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Scale-up on electrokinetic remediation: Engineering and technological parameters

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HIGHLIGHTS

- Moisture and compaction of soil must be re-establish in Scale-up of EKR.
- Degree of compaction of soil depends on moisture, type of soil and EKR reactor.
- Scale of EKR process determines the energy consumption in the treatment.
- Electroosmosis and electromigration processes are favoured in prototype scale.
- In real scale EKR processes it is important determine evaporation and leaks effects.

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ABSTRACT

This study analyses the effect of the scale-up of electrokinetic remediation (EKR) processes in natural soils. A procedure is proposed to prepare soils based on a compacting process to obtaining soils with similar moisture content and density to those found in real soils in the field. The soil used here was from a region with a high agrarian activity (Mora, Spain). The scale-up study was performed in two installations at different scales: a mock-up pilot scale (0.175 m^3) and a prototype with a scale that was very similar to a real application (16 m^3). The electrode configuration selected consisted of rows of graphite electrodes facing each other located in electrolyte wells. The discharge of 20 mg of 2,4-dichlorophenoxyacetic acid [2,4-D] per kg of dry soil was treated by applying an electric potential gradient of 1 $V\,cm^{-1}$. An increase in scale was observed to directly influence the amount of energy supplied to the soil being treated. As a result, electroosmotic and electromigration flows and electric heating are more intense than in smaller-scale tests (24%, 1% and 25%, respectively respect to the values in prototype). In addition, possible leaks were evaluated by conducting a watertightness test and quantifying evaporation losses.

1. Introduction

Currently, soil contamination is an important environmental problem. This type of contamination is not immediately evident when it occurs, and because of the mobility of the contaminants, many years can pass before the negative effects on human health and the environment become apparent. In recent years, many technologies have been developed to mitigate this problem [1–6], including electrokinetic remediation (EKR) [7–13]. This treatment is based on the application of an electric potential gradient between a set of electrodes located within a potentially contaminated soil [14]. The generation of an electric field in the soil makes it possible to develop various processes that, in turn, facilitate soil decontamination. These processes may be of (i) a physical nature, such as electric heating resulting from the ohmic drops generated by the high ionic-resistance properties of soils; (ii) an electrochemical nature, such as reduction-oxidation processes consisting of

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electrochemical reactions on the electrode surface; or (iii) an electrokinetic nature, such as (a) electromigration (the movement of ions contained in the soil), (b) electrophoresis (the movement of charged particles), and (c) electro-osmosis (the movement of water contained in the soil because of electric field action).

The fact that several different decontamination processes are developed in a single technology makes EKR a very attractive technique. EKR can be applied as an ex situ or in situ soil remediation method for low-permeability and heterogeneous soils, including both saturated and partially saturated soils. In addition, this technology is not selective to a unique group of contaminants; instead, it can be used to treat soils contaminated by inorganic ionic compounds, heavy metals, organic contaminants, and any combination thereof. It is also important to mention that because of its high operational flexibility, it can be easily integrated with conventional soil-treatment technologies and in the subsequent treatment of the generated effluents.

Because it is a young technology, much of the knowledge on EKR is limited to results obtained in studies conducted at a reduced scale. In these studies, it is common to use airtight cylinders or prismatic cells as electrokinetic reactors [15–21]. Working at these scales allows the soil to be isolated from its surroundings, considerably reducing the variables that must be controlled during treatment. This experimental strategy has allowed for the analysis of the various electrokinetic processes that occur in the soil, revealing their magnitude and identifying the influencing variables. However, it is important to note that experimental working conditions differ from field conditions. Therefore, the extrapolation of these results to real applications is questionable, leading to the need to scale the process.

It is always important to control the state of the soil to reproduce similar conditions to those found in the field; this is especially true when scaling-up tests. Indeed, it is the only way of controlling the initial conditions of the soil to guarantee its homogeneity and avoid the development of preferential flow paths. In addition, it is very important to account for the interactions between the system and its surroundings (in terms of both lateral flow and atmospheric interaction processes), unlike in reduced-scale tests, where these processes were artificially restricted.

The main objective of this work is the analysis of the scale-up of EKR processes applied to decontamination of a natural soil polluted with a common pesticide (2,4-D). Two EKR reactors has been utilized: a mock-up EKR reactor (MER) at a pilot scale with a volume of 0.175 m^3, and a prototype (PER), with a capacity of 16 m^3, close to real scale. In both cases, the same soil-preparation procedure and experimental setup were maintained. We have studied the influence of the scale-up both in technical and/or engineering aspects (compacting soil studies, performance and development of EKR tests and check-up of possible leaks in reactors EKR) and the behaviour of different variables during the EKR process(energy consumption, temperature and electrokinetic flows).

2. Materials and methods

2.1. Materials

In this study, to reproduce real-world conditions and increase the reliability of the results obtained, we used a natural soil from a region of high agrarian activity in Mora de Toledo (Toledo, Spain), which is vulnerable to contamination problems from pesticides.

The soil mineralogical composition (Quartz 7%, Feldspar 15%, Calcite 4%, Kaolinite 26%, Smectite 28%, Illite 20% and Organic content 0%) was determined by X-ray diffraction analysis (see Section 2.3). According with the standards ASTM D2487 [22] and ASTM D4318 [23], the soil is a low plasticity clay (CL) (see Supplementary material, Fig. S1), whilst in accordance with the texture classification of the United States Department of Agriculture (USDA) [24] is a silty loam (4.9% clay, 68.2% silt and 26.9% sand; see Fig. S2 in the Supplementary material).

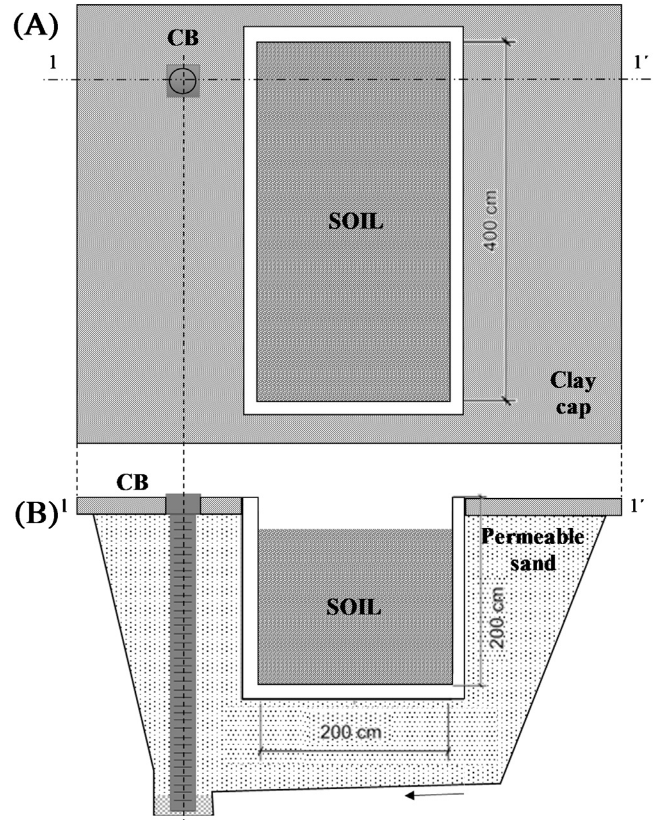

Fig. 1. (A) Plan view and (B) 1-1' section of PER. CB, control borehole.

As commercial herbicide model a 2,4-dichlorophenoxyacetic acid (2,4-D) was used. It is a weak acidic molecule (pKa = 2.6) with an octanol/water partition coefficient of 2.83 (log K_{ow}) and vapour pressure of 1.9×10^{-5} Pa (at 25 °C).

2.2. Experimental design

As mentioned in the Introduction, two analogous EKR installations with a notable scale difference were employed: a pilot-scale MER and a PER with a scale that was similar to a real application.

The MER is similar to those used in previous studies [25–28]. It has a prismatic shape and is constructed of methacrylate plates. The useful capacity for soil treatment is 0.175 m^3. In contrast, the PER consists of two EKR reactors with soil-treatment capacities of 16 and 32 m^3. The work developed in this study used the 16 m^3 PER. The walls (height of 2 m) and slab (surface area of 4×2 m^2) of the PER were built with 30-cm-thick HA-35/B/20/Qc concrete, reinforced with a #15 × 15Ø12 double-welded wire mesh. To improve the watertightness of the PER, seal joints were used at the interface edges between the concrete elements (slab and walls) to minimize possible leaks. In addition, an impermeable coating was applied on the inside surface of the PER. A geotextile and a geomembrane were placed under the concrete. A layer of permeable sand was placed below the geomembrane with a slight slope to favour the drainage of fluids or possible leaks towards a control borehole (CB) located around the prototype, making it possible to continuously sample material during plant operation. Fig. 1 shows a scaled drawing of the plan and section of the PER.