



# Mathematical model for hydraulically aided electrokinetic remediation of aquifer and removal of nonanionic copper

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## Abstract

One of the most cost-effective in situ technologies for soil and groundwater (i.e., aquifer) remediation is electrokinetic remediation. In electrokinetic remediation, electromigration due to electric field is combined with hydromigration due to hydraulic flow by purge water to remove pollutants from aquifers through the pore water. This study aims at investigating theoretically the role of electromigration (as active movement) of pollutants and the role of hydromigration (as passive movement) of pollutants in electrokinetic remediation, and making it clear that the control variables for electrokinetic remediation are the applied voltage and the hydraulic flow rate. These aims are pursued by construction of a mathematical model based on physico-chemical considerations and by model simulations of the electrokinetic remediation applied to the virtual aquifer polluted by heavy metals of copper sulfate. According to numerical simulations with the model: (1) heavy metal (nonanionic copper) is removed from the upstream anode region and accumulated in the downstream cathode region; (2) to carry away the heavy metal outside the aquifer (global removal), hydromigration by purge water flow is essential; and (3) electromigration contributes mainly to the redistribution of heavy metals within the aquifer (local removal and local accumulation).

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## 1. Introduction

Shortage of water resources arises everywhere in the whole world, from increasing need for not only municipal use but also industrial use. This forces us to exploit more groundwater, which has served for a long time as the major good-quality water resource. However, in many aquifers, groundwater

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has been seriously contaminated by the migration of various hazardous organic and inorganic chemicals from the disposal of municipal and industrial wastes. Continuous increase in water demand makes it urgent to clean up the contaminated aquifers immediately, in addition to the development of new water resources.

Many new techniques have been presented for the remediation of groundwater and soil. One of the most cost-effective in situ technologies is electrokinetic remediation, which consists of electromigration and hydromigration. This method utilizes the electromigration of charged pollutants in an electric field and hydromigration by purge water in soil pore. However, understanding of pollutant removal by electromigration in pore water is not only experimentally but also theoretically quite insufficient. This is because the technique is relatively new and innovative for decontamination, although in civil engineering, electroosmotic flow generated by the electrokinetic method has been utilized for practical soil dewatering (Wan and Mitchell, 1976).

This paper is devoted, firstly, to developing a mathematical model for electrokinetic remediation based on physico-chemical mass transport theory and, secondly, to simulating nonsteady characteristics of the transport of heavy metals by electromigration and hydraulic flow in pore waters of aquifers. However, only a few studies (Alshawabkeh and Acar, 1992; Eykholt and Daniel, 1994; Rødsand et al., 1995; Segall and Bruell, 1992; Shapiro et al., 1989; Taha et al., 1997) can be consulted to construct such a mathematical model for aquifer remediation, taking the electromigration of heavy metals into consideration.

The electrokinetic remediation of aquifers utilizing electromigration consists of: (1) installing electrodes (anode and cathode) into the contaminated zone, which should be saturated with groundwater or purge water; (2) injection of purge water into the anode well and taking out contaminated water from the cathode well, which brings about hydraulic flow in pore water; and (3) applying a fixed low-voltage direct current between the electrodes to start electromigration of charged species, as shown in Fig. 1.

Heavy metals are typically ionized into cations (e.g.,  $\text{Cu}^{2+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Cd}^{2+}$ , and so on) in groundwater. In electric fields, an electrokinetic driving force acts on

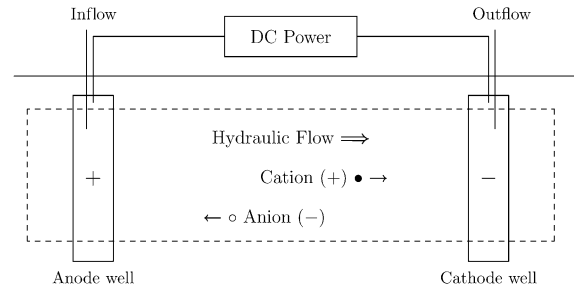


Fig. 1. Schematic representation of electrokinetic remediation. Chemicals [i.e., cations (heavy metals) and anions] are transported by the hydraulic flow caused by purge water in conjunction with electromigration caused by the applied voltage.

the ionized heavy metals (cations) and causes electromigration in pore water. The force is directed toward the cathode and superposed on the hydraulic flow due to purge water. Therefore, the heavy metals are accelerated and migrate to the cathode well where they are swept out through the drainage of waste water. On the other hand, because the electrokinetic driving force on anions (e.g.,  $\text{CO}_3^{2-}$ ,  $\text{SO}_4^{2-}$ , and so on) is directed toward the anode (i.e., in the direction opposite to the hydraulic flow), the migration of anions is retarded or even driven in opposite to the hydraulic flow. Then, the cationic heavy metals are separated from anions and transported with increasing speed to the downstream well.

## 2. Mathematical model of electrokinetic remediation

The mathematical model is based on mass conservation law and consists of governing equations and its boundary conditions. The model is characterized especially by electromigration of charged species under the electric field. Electromigration can be easily controlled by the applied voltage between the buried electrodes. The model contains three kinds of chemical reaction as: (a) the homogeneous liquid-phase reaction (dissociation equilibrium) in pore water, which appears in the governing equation as the reaction term; (b) the heterogeneous interface reaction between pore water and soil surface (adsorption and desorption), which is considered in the governing equation as the retardation factor; and (c) the electrode reaction at electrode surface (electrolysis), which

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