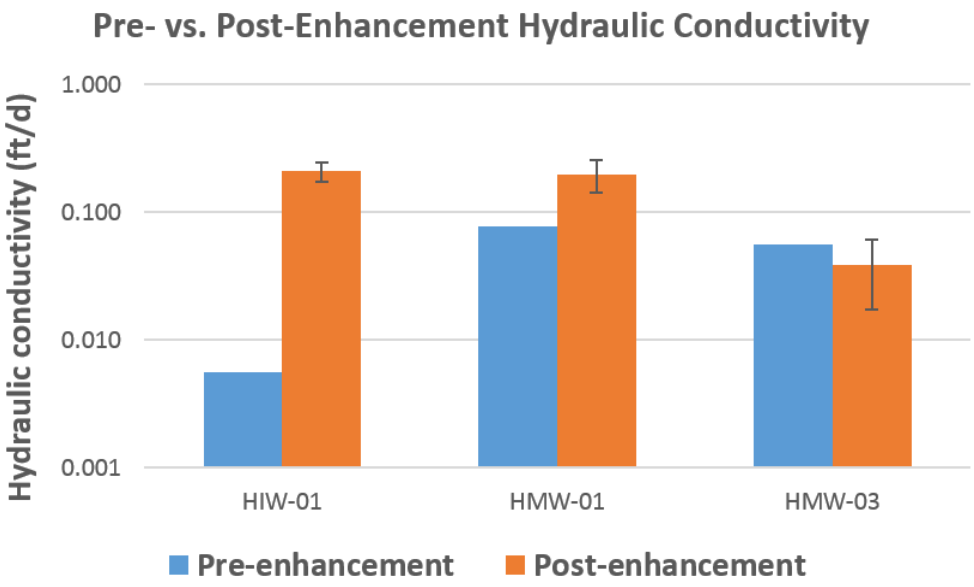


4.2 AMENDMENT DELIVERY

Despite the challenging subsurface conditions, more than 70% of the target injection volume was introduced into the subsurface via Hydraulic Permeability Enhancement at LCAAP. 100% of the target injection volume was achieved using Pneumatic Permeability Enhancement at LCAAP. Between 99% and 100% of the target injection volume was achieved within the treatment area at the MCB-CP and GFAFB sites.

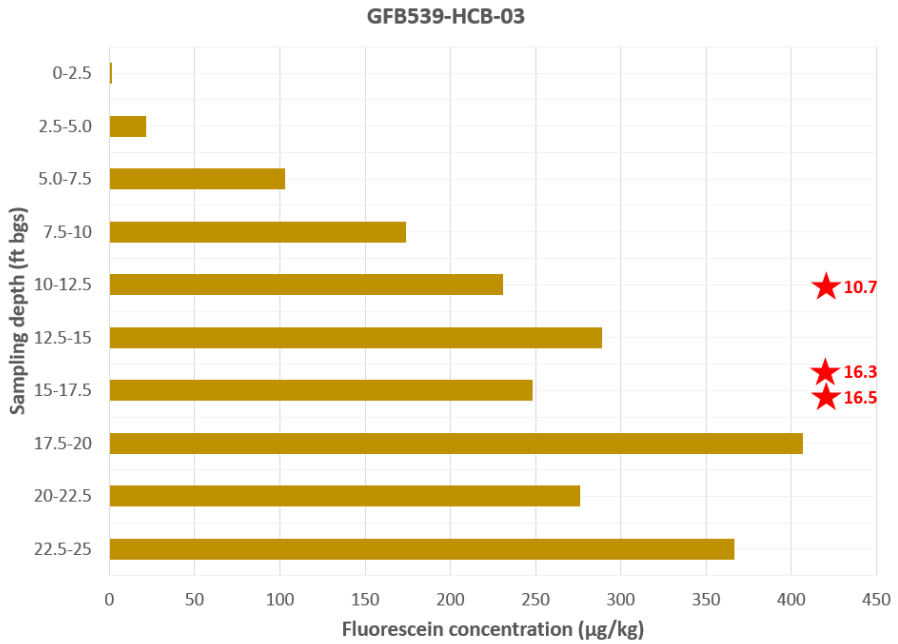
4.3 IMPACTS OF PERMEABILITY ENHANCEMENT ON BULK HYDRAULIC CONDUCTIVITY

Increases in hydraulic conductivity were expected at MCB-CP and LCAAP because a sand proppant was used at both sites. Orders of magnitude increases in hydraulic conductivities were observed at MCB-CP at the permeability location following emplacement of the sand proppant (as shown in below figure). However, no changes in hydraulic conductivities were observed within the hydraulic demonstration area at LCAAP even though a sand proppant was used. It was discovered midway through the project the demonstration area for hydraulic permeability enhancement had unknown subsurface conditions that significantly impacted the amendment emplacement.

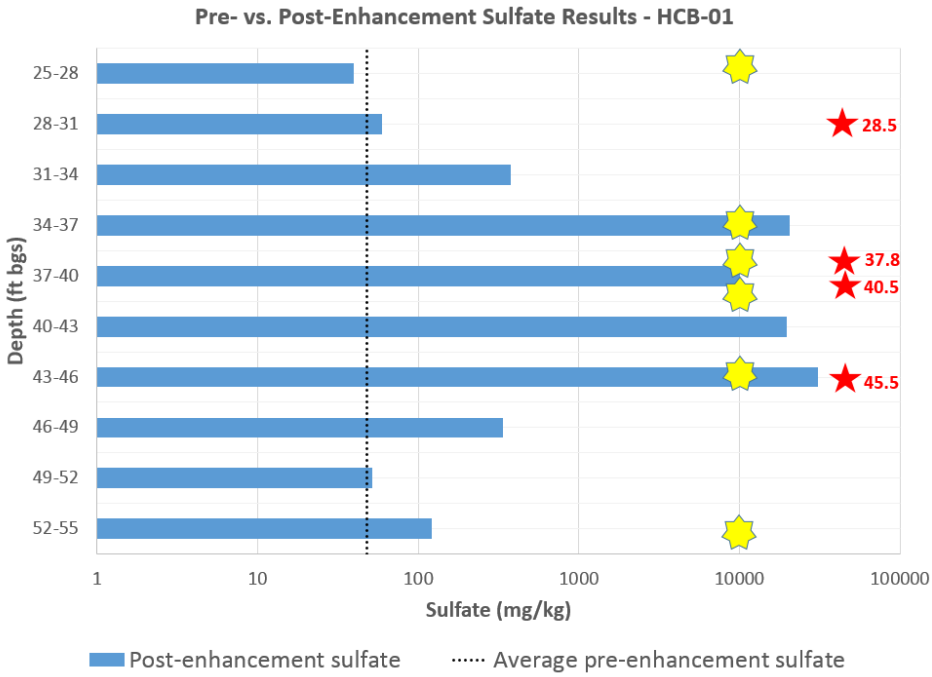


4.4 EFFECTIVENESS AND ACCURACY OF TILT METER MONITORING

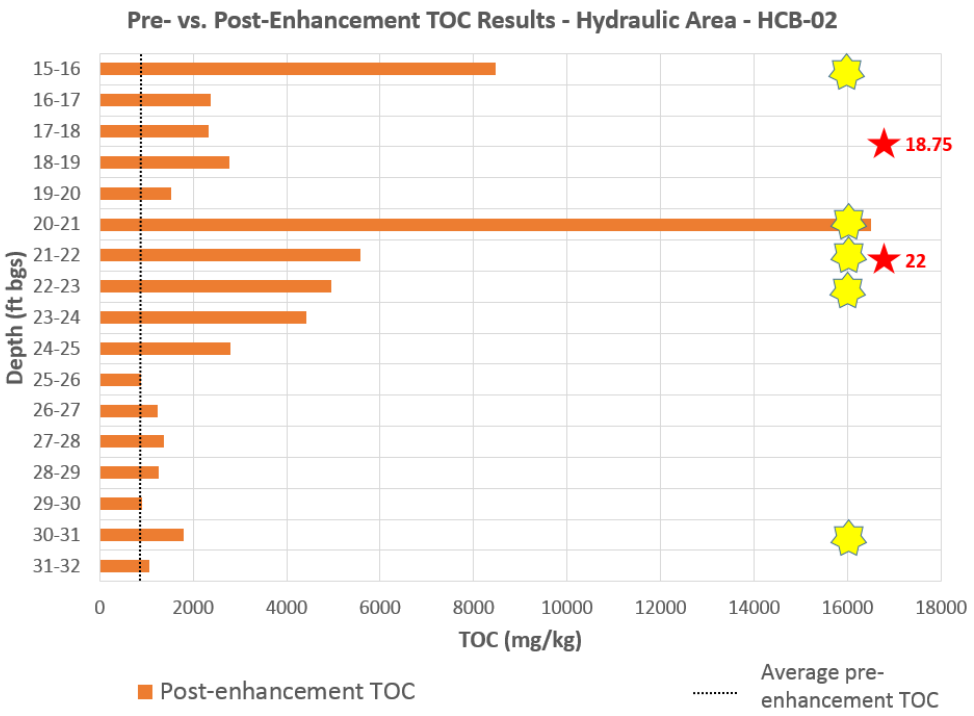
At all three demonstration sites where a tilt meter monitoring technique was employed, post-enhancement confirmation boring locations impacted by the permeability enhancement work were generally located within the predicted horizontal extent of the fracture network. In addition, the predicted fracture-intercepting depths provided by modeling (denoted by the red stars in the below figure) correlated very well with the actual depths where fractures were visually observed or confirmed analytically. At GFAFB, elevated fluorescein concentrations indicative of amendment delivery were observed within one to two feet of the tilt meter-predicted depth-discrete intervals where the initiated fracture network intercepts the confirmation borehole; an example of this correlation is shown in the below figure. At the other confirmation boreholes (GFB539-HCB-04, -05, and -08) located outside the ROI of permeability enhancement (as verified by the lack of fluorescein in depth-discrete composite soil samples), the lack of fracture interception was also predicted by tilt meters.



At MCB-CP, three of the four fracture-intercepting depth-discrete intervals predicted by tilt meter (denoted by the red stars in the below figure) coincided with intervals where fractures were visually observed during post-enhancement confirmation sampling and lithologic logging. Also, orders-of-magnitude increases in total sulfate concentrations were analytically verified at one (HCB-01) of the two post-enhancement confirmation boreholes as shown in the figure below. At the other confirmation borehole (HCB-02), no fractures were visually observed, consistent with the 3D visualization (which shows that this boring location is at the edge of the fracture network) and the absence of the orders-of-magnitude increases in total sulfate concentrations observed at HCB-01.



At both post-enhancement confirmation boreholes within the hydraulic demonstration area at LCAAP, all six tilt meter-predicted fracture-intercepting depth intervals (denoted by the red stars) were within one to three feet of those where fractures were either visually observed or the highest increases in TOC concentrations were observed; an example of this correlation is shown in the below figure. Similar correlations between tilt meter modeling predictions and confirmation sampling results were observed at two of the three post-enhancement boreholes within the pneumatic demonstration area. Specifically, at PCB-01 and PCB-02, the fracture-intercepting depths predicted by tilt meter were generally within one to two feet of the highest increases in TOC concentrations. Such correlation was not observed at PCB-03; however, the predicted fracture interceptions thereof might have emanated from the nearby PIW-01 that was not monitored by tilt metering. Collectively, these results indicated that tilt meter monitoring is a non-intrusive and cost-effective geophysics technique for fracture monitoring during permeability enhancement.



4.5 EFFECTIVENESS AND ACCURACY OF EC LOGGING

No significant increases in EC were observed within the target treatment depth interval at GFAFB. However, no evidence of amendment delivery into the two EC locations was observed. This lack thereof was also analytically confirmed via soil confirmation sampling and subsequent fluorescein analysis. Specifically, no significant detection of fluorescein was detected at the two post-enhancement confirmation boreholes located in the vicinity of the two EC locations. Collectively, the limited data collected at this site renders inconclusive the evaluation of EC as an effective geophysics tool for fracture monitoring.

4.6 EFFECTIVENESS AND ACCURACY OF ERT

Significant changes in ERT signals were generally correlated with other observations at each of the three demonstration areas (hydraulic and pneumatic areas at LCAAP and hydraulic at GFAFB). For the pneumatic cell at LCAAP, little change was observed following amendment emplacement, which was consistent with the TOC groundwater data. For the hydraulic cell at LCAAP, modest changes were observed following enhancement activities, with such changes generally localized around the monitoring well locations where the electrodes were deployed. At GFAFB, ERT imaging showed the most dramatic changes pre- and post-injection, and these changes were generally correlated with increases in TOC and fluorescein as measured from the groundwater monitoring network. ERT was also able to show a time-lapse evolution of the injected amendment over time. Overall, while ERT visualization of post-enhancement amendment distribution was not of sufficiently high resolution throughout the target areas to map and identify individual fractures, it was useful for assessing overall distribution of the emplaced amendment.

4.7 EASE OF USE

Proper applications of hydraulic permeability enhancement require proprietary injection equipment and materials, and therefore highly specialized personnel to aid in project planning, design, execution, and evaluation. Most of the equipment required to perform hydraulic permeability enhancement is generally commercially available, although some modification and optimization are necessary. On the other hand, proprietary chemical reagents are required to properly inject a solid amendment into the subsurface. Therefore, there are very few vendors that have consistently demonstrated the ability to successfully perform hydraulic permeability enhancement. Similar to hydraulic permeability enhancement, the aboveground and downhole equipment used to facilitate pneumatic permeability enhancement is mostly commercially available. Injection skids are often constructed in a modular configuration to allow for ease of transport, access, and adaptability to site-specific settings. There are several vendors in North America that have commercialized permeability services.

Real-time decision-making is often required during implementation of both hydraulic and pneumatic permeability enhancement. Therefore, the personnel providing the technical oversight need to be familiar with the site conceptual model, understand the overall objective of the injection program, communicate any issues encountered to the project team, and help make the necessary adjustments. In addition, because some applications of permeability enhancement are performed under relatively high pressures, it is imperative that these personnel be familiar with the health and safety concerns associated with permeability enhancement and are qualified to supervise and provide input as necessary.

There are several types of issues that may be encountered throughout the different stages of a permeability enhancement project including planning, design, implementation, and evaluation. Despite its recent commercialization as an *in situ* delivery technique at sites with challenging lithologies, permeability enhancement is still a relatively novel technique in the remediation industry. In addition, the technology, especially the hydraulic approach to permeability, also suffers from the poor public perception of hydraulic fracturing in the oil and gas industry, although the two techniques differ vastly. In several instances during the planning phase of this demonstration project, it was necessary to communicate the differences between the permeability enhancement techniques employed for environmental purposes versus oil and gas recovery applications.

In other cases, concerns regarding vertical contaminant migration, damages to existing nearby infrastructure, and amendment surfacing had to be alleviated by detailed discussion in planning documents, webinar presentations, and/or telephone conferences among the parties of interest. Overall, concerns were resolved relatively promptly and easily by modifying the approved demonstration plan and preparing additional site-specific planning documents, conducting additional performance monitoring or slightly changing the injection approach.

Another issue encountered at several sites during demonstration of permeability enhancement was the lack of site-specific information—some information was not known even to the onsite points of contact. For example, past disturbances and presence of dense non-aqueous phase liquid observed at the hydraulic demonstration area at LCAAP was not known by any party involved, thus rendering the direct comparison between the hydraulic and the pneumatic approach to permeability enhancement incomplete, as the two demonstration areas are vastly different in terms of lithology

and contaminant profile. Similarly, the need to be escorted by a government officer for all non-U.S. citizens at LCAAP was not apparent until arrival at the site. This issue was immediately resolved with the help of the regulatory agencies involved in environmental restoration efforts at LCAAP.

5.0 COST ASSESSMENT

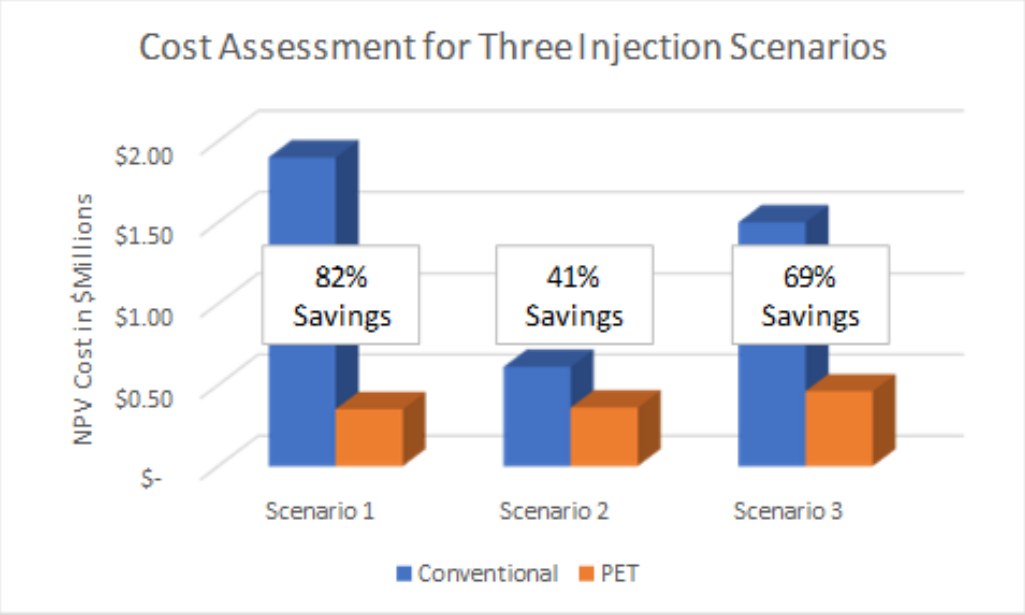
The primary cost drivers in implementation of permeability enhancement include site-specific lithology and treatment depth; site location as it directly impacts equipment mobilization charges which may account for a significant portion of the overall cost; and material cost for the remedial amendment to be emplaced. For monitoring technologies, including tilt meter, ERT, and EC, cost drivers vary by technology due to their implementation approach. For tilt meter, cost components include mobilization, onsite support, and data interpretation. Cost drivers for ERT and EC primarily are related to lithology and depth. Because ERT requires installation of electrodes on the outside of well casing, the type of drilling and depth of the target formation are of key importance. EC is only applicable in unconsolidated formations that can be drilled using direct-push drilling technology (DPT); the cost for mobilization of the EC tooling is minimal (assuming a DPT rig is already onsite), and overall cost for use is typically tied to a daily rate for use of the DPT rig. Therefore, EC cost drivers are primarily tied to formation depth and ease of DPT drilling; deeper or denser formations will likely require more field time to obtain data due to slower drilling conditions than shallower, less dense formation types.

Comparisons of implementation costs for real-life examples of conventional injection techniques (i.e., injection wells) versus permeability enhancement as applied at the sites were completed. Three specific scenarios were considered:

1. Scenario 1 was the clay/weathered shale source area at Lake City Army Ammunition Plant, and compared permeability enhancement technology to gravity-fed injection in convention wells actually performed at the site. The cost to achieve a similar percent reduction of contaminants via conventional injection as achieved using permeability enhancement technology was used as the basis for comparison. The cost assessment showed an estimated cost savings of 82% for this case.

2. Scenario 2 considered the glacial till source area at Grand Forks Air Force Base (see figure below). The "conventional" injection in this case comprised the use of 1-inch wells with pre-packed screens installed via DPT for injection. A similar analysis as for Scenario 1 revealed an estimated cost savings of 41% using permeability enhancement for Scenario 2. This was considered highly conservative for reasons discussed in the body of the report.

3. As we did not have good comparative data for conventional injections at Marine Corps Base Camp Pendleton, Scenario 3 considered an interbedded sand/silt/clay source area at the Bountiful/Woods Cross Superfund Site where a direct comparison could be made between permeability enhancement technology and slightly pressurized injections in conventional injection wells. The analysis showed an estimated 69% reduction in costs relative to conventional injection to achieve the same contaminant reduction.



(Net Present Value [NPV] and Permeability Enhancement Technology [PET])

6.0 IMPLEMENTATION ISSUES

A variety of regulatory, procurement, and end-user issues may be encountered during permeability enhancement implementation. Regulatory issues may include overcoming the often-negative connotation associated with hydraulic fracturing for oil and gas and concerns regarding vertical migration of site contaminants as a potential unintended result of permeability enhancement technology. Procurement issues regarding permeability enhancement technology implementation generally center around the use of specialized equipment, chemistry, and technical knowledge that are only offered by few commercial vendors as well as the patented nature of certain permeability enhancement technology applications. End-user concerns with respect to permeability enhancement technology include the use of nonstandard equipment required for implementation, hazards associated with high-pressure injections, and amendment surfacing. Note that in nearly all cases, proper planning and engineering controls can be used to mitigate concerns associated with field implementation of permeability enhancement technology.

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7.0 PUBLICATIONS

It is anticipated that several peer-reviewed journal articles will be published to document the findings of this ESTCP project.