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

Kent Sorenson, Ph.D., P.E.; Zoom Nguyen; Nathan Smith, PMP; Ryan Wymore, P.E.

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Abstract

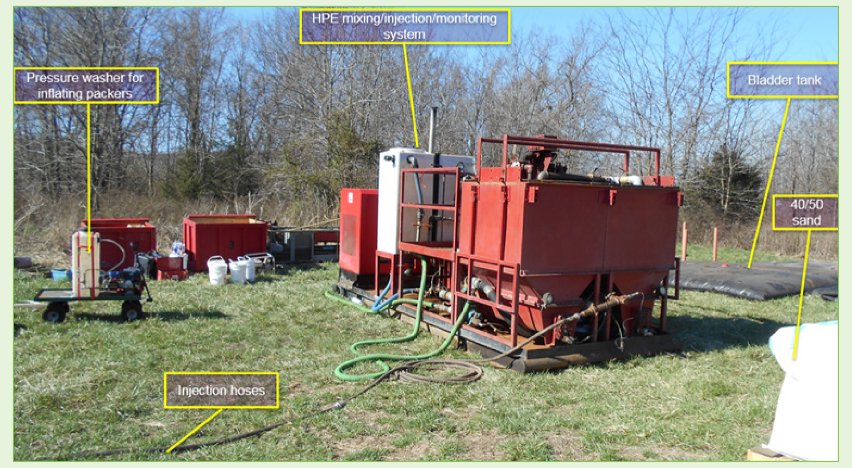
At sites with low hydraulic conductivities of approximately 10^{-5} cm/s or lower, specialized in situ delivery techniques are required to distribute amendments effectively. The three most prevalent methods in use today are pressurized direct push injection (DPI), hydraulic permeability enhancement (HPE), and pneumatic permeability enhancement (PPE) (ESTCP 2014). Pressurized DPI is commonly used because of its low initial cost. However, distribution of amendments using this technique is often uncontrolled and unverified. Unfortunately, the high life cycle cost of poor amendment distribution is seldom considered when selecting an appropriate in situ delivery strategy. In addition, rapid diagnostic tools for assessing amendment distribution to facilitate real-time optimization of the selected strategy have not been well documented. In recent years, many technologies have been developed to address the challenge of achieving an effective distribution of treatment amendments in low permeability and fractured media. These advances include HPE and PPE technologies, both of which can emplace amendments into low permeability media, and advancements in tiltmeter monitoring for high-resolution subsurface distribution mapping of amendments.

This demonstration project provided a rigorous comparison of the costs and benefits of the hydraulic and pneumatic approaches for enhanced amendment delivery and distribution in low permeability media and an analysis of the state-of-the-art tiltmeter and other advanced geophysics monitoring tools to quantify employed fracture networks. The demonstration was performed at three Department of Defense (DoD) facilities representing a variety of low permeability lithologies, with HPE completed at all three and PPE at one.

Technology Application

Site 1 – Lake City Army Ammunition Plant (LCAAP)

Both hydraulic and pneumatic approaches to permeability enhancement were demonstrated at LCAAP, where a weathered shale residuum presented challenges to successful cleanup using less robust injection approaches (gravity-fed emulsified oil injection via wells). HPE was implemented by injecting sand slurries into the contaminated formation using direct push technology drilling (top-down) or straddle packer assemblies to isolate target intervals, followed by installation of an injection well and subsequent injection of emulsified oil. PPE was implemented using a hybrid approach, where a straddle packer setup was used to isolate the target zone and fractures were initiated using nitrogen gas, followed by pumping of a dilute emulsified oil solution.

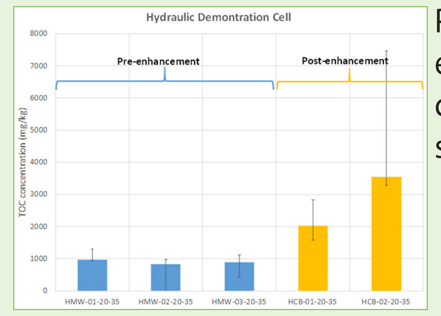


Aboveground setup of HPE at LCAAP

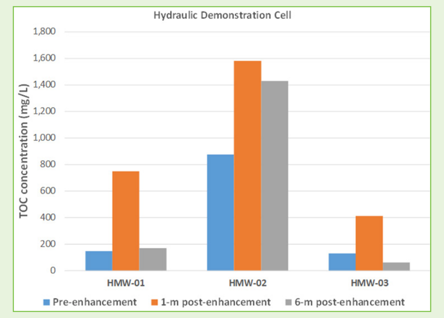
Aboveground setup of PPE at LCAAP

Results:

Approximately 80% of the target solid amendment was injected in the hydraulic demonstration cell, and 100% of the subsequent target emulsified oil liquid volume was injected. Lower than anticipated volumes were achieved during initial sand emplacement due to presence of previously unknown subsurface disturbances, which led to slurry surfacing. Following the demonstration, significant increases in total organic carbon (TOC) were observed in soil and groundwater. Despite achieving the target amendment injection volume in the pneumatic demonstration cell, no significant increases in TOC in soil were observed. Some increases in TOC concentrations in groundwater were observed within the pneumatic demonstration cell, albeit transient and significantly lower than those observed in the hydraulic demonstration cell. Data evaluation indicated that a radius of influence (ROI) of approximately 10 and 25 feet for PPE and HPE, respectively, was obtained. Tiltmeter 3-D imaging demonstrated the distribution for both technologies. At both post-enhancement confirmation boreholes within the hydraulic demonstration area, all six depths where tiltmeters predicted that fractures would intercept the boreholes were within 1 to 3 feet of fractures that either were visually observed or elevated TOC concentrations were observed. Similar correlations between tiltmeter modeling predictions and confirmation sampling results were observed at two of the three post-enhancement boreholes within the pneumatic demonstration area, with the fracture-intercepting depths predicted by tiltmeter generally within 1 to 2 feet of the highest increases in TOC concentrations.

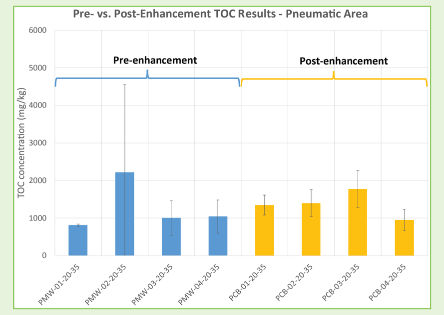


Pre-versus post-enhancement TOC concentration in soil at LCAAP (HPE)

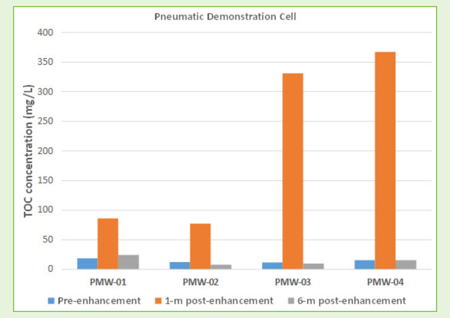


Pre-versus post-enhancement TOC concentration in groundwater at LCAAP (HPE)

3-D visualization of the fracture network at LCAAP (HPE on left and PPE on right)



Pre-versus post-enhancement TOC concentration in soil at LCAAP (PPE)



Pre-versus post-enhancement TOC concentration in groundwater at LCAAP (PPE)

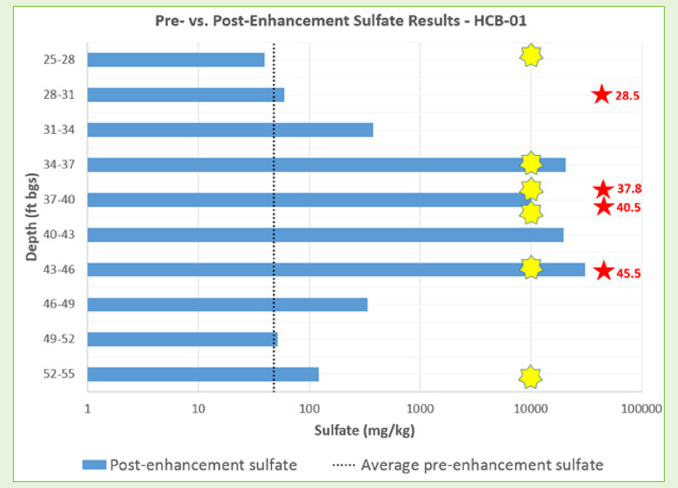
Site 2 – Marine Corps Base Camp Pendleton (MCB-CP)

HPE was demonstrated at MCB-CP, where a weathered sandstone and siltstone formation presented challenges to successful cleanup using standard injections. HPE was implemented by injecting sand slurries into the contaminated formation using a straddle packer approach to isolate the target depth intervals, followed by installation of an injection well and subsequent injection of persulfate.

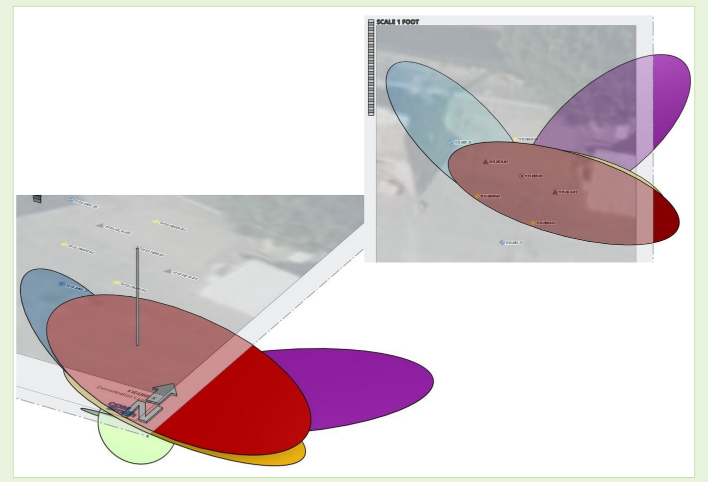
Aboveground setup of HPE at MCB-CP

Results:

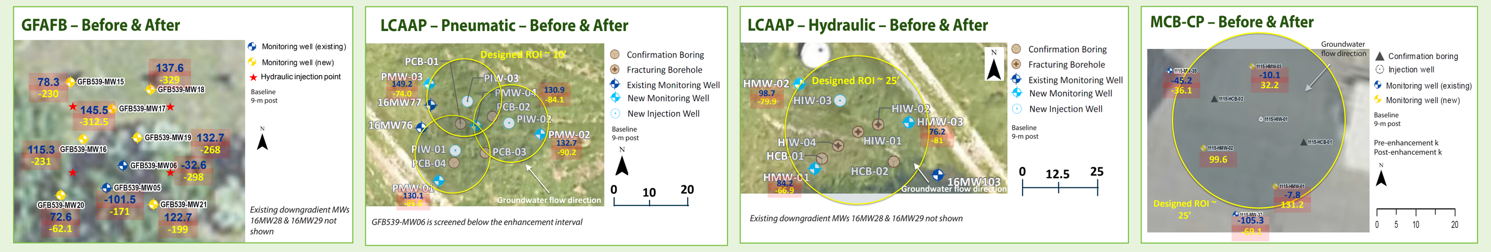
The entire target volume of sand slurry was injected into the subsurface, although one depth interval did not achieve target volume due to surfacing. The remaining volume was injected into an adjacent interval to compensate. The target volume of the subsequent persulfate solution also was injected. Significant increases (up to 2 orders of magnitude) in hydraulic conductivity were observed at the permeability enhancement initiation point and nearby monitoring wells, with an estimated ROI reaching 22.5 to 25 feet. At both post-enhancement confirmation boreholes, strong correlation to predicted depths from the tiltmeter modeling were observed.



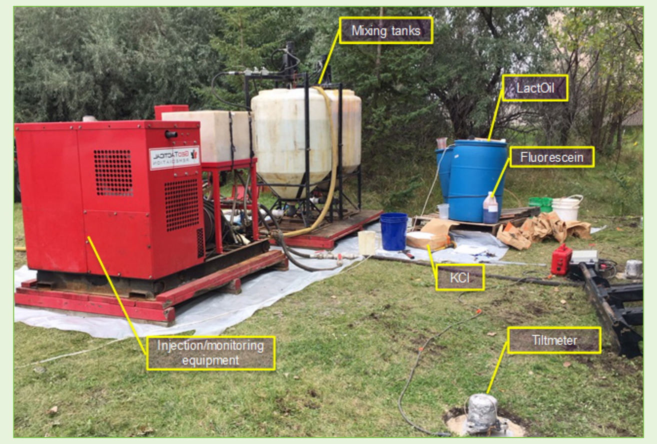
Correlation between Intervals with elevated sulfate concentrations and tiltmeter predicted interception depths (denoted by red stars) and actual depths where fractures were visually observed (denoted by yellow stars) at HCB-01 at MCB-CP



3-D visualization of the fracture network at MCB-CP



Site 3 – Grand Forks Air Force Base (GFAFB)



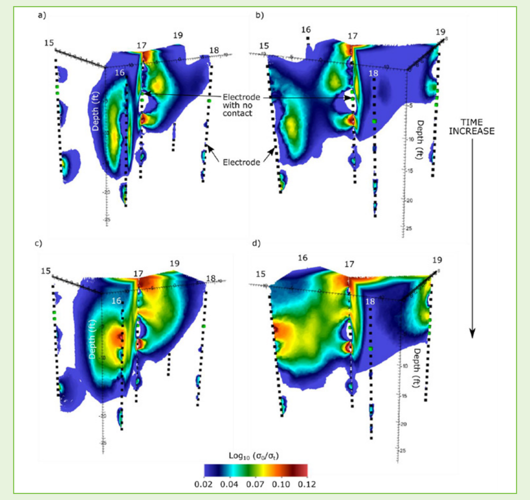
Aboveground setup of permeability enhancement at GFAFB

HPE was demonstrated at GFAFB, where a shallow (less than 20 feet below ground surface) glacial till has prevented successful implementation of bioremediation using a grid of 1-inch pre-pack DPT-pushed injection wells with emulsified oil injection. HPE was implemented by injecting an emulsified oil solution (including a fluorescein tracer dye) directly through DPT-pushed tooling using a top-down approach. Tiltmeter, electrical conductivity (EC) logging, and electrical resistivity tomography (ERT) were used to detect and model amendment distribution.

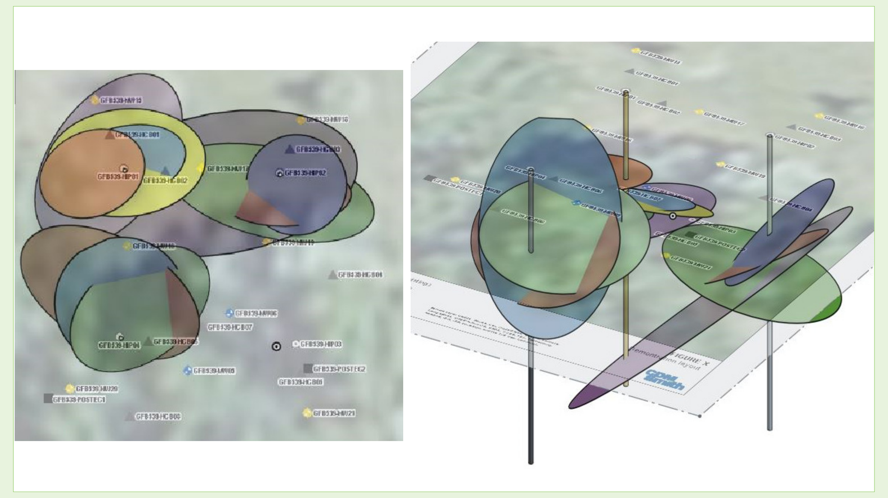
Results:

The entire target volume of solution was injected into the subsurface, with minimal surfacing despite the shallow depth. The estimated ROI reached 10 feet, with visual evidence of distribution observed at monitoring wells and confirmation borings. Previous injections had not generated any evidence of direct amendment delivery at monitoring wells. ERT data were processed for presentation of both 2D and 3D images. The results were generally in qualitative agreement with the amendment distribution measurements by other methods. EC results generally did not show a strong correlation with analytical verification of the emplaced amendments seen at nearby confirmation boreholes.. Based on the limited EC data obtained at GFAFB, EC did not appear to be an effective geophysics-monitoring tool in application of permeability enhancement. Similar to both MCB-CP and LCAAP, tiltmeter results correlated well with the field-analyzed fluorescein results obtained at nearby boreholes during post-enhancement confirmation sampling. Additionally, the tiltmeter-predicted, fracture-intercepted depth intervals, correlate well with the actual depth intervals where increases in fluorescein were observed.

Fluorescein observed at a nearby monitoring well during HPE at GFAFB (inside well casing, not along casing)



Pre-versus post-enhancement subsurface conductivities over time elucidated by downhole ERT monitoring technique at GFAFB



3-D visualization of the fracture network at GFAFB

Conclusion

The demonstration project succeeded in providing the data necessary to complete a robust analysis of using permeability enhancement in a variety of lithologies. HPE was successfully implemented at all three sites and achieved—in some cases exceeded—the desired distribution goals, greatly enhancing long-term treatment effectiveness. PPE was successfully implemented at LCAAP and achieved desired distribution, although the long-term effectiveness was not as evident as that of HPE based on more rapid decline in TOC. Tiltmeter monitoring was validated as an appropriate approach for monitoring fracture emplacement, with confirmation data correlating well with modeled fracture depths. EC did not appear to provide adequate monitoring capability for detection of fracture intervals. ERT detected some changes in the subsurface because of amendment injection, although primarily within the immediate vicinity of the monitored boreholes. Greater success was observed with the technology at GFAFB where cross-borehole detection of conductivity changes were observed.

The final demonstration products include the final technical report, which presents the overall demonstration project evaluation, and a robust guidance document that will provide remediation managers with information to determine whether permeability enhancement is an appropriate technology for their sites. The guidance document provides additional information on important considerations for implementation of permeability enhancement and suggestions for appropriate use of the monitoring technologies.