Journal of Soil Contamination, 8(6):617–635 (1999)

Optimization of 2-D Electrode Configuration for Electrokinetic Remediation

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A practical evaluation of one- and two-dimensional applications of electric fields for in situ *extraction of contaminants is provided. The evaluation is based on contaminant transport by electroosmosis and ion migration. Parameters evaluated include electrode requirements, effectiveness of electric field distribution, remediation time, and energy expenditure. Formulation is provided for calculating cost components of the process, including electrode, energy, chemicals, posttreatment, fixed, and variable costs. Equations are also provided for evaluating optimum electrode spacings based on energy and time requirements. The derivations show that spacing between same-polarity electrodes is as significant in cost calculations and in process effectiveness as that between anodes and cathodes. Decreasing the same-polarity electrode spacing to half the anode-cathode spacing will result in a 100% increase in electrode requirements, but will decrease the area of the ineffective electric field by one half. Selection of the voltage gradient impacts the optimum electrode spacing. The analysis show that a minimum exists in the cost versus electrode spacings relationship.*

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KEY WORDS: *soil, remediation, electroosmosis, ion migration, electrokinetics, heavy metals.*

1058-8337/99/$.50

Introduction

THE use of direct electric currents has emerged as an innovative technique for *in situ* extraction of contaminants from fine-grained soils. An electric current is applied across electrodes inserted in the soil to generate an electric field, which causes contaminant transport by electroosmosis and ionic migration (Acar and Alshawabkeh, 1993). Electroosmosis mobilizes the pore fluid in the soil medium, usually from the anode toward the cathode, while ionic migration effectively separates the anions and cations by their transport to the anode and cathode, respectively. This transport coupled with geochemical reactions (e.g., desorption, dissolution, and complexation) constitute the fundamental mechanisms of the electrokinetic remediation process. Generally, extraction and removal are accomplished by electrodeposition, precipitation, or ion exchange either at the electrodes or in an external extraction system.

The scientific basis of this technology is documented extensively in the literature, including its potential for *in situ* removal of inorganic species (Runnels and Larson, 1986; Lageman *et al.,* 1989; Acar *et al.,* 1990; Pamukcu *et al.,* 1990; Hamed *et al.,* 1991; Probstein and Hicks, 1993; Runnels and Wahli, 1993; Acar *et al.,* 1994; Eykholt and Daniel, 1994; Acar and Alshawabkeh, 1996; Yeung *et al.*, 1996; Reddy *et al.*, 1997; Wong *et al.*, 1997), radionuclides (Ugaz *et al.*, 1994) and some organic species from soils (Shapiro *et al.*, 1989; Acar *et al.*, 1992; Bruell *et al*., 1992; Shapiro and Probstein, 1993; Pamukcu and Wittle, 1992; Acar *et al.,* 1993). Recent developments of electrokinetic remediation are summarized in nineteen papers presented in a special issue of the *Journal of Hazardous Materials* (Acar and Alshawabkeh, 1997).

However, studies on practical aspects of electrokinetic remediation are rare. Schultz (1997) provided economic modeling and calculations of optimum spacings, time, and energy requirements of one-dimensional (1-D) field applications based on electroosmotic transport. Alshawabkeh *et al.* (1999) discussed practical aspects of 1-D full-scale *in situ* applications. These studies also address optimum conditions for 1-D applications. Field application requires optimizing the process by adopting the best 1-D or 2-D electrode configuration and spacing. No experimental data are yet available on 2-D or radial applications, thus the impact of 2-D electrode configuration is not well understood.

Few theoretical formulations and numerical models exist for electrokinetic remediation (Shapiro *et al.,* 1989; Alshawabkeh and Acar, 1992; Shapiro and Probstein, 1993; Jacobs *et al.*, 1994; Alshawabkeh and Acar, 1996; Haran *et al.*, 1997). While these models are developed for only 1-D applications, they are still quite sophisticated because they describe a system of partial differential (transport) and nonlinear algebraic (geochemical equilibrium) equations and require extensive computational time. These models also require evaluation of many soil and contaminant parameters. Further, 2-D and nonlinear distribution of the electric field significantly controls transport and extraction of metals, and thus will complicate numerical modeling attempts. A practical theoretical approach is needed for optimizing electrode configuration for full-scale field implementation.

This article provides a practical approach for evaluating the performance of 1-D and 2-D electrokinetic remediation and compares selected electrode configurations with respect to time, energy requirements, and optimum spacings. This study also provides a methodology for design and cost evaluation of the technology. The formulations are based on simplifying assumptions and should be used for preliminary design when it is not possible or practical to use highly sophisticated analysis or design models.

Electrode Requirements

The number of electrodes required for 1-D applications depends on spacing between electrodes of the same-polarity (e.g., anode-anode or cathode-cathode spacing). Decreasing spacing between same-polarity electrodes minimizes the area of inactive electric field, but increases the cost of the process. The same situation applies for 2-D configurations. In general, the goal of 2-D applications is to achieve axi-symmetrical (or radial) flow toward a center electrode. The derivations will focus on extraction of positively charged heavy metals, thus locating the cathode as the center electrode allows accumulation of the cationic contaminants in a smaller zone around the cathode. Outer electrodes (anodes) are placed at specific distances from the center cathode to achieve relatively radial flow. The electrodes can be placed in a hexagonal or square configuration. Hexagonal (honeycomb) electrode configuration consists of cells, each contains a cathode surrounded by six anodes. The square configuration consists of a cathode and four (or possibly eight) anodes surrounding the cathode. Hexagonal and square grids generate 2-D, nonlinear electric fields. Areas of inactive electric fields will develop depending on the configuration selected. Because this impacts the cost of electrodes, it will be necessary to select the configuration with the optimum number of electrodes per unit area while minimizing the area of the ineffective electric fields.

Table 1 provides a comparison of number of electrodes required per unit surface area for 1-D, 2-D hexagonal, and 2-D square configurations. Three cases are provided for 1-D arrangement where the same-polarity electrode spacing equals (a) the anode-cathode spacing, (b) one-half the anode-cathode spacing, and (c) one-third the anode-cathode spacing. Number of electrodes is calculated based on a unit surface (plane) area. Considering a unit cell, the number of electrodes per unit area can be given by,

TABLE 1
Impact of Electrode Configuration on Electrode Requirements and Size of Ineffective Areas

Config.	Electrode spacing		No. of Electrodes per cell (F_1)	Area of cell (A_{cell})	No. of electrodes per unit area		Ineffective Area	
	Opp. Charge	Same charge			N	% increase	A_{Ineff}	% of A_{cell}
1-D	L_E	L_E	1	L_E^2	$1/L_E^2$	0	$L_E^2/2$	50%
1-D	L_E	$L_E/2$	2	L_E^2	$2/L_E^2$	100%	$L_E^2/4$	25%
1-D	L_E	$L_E/3$	3	L_E^2	$3/L_E^2$	200%	$L_E^2/6$	17 %
Square	R_E	$\sqrt{2}\ R_E$	2	$2\ R_E^2$	$1/R^2$	0	$R_E^{\ 2}$	50%
Hex.	R_E	R_E	3	$3(\sqrt{3})R_E^2/2$	$\sqrt{(4/3)}/R_E^2$	15.5%	$3R_E^2/4$	29%

$$N = \left[\frac{F_1}{L_E^2}\right]_{1D\ flow} = \left[\frac{F_1}{\pi R_E^2}\right]_{2D\ flow} \tag{1}$$

where N (L^{-2}) is the number of electrodes per unit surface area of the site to be treated, L_E (L) and R_E (L) are 1-D and 2-D anode-cathode spacing, respectively, and F_1 (dimensionless) is a shape factor depending on electrode configuration. F_1 is calculated by adding the number of electrodes serving a unit cell. If one electrode is serving more than one cell, then a fraction of the electrode is serving each cell. Table 1 shows the values of F_1 for selected configurations. The results show that 1-D configurations with same-polarity electrode spacings of one-half and one-third anode-cathode spacings require a 100 and 200% increase in number of electrodes, respectively, when compared with the 1-D case of equal electrode spacings. Hexagonal configuration requires a 15% increase in number of electrodes when compared with a 2-D square configuration. Electrode requirements clearly affect the uniformity of electric fields and development of ineffective areas. Thus, it is necessary to evaluate the impact of increasing the electrodes on the development of ineffective spots.

Electric Field Distribution

Numerical simulations of contaminant transport under electric fields use nonlinear, 1-D electric-field distributions for predicting species transport (Alshawabkeh and Acar, 1992; Shapiro and Probstein, 1993; Alshawabkeh and Acar, 1996, Jacobs *et* *al.*, 1996). Similar numerical procedure can be used for 2-D applications. Another possibility is to assume uniform steady-state conditions and use the Laplace equation to describe the 2-D electric-field distribution. Analytical solutions, numerical methods, or conformal mapping can be used for solving the Laplace equation. However, these solutions do not provide a mechanism for comparing the effectiveness of different configurations. An approximate and practical approach is adopted in this article for evaluating the area of ineffective electric fields. Electric field distributions show that the ineffective area for each cell has the shape of a curvilinear triangle with the base being the distance between electrodes of the same polarity (Figure 1). The height of this triangular area is approximate and

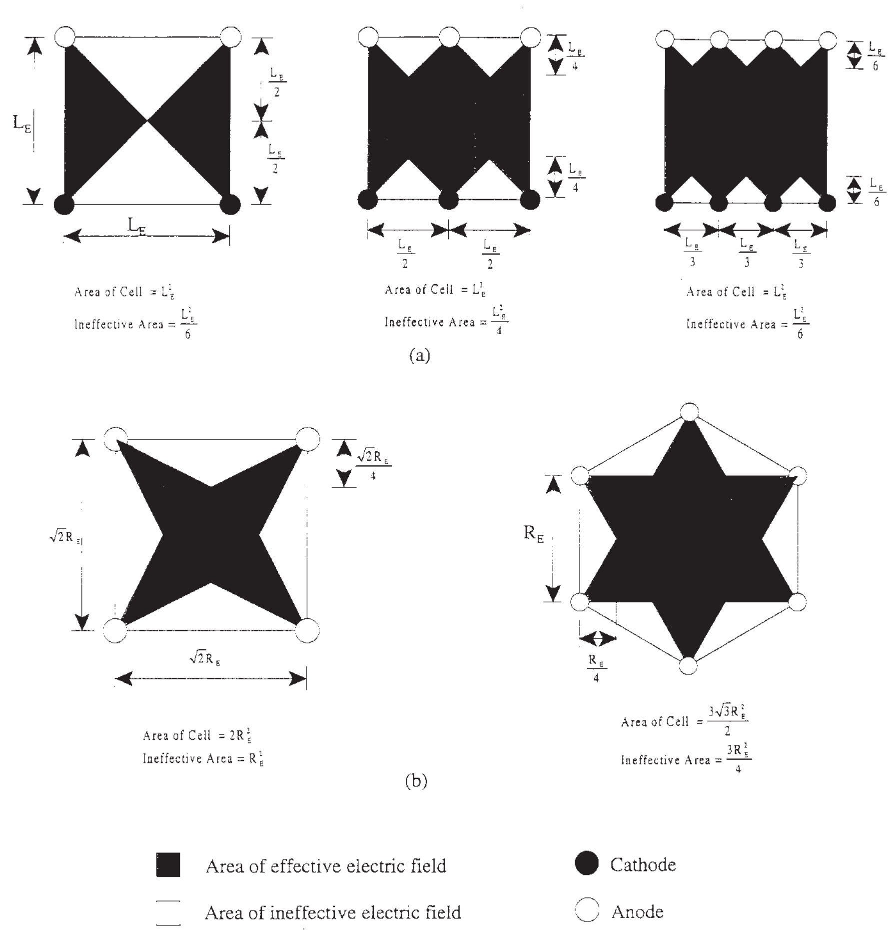

FIGURE 1

Approximate evaluation of ineffective areas for (a) 1-D and (b) 2-D electrode configurations.

depends on processing time, electrode spacings, and alignment. The height of this triangle is expected to be larger in the case of 1-D compared with 2-D applications due to electrode alignment. This height is assumed as half the length of the triangle base for 1-D applications and a quarter the length of the base for 2-D applications. This assumption provides a practical method for comparing the efficiency of different configurations.

Figure 1 shows approximate distributions of the resulting inactive spots for selected configurations. Approximate calculations of the percentage of ineffective area for each configuration are summarized in Table 1. For the 1-D configurations, the ineffective area is half the total area when the same-polarity electrode spacing equals the anode-cathode spacing. Thus, it is not practical to use such a scheme unless remediation is implemented in two stages where electrode polarity can be changed. This is also the case for the 2-D square arrangement.

Remediation Time Requirements

1-D Transport

The time required for remediation is a function of contaminant transport rates and electrode spacings. Schultz (1997) and Alshawabkeh *et al*. (1999) provide a practical method for calculating time requirements for 1-D applications. As electroosmotic advection and ionic migration are the prominent transport mechanisms, hydrodynamic dispersion can be neglected to simplify the analysis (Acar and Alshawabkeh, 1993). Assuming linear electric field distribution and a homogeneous soil medium, the time required for remediation in 1-D is given by (Alshawabkeh *et al*., 1999),

$$T_R = \frac{1}{\beta} \frac{L_E}{\sigma^* i_e} \tag{2}$$

where T_R (T) is the time required for clean-up, σ^* (Siemens L^{-1}) is the effective electric conductivity of the soil medium, i_e (VL^{-1}) is the voltage gradient, and β ($L^3\ C^{-1}$) is a lumped property of the contaminant and the soil that measures the rate of reactive transport of a species relative to the electric conductivity of a medium, which is given by,

$$\beta = \frac{(u^* + k_e)/R_t}{\sigma^*} \tag{3}$$

where k_e ($L^2\ V^{-1}\ T^{-1}$) is the coefficient of electroosmotic permeability, u^* ($L^2\ V^{-1}\ T^{-1}$) is the effective ionic mobility of the species in soil, and R_t (dimensionless) is a time-delay factor to account for the time required for contaminant desorption and dissolution. The value of R_t depends on soil type, pH, and type of contaminant. Sorption retardation factor (R_d) can be used as an estimate of R_t (R_t = 1 for nonreactive contaminants). However, the values of R_t might be different than R_d because R_t should account for time-delay due to all chemical reactions (solubilization, complexation, and desorption), while R_d values account only for sorption. Typical values of β for contaminated fine-grained soils are estimated to be in the range of 1×10^{-8} to 1×10^{-6} m^3/C (Alshawabkeh *et al*., 1999). If time is to be calculated using current density, Eq. 2 becomes,

$$T_R = \frac{1}{\beta}\frac{L_E}{I_d} \tag{4}$$

where I_d (Amps L^{-2}) is the electric current density.

2-D Radial Transport

The approach provided below for 2-D applications assumes radial electric field distribution (Figure 2). R_w represents the radius of center well (assumed cathode), R_E represents the cathode-anode spacing, and Z is the depth of the site. The difference between this case and the 1-D case is that the current density in radial flow is a function of the radial distance (r); however, in both cases the total current is constant. The electric current per unit depth for the radial transport is given by,

$$I_z = (2\pi r)\sigma^* i_r \tag{5}$$

where I_Z (Amp L^{-1}) is the current per unit depth and i_r (VL^{-1}) is the radial voltage gradient.

Contaminant transport rate depends on the voltage gradient, which is a nonlinear function of the radial distance. Ignoring dispersion and accounting for ion migration and electroosmosis, the radial velocity of ions transport is given by

$$v(r) = \frac{(u^* + k_e)}{R_t} i_r \tag{6}$$

where v(r) (L T^{-1}) is the radical velocity of species transport. Substituting i_r from Eq. 5 into Eq. 6 leads to,

$$v(r) = \beta \frac{I_Z}{2\pi r} \tag{7}$$

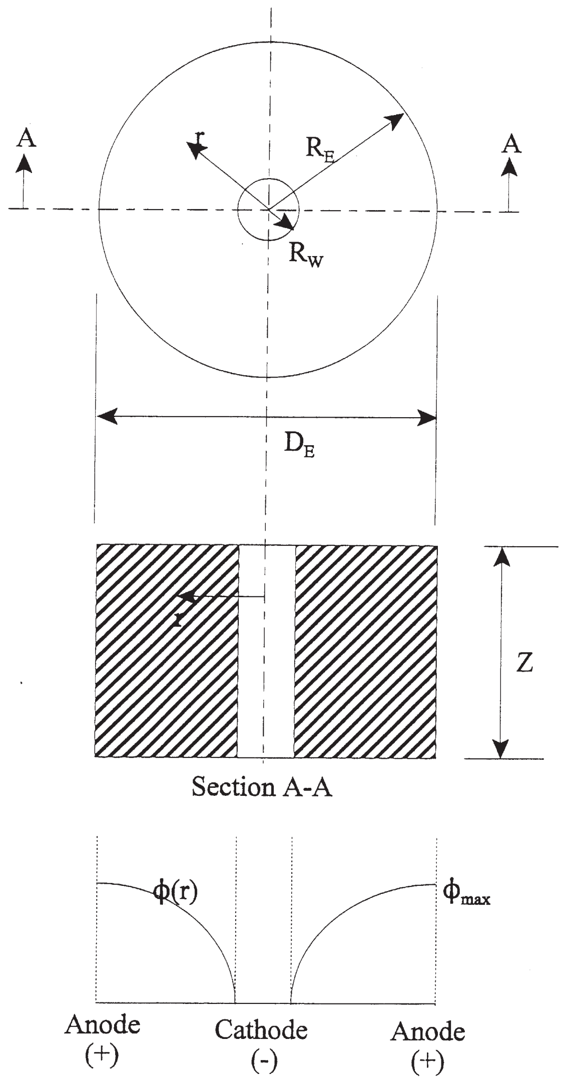

FIGURE 2

A schematic showing radial electric field distribution.

The velocity of contaminant transport is a nonlinear function of the radial distance even if the soil is homogeneous and isotropic. The time required for the contaminants to transport from the outside anodes to the center cathode is calculated by integrating dt = dr/v(r) from R_W to R_E, leading to

$$T_R = \frac{\pi}{\beta}\frac{\left(R_E^2 - R_W^2\right)}{I_Z} \tag{8}$$

Because $(R_W)^2 << (R_E)^2$, Eq. 8 can be simplified as,

$$T = \frac{\pi}{\beta} \frac{R_E^2}{I_Z} \tag{9}$$

In order to provide time evaluation as a function of the voltage, a modified variable (r') is introduced to simplify the formulation,

$$r' = \ln \frac{r}{R_W} \quad dr' = \frac{dr}{r} \tag{10}$$

The transformed voltage gradient with respect to r' ($i_{r'}$) is independent of r', and is given by,

$$i_{r'} = \frac{I_Z}{2\pi\sigma^*} \tag{11}$$

Substituting the value of I_Z from Eq. 12 into Eq. 10 yields,

$$T_R = \frac{1}{\beta} \frac{R_E^2}{\sigma^* i'_r} \tag{12}$$

The form of Eq. 12 for radial transport is similar to the form of Eq. 2 for 1-D transport. In both cases, β and σ^* are soil properties and the gradients i_e and $i_{r'}$ are constants. However, comparing the two equations shows that while T is a function of the linear distance between the electrodes for 1-D case, it is a function of square the radial distance for 2-D applications. This is important for selection of electrode spacings. Selection of radial spacing for 2-D radial cases is much more critical than for 1-D cases as time and cost of remediation will significantly increase when increasing radial spacing.

COST

The total costs for full-scale *in situ* implementation of electrokinetic remediation can be divided into five major components (Alshawabkeh *et al.,* 1999): (1) costs for fabrication and installation of electrodes, (2) cost of electric energy, (3) cost of enhancement agents, if necessary, (4) costs of any posttreatment, if necessary, and (5) fixed costs. Impacts of electrode configuration and spacing on these cost components are addressed separately.

Electrode cost depends on the number of electrodes per unit surface area and is given by,

$$C_{electrode} = C_1 N \tag{13}$$

where $C_{electrode}$ (\$ L^{-3}) is electrode costs per unit soil volume, N (L^{-2}) is the number of electrodes per unit surface area, which is given by Eq. 1, and C_1 (\$ L^{-1}) is the cost of electrodes per unit depth. Values for N are provided in Table 1 for different configurations. Increasing electrode spacings decreases the value of N and hence decreases total electrode costs. For the 1-D case, spacings between electrodes of same polarities significantly impact this cost component.

Several factors impact energy requirements and cost for electrokinetic remediation at a specific site. These factors include soil properties, contaminant properties, electrode configuration, and processing time. Energy consumption changes during processing due to changes in electric conductivity. However, energy calculations could by simplified by averaging soil electrical conductivity throughout the process. Accordingly, energy expenditure per unit volume of contaminated soil is given by the following equation

$$W = \left(\frac{\phi_{max} I_d T_R}{L}\right)_{1D-flow} = \left(\frac{\phi_{max} I_Z T_R}{\pi\left(R_E^2 - R_W^2\right)}\right)_{radial-flow} \tag{14}$$

where W (J L^{-3}) is energy expenditure per unit volume of soil and ϕ_{max} (V) is the applied voltage. Substituting Eqs. 4 and 8 into Eq. 14 results in the following equation for both 1-D and radial cases,

$$W = \frac{\phi_{max}}{\beta} \tag{15}$$

Eq. 15 shows that the same energy expenditure is expected for both 1-D and radial applications, assuming that the same total voltage is applied and each case is processed for specific required time (Eq. 4 for 1-D and Eq. 8 for radial case). This indicates that energy requirement could be considered independent of electrode configuration if energy source (maximum voltage) is the controlling factor. In other words, two 1-D schemes (for one specific site) with different spacings should result in the same energy expenditure if the same total voltage is used in both schemes. The difference between the two would be in terms of time requirements. However, electrode configuration is a design factor if the energy source is not the limiting factor. Based on energy expenditure evaluation, the following energy cost equation provided by Alshawabkeh *et al.* (1999) for 1-D conditions is also valid for 2-D, radial conditions,

$$C_{energy} = \frac{C_2 \phi_{max}}{3,600,000\ \beta} \tag{16}$$

where C_{energy} (\$ L^{-3}) is electric energy cost per unit volume of soil treated, and C_2 (\$/kWh) is electric energy cost. Eq. 16 is valid for both 1-D and radial conditions.

Enhancement agents and chemicals are used to improve the efficiency of electrokinetic remediation. Chemical's cost is a significant component of the total cost of the processes. Chemicals are used for either neutralizing pH conditions, or enhancing solubility of target contaminants, or both. The cost of chemicals required for pH neutralizing is considered in this evaluation. This cost is dependent on the electric current and is given by the following equations,

$$C_{n-chemical} = C_3 \frac{I_d}{L} \frac{M_W}{\alpha F} T_R \quad \text{for } 1-D \tag{17}$$

$$C_{n-chemical} = C_3 \frac{I_Z}{\pi\left(R_E^2 - R_W^2\right)} \frac{M_W}{\alpha F} T_R \quad \text{for Radial} \tag{18}$$

where $C_{n\text{-}chemical}$ (\$ L^{-3}) is the cost of chemicals required to neutralize electrolytes per unit soil volume, C_3 (\$ M^{-1}) is the cost of the neutralizing chemical, M_W (MM^{-1}) is the molecular weight of the chemical, α (dimensionless) is a factor depending on the stoichiometry of the neutralizing reaction, and F is Faraday's constant (96,485 C/*mol-electron*). Substituting the time required for remediation in both 1-D and radial cases will result in the following equation:

$$C_{n-chemical} = \frac{C_3}{\beta} \frac{M_W}{\alpha F} \tag{19}$$

Eq. 19 shows that chemical costs is independent of electric current or spacing and is dependent on soil characteristics. This is due to the fact that electric current and electrode spacings impact time requirements. For example, increasing the current will decrease the time required for remediation, such that the same total charge is introduced for any electric current value.

Posttreatment costs should also be considered if effluent treatment is required. These costs are highly site and contaminant specific. An estimate of effluent treatment costs could be evaluated per unit volume of the soil as follows,

$$C_{post\text{-}treat} = C_4 \frac{nk_e}{\beta\sigma *} = C_4 \frac{nR_t k_e}{u * + k_e} \tag{20}$$

where $C_{post\text{-}treat}$ (\$ L^{-3}) is the post treatment cost per unit volume of the soil, C_4 (\$ L^{-3}) is the cost of treatment per unit volume of the electrolyte (effluent) collected and n is the soil porosity. Volume of effluent depends on the ratio of transport under electroosmosis relative to total transport rate. In order to minimize the volume, it is necessary to maximize transport by ionic migration and minimize transport by electroosmosis. If electroosmosis is the only mechanism used for contaminant transport (e.g., for noncharged contaminants), then cost of treatment will be equal to (C_4 n R_T), which indicates that the cost depends on the number of pore volumes required for remediation. If the contaminant is readily available for transport, then $R_t = 1$ and one pore volume is sufficient for remediation. However, if extraction is retarded due to geochemical reactions, then the pore volumes required will increase depending on the value of R_t. Catholyte recycling, if used, will add another component that should be considered for evaluation of total volume of water collected.

Other costs for full-scale implementation include mobilization and demobilization costs of various equipment, site preparation, security, progress monitoring, insurance, labor, contingency, and miscellaneous expenses. The equipment will not be consumed in a particular project. However, there are capital, depreciation, or rental costs involved. These cost components will be divided into fixed (e.g., mobilization and demobilization) and variable (e.g., monitoring, insurance, rentals) components. Variable costs are simply evaluated by multiplying the cost rate by the total time required for remediation, i.e.,

$$C_{variable} = \frac{C_5}{\beta} \frac{L}{\sigma * i_e} \quad \text{for 1-D} \tag{21}$$

$$C_{variable} = \frac{C_5}{\beta} \frac{R_E^2}{\sigma * i_{r'}} \quad \text{for radial} \tag{22}$$

where $C_{variable}$ (\$ L^{-3}) is the total variable cost per unit soil volume, and C_5 (\$ L^{-3} T^{-1}) is the variable cost rate per unit soil volume. C_5 is evaluated by estimating the variable daily cost (for monitoring, insurance, rentals, ... etc) and dividing by the total volume of the contaminated soil. C_5 is highly dependent on the size of the site and decreases as volume of contaminated soil increases.

Example Cost Evaluations

The following example is considered to show the role of each cost component. In this example, a contaminated area of 30 m × 60 m is assumed. The depth of contamination is assumed to be 3 m. The soil is a saturated, silty clay. The porosity, tortuosity factor, electrical conductivity, and coefficient of electroosmotic permeability of the soil are determined from preliminary laboratory analyses to be 0.4, 0.3, 0.02 S/m, and 2×10^{-9} m^2/V-s, respectively. The ionic mobilities of target contaminants are taken to be 5×10^{-8} m^2/V-s. The value of R_t is assumed to be 4 and the value of β is thus calculated to be 1×10^{-7} m^3/C.

The mobilization cost of a drilling rig and the labor cost of a two-man operating crew are taken to be \$1000 per day to evaluate C_1 in Eq. 13 (Alshawabkeh *et al.*, 1999). For boreholes to be drilled without installation of casing and sampling, a continuous flight auger can achieve approximately 65 m a day. Therefore, the drilling cost is estimated to be \$15 per linear meter. Costs for fabrication and installation of electrodes are approximately \$5 per linear meter as the electrodes are reusable, and C_1 is taken as \$20 per linear meter. The electricity cost C_2 is assumed \$0.04 per kWh. Cost of enhancement reagent (molecular weight assumed 100 g/mole) is taken as \$2/kg. Variable cost rate is calculated based on two-man crew, 14 h per week, at a rate of 25 \$/man-hour. Accordingly, the variable rate will be around 0.001 \$/m^3-hour, including 30% increase for insurance. Total cost of other components, including posttreatment and fixed costs, is taken as \$25/m^3.

Two configurations will be considered: (a) 1-D, where the same-polarity electrode spacing equals one-third the anode-cathode spacing and (b) 2-D hexagonal configuration. In both cases $F_1 = 3$. Impact of electrode spacing on electrode, energy and variable costs is demonstrated in Figure 3 for the 1-D configuration and

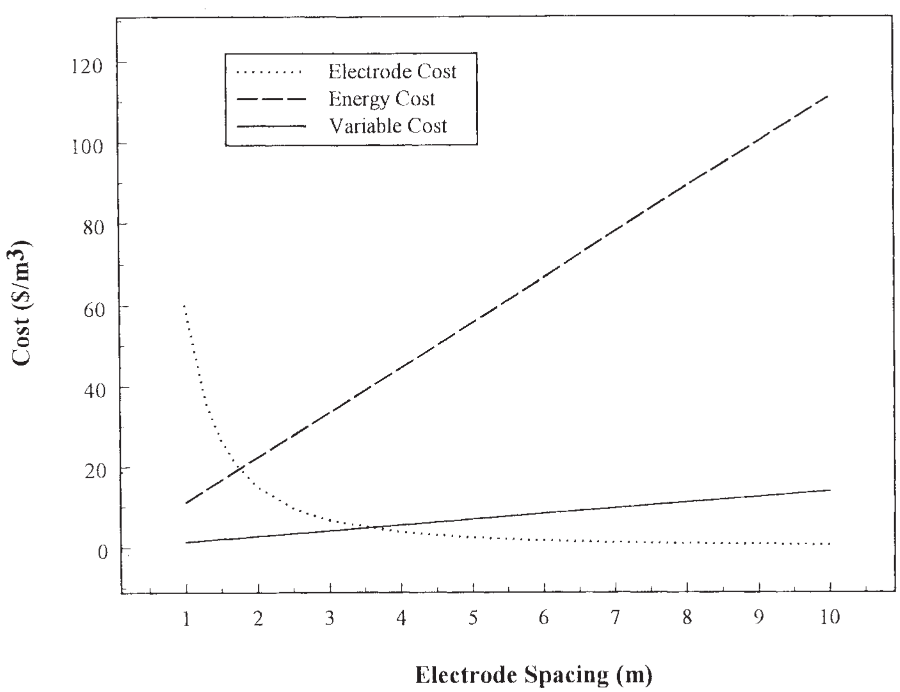

FIGURE 3

Impact of electrode spacing on electrode, energy and variable costs for 1-D application (refer to text for parameter values).

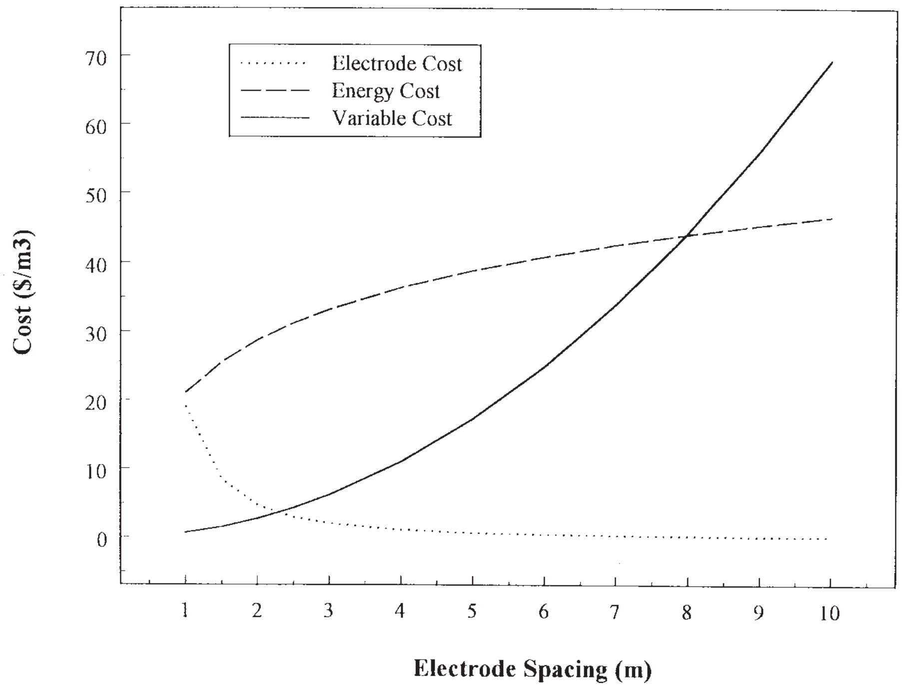

FIGURE 4

Effect of electrode spacing on electrode, energy and variable costs for 2-D application (refer to text for parameter values).

in Figure 4 for the hexagonal configuration. In these figures, a 1-D electric gradient i_e of 100 V/m and a transformed radial electric gradient $i_{r'}$ of 100 volt are assumed for cost evaluations. For the two schemes provided, increasing electrode spacing showed a significant decrease in electrode costs. For 1-D case, increasing electrode spacing from 1 m to 2 m resulted in a more than 80% decrease (from $60/m^3 to about $10/m^3) in electrode costs. However, increasing electrode spacing beyond 2 m did not result in a comparable decrease in electrodes cost. Similar behavior is noted in the hexagonal case.

Increasing electrode spacing results in a linear increase in energy and variable costs in the 1-D case. As indicated earlier, increasing electrode spacing will increase the total voltage applied (assuming constant voltage gradient), increase energy expenditure, and cost. Similarly, increasing electrode spacing increases time requirements and, consequently, variable costs. For the hexagonal case, the increase of energy and variable costs is a nonlinear function of electrode spacing, as shown in Figure 4.

Impact of electrode spacing on total costs and time requirements for both the 1-D and hexagonal cases is displayed in Figures 5 and 6, respectively. Increasing

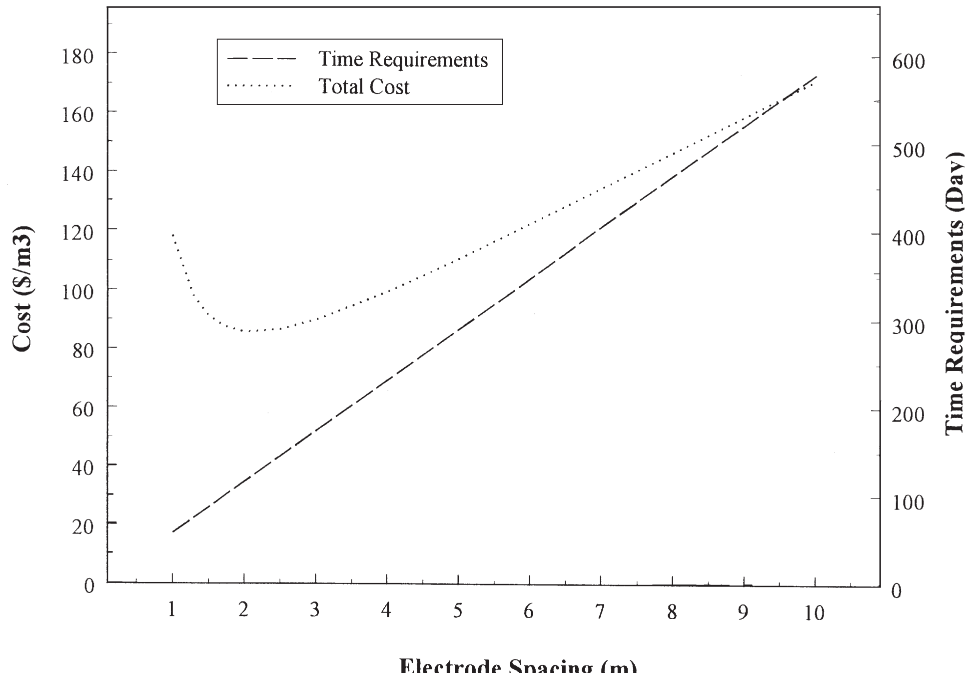

FIGURE 5

Time requirements and costs as a function of electrode spacing for 1-D applications (refer to text for parameter values).

electrode spacing has more impact on the time requirements for the hexagonal case when compared with the 1-D case. This is again because time requirements are related to square of the radial electrode spacing. Accordingly, selection of the optimum electrode spacing is more critical for 2-D applications when compared with 1-D applications. Furthermore, minimum exists in the cost versus electrode spacings relationship. It is necessary to provide a mechanism for selecting the optimum electrode spacing that will minimize cost, time, or both.

Optimum Electrode Spacings for Radial Applications

Assuming posttreatment, chemicals, and fixed costs are independent of electrode spacing, the optimum electrode spacing can be obtained for 2-D applications by equating the partial derivative of C_{total} with respect to R_E to zero, which renders the following equation,

$$R_{E-opt}^2 = \frac{7,200,000\ \beta C_1 F_1 i_{r'} \sigma *}{3,600,000\ \pi C_5 R_{E-opt}^2 + \pi C_2 i_{r'}^2 \sigma *} \qquad (23)$$

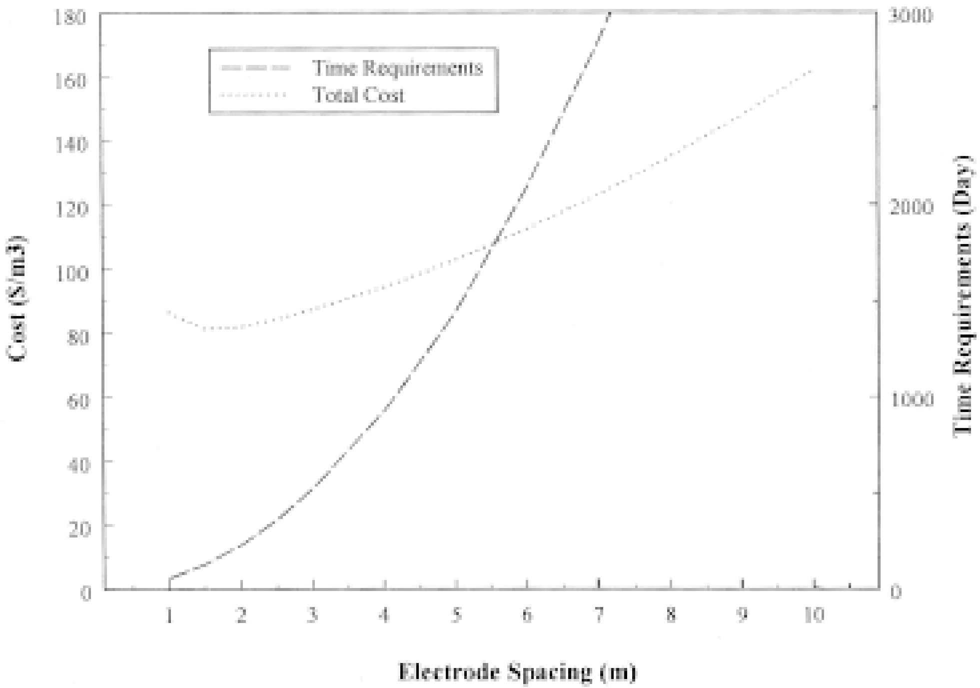

FIGURE 6

Time requirements and costs as a function of electrode spacing for 2-D applications (refer to text for selected parameter values).

Eq. 23 provides an estimate for the optimum electrode spacing that minimizes the total costs of 2-D applications as a function of the properties of the contaminated soil and electric field strength. The optimum spacing is also dependent on electrode costs (C_1), energy costs (C_2), variable costs (C_5), and electrode configuration (F_1). Eq. 23 provides a formulation that demonstrates the impact of the cost ratios C_2/C_1 (energy cost/electrodes cost) and C_5/C_1 (variable cost/electrodes cost) on optimum electrode spacings.

If time is the limiting factor, then substituting the value of $i_{r'}$ from Eq. 12 into Eq. 23 yields the following equation.

$$R^2_{E-opt} = \frac{7,200,000\ \beta^2 C_1 F_1 \sigma * T_R}{3,600,000\ \pi\sigma * \beta^2 T^2 C_5 + \pi C_2 R^2_{E-opt}} \qquad (24)$$

Thus, the procedure for design of field implementation is to decide whether the limiting factor is time or energy.

Summary and Conclusions

This study provides a preliminary design approach under simplifying assumptions for 1-D and 2-D *in situ* implementation of electrokinetic soil remediation. A practical approach is provided for evaluating electrode requirements and development of ineffective electric field spots for different 1-D and 2-D electrode configurations. Formulation is provided for calculating cost components of the process, including electrode, energy, chemicals, posttreatment, fixed, and variable costs. Equations are also provided for evaluating optimum electrode spacings based on energy and time requirements. The following specific conclusions are derived from the formulation provided in this article:

- For a constant voltage gradient, the time required for remediation by electric field is linearly related to anode-cathode spacing for 1-D, and to square of the spacing for 2-D, radial applications.
- For 1-D applications, the spacing between same-polarity electrodes is as significant (in cost calculations and in process effectiveness) as that between anodes and cathodes. Decreasing the same-polarity electrode spacing to one half the anode-cathode spacing can result in a 100% increase in electrode requirements, but decrease the area of ineffective electric field by one-half.
- Total energy requirements can be estimated based on the total voltage and the value of a lumped reactive transport parameter (β). This is assuming that the process will run at optimum conditions, specifically optimum time requirements.
- Selection of the voltage gradient impacts selection of the optimum electrode spacing. The analysis show that a minimum exists in the cost vs. electrode spacings relationship.

ACKNOWLEDGMENTS

Partial support for this project was provided by the U.S. Army Corps of Engineers (USAE) Waterways Experiment Station (WES) under the Installation Restoration Research Program (IRRP). Dr. John Cullinane served as the program director at WES during the study. Permission to publish this information was granted by the Chief of Engineers of USAE. Partial support was also provided by Electrokinetics Inc. of Baton Rouge, Louisiana. The support is gratefully acknowledged. In addition, Dr. Charles D. Shackelford, Dr. Krishna Reddy, Dr. M. Fazle Rabbi, Mr. Brian Duval, and an anonymous reviewer provided valuable criticism.

REFERENCES

Acar, Y. B. and Alshawabkeh, A. 1993. Principles of electrokinetic remediation. *Environ. Sci. Technol.* **27(13),** 2638–2647.

Acar, Y. B. and Alshawabkeh, A. 1996. Electrokinetic remediation. I. Pilot-scale tests with lead spiked kaolinite. ASCE *J. Geotech. Eng.* **122(3),** 173–185.

Acar, Y. B. and Alshawabkeh, A. N. 1997. Electrochemical decontamination of soil and water, Special Issue of *Journal of Hazardous Material*, Elsevier Publications, 55(1–3), 322 p.

Acar, Y. B., Gale, R. J., Putnam, G. A., Hamed, J., and Wong, R. L. 1990. Electrochemical processing of soils: theory of pH gradient development by diffusion, migration, and linear convection. *Environ. Sci. Health* **A25(6),** 687–714.

Acar, Y. B., Alshawabkeh, A., and Gale, R. J. (1993). Fundamentals of extracting species from soils by electrokinetics. *Waste Manage.* **13(2),** 141–151.

Acar, Y. B., Hamed, J. T., Alshawabkeh, A., and Gale, R. J. 1994. Cd(II) removal from saturated kaolinite by application of electrical current. *Géotechnique* **44(3),** 239–254.

Acar, Y. B., Li, H., and Gale, R. J. 1992. Phenol removal from kaolinite by electrokinetics. ASCE *J. Geotech. Eng.* **118(11),** 1837–1852.

Alshawabkeh, A. N. and Acar, Y. B. 1992. Removal of contaminants from soils by electrokinetics: a theoretical treatise. *Environ. Sci. Health* **A27(7),** 1835–1861.

Alshawabkeh, A. N. and Acar, Y. B. 1996. Electrokinetic remediation. II. Theoretical model. ASCE *J. Geotech. Eng.* **122(3),** 186–196.

Alshawabkeh, A. N., Yeung, A., and Bricka, R. M., 1999. Practical aspects of *in situ* electrokinetic remediation. ASCE *J. Environ. Eng.* **125(1),** 27–35.

Bruell, C. J., Segall, B. A., and Walsh, M. T. 1992. Electroosmotic removal of gasoline hydrocarbons and TCE from clay. ASCE *J. Environ. Eng.* **118(1),** 68–83.

Eykholt, G. R. and Daniel, D. E. 1994. Impact of system chemistry on electroosmosis in contaminated soil. ASCE *J. Geotech. Eng.* **120(5),** 797–815.

Hamed, J., Acar, Y. B., and Gale, R. J. 1991. Pb(II) removal from kaolinite using electrokinetics. ASCE *J. Geotech. Eng.* **117(2),** 241–271.

Haran, B. S., Popov, B. N., Zheng, G., and White, R. E. 1997. Mathematical modeling of hexavalent chromium decontamination from low surface charged soil, Electrochemical Decontamination of Soil and Water, Special Issue of *Journal of Hazardous Material*, 55(1–3, 93–108.

Jacobs, R. A., Sengun M. Z., Hicks, R. E., and Probstein, R. F. 1994. Model and Experiments on Soil Remediation by Electric Fields, *Environ. Sci. Health* **A29(9),** 1933–1955.

Lageman, R., Wieberen, P., and Seffinga, G. 1989. Electro-reclamation: theory and practice. *Chem. Industry (London)* **9,** 585–590.

Pamukcu, S., Khan, L., and Fang, H. 1990. Zinc Detoxification of Soils by Electroosmosis, Electrokinetic Phenomena in Soils, Transportation Research Record, TRB, Washington, D.C.

Pamukcu, S. and Wittle, J. K. 1992. Electrokinetic removal of selected heavy metals from soil. *Environ. Progress* AIChE, **11(4),** 241–250.

Probstein, R. F. and Hicks, R. E. 1993. Removal of contaminants from soils by electric fields. *Science* **260,** 498–504.

Reddy, K. R., Parupudi, U. S., Devulapalli, S. N., and Xu, C. Y. 1997. Effect of soil composition on removal of chromium by electrokinetics, Electrochemical Decontamination of Soil and Water, Special Issue of *J. Hazardous Material* **55(1–3),** 81–92.

Runnells, D. D. and Wahli, C. 1993. *In situ* electromigration as a method for removing sulfate, metals, and other contaminants from ground water. *Ground Water Monit. Remed.* **13(1),** 121–129.

Runnels, D. D. and Larson, J. L. 1986. A Laboratory Study of Electromigration as a Possible Field Technique for the Removal of Contaminants from Ground Water, *Ground Water Monit. Rev.* pp. 81—91, Summer 1986.

Shapiro, A. P. and Probstein, R. F. 1993. Removal of contaminants from saturated clay by electroosmosis. *Environ. Sci. Technol.* **27(2),** 283–291.

Shapiro, A. P., Renaud, P. C., and Probstein, R. F. 1989. Preliminary studies on the removal of chemical species from saturated porous media by electroosmosis. *PCH PhysicoChem. Hydrodyn.* **11(5/6),** 785–802.

Schultz, D. S. 1997. Electroosmosis technology for soil remediation: laboratory results, field trial and economic modeling, Electrochemical Decontamination of Soil and Water, Special Issue of *Journal of Hazardous Material* **55(1–3),** 81–92.

Ugaz, A., Puppala, S., Gale, R. J., and Acar, Y. B. 1994. Electrokinetic Soil Processing: Complicating Features of Electrokinetic Remediation of Soils and Slurries: Saturation Effects and the Role of the Cathode Electrolysis, *Chem. Engineering Communications*, Gordon and Breach Science Publishers, New York, 129, Dec. 1994, pp. 183–200.

Wong, J. S., Hicks, R. E., and Probstein, R. F. 1997. EDTA-enhanced electroremediation of metal contaminated soils, Electrochemical Decontamination of Soil and Water, Special Issue of *Journal of Hazardous Material* **55(1–3),** 61–80.

Yeung, A. T., Hsu, C., and Menon, R. M. 1996. EDTA-enhanced electrokinetic extraction of lead. ASCE *J. Geotech. Eng.* **122(8),** 666–673.