

Field Experience with Electrokinetics at a Superfund Site

SUNIRMAL BANERJEE, J. J. HORNG, AND JOHN F. FERGUSON

The results of a field study concerning the technical feasibility of electrokinetic remediation technique at a Superfund site are discussed. The technique of remediation is based on the migration of ionic contaminants under the action of a dc electric field, but for field application of the remedial action, effective combination of dc field application and the pump-and-treat method is required. A matrix of properly designed extraction wells (from which contaminated groundwater can be withdrawn) and an array of wells surrounding each of these wells in a square or hexagonal pattern are needed. The application of a dc field across the contaminated ground, using electrodes placed in both the central as well as the surrounding wells, can enhance the removal of contaminants from the subsurface system. This technique was explored on the premises of United Chrome Products, Inc., in Corvallis, Oregon, where the shallow subsoils and the unconfined groundwater regime were heavily contaminated with chrome plating wastes. On the basis of the analyses of the acquired data on the concentration of various ionic species, it was concluded that electrokinetic treatment combined with occasional withdrawal of effluents can be more effective than the conventional pump-and-treat method.

The currently available waste management alternatives can be grouped into several broad categories: (a) source control, (b) effluent control, (c) physical removal, (d) encapsulation, (e) stabilization, and (f) in-place decontamination. Needless to say, the first two alternatives, which require prior design of a controlled facility, do not pertain to the superfund sites. At these sites, existing subsurface contamination resulting from uncontrolled point-source discharges and accidental spills, more often than not involves large volumes of ground and groundwater. As such, remediation by physical removal of huge masses of contaminated soils for transport to and disposal at an off-site facility becomes overly expensive, and may sometimes cause greater damage to the environment than if the affected soils were left in place. Encapsulating the contaminated mass with impermeable barriers is useful primarily as a temporary measure for arresting the spread of the contaminants. Stabilization of the ground by application of heat or chemicals, on the other hand, may not be desirable if the land must be restored and rehabilitated.

Regulators have recognized the technical limitations, time requirements, and costs of the above alternatives, and a search is underway (1) for in situ techniques that use physical, chemical, thermal, and biological processes to treat the contaminants without removing them from the subsurface system. Currently, a large number of innovative in situ treatment schemes are in the developmental stage. Because there is no unique approach to remediation for the wide variety of contaminants and possible site characteristics, combinations of remedial measures are also being researched and tested.

One of the most widely used methods for treatment of groundwater contaminated with heavy metals is the removal-recovery or pump-and-treat method. Although pump-and-treat is a relatively low-cost process, the long time frame required to achieve the desired effects may sometimes become unacceptably slow, especially in low-permeability soils and areas where the contaminants tend to sorb. In order to investigate the potential of the electrokinetic technique, a field study (2) sponsored by the U.S. Environmental Protection Agency (EPA) was undertaken at a superfund site at Corvallis, Oregon. This technique, based on electrically induced transport of chemicals, was studied both by itself and in combination with the pump-and-treat method. The performance data from bench-scale and field experiments were collected and analyzed.

BACKGROUND

The Superfund site in Corvallis, Oregon, is an abandoned industrial hard-chrome plating facility, previously owned by United Chrome Products, Inc. (UCPI), located next to the Corvallis Airport, south of Airport Road. UCPI operated an industrial hard-chrome plating facility at the site from 1956 to 1985. The facility (Figure 1) consisted of a single building that housed two large plating tanks at the northwest corner, an office in the central northeast end, and a shop that covered the rest of the building. Adjacent to the west side of the building were a few storage tanks, an acid bath, a base bath, and a dry well or gravel pit. As a general practice, the operators discharged the wastes produced at the facility into the dry well constructed specifically for this purpose by digging a hole and backfilling the pit with sand and gravel.

The wastes discharged into the gravel pit generally included floor washing and rinse water collected in a sump within the building, other wastes like spent plating tank solutions, and sludges from the plating tanks. An estimated volume rate of 1,000 gal/year of such waste was discharged into the pit until 1982 when the practice was reportedly stopped.

In 1975, when UCPI submitted an application for an NPDES discharge permit to the Oregon Department of Environmental Quality, the problems at the site came to their attention. Investigations revealed elevated levels of chromium and other heavy metals in the sediment and the water of the nearby drainage ditches. In 1982, the site was determined to be a potential source of contamination of the surface drainage courses as well as the groundwater aquifers unless appropriate steps were taken.

Soon after, investigations of the soil and water conditions at the UCPI site were conducted by Ecology and Environ-

Department of Civil Engineering, University of Washington, Seattle, Wash. 98195.

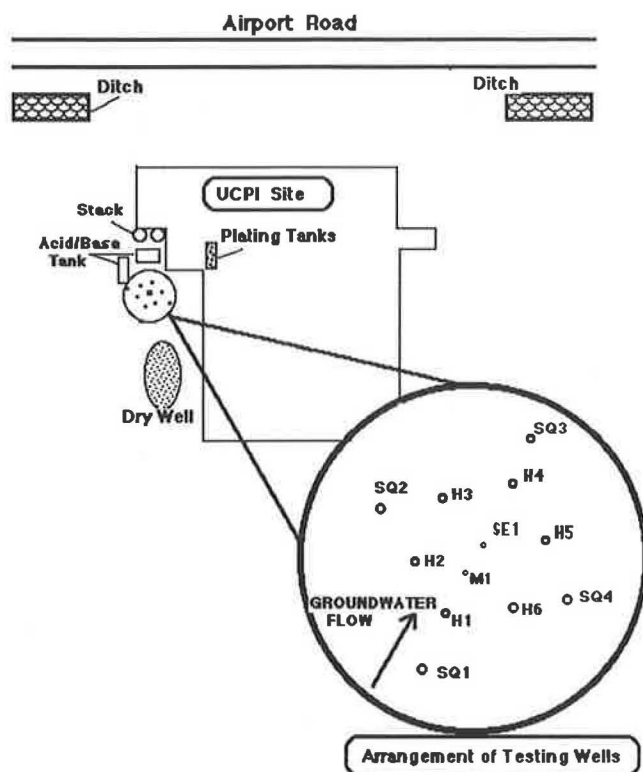


FIGURE 1 Site and well location plan.

ment, Inc. (3), on behalf of the Hazardous Site Control Division, EPA, Region X. On the basis of this study and the serious extent of contamination of the subsurface soils and groundwater at the site revealed by these investigations, the UCPI site was classified as a Superfund site.

UCPI terminated operations at the site in May 1985. A CERCLA remedial investigation and feasibility study was also completed by CH2M Hill (4).

HYDROLOGIC SETTING

The project site is located on the alluvial plains of the Willamette River Valley and occupies about 1.5 acres of relatively level ground. The surface run-off from the site drains into an open ditch that runs along the northern edge of the site and is carried to Dry Creek located approximately 1½ mi southeast of the site. Dry Creek is a secondary tributary of the Willamette River, so the surface run-off from the site eventually discharges into the river.

The subsurface conditions are generally characterized by unconsolidated deposits of clay, silt, and gravel, which can be broken into three distinct units: an upper aquifer, a lower aquifer, and an aquitard separating the two aquifers. At the drilling locations, the upper soils in the profile consist of about 2 to 3 ft of miscellaneous fill or top soil and 15 to 20 ft of clayey silt to silt, ranging from mottled grayish brown to bright yellow in color and extending to depths of 17 to 21 ft below the ground surface. The less pervious soil layer, which separates the saturated pervious zones, consists of light-blue to dark-gray clay to silty-sandy clay ranging in thickness from 2.5 to 12 ft. The bottom of this layer extends 22 to 29 ft in depth below the ground surface over this site. Finally, the

lower aquifer consists of wet, fine-to-coarse sands and gravels and is at least 15 ft thick over the site. A typical subsurface profile is shown in Figure 2. The groundwater table at the site fluctuates seasonally between 0 to 10 ft in depth. During the long, wet winters the site becomes water-logged because of infiltration of rain water. The groundwater table rises to the ground surface and the flow along the local drainage courses comes in contact with the groundwater in the shallow unconfined aquifer. In general, there is little flow of groundwater through the site, and the groundwater table has a slope of about 5 ft/mi (0.0009 ft/ft) in the north-northeast direction.

CHARACTERIZATION OF CONTAMINATION

The activities of UCPI had a serious impact on the local environment. The on-site soils, the groundwater in the upper aquifer, and the surface water are heavily contaminated with inorganic contaminants, viz., arsenic, barium, chromium, copper, iron, and lead. These substances are present in concentrations that exceed the primary drinking water standards. The most important of these contaminations is chromium. Elevated levels of chromium were detected in the vicinity of the gravel pit and the plating baths inside the building. The leaking of the plating tanks and disposal of waste waters in the gravel pit seem to be the primary causes of the soil and groundwater contamination at the site.

Presently, most of the contaminants are confined within the near-surface soils, and the nearly static groundwater regime has not allowed the contaminant plume to extend beyond several hundred feet down gradient from the source point. The boundaries of the plume are not well defined at the present time.

The distribution of contaminants within the affected soils has been found to vary with depth and distance from source points. The soils immediately overlying the confining silty clay layer in the vicinity of the source points show the highest concentrations of chromium (Figure 3). Chromium concentrations as high as 15 000 mg/L have been measured in the groundwater at one of these points. Concentrations about 200 times the primary drinking standard of 0.05 mg/L have been measured in the surface water.

The site poses a significant threat to the environment of the region because in the future, the contaminated groundwater from the site could eventually pollute the existing city wells and the surface drainageways, dangerously elevating the level of pollutants.

METHODOLOGY

Application of a dc electric field across an electrolyte brings about a host of complex interrelated phenomena that are collectively referred to as electrokinetics. In a stationary porous medium, fluid flow through the pores of the medium occurs in conjunction with the excess cations in the diffuse layer, and the process is called electroosmosis. In cases of the dispersion of solid particles in an otherwise stagnant fluid, movement of the solid particles can occur and the phenomena is called electrophoresis. Several other electrokinetic effects are currently used, including streaming current (flow of electric charge under the action of a hydraulic gradient), sedi-

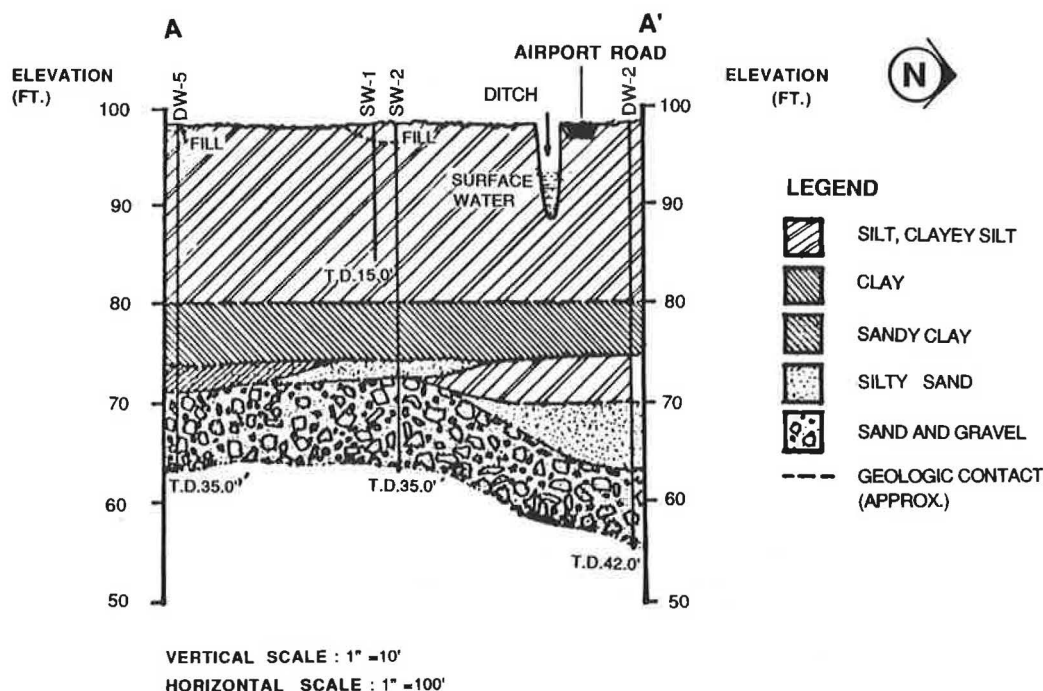


FIGURE 2 Typical subsurface profile at UCPI site (3).

mentation potential (electrical potential induced by movement of solid particles in a stagnant fluid) and dielectrophoresis (movement of uncharged matter in a nonuniform electric field). These processes, however, are generally used for purposes other than engineering.

Several basic processes are responsible for the transport of charge and matter caused by the application of a dc field across an electrolyte. These include ionic migration (drift of dissociated ions of the solute through the bulk solution towards the appropriate electrodes), ionic diffusion (movement of ions from regions of higher concentrations to regions of lower concentration), electrodic reactions (chemical reactions required for transfer of charge to and from the electrodes), as well as many other possible electrochemical reactions.

In the past, electrokinetics have been used in electroosmotic dewatering, electrical thickening, electrophoretic separations, and electrophoretic depositions, among other applications. Over the last two decades, extensive research efforts have been focused on seeking more novel applications of electrokinetics. It has been shown that the potential applications could address problems as diverse as injection and control of grouting in soils (5,6), electroreclamation of soils (7-9), and removal of corrosive chlorides from bridge decks (10). These studies suggest that electrokinetic treatment exhibits potential as a new approach to the decontamination of waste sites involving inorganic (heavy-metal) contaminants.

The basic concept involves the migration of ionic contaminants toward collection wells by application of a dc electric field, and the withdrawal of an enriched solution from the well by pumping.

EXPERIMENTAL PROCEDURES

The experimental program was designed to explore the removal of anionic chromium by a treatment scheme that com-

bines both hydraulic advection and electrokinetic migration. Eleven 15-ft-deep wells with 4-in.-diameter slotted PVC casings were installed in an arrangement as shown in Figure 1. The wells labeled from H1 to H6 were placed at the vertices of a regular hexagon at 5-ft spacing. The wells labeled from SQ1 to SQ4 were arranged in a square pattern at 8-ft spacing. The central well SE1 and these other wells were designed to serve as electrode locations. During the experiments, steel reinforcing bars were placed in the appropriate wells to serve as electrodes. Two pairs of monitoring wells, M1 and L1, M6 and L6, were also installed along the lines joining the central well and H1 and H6, respectively. The line connecting SQ1 and SQ3 aligned approximately in the direction of the prevailing groundwater flow.

The dc field was supplied by a dc power supply (Lambda, Model LES-F-03-OV). The potentials and currents were monitored by a multimeter at the output end of the power supply. A microcomputer (AT&T PC 6300) based data acquisition system (Burr-Brown PCI-2000) was also used to keep continuous records of voltage and current. The water level at the wells was measured by a level indicator (Slope Indicator, Model 5145) and recorded manually.

The groundwater was sampled from selected wells by two GEOPUMPS, (peristaltic pumps) at constant depths of 11 and 14 ft below ground surface. The temperature, specific resistance, dissolved oxygen, and pH of the samples were measured immediately after retrieval. Concentrations of total Cr, Cr (VI), and other cations were measured by the Environmental Engineering Laboratory at Oregon State University within 24 hr. Cations and anions were also analyzed later in the acidified samples by atomic absorption (AA) spectrophotometry, ion chromatography (IC), and inductively coupled plasma atomic emission spectrometry (ICP) at the University of Washington in Seattle.

The field experiments involved the determination of initial (background) conditions and the effects of pumping and com-

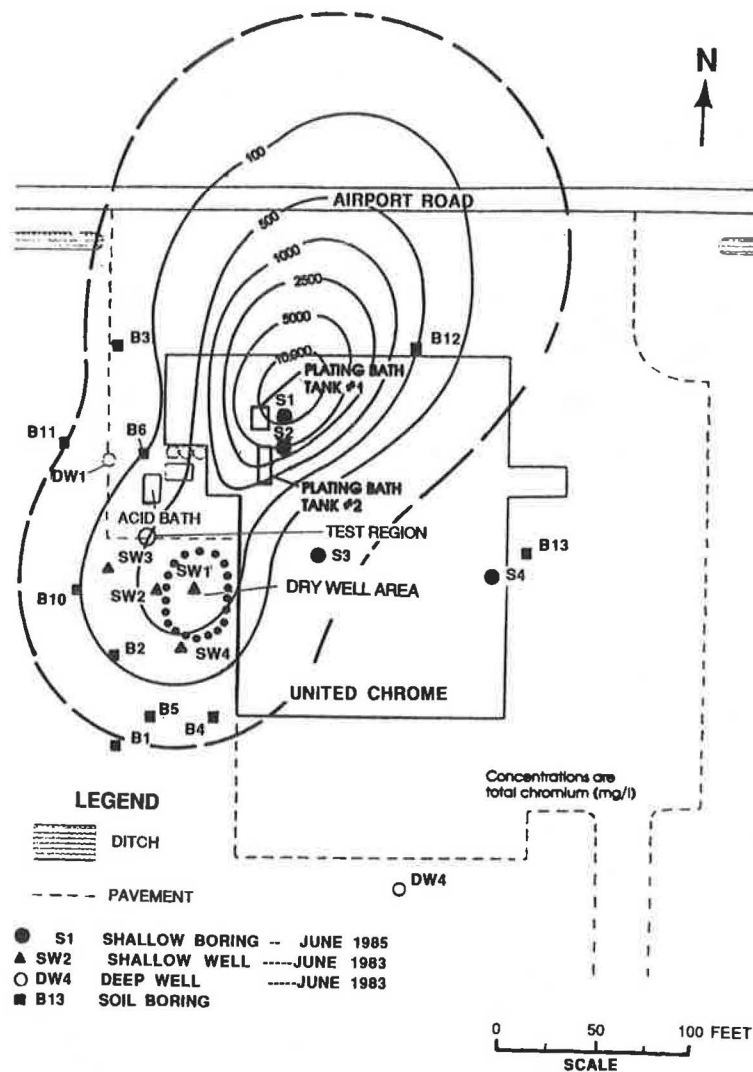


FIGURE 3 Approximate contours of total chromium concentration (4).

bined treatment. Two types of combined treatment were tested: (a) electrokinetic treatment with continuous pumping, and (b) electrokinetic treatment with pulsed or periodic pumping. Different pumping rates, electrical currents, and voltage drops were used in these tests. In between successive experiments, all the wells were purged by withdrawing groundwater in the amount of three times the well volume. All but one of the tests used the hexagonally arranged wells (as cathodes) and the central well (as anode) in order to achieve a more radially uniform potential field; the other test was performed with a triangular arrangement of electrodes. All of the wells were used to monitor the treatment effects.

RESULTS AND DISCUSSION

Spatial Distribution of Chromium

Before the beginning of the field tests, two sets of samples from all wells were taken at different depths (11 and 14 ft below the well surface) to ascertain the spatial distribution of chromate. Between the two sets of sampling, one well volume of water was withdrawn from all wells to achieve redistribution

of the polluted groundwater. Although total chromium concentration greater than 100 mg/L was found in wells SE1 (390 mg/L), H1 (218 mg/L), H5 (205 mg/L), H6 (500 mg/L), SQ1 (615 mg/L), and SQ4 (245 mg/L), a much lower total chromium concentration (ranging between 1 and 78 mg/L) was found in wells H2 (9 mg/L), H3 (2 mg/L), H4 (18 mg/L), SQ2 (1 mg/L), and SQ3 (78 mg/L). Also, the concentrations in the aquifer were noted to increase with depth, possibly because of higher density of the solution. This nonhomogeneity of the distribution of the contaminant made the interpretation of the test results significantly more difficult.

Aquifer Characteristics

During the pumping tests, the changes of groundwater level in wells indicated nonhomogeneous hydrogeological conditions in the test region. The groundwater level changes were different in the direction of SE-M1-H2-SQ1 than in the direction of SE1-H4-SQ3 (Figure 1). Theoretical drawdown curves were developed from the modified Theis solution using transmissivity (T) of 0.45 and storage coefficient (S) of 10^{-6} . It should be mentioned that these values of T and S are

markedly different from T of 0.305 and S of 0.14 (4), which were used to make design calculations to establish rate of pumping. In addition, no significant changes in groundwater levels during electrokinetic treatment (by itself) indicated that the influence of electroosmotic flow was small.

Temperature

While dc power was being applied, the water temperature in SE1 was slightly higher ($<1^{\circ}\text{C}$) than the temperature in the other wells. This increase of temperature was probably caused by the heating effect at the anode. No similar trend was observed at the cathodes. However, the fluctuations of ambient temperature had more significant influence on the temperature of the wellwater than did the heating effect caused by the applied dc power.

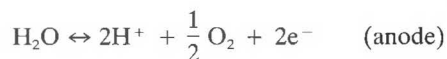
Potential Distribution

For cylindrical geometry of the electrode arrangement, the theoretical solution for the potential distribution is available in the literature (5). The measured values of the potentials and the theoretical values are compared in the normalized plot (Figure 4). The agreement between the experimental and the theoretical curves is reasonable. Some potential drops (usually called polarization or activation overpotentials) do take place at electrode-solution boundary layers so that effective voltage across the electrolyte is given by the voltage at the power supply minus the sum total of the overpotentials. The potential gradient, which is the driving force for ionic migration, is much higher in the immediate neighborhood of the central anode or cathode than elsewhere. This implies that the ionic migration would be expected to be much more effective in the central region than elsewhere.

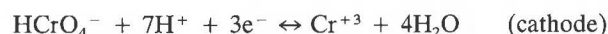
Electrode Reactions and pH

The observed changes in pH of the samples exhibited consistent trends in these experiments. A relatively small de-

crease of pH was noted at the well during pumping tests. But, electrokinetic treatment brought about much larger changes in pH at wells that served as working electrodes. An increase in pH at the cathodes and a decrease at the anodes were invariably associated with the treatment. The pH changes at the electrodes, in fact, occur because of the electrodic reactions. The major reactions occurring at the electrodes were water electrolysis at the anode and the cathode:



and redox reactions such as the reduction of chromate at the cathode and the dissolution of the anode:



These reactions were supported by the pH increase from 5 to above 12 at the cathodes and the rapid increases of iron concentration and iron precipitates at the anode. Anode oxidation had long been noted in many engineering applications of electrokinetics (11–13) and electroosmosis and resulted in pH variations at the anode between 2 and 5.5 during the treatment.

Chromate Removal

Evaluation of the effectiveness of three different treatment procedures in removing chromate and dichromate from the upper aquifer was of primary concern in these experiments. The treatment procedures explored in these experiments include (a) extraction of contaminants by pumping, (b) combined electrokinetic and pumping treatment, and (c) electrokinetic treatment with occasional withdrawal of effluents. Separate experiments were performed to explore these effects. In the last group of electrokinetic experiments, effluents from the anode were extracted at the nominal rate of 2 gal every 12 hr.

During the continuous pumping tests, it was observed that in comparison to the initial chromium concentration, the chromium concentration of the pumped water was considerably higher (Figure 5). While this higher concentration was maintained as long as the pump was running, at the end of the pumping the concentrations rapidly decreased and gradually increased back to initial concentration. In all of these experiments, continuous pumping caused mixing of the contents of the well and more concentrated solutions from greater depths were extracted during pumping. At the end of pumping, dilution caused by influx of fresh groundwater quickly reduced the concentration. In spite of different rates of pumping (0.17 and 0.26 gal/min), the concentrations in the central well were about the same during both of the pumping tests.

In order to study the combined effects of continuous electrokinetic and pumping treatment, the other test was carried out with a pumping rate of 0.16 gal/min and at a constant dc current of 6 amperes. Again, an immediate increase in total

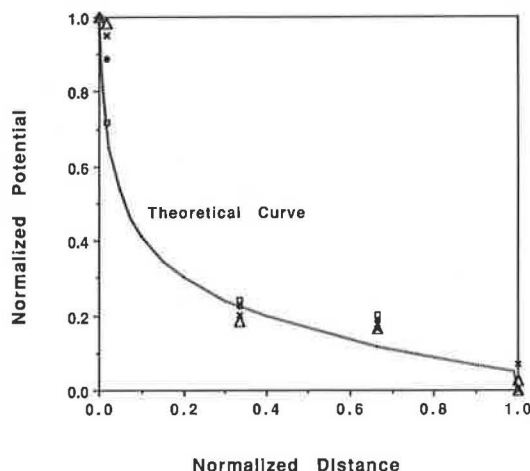


FIGURE 4 Variation of normalized electrical potential with distance from anode.

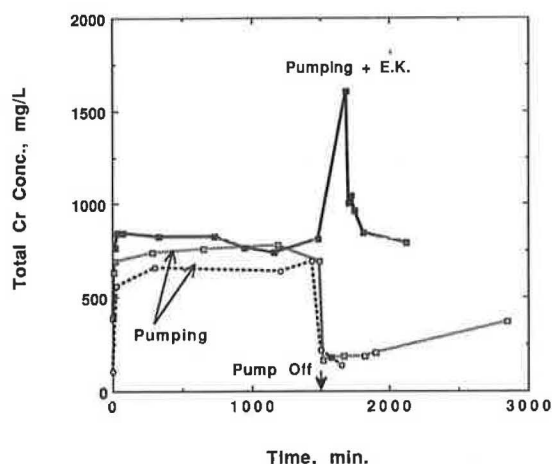


FIGURE 5 Total chromium concentrations during pumping with and without electrokinetic treatment.

chromium concentration at the central wall had occurred during this experiment. The concentration sustained during this experiment was slightly higher (800 mg/L) than the corresponding concentration (770 mg/L) noted in the pumping tests. The posttreatment concentrations were different in this test. For several hours after the termination of treatment, a higher level of chromium concentration than in the pumping tests was sustained in this test. This difference seems to suggest that during the treatment period the effects of pumping might have obscured the effects of electrokinetic migration, but with the influx of groundwater towards the central well at the end of treatment, the migrating front of higher concentration advected toward the central well.

The other group of experiments (electrokinetic treatment with occasional extraction of effluents) used the central well as the anode. Figure 6 shows the chromium concentration versus time curves at the anode obtained from these tests. Generally, the trend of concentration changes indicates an increase in concentration during treatment with an abrupt decrease on withdrawal of the effluents. The overall effect, however, was a gradual reduction of concentration. The response in Experiment 4 was particularly pronounced for two reasons: (a) higher initial concentration; and (b) higher applied current. The different rates of response indicate that the electrokinetic migration process is dependent on initial or pretreatment concentration and the total current. The dependence of the treatment effect on initial concentration is clearly shown in Figure 7; chloride ions responded more vigorously to the same treatment because of higher initial concentration of chlorides. Meanwhile, the concentration of anionic chromium at the cathodes decreased significantly.

Removal of Chloride and Other Ions

Obviously, advection and migration were the two major transport processes involved in these field experiments, diffusion being of minor importance except in the vicinity of the electrodes. Although ion migration is a discriminative process (in the sense that it drives cations towards the cathode and anions to the anodes), advective transport of both cations and anions

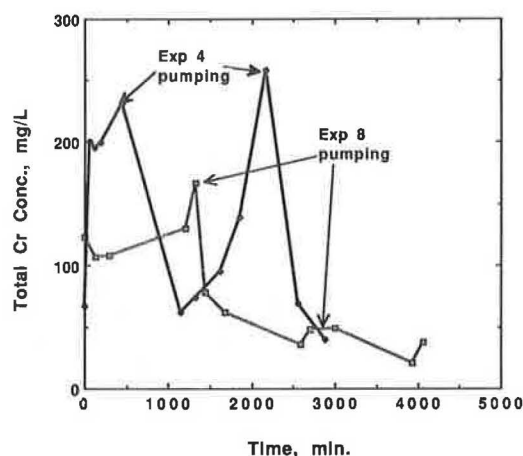


FIGURE 6 Total chromium concentrations during electrokinetic treatment with periodic pumping.

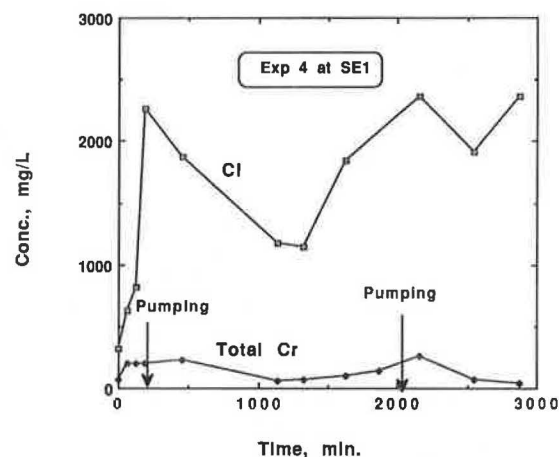


FIGURE 7 Total chromium and chloride concentrations at anode during electrokinetic treatment with periodic pumping.

occurs in the prevailing direction of overall flow of the electrolyte. On the other hand, in the absence of advection, ionic transport depends strongly on the strength of the applied field (or current density), charge number (or valence), and diffusivities of ions. In other words, ionic species with higher diffusivity and lower charge number (chloride, for instance) can be expected to transport faster than other ions. But, when advective and electrokinetic transport are combined, the effects of migration may be masked by that of advection because the former process is much slower (flow velocity of the order of 10^{-5} cm/sec under a unit field strength). Furthermore, other side effects such as electrode dissolution of the anode and electrolysis of water at the cathode would affect the removal of ions because these effects may introduce additional competing ions.

The evidence of ion migration is conspicuous in the results of the group of experiments in which the two treatment processes were combined. Figure 8 shows the results of pumping and combined tests at the well SE1. The chloride ion migration was greater than that of chromate ions because of their monovalence, higher mobility, and of course, higher concen-

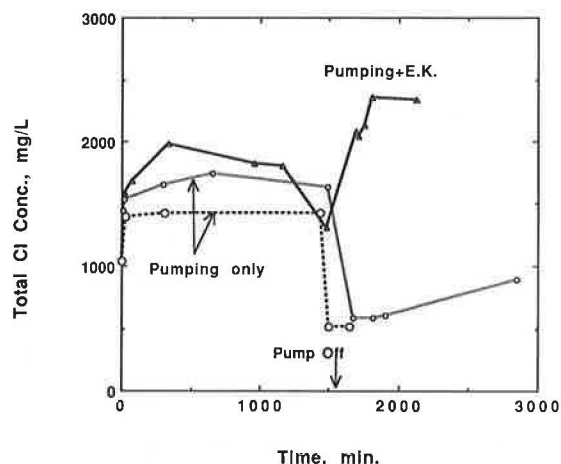


FIGURE 8 Chloride concentrations during pumping with and without electrokinetic treatment.

tration. All of the cationic species except iron decreased in concentration at the anode. The trends of iron and chloride concentration changes were similar, implying that dissolution of the anode was accompanied by migration of anions to the anode.

Figure 9 shows the concentrations of the major ions at the cathode during electrokinetic treatment with occasional withdrawal of effluents. Increase of sodium and calcium ion con-

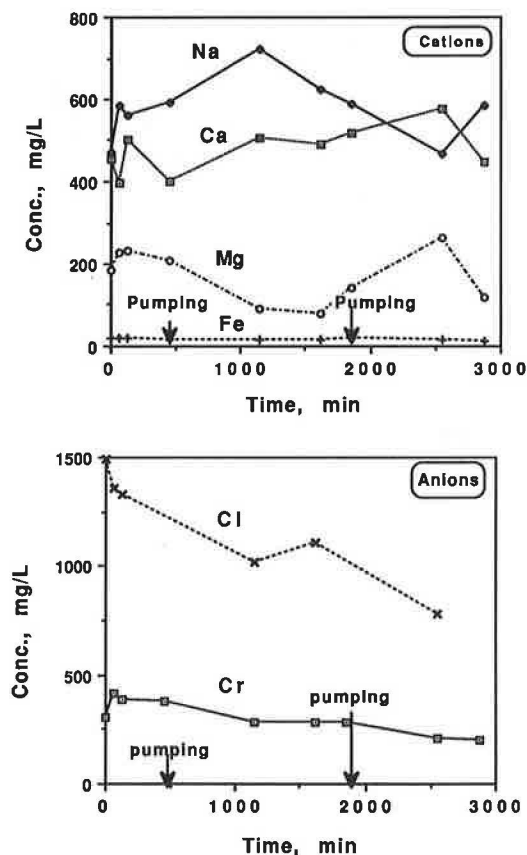


FIGURE 9 Major cation and anion concentrations at cathode during electrokinetic treatment with periodic pumping.

centrations and decrease of both chloride and chromate concentrations are also direct effects of ion migration. These effects are relatively smaller than those at the anode because of the lower potential gradient in the vicinity of the cathode as discussed previously.

Final Remarks

By comparing the variation of concentration of chloride ions, it can be seen (Figure 10) that the electrokinetic applications of low current (5 amp) yielded less transport of anions than high current (10 amp) did. The use of constant voltage (30 volts) not only yielded higher currents—initial current at 17 amp, 10 amp after 6 hr, and 6 amp after 24 hr—but also induced more migration of chloride ions in 24 hr. If the chromate ions were the major anions, the removal efficiency of chromate by the combined treatment would be much higher.

After several tests, the chromate concentration in the central well SE1 was low (<50 mg/L) even after several pumping and purging cycles. This reduction of chromate near the region of the central well was caused by the combined treatment. In order to assess the effectiveness of the combined treatment schemes, the mass of chromium removed per well volume of effluent withdrawn was computed from the results of the appropriate experiments. The total mass of chromium recovered per well volume of effluents by pumping, combination of electrokinetics with continuous pumping, and combination of electrokinetics with occasional pumping were, approximately, 4.77, 5.15, and 9.23 g, respectively. Finally, passage of electric current may provide the impetus for desorbing offensive ions that may otherwise be firmly attached to the soil solids and would not be removed by pumping.

CONCLUSIONS

The feasibility of electrokinetic treatment to accelerate removal of chromate from soils was evaluated in this study. Although the field heterogeneity had an obscuring effect, proper combination of pumping with the electrokinetic treatment substantially shortened the time frame of treatment. The

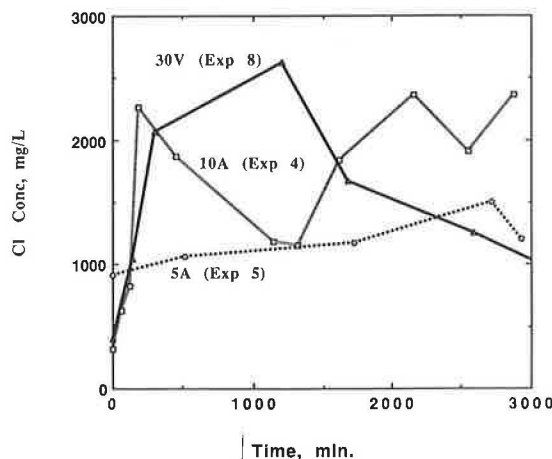


FIGURE 10 Chloride concentrations at anode for constant-current and constant-voltage applications.

major conclusions that can be drawn from this study are the following:

1. In electrokinetic treatment, electrically induced ion migration plays a significant role. However, the process of ion migration is slow and its effect may be enhanced or suppressed by the effects of advective groundwater movement or pumping.

2. The factors that influence the results of electrokinetic applications include (a) geological and hydrogeological setting, (b) nature of pollutants, and (c) operational conditions. The favorable geological and hydrogeological factors include moderate permeability of soils, nearly static groundwater, and moderately large areal extent of the site. The chemistry and the composition of the ion species are decisive factors that control the mobility of the contaminants within the subsurface system. The experimental constraints, e.g., direction of electrical field, the type of application (constant voltage or constant current), the direction of fluid flow, the electrode material, and the electrodic reactions can significantly influence the overall outcome.

3. Two types of pumping operations were used in conjunction with electrokinetic treatment; continuous pumping is suitable for removing pollutants at high concentrations and periodic pumping is more effective for concentrating pollutants at low concentrations.

4. Electrodic reactions may introduce other side effects during treatment, for instance, electrolysis of water may change the chemistry of the ion species, and the pH of water and the dissolution of metal electrodes may introduce other species into the system.

The present knowledge is not sufficiently developed that a mathematical or theoretical model of the treatment effects can be formulated. In addition, the treatability of particulate and colloidal pollutants and the mixtures of inorganic and organic contaminants has not been studied. These research needs must be addressed before the potentials of the technique can be fully realized.

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REFERENCES

1. R. D. Hill. Demonstration of New and Innovative Hazardous Waste Treatment Technologies—The SITE Program. *Proc., 61st Annual Conference of the Water Pollution Control Federation*, Dallas, Tex., Oct. 1988.
2. S. Banerjee, J. J. Horng, J. F. Ferguson, and P. O. Nelson. *Field-Scale Feasibility Study of Electrokinetic Remediation*. Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1989.
3. Ecology and Environment, Inc. *Field Investigation of Soil and Water Conditions at United Chrome Products, Inc., Corvallis, Oregon*. TDD R10-8308-04. Seattle, Wash., 1983.
4. CH2M Hill. *Remedial Investigation Report—United Chrome Products Site, Corvallis, Oregon*. USEPA 106.OL32.0, U.S. Environmental Protection Agency, Seattle, Wash., 1985.
5. M. I. Esrig. Pore Pressures, Consolidation, and Electrokinetics. *Journal of the Soil Mechanics and Foundations Division, ASCE*, Vol. 94, No. SM4, July 1968, pp. 899–921.
6. T. Yamanouchi and S. Matsuda. Stabilization of Sand Feasible to Liquefaction by Means of a Kind of Grouting Applying Electro-Osmosis. *Proc., Symposium on Recent Developments in the Analysis of Soil Behavior*, University of New South Wales, Australia, 1975, pp. 411–421.
7. H. J. Gibbs. Research on Electro-Reclamation of Saline-Alkali Soils. *Transactions of the American Society of Agricultural Engineers*, Sept. 1966, pp. 164–169.
8. R. Hammet. *A Study of the Process Involved in the Electro-Reclamation of Contaminated Soils*. M.Sc. thesis, University of Manchester, Manchester, England, 1980.
9. A. N. Puri and B. Anand. Reclamation of Alkali Soils by Electrodialysis. *Soil Science*, Vol. 42, 1936, pp. 2327.
10. J. E. Slater, L. R. David, and P. J. Moreland. Electrochemical Removal of Chlorides From Concrete Bridge Decks. *Material Performance*, Vol. 15, Nov. 1976, pp. 21–26.
11. L. Casagrande. Electro-Osmosis in Soils. *Geotechnique*, Vol. 1, 1949, pp. 1959–1977.
12. B. A. Segall, C. E. O'Bannon, and J. A. Matthias. Electroosmosis Chemistry and Water Quality. *Journal of Geotechnical Division, ASCE*, Vol. 106, No. GT10, 1980, pp. 1148–1152.
13. R. H. Sprute and D. J. Kelsh. *Electrokinetic Consolidation of Slime in an Underground Mine*. Report of Investigation 8190, Spokane Mining Research Center, Spokane, Wash., 1976.

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