Electrokinetic-Enhanced Remediation

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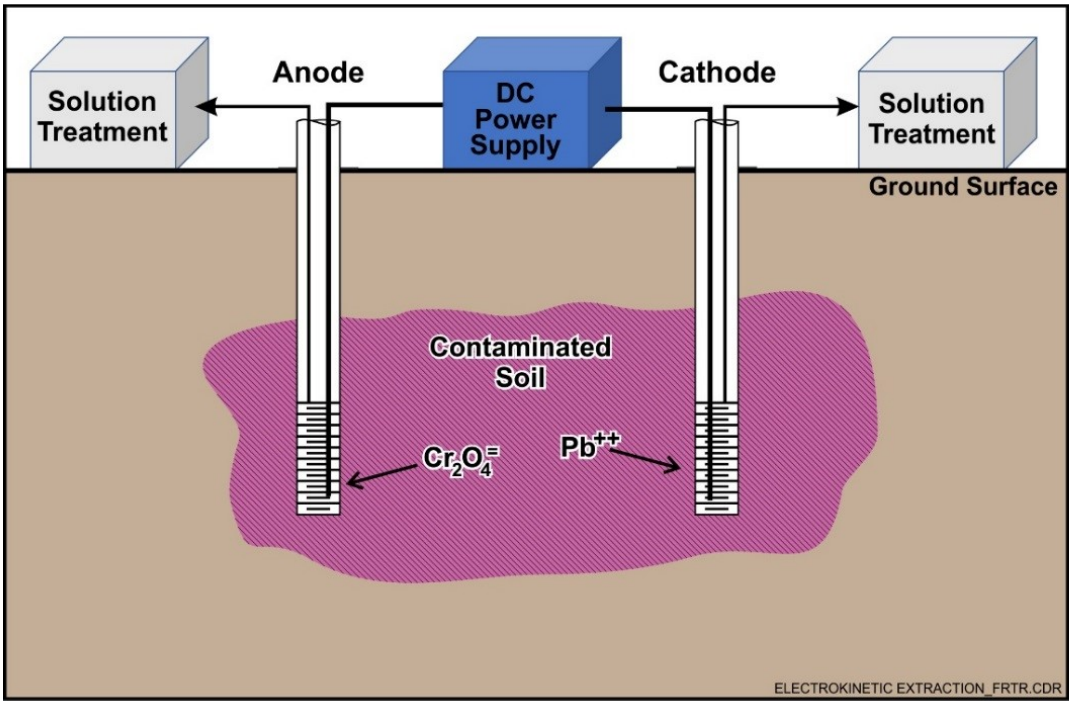
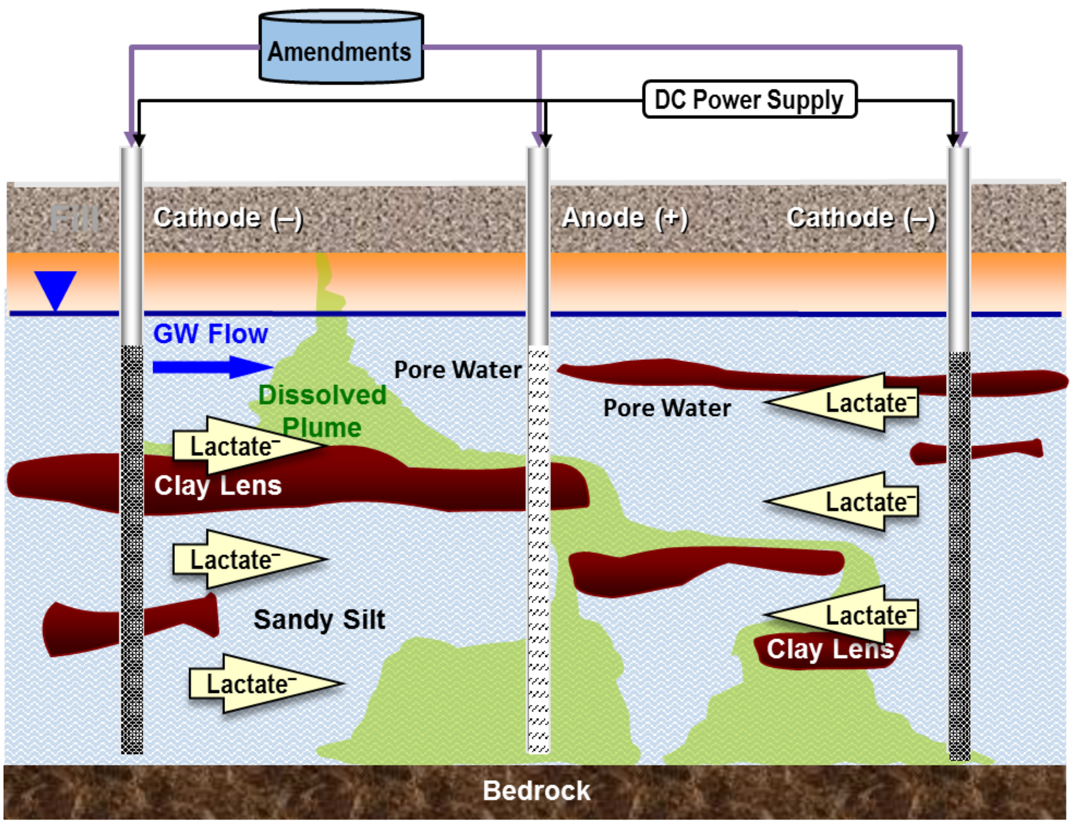
Schematic



Electrokinetic Extraction



Electrokinetic-Enhanced Amendment Delivery

Introduction

Electrokinetic remediation is the process of applying an electrical current to the subsurface to create movement of ions with the objective of facilitating the removal of contaminants through a variety of processes. Early applications focused on the direct removal of heavy metals, radionuclides, and polar or ionizable organic contaminants from soils, sludges, and sediments. More recently, electrokinetics has been applied to facilitate distribution of various amendments required for in situ remediation technologies such as in situ chemical oxidation (ISCO) and enhanced reductive dechlorination (ERD). Regardless of the treatment objectives and application methods, all in situ electrokinetic applications require the installation of several inert electrodes in the aquifer. Application of a low-voltage direct current (DC) is applied to create the voltage gradient and electrical field to more evenly distribute amendments and remove contaminants from the aquifer.

Other Technology Names

Lasanga^{TM}
EK-Bioremediation (EK-Bio)
EK-In Situ Chemical Oxidation (EK-ISCO)
EK-Thermally Activated Persulfate (EK-TAP)
Electrokinetics
In Situ Electrokinetic Extraction (ISEE)
Electrokinetic Remediation Technology (EKRT)
Surface CoverElectrokinetic Biofence

Description

Electrokinetic remediation is performed by applying a current to electrodes that have been installed in the aquifer. One set of electrodes acts as anodes, which are positively charged, and the other set acts as cathodes, which are negatively charged. The electrical current applied to the electrodes creates an electric field in the subsurface, which promotes movement of amendments and groundwater through two primary processes:

- **Electromigration**, which is the movement of charged dissolved ions through an aqueous medium toward the electrode with a polarity opposite the ion charge, and
- **Electro-osmosis**, which is the movement of pore fluid and dissolved constituents within a porous medium that typically occurs from the anode toward the cathode because of the negative charge characteristic of the soil particle surface (Cameselle et al., 2013).

Electrokinetic remediation was initially developed to facilitate removal of metal contaminants, referred to as electrokinetic extraction. Electrokinetic extraction is performed by applying an electrical current across electrode pairs that have been implanted in the ground on each side of the contaminated soil mass. The current causes electromigration of metal ions toward the electrodes as well as electro-osmosis of the pore water. The contaminants present in the dissolved phase are transported towards respective electrodes depending on their charge. The direction and rate of movement of ionic metal species depend upon the magnitude of the charge and also the magnitude of the electro-osmosis-induced flow velocity. The contaminants may be isolated and contained by electroplating, precipitation, or co-precipitation at the electrode surface or may be removed by pumping water near the electrode, complexing with ion exchange resins, or using an external extraction system placed in a unit cycling the processing fluid. Surfactants and complexing agents can be used to increase solubility and assist in the movement of the contaminant.

A recent technological advancement is the use of electrokinetics to facilitate distribution of amendments in the aquifer. This technology has been successfully demonstrated to distribute amendments required for ISCO (e.g., permanganate and persulfate) and ERD (e.g., lactate). Electrokinetics leverages the electrical properties of oxidants, activating agents, electron donors, and bioaugmentation cultures to promote distribution across an electric field. Select remediation reagents are added to electrode wells and/or supplemental supply wells. Similar to electrokinetic extraction, an electrical current is applied to the electrodes to establish an electric field in the subsurface promoting electromigration and electro-osmosis. The electric field transports the amendments through the formation toward the electrode of opposite charge regardless of stratigraphy encountered. In addition, heat is generated at the electrodes, which potentially can facilitate desorption of contaminants from soil and in the case of ISCO using persulfate, can act as an activating agent. The process, using electrical gradient as the driving force rather than hydraulic force, is highly efficient in clay-rich strata and can result in migration of ions and dissolved compounds at the rate of several meters a month in tight clays. For heterogeneous systems, where significant contaminant mass tends to remain in low permeability regions, application of electrokinetic amendment delivery can result in relatively uniform distribution of select remediation reagents into the low permeability layers, greatly reducing back diffusion and overall remedy duration and costs.

Development Status and Availability

The following checklist provides a summary of the development and implementation status of electrokinetic remediation:

- ☐ At the laboratory/bench scale and shows promise
- ☒ In pilot studies
- ☒ At full scale

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- ☐ To remediate an entire site (source and plume)
- ☒ To remediate a source only
- ☐ As part of a technology train
- ☐ As the final remedy at multiple sites
- ☐ To successfully attain cleanup goals in multiple sites

Electrokinetic remediation is available through the following vendors:

- ☐ Commercially available nationwide
- ☒ Commercially available through limited vendors because of licensing or specialized equipment
- ☒ Research organizations and academia

Applicability

Contaminant Class Applicability Rating for Electrokinetic Remediation

(Rating codes: ● Demonstrated Effectiveness, ◐ Limited Effectiveness, ○ No Demonstrated

Effectiveness,
◊ Level of Effectiveness dependent upon specific contaminant and its application/design, I/D Insufficient Data)

Nonhalogenated VOC	Halogenated VOC	Nonhalogenated SVOC	Halogenated SVOC	Fuels	Inorganics	Radionuclides	Munitions	Emerging Contaminants
I/D	●	I/D	●	○	◐	◐	◐	I/D

Electrokinetics is a versatile technology, and therefore can be used to facilitate treatment of a wide range of compounds. Electrokinetic extraction targets contaminant groups such as metal ions, anions, and water-soluble organics with sufficient polarity (or polarizability). Applications have demonstrated effective removal of inorganic and radionuclide contamination; however, costs can be prohibitively high. Surfactants and other solubilizing agents can be added to facilitate removal of contaminants strongly sorbed to soil.

Electrokinetic-enhanced amendment delivery can be used to distribute reagents required for ISCO and ERD. Hence, chlorinated and non-chlorinated volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) potentially can be treated. The technology also has been used in conjunction with permeable reactive barriers to remove contaminants including chromium and perchloroethylene (Cameselle et al., 2013), and bench-scale studies have demonstrated successful removal of arsenic, copper, chromium, and lead (Buchireddy et al., 2008; Alshawabkeh et al., 2005). Bench-scale studies have been conducted demonstrating that munitions and radionuclides also may be removed using electrokinetics (Gent et al. 2008 and 2012; Kyeong-Hee Kim et al., 2003). Electrokinetic remediation has not been used to treat non-aqueous phase liquid fuels.

This technology is applicable at sites containing fine-grained soils with varied permeabilities, high moisture content, and low salinity. Electrokinetics has been used for decades in the oil recovery industry to remove water from soils; however, the in situ application of electrokinetics to remediate contaminated soil has not been widely implemented in the field and has been limited mostly to pilot test demonstrations. Several pilot tests recently have been performed and demonstrated the efficacy of electrokinetic-enhanced amendment delivery for EK-Bio and EK-ISCO applications (NAVFAC, 2017; NIRAS and Geosyntec, 2017).

Cost

Similar to many in situ remediation technologies, the most critical cost factors are associated with the contaminant mass to be treated, the nature and extent of contamination (i.e., size of the treatment area), and number of electrodes/wells required. In addition, the contaminant type and treatment objectives (e.g., containment, source treatment) can have an impact on cost. Major cost drivers include:

Upfront Costs

- Areal extent of contamination requiring treatment, which impacts the number of electrodes required
- Depth of contamination, which impacts electrode design
- Power availability
- Nature of contamination and electrokinetic application method
- Aquifer electrical conductivity influences design, including number and spacing of electrodes, which generally ranges from 10 to 20 feet for electrokinetic applications that promote the distribution of amendments.

Operation and Maintenance Costs

- Number of electrodes
- Treatment duration
- Power requirements and utility rates
- Recovery and recyclability of contaminants (e.g., precious metals)

The list above highlights those cost dependencies specific to electrokinetic-enhanced remediation and does not consider the dependencies that are general to most in situ remediation technologies. Click here for a general discussion on costing which includes definitions and repetitive costs for remediation technologies. A project-specific cost estimate can be obtained using an integrated cost-estimating application such as RACER® or consulting with a subject matter expert.

Duration

Application duration is dependent on the treatment objectives and the specific type of electrokinetics that is applied. For instance, the duration of electrokinetics applied as a permeable reactive barrier to prevent further downgradient plume migration would be indefinite until the source strength was reduced, either naturally or using another technology. The timeframe required to treat a source area is dependent on several factors including size of treatment area, spacing of electrodes, type of contaminants, type of treatment (e.g., biodegradation or chemical oxidation) selected, and aquifer conductivity and lithology.

A typical ion migration rate of 2.5 cm/day is reported for applications of electrokinetic extraction (GWRATC, 2007). Migration of amendments applied using EK-ISCO and EK-Bio have been reported to have similar rates, ranging from 3 to 5 cm/day (NAVFAC, 2017; NIRAS and Geosyntec, 2017). Assuming an application rate of 3 cm/day and an electrode spacing of 3 m, 100 days would be required to transport the contaminants and/or amendments through the treatment area between electrode pairs. However, additional time would be required for installation and subsequent monitoring. Total treatment time may take one or more years depending on the selected treatment mechanism. The overall remedy implementation durations are highly dependent on site-specific conditions and remedial action objectives.

Implementability Considerations

The following are key considerations associated with applying electrokinetic remediation:

- Acid (H+) is generated at the anode and base (OH-) is generated at the cathode. Because hydrogen is more mobile than hydroxide, an acid front can potentially travel toward the cathode (Cameselle et al., 2013). As a result, a pH gradient is created in the aquifer that can impact aquifer geochemical conditions and should be accounted for in the design (Cameselle et al., 2013).
- Electrode polarity can be changed during operation, effectively converting cathode to anode and vice versa, which can help to address pH changes and possibly facilitate more efficient distribution of amendments and transport of contaminants.
- Electrokinetic systems can be designed to effectively deliver amendments into low permeability clays.
- Subsurface electrical conductivity is highly dependent on soil moisture. The transport of amendment still occurs in connected pore fluid between points. So

far, field-scale applications have been in the saturated formation.

- If the target contaminants are strongly sorbed to soil, it may be necessary to add a surfactant or other reagent to promote desorption since electro-osmosis and electromigration are aqueous-phase phenomena.
- Limited data are available for full-scale applications. Adequate bench-scale and pilot-scale testing should be performed prior to designing a full-scale system.

Resources

Alshawabkeh, Akram & Bricka, R & Gent, David. Pilot-Scale Electrokinetic Cleanup of Lead-Contaminated Soils (2005)
Journal of Geotechnical and Geoenvironmental Engineering: 131:3(283)
This journal article describes the results of two experiments using electrokinetics to remove lead from soil.

Buchireddy, Prashanth & Bricka, R & Gent, David. Electrokinetic Remediation of Wood Preservative Contaminated Soil Containing Copper, Chromium, and Arsenic (2008)
Journal of Hazardous Materials. 162. 490-7.
10.1016/j.jhazmat.2008.05.092.
This journal article describes results of bench-scale column tests using electrokinetics to remove copper, chromium, and arsenic from soil.

Cameselle, C. S. Gouveia, D.E. Akretche and B. Belhadj. Advances in Electrokinetic Remediation for the Removal of Organic Contaminants in Soils (2013) (PDF) (23 pp, 604 KB)
Open Access Book Chapter in Organic Pollutants - Monitoring, Risk and Treatment, DOI: 10.5772/54334
This article provides an overview of the status of electrokinetic remediation technologies.

EPA. CLU-IN. Electrokinetics: Electric Current Technologies
This Web site provides an overview and links to guidance for the application of electrokinetics.

Gent, David, Wani, Altaf, Alshawabkeh, Akram, L. and Jeffery Davis. Electrolytic Alkaline Decomposition of a Munition Constituent (RDX) Contaminated Groundwater (2008)
Geotechnical Special Publication. 431-438. 10.1061/40970(309)54.
This publication describes the bench-scale application of electrokinetics and alkaline hydrolysis processes to treat RDX contamination.

Gent, David, Wani, Altaf, and Akram Alshawabkeh. Experimental Design for One Dimensional Electrolytic Reactive Barrier for Remediation of Munition Constituent in Groundwater (2012)
Electrochimica acta: 86. 130-137. 10.1016/j.electacta.2012.04.043.
This journal article presents results of electrokinetic column studies to treat RDX.

Gill, R.T, Harbottle, M.J., Smith, J.W.N, Thornton, S.F. Electrokinetic-enhanced bioremediation of organic contaminants: A review of processes and environmental applications (2014)
Chemosphere: 107 pp. 31-42
This journal article presents the state of knowledge for combining electrokinetics with bioremediation and identifies additional research needs.

Ground-Water Remediation Technologies Analysis Center (GWRTAC). Electrokinetics (1997) (PDF) (21 pp, 129 KB)
This document provides an overview of electrokinetic extraction technologies.

Kyeong-Hee Kim, Soon-Oh Kim, Chang-Woo Lee, Myung-Ho Lee & Kyoung-Woong Kim. Electrokinetic Processing for the Removal of Radionuclides in Soils (2003)
Separation Science and Technology Vol. 38 , Issue 10
This journal article describes a study using electrokinetics to remove uranium and strontium from clay soils.

NIRAS and Geosyntec. Pilot test of Electrokinetically Delivered Thermally Activated Persulfate, EK-TAPTM Final Report (2017) (PDF) (69 pp, 3.94 MB)
This document describes a pilot test application of electrokinetics to facilitate distribution of thermally-activated persulfate to treat groundwater contaminated with tetrachloroethylene.

Remediation Innovative Technology Seminar (RITS). Enhanced In Situ Bioremediation - State of the Practice (2017) (PDF) (94 pp, 5.78 MB)
This seminar provides background information and a case study of the application of electrokinetics-enhanced bioremediation.

Vocciante, M., A. Caretta, L. Bua, R. Bagatin, and S. Ferro. Enhancements in ElectroKinetic Remediation Technology: Environmental assessment in comparison with other configurations and consolidated solutions (2016)
Journal of Chemical Engineering
This study evaluates the potential for electrochemical extraction to be a cost-effective and sustainable remedy compared to other potential remedial alternatives such as excavation and landfill disposal.

1. Known full-scale applications are limited at this time. ↩

2. Known full-scale applications are limited at this time. ↩