FACT SHEET

Electrokinetic-Enhanced In Situ Remediation

Introduction

Source zone treatment can be challenging at low-permeability sites where contaminants remain in clay layers and diffuse back into groundwater over time. Electrokinetic (EK)-enhanced in situ remediation offers a promising approach for treating source zones at these complex sites. An EK-enhanced delivery method can achieve a more uniform distribution of amendments into the target treatment zone in a low-permeability formation compared to hydraulic-based methods. EK-enhanced delivery methods can be used to implement in situ bioremediation, in situ chemical oxidation (ISCO), and in situ chemical reduction (ISCR).

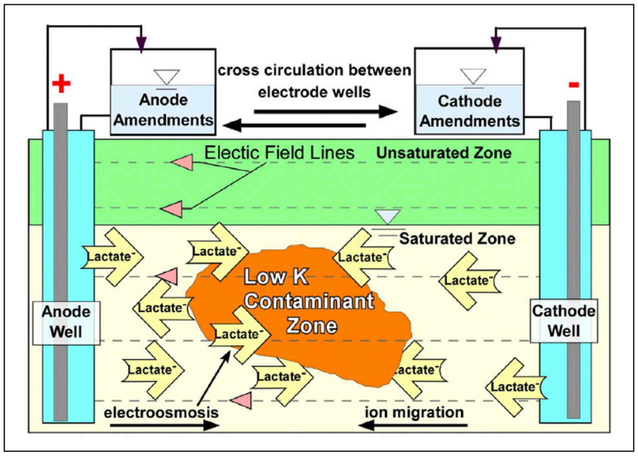

Figure 1. EK-Enhanced Remediation Schematic (Courtesy of Cox et al., 2018)

Technology Background

Using a conventional hydraulic injection technique, the introduction of an amendment solution can be impeded by preferential flows and incomplete distribution in low-permeability formations. In contrast, EK-based amendment delivery relies upon establishing an electrical voltage gradient between two locations within the saturated zone (Figure 1). The application of a direct-current (DC) electric field then promotes movement of the amendment within the subsurface via electromigration (ion migration) and electro-osmosis (via pore fluid) (Federal Remediation Technologies Roundtable [FRTR], 2020). Unlike hydraulic properties that can vary by orders of magnitude, the electrical properties of various soil types from coarse sand to silty clay are relatively similar. This similarity in electrical properties across soil types supports a more uniform distribution of amendments through EK-enhanced processes in low-permeability and heterogenous geological materials. Field experiences to date have achieved effective net transport rates generally in the range of 3 to 5 cm/day in these challenging formations.

How Does It Work?

Remediation amendments such as lactate, permanganate, and persulfate are present as anions with a negative charge. Even nanoscale zero-valent iron with surface modifiers and some microbes carry an overall net charge on the surface. These ionic compounds can migrate within an electric field. To deploy the EK technology, cathode (-) and anode (+) wells are installed below the water table (Figure 1). When DC electric power is applied, the aquifer acts as a conductor and an electric field is established between paired electrode wells. Charged ions can then migrate within the subsurface electric field through EK-enhanced processes. Amendments can be supplied directly into the electrode wells and into supply wells placed at strategic locations within the path of EK transport. Recent field-scale applications of EK-enhanced amendment delivery have employed a relatively low voltage (typically below 120 volts) and low electrical current (typically below 10 amps), reflecting the low energy-demand of this technology compared to traditional thermal remedial methods. Certain engineering controls, (e.g., cross-circulation between electrode wells and the addition of pH control solution), may be applied to maintain appropriate geochemical conditions.

How Can It Help?

Overall, EK-enhanced in situ remediation can help by:

- promoting a more uniform delivery of amendments into clays and under heterogenous geological conditions;
- delivering a wide variety of amendments and microbial cultures for the treatment of chlorinated and non-chlorinated contaminants;
- treating residual contaminant mass stored in clay layers and minimizing rebound resulting from back diffusion; and
- using relatively low electrical power to enhance amendment distribution in challenging geologic formations.

Case Study 1: Naval Air Station Jacksonville | **Case Study 2: Superfund Site, North Carolina** | **Conclusions**

CASE STUDY 1

Naval Air Station Jacksonville, Florida

Project Objective: A pilot-scale technology demonstration of EK-enhanced bioremediation (EK-BIO) was conducted at Naval Air Station (NAS) Jacksonville, Florida. The project was funded by the Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP). The purpose of the demonstration (ESTCP Project ER-201325) was to evaluate and validate the performance of EK-BIO in promoting effective distribution of bioremediation amendments (including lactate and a microbial culture) in a low-permeability formation (Cox et al., 2018).

Site Background: The EK-BIO pilot-scale demonstration was conducted at the site of a former dry-cleaning facility in former Building 106, Operable Unit 3, at NAS Jacksonville. Historical waste management practices at the dry cleaner led to the release of tetrachloroethene (PCE) into the subsurface. Chlorinated volatile organic compounds (CVOCs), including PCE, trichloroethene (TCE), cis-dichloroethene (cDCE), and vinyl chloride (VC), were detected in groundwater at concentrations up to 10,000 micrograms per liter (µg/L). Contamination was found in both the shallow sand aquifer (5 to 16.5 feet [ft] below ground surface [bgs]) and the underlying low-permeability clay layer (16.5 to 24 ft bgs). Site characterization data indicated that PCE had penetrated the upper 5 ft of the clay unit, with porewater PCE concentrations in the clay detected up to 40,000 µg/L. The site characterization data confirmed that the clay layer served as a persistent source of contamination to the overlying sand aquifer.

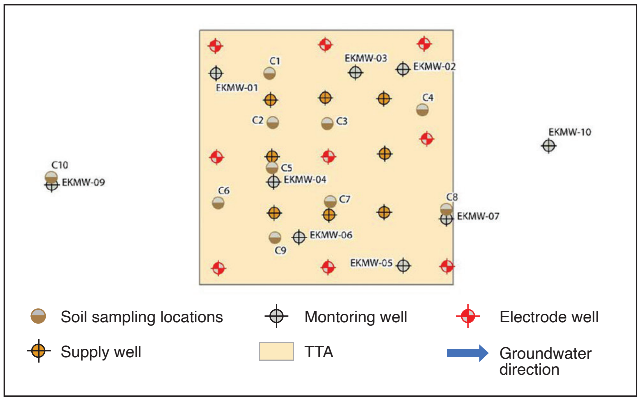

Figure 2. Well Network for the NAS Jacksonville EK-BIO System (Courtesy of Cox et al., 2018)

Within the 160-square-foot (ft^2) demonstration area, a network of 9 electrode wells and 8 supply wells were installed at depths ranging from 19 to 23 ft bgs and screened across the clay unit (Figure 2). Each electrode consisted of a titanium rod (0.75 inches in diameter, 4 ft in length) with a mixed metal oxide coating. An electrical cable connected each electrode in an electrode well to a DC power unit at the system control. The method of connecting individual electrodes to the positive/negative ports of DC power led to two different electric field orientations in two operational stages. During each stage of operation, six of the nine electrode wells served as cathodes, while the other three served as anodes. Lactate and the microbial culture were introduced into the electrode wells and supply wells, while the pH control reagent was applied to the supply wells. A total of 555 kilograms (kg) of lactate was delivered to the target treatment zone, with over 2,548 gallons of solution applied. After the initial 75 days of operation, the system was paused to perform bioaugmentation with KB-1®, a microbial culture containing *Dehalococcoides (Dhc).*

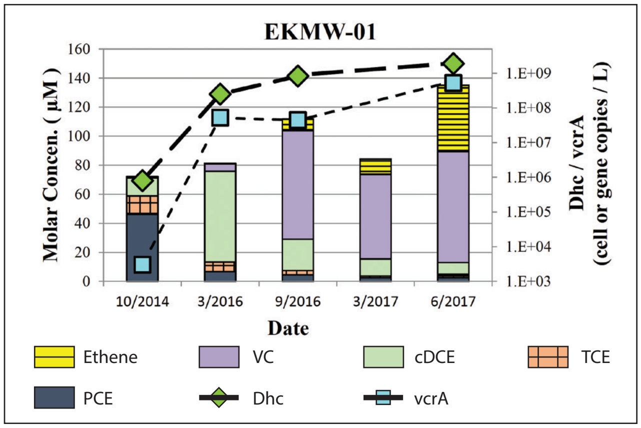

Figure 3. CVOCs and Microbial Population Changes Before and After the EK-BIO Operations (Courtesy of Cox et al., 2018)

Results: The EK-BIO pilot system was operated over 16 months (Stages 1 and 2, each operating for 5 months with a 6-month incubation period between stages). The EK-BIO system was found to distribute the amendments effectively into the low-permeability portion of the aquifer at a relatively low energy cost. The total electricity consumption was 1,600 kilowatt-hours (kW-hr). Monitoring results showed total organic carbon content in the groundwater increased eightfold within the clay unit. Microbial growth and reductive dechlorination functional genes expression were detected. The microbial analysis showed increases of *Dhc* biomarker and *VC reductase (vcrA)*. Figure 3 shows CVOC and biomarker results from one representative monitoring well. CVOC mass removal and transformation to ethene was observed across the EK-BIO pilot test plot. PCE concentrations decreased between 70% to 95% from the baseline levels in the monitoring wells screened across the clay layer.

Outcome: EK-BIO performance data collected from within the clay layer demonstrated adequate lactate distribution, increases in *Dhc* and *vcrA* biomarkers, and effective CVOC mass removal.

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CASE STUDY 2

Superfund Site, North Carolina

Project Objective: A pilot-scale test of EK-enhanced in situ chemical oxidation (EK-ISCO) was performed for PCE source zone remediation at a former textile plant in Oxford, North Carolina. The pilot test was designed to: 1) evaluate the ability to distribute sodium permanganate in the target treatment zone, 2) monitor potential geochemical changes, and 3) determine the engineering design parameters for the full-scale EK-ISCO system (Black and Veatch and Geosyntec Consultants, 2020).

Site Background: The remedial investigation at this site identified a drum storage pad where PCE spills impacted soil and groundwater. PCE concentrations in the vicinity of the drum storage pad ranged from 730 to 2,400 µg/L in the depth interval (20 to 50 ft bgs) targeted by the pilot test. The site has highly heterogenous geological conditions, with 20 ft of surficial fill (clayey sand) underlain by saprolite (fine sand and clayey silt) to a depth of 70 ft bgs. Underlying the saprolite is a coarser sand formation that represents a relatively high-flux zone above the bedrock.

For the pilot test, 2 electrode wells were installed 12 ft apart. In addition, 1 supply well was installed 2 ft from the cathode well (Figure 4). The electrode and supply wells were constructed of 4-inch-diameter polyvinyl chloride (PVC) screened within the saprolite unit. Each electrode well contained 2 titanium-base electrodes measuring 2 ft in length placed at 25 ft bgs and 40 ft bgs, respectively. Over the 57 days of the pilot test, a total of 136.5 kg of permanganate was delivered to the supply well, with over 535 gallons of solution applied. A pH buffer solution (1,530 gallons of sodium bicarbonate) was added to the electrode wells during the pilot test.

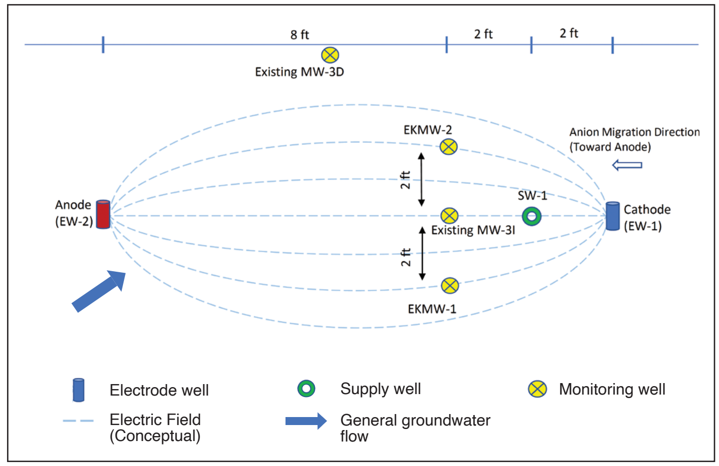

Figure 4. Well Network for the EK-ISCO System (Courtesy of Black and Veatch and Geosyntec Consultants, 2020)

Results: The EK-ISCO pilot test was found to distribute permanganate into the target treatment zone at the levels required to meet the site-specific total oxidant demand. The net permanganate transport rate was calculated at 1.3 to 4.1 feet per month (ft/month) based on the pilot test monitoring results. Total electricity consumption was fairly low at 152 kW-hr.

Monitoring results showed evidence of CVOC removal and oxidation reduction potential (ORP) increases in the wells (Figure 5). CVOC concentrations were observed to decrease between 74% and 90% from the baseline levels. With residual permanganate still present in the monitoring wells, additional treatment of CVOCs likely continued after the pilot test monitoring was completed. In addition, post-pilot soil sampling confirmed permanganate distribution laterally over an area of up to 41.3 ft^2 and vertically up to 37 ft bgs. The successful pilot test results supported the plan to move forward with a full-scale EK-ISCO remedy as part of the treatment train for the source area at this Superfund site.

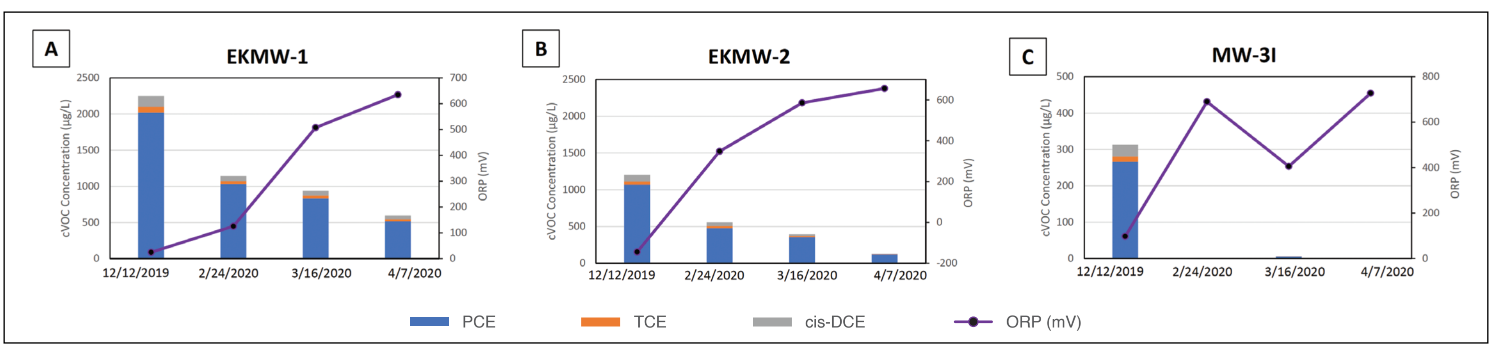

Figure 5. CVOC and ORP Monitoring Results from the EK-ISCO System (Courtesy of Black and Veatch and Geosyntec Consultants, 2020)

Outcome: The EK-ISCO pilot test successfully distributed permanganate into the target treatment zone at the levels required to meet the site-specific oxidant demand. With EK-ISCO application, CVOC levels in groundwater decreased between 74% and 90% from the baseline levels.

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Conclusions

Conclusions

The application of EK-enhanced in situ remediation technologies has undergone decades of research and development. As highlighted above, projects at the field-scale have demonstrated that EK-enhanced delivery methods can effectively distribute select amendments in low-permeability materials. This contrasts with hydraulics-based methods, which tend to displace pore water in preferential pathways and achieve only limited contact with residual contamination stored in clay layers. To date, EK methods have been used for several applications at the field scale, including bioremediation (e.g., lactate), ISCO (e.g., permanganate, persulfate), and ISCR (e.g., nanoscale zero-valent iron). Lessons learned and considerations for applying and implementing EK technologies are summarized below:

- EK-enhanced methods are most applicable to complex sites with fine-grained soils, highly variable or low permeabilities, high moisture content, and low salinity (FRTR, 2020). Although low-permeability sites with clay layers are the focus of EK applications, the technology can also be beneficial at sites with alternating, heterogenous sandy and coarse layers where hydraulic methods are challenged by preferential flow pathways.
- EK transport relies upon the pore water functioning as an electrical conductor and is applicable for target zones below the water table. The depth of the target treatment zone should be compared to the variable water table at sites with significant seasonal fluctuations.
- The treatment zone should be accessible for construction of a network of electrode wells. Typical spacing between electrode wells is in the range of 15 to 20 ft. While a larger well spacing may be possible, the presence of buildings or other structures over the source zone could limit the ability to install vertical wells at the required spacing. The depth of the contamination is not a particular limiting factor for EK-based technologies. An adequate power supply should also be available at the site, and careful considerations should be taken related to nearby subsurface utilities or metallic infrastructure.
- The types of contaminants present should be considered when selecting the remedial approach, including bioremediation, ISCO, or ISCR. In addition, the site biogeochemical conditions must be compatible with the selected remedial approach. The amendment selection process can follow a standardized approach to determine applicable amendments based on the site-specific contaminants and site conditions. Treatability studies can then be used to determine whether the identified remedial amendment is amenable to EK transport, the amendment demand required by the aquifer materials, and the site-specific net EK transport rate of the amendment.
- Pilot tests can be used to determine the feasibility of implementing the EK technology at a given site. A pilot test will provide the needed parameters to support the full-scale remedial design. The types of information collected from pilot testing include well spacing for the electrode and supply wells, amendment dosing method and amounts, pH control approach, and other EK operation and maintenance (O&M) requirements.
- Key considerations when implementing EK-enhanced in situ remediation include maintaining saturated conditions around the electrode wells, which can dry out due to electro-osmosis, and controlling pH within acceptable levels. In addition, an adequate remedial timeframe should be considered in O&M planning, as the delivery rate of EK applications can be on the order of several centimeters per day or feet per month. Although the initial amendment application may take longer, the EK approach—more than hydraulic methods—can avoid the need for multiple injections due to contaminant rebound.

Disclaimer

References

Black and Veatch Special Projects Corporation and Geosyntec Consultants. 2020. Electrokinetic-Enhanced In Situ Chemical Oxidation (EK-ISCO) Pilot Test Report. Prepared for the United States Environmental Protection Agency. May.

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