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

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.

KEYWORDS

Natural soil, scale-up, electrokinetic remediation, 2,4-D, herbicide.

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 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 have been utilized: a mock-up EKR reactor (MER) at a pilot scale with a volume of 0.175 m³, and a prototype (PER), with a capacity of 16 m³, 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 2.3 Analytical techniques). According with the standards ASTM D2487 [22] and ASTM D4318 [23], the soil is a low plasticity clay (CL) (see Supplementary material, Figure 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 Figure S2 in the Supplementary material).

As commercial herbicide model a 2,4-dichlorophenoxyacetic acid (2,4-D) was used. It is a weak acidic molecule ($pK_a=2.6$) 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 m³.

In contrast, the PER consists of two EKR reactors with soil-treatment capacities of 16 and 32 m³. The work developed in this study used the 16m³ PER. The walls (height of 2 m) and slab (surface area of 4×2 m²) of the PER were built with 30-cm-thick HA-35/B/20/Qc concrete, reinforced with a #15x15Ø12 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. Figure 1 shows a scaled drawing of the plan and section of the PER.

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

Similar to previous tests conducted by the authors [25, 29], an electrode configuration was selected with two rows of electrolyte wells facing each other in both EKR reactors. Before positioning the wells and electrodes in the soil, a layer of sand was placed on the surface of the testing equipment (in the MER, this layer was 3 cm thick, and in the PER, it was 10 cm thick) as a capillary barrier [30, 31] to reduce the evaporation of water from the system.

1 In the case of the MER, the electrode material used for both the anodes and cathodes
2 consisted of graphite bars measuring $1 \times 1 \times 10 \text{ cm}^3$. These electrodes were positioned
3 inside the semipermeable electrolyte wells composed of polyvinyl chloride (PVC)
4 cylinders (5 cm in diameter and 20 cm in depth). The inter-electrode distance between
5 the rows of anodic and cathodic wells was 38 cm. In the PER, cylindrical graphite
6 electrodes of considerable size (15 cm in diameter and 100 cm in length; approximately
7 ten times the size of those used in the MER) were used with an anode-cathode separation
8 of 3 m. The electrolyte wells used were hollow PVC cylinders with lateral perforations
9 to facilitate the flow and transfer of electrolytes. The diameter and depth of the wells are
10 important (31.5 cm in diameter and 140 cm in depth), and thus, they were installed
11 carefully to avoid wall collapse. Figure 2 shows the schematic of the setup used. Given
12 that the mean value of the undrained shear strength of the soil was near 68 kPa (ASTM
13 D-3080[32] standard), it was possible to excavate all the material from the wells with an
14 auger without having to add bracing. The final hole casing was achieved only after
15 finishing the hole drilling. However, in weaker soils, it will likely be necessary to use a
16 casing as the drilling progresses. In all cases, it is essential to clean the well after drilling.
17 To that end, it is useful to use an industrial vacuum to suction out the debris found in the
18 walls and bottom of the well.

Figure 2. Placement of electrolyte wells in the PER.

Figure 3 shows the location of the instrumentation. A level-control system was coupled to the electrolyte wells and connected to a feed tank to regulate the volume of electrolyte (water) added to the soil. In both EKR reactors, thermocouples and tensiometers were installed to monitor the temperature and degree of saturation of the soil throughout the test. In addition, in the PER, 6 pH and 6 conductivity gauges were installed to continuously measure those variables. These variables were remotely controlled and monitored through the use of a Supervisory Control And Data Acquisition (SCADA) software package. For the MER, pH and conductivity were analysed through sampling with rhizons.

1

2 **Figure 3.** Schematic of the instrumentation distribution in the EKR plants: (A) MER
3 and (B) PER.

4

In both installations, electric current was supplied from a power source. In the MER, a SM 400-AR-8 DELTA ELEKTRONIKA BV source was used with working intervals of 0 to 400 V for voltage and 0 to 8 A for intensity. In the PER, a more powerful source was installed: 7.5 kW (0-1000 V and 0-25 A) by MAGNA POWER ELECTRONICS.

2.3. Analytical techniques

2.3.1 Soil analysis

The gravimetric water content, w , and dry density, ρ_d , of natural soil were determined based on standards ASTM D2216[33] and ASTM D7263[34]. Undrained shear strength of the soil was measured according to a direct shear test, following the ASTM D-3080[32] standard. The mineralogical composition was determined by X-Ray diffraction analysis. Particle size distribution from a size smaller than silt (2000 μm) up to 0.4 μm was obtained using a laser diffraction particle size analyser with an aqueous module.

2.3.2 Pesticide analysis

The 2,4-D concentration in the aqueous phase was determined using UV– visible spectrometry at a wavelength of 283 nm.

3. RESULTS AND DISCUSSION

3.1. Engineering Parameters.

3.1.1. Conditioning of Extracted Natural Soils

The main objective when scaling is to reproduce a real application. Therefore, as indicated in the introduction, it is essential to use soils with hydro-mechanical properties that are analogous to those in the field. A priori, this is not simple because during extraction, transport, and/or storage before the experiment, the macroscopic structure becomes

1 altered, resulting in values that differ from those expected for a treated soil in a real
2 application. This may considerably distort the development of the electrokinetic transport
3 processes that occur during treatment. Therefore, it is necessary to develop an initial
4 conditioning of the soil that allows the re-establishment of these properties and ensures
5 the homogeneity of the soil being tested.

6 To determine how the soil preparation influences its hydro-mechanical behaviour, an
7 infiltration test was performed using a dye tracer (see Supplementary material, Figure
8 S3): phenolphthalein in basic medium [35-37]. Therefore, given the authors' previous
9 experience in the treatment of kaolins [29, 38, 39], two samples of commercial kaolin
10 with a w of 23.4% were tested. The first one was compacted using the Standard Proctor
11 procedure in accordance with ASTM D689[40] (sample 1: $\rho_d=1.37 \text{ g cm}^{-3}$, and void ratio
12 $e=0.90$). For the second one, after mixing the kaolin thoroughly to achieve the desired
13 moisture content, the sample was simply placed into the mould (sample 2: $\rho_d=0.98 \text{ g cm}^{-3}$,
14 $e=1.65$). Figure S3 shows that in sample 1 (compacted), the front of the dye tracer is
15 practically flat, without appreciable digitations. However, in sample 2, a different
16 behaviour is observed. Here, the front exhibits notable roughness, indicating the existence
17 of differentiated porosity regions, which will significantly complicate the interpretation
18 of any EKR test. In addition, the flow is much faster because of the formation of
19 preferential flow paths, which distort what would occur in field conditions with reduced
20 porosity. These results clearly indicate that there is a need to previously condition the soil
21 to be treated.

3.1.2 Compacting Process of natural soil into EKR reactor

Before extracting the soil to be tested from the study area, its w and ρ_d were determined (see 2.3 Analytical techniques), obtaining characteristic values of 12.5% for w and 1.55 g cm⁻³ for ρ_d . These values were used as “target values” in both the MER and PER. To achieve the target values, we investigated the compaction necessary to reach 1.55 g cm⁻³ for ρ_d with w fixed at 12.5%. Different compaction energies, E_c were tested, and the results are shown in Figure S4 (see Supplementary material). This allowed for identifying the optimal value of E_c : 250 kJ m⁻³ that will be used to the compacting process of soil into EKR reactors.

First, in both the MER and PER, a layer of permeable material was incorporated. A granular material (double layer of gravel and sand) with larger particle sizes than the soils tested was also included. To avoid mixing of the soils with the granular base, a layer of geotextile was placed over the sand (see Supplementary material, Figure S5 and Figure 5). In addition, in the case of the PER, a layer of geotextile was placed in the bottom to facilitate dismantling of the setup after ending the tests and protect the installation.

The excavated soil was stored in a deposit with controlled humidity conditions, imposing a w of 12.5%. Subsequently, the material was placed in successive layers of controlled height. For the MER, 5 layers were used, each with a height of 5 cm. The E_c was transmitted to the soil through an Army-type compaction hammer (see Supplementary material, Figure S5). To evaluate the compaction efficiency, an initial test was performed, which demonstrated that applying an E_c of 250 kJ m⁻³ (defined in the previous compaction study, Figure S4) achieved a ρ_d that was approximately 10% lower than the target ρ_d . This was likely because the lateral confinement was not as desired because of the deformability

1 of the methacrylate walls compared to the metallic Proctor mould used to obtain the
 2 values in Figure S4. As a result, the E_c applied was lower. To solve this problem, an E_c
 3 of 290 kJ m³ was applied, corresponding to 15% higher than that shown in Figure S4.
 4 Once the soil was placed in the reactor, small samples were taken throughout the entire
 5 surface of the MER to contrast the values obtained. As seen in Figure 4 (A), the value of
 6 ρ_d shows good agreement with the desired value, indicating that the general compaction
 7 procedure was appropriate and that the strategy of increasing E_c was efficient. The values
 8 of w (Figure 4 (B)) confirm this conclusion.

9

10 **Figure 4.** Control tests of w and ρ_d performed after placing the soil in the EKR reactors
 11 used: (A) histogram of ρ_d in MER, (B) histogram of w in MER, (C) histogram of ρ_d in
 12 PER, and (D) histogram of w in PER.

13

1 When placing the soil in the PER, the procedure followed was similar to that developed
2 in the MER described above, with certain modifications relating to the significant change
3 in scale (see Figure 5). The first modification was related to soil compaction, carried out
4 by using an IMCOINSA 21215 vibrating plate with a compaction surface of 0.2 m².
5 Provided that the concrete walls are stiffer than the methacrylate plates used in the MER,
6 better lateral confinement of the soil was achieved in the PER, and it was not necessary
7 to apply an extra compaction energy. In this case, 7 layers of 20 cm each one were placed.
8 As for the MER setup, a control test of the obtained w and ρ_d was performed after each
9 layer had been compacted. The histograms of the values of ρ_d and w are shown in Figure
10 4 (C) and (D), respectively. In contrast to the MER, given the volume of soil used in the
11 PER, controlling the moisture content was more difficult. However, the resulting
12 deviation was low: 2.9% with respect to the target value. The dispersion was similar
13 (coefficient of variation of 3.3%) for ρ_d (mean value of 1.58 g cm⁻³, typical deviation of
14 0.051 g cm⁻³). As a result, the setup procedure can be considered satisfactory.

Figure 5. Setup procedure of the PER reactor. Dimensions in cm.

3.1.3 Perimeter Control of the EKR reactor

Regarding the correct characterization of the hydraulic behaviour of the system, special precautions must be taken in scaled tests to control the occurrence of potential leaks from the PER to its surroundings. In MERs, given their size, it is sufficient to take some basic control measures to detect these processes. Normally, they tend to occur in the joints between lateral methacrylate plates or at the base as a result of damage caused during the compacting process. Therefore, even if a watertightness test were conducted before starting the test (filling with water and looking for leaks), some leaks would not be detected because they are generated after compacting the soil. However, given the stiffness of the PER walls, the damage produced during soil compaction is relatively small, and tests to check watertightness are useful for detecting relevant leaks that can be repaired before conducting the test.

Even when the joints between the concrete elements are conditioned with impermeable elements, such as those used in water deposits, small leaks may still occur. If they are minimized, they may not significantly distort the processes being studied and, as a result, would not affect the execution of the tests. However, they should be quantified to ensure that their influence is small. Figure S6 (see Supplementary material) shows a schematic of the watertightness test performed, and Figure S7 (see Supplementary material) presents the evolution of the normalized water mass with respect to the initial mass of the system. As seen, a continuous loss of mass occurred. However, during the two months of the test, this loss was less than 7% of the total mass of the system. The leak amounted to approximately 1.96 mm day^{-1} , which is very low ($1.51 \pm 0.35 \text{ mm day}^{-1}$) and is similar to the estimated evaporation rate in the tarp-covered evaporimeter tank used in the evaporation test described in section 3.2.3. Thus, practically all the water losses observed result from evaporation. This process was minimized by the impermeable effect of a tarp

(see Figure S6). Therefore, it is possible to analyse the electrokinetic processes in the PER by assuming impermeable surroundings.

Although the PER used did not exhibit leaks during the watertightness test, it is possible for a leak event to occur during the execution of the EKR test, which would be difficult to identify. For this reason, a drainage well should be located near the perimeter of the EKR reactor to monitor and control leaks (CB, Figure 1).

3.2. Technological Parameters.

EKR process was carried out to remove a discharge of commercial pesticide in the form of 20 mg of 2,4-dichlorophenoxyacetic acid (2,4-D) per kg of soil. The discharge was performed via the central well of the EKR reactors (Figure 3). Then, the contaminant was allowed to propagate freely in the system for 60 h, when constant suctions readings were obtained from the tensiometers. The treatment was subsequently initiated by applying an electric potential gradient (E_z) of 1 V cm⁻¹.

3.2.1 Influence of the Change in Scale on Energy Consumption

Even when imposing the same E_z of 1 V cm⁻¹ (potentiostatic mode of operation), the electric load applied in the PER was different from that used in the MER. To clarify, Figure 6 shows the analysis of the change in electric current, I , and energy consumption, ρ_{EC} (Eq. 1), with time.

$$\rho_{EC} = \frac{\int I \cdot E \cdot dt}{V_{soil}} \quad \text{Eq.1}$$

Figure 6. Behaviours of I ($\blacktriangle$) and ρ_{EC} ($\blacksquare$) with time during an EKR process. PER, filled markers; MER, unfilled markers. $E_z = 1 \text{ V cm}^{-1}$

Although the profile of the evolution of I was similar on both scales, the values obtained in the PER were much higher, reaching a maximum value of 25 A compared to 0.6 A in the MER. In addition, given that the inter-electrode distance in the PER was 3 m, it became necessary to apply a high E (300 V) to reach the desired E_z . In the tests conducted in the MER, the separation between electrodes was considerably smaller (0.38 m); thus, to work with the same E_z , only 38 V was applied. This increased not only the volume of soil analysed, V_{soil} , (10.4 m³ in the PER compared to 0.10 m³ in the MER) but also, as seen in Figure 6, the ρ_{EC} . The first 100 h of experiment, a great increment of ρ_{EC} can be observed. This stage are related with the transitory phenomena (onset of the mobilization of water, ions and pH fronts) that occurs up to achieve a quasi-stationary state. Over 300 h of testing, the ρ_{EC} in the PER was 180 kWh m⁻³, approximately double that of the MER. This effect is associated with the change in scale and exerts an important influence on the phenomena that develop in the soil during the EKR process.

3.2.2 Influence of the Change in Scale on Electrokinetic Flows

As seen in Figure 7, the electro-osmotic flow, J_{eo} , is considerably different. In the PER, water transport at the beginning of the test is evident, reaching an average J_{eo} of $5.5 \times 10^{-7} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$. However, in the MER, J_{eo} is practically zero at the beginning of the test, stabilizing at a value approximately equal to 24% of the PER value ($1.4 \times 10^{-7} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$).

Figure 7. Behaviour of J_{eo} during the EKR process. (●) PER (10.4 m^3 of soil); (▲) MER (0.10 m^3 of soil). $E_z = 1 \text{ V cm}^{-1}$.

The change in scale also has an important effect on the process of electromigration. Given the anionic nature of the pesticide, the quantity of 2,4-D mobilized towards the anodic wells was monitored. Figure 8 shows the behaviour of the electromigratory flow, J_{em} , of 2,4-D, which was two orders of magnitude higher in the PER than in the MER.

Figure 8. Behaviour of the J_{em} of 2,4-D mobilized towards the anodic wells during the EKR process. (●) PER (10.4 m³ of soil); (▲) MER (0.10 m³ of soil). $E_z = 1 \text{ V cm}^{-1}$.

The significant differences in J_{eo} and J_{em} lead to reasonable doubts regarding the validity of making predictions about the effectiveness of a process using results obtained from reduced-scale tests.

3.2.3 Influence of the Change in Scale on Soil Temperature

When the ρ_{EC} applied to the soil was increased, the average temperature was also incremented due to electric heating process. This is illustrated in Figure 9, which shows the increase in average temperature, ΔT , recorded in the tests conducted at the two scales analysed. In test conducted in PER, the increase observed is more significant, achieving a maximum of 11°C, and stabilizing in 8 °C approximately, while MER test only shows an increase of 2°C. It is interesting to note that the difference between the temperature in both EKR reactors is more pronounced, because of the PER is outside (average room temperature, 11.2°C) and MER is inside laboratory (average room temperature, 21.6°C).

Figure 9. Behaviour of the average ΔT of the soil during an EKR process. (●) PER (10.4 m³ of soil); (▲) MER (0.10 m³ of soil). $E_z = 1 \text{ V cm}^{-1}$.

The increase in the system temperature can favour the intensification of various processes, such as the evaporation of soil water. This phenomenon is of great importance in the development of EKR tests because it can cause shrinkage cracks on the surface of the soil, which considerably distort the development of EKR processes and, as a result, the interpretation of the results obtained [30]. To minimize evaporation, it is useful to include capillary barriers on the surface of the soil [30, 31], as noted in section 3.1.2 (see Figure 5 and Supplementary material, Figure S5). In addition, it is also advisable, once the instrumentation is installed, to place an impermeable tarp on the surface of the EKR reactors. Thus, an atmosphere is generated over the sand that contains high relative moisture, significantly reducing evaporation during the test. To demonstrate this effect, we monitored the simultaneous losses of water, Δh_w , through evaporation in both evaporimeter tanks, one of which was in direct contact with the atmosphere and the other of which was covered with an impermeable tarp. Figure S8 in the Supplementary material shows how Δh_w increases linearly with time in the tank open to the atmosphere, reaching

an evaporation rate of $5.14 \pm 0.35 \text{ mm day}^{-1}$. However, the Δh_w observed in the tarp-covered reactor was reduced by approximately 70%, exhibiting an evaporation rate of $1.51 \pm 0.35 \text{ mm day}^{-1}$.

4. CONCLUSIONS

The main conclusions obtained from this study are as follows:

- To reproduce the behaviour of real soil subjected to EKR, the soil must be conditioned before being placed in the EKR reactor to re-establish similar values of the moisture content and degree of compaction to those found in field conditions.
- The necessary E_c to achieve the desired level of compaction directly depends on the moisture content and type of soil being tested and indirectly depends on the stiffness of the EKR reactor where the soil is to be placed.
- Even when the same soil-preparation and placement processes are followed in the EKR reactors, both of the reactors are of significant size, and the same E_z (1 V cm^{-1}) is applied, the change of scale considerably influences the amount of electric energy consumed in the process and, consequently, the intensity with which the different electrokinetic processes are developed. Therefore, it seems reasonable to question predictions of real treatment effectiveness obtained by extrapolating the results of small-scale tests.
- In a PER, in addition to the electrokinetic processes resulting from the application of an electric field, other phenomena related to the soil/PER interactions with its surroundings, such as evaporation and possible leaks, are important. Thus, these processes should be identified and quantified because they influence the

development of the EKR process itself, altering the water content of the soil and possibly promoting the formation of cracks in the soil. All of these processes could significantly distort the interpretation of the test results.

- Perimeter control of the EKR reactor is a very important aspect at scales that are close to real scale. Thus, a drainage well that allows for the identification of possible leaks during the development of EKR tests should be included.

APPENDIX A: Nomenclature of variables and abbreviation

Parameter	Description	Units
w	gravimetric water content	g g^{-1}
ρ_d	dry density	g cm^{-3}
e	void ratio	$\text{cm}^{-3} \text{ cm}^{-3}$
E_c	compaction energy	kJ m^{-3}
E_z	electric potential gradient	V cm^{-1}
E	electric potential	V
I	electric current	A
V_{soil}	volume of soil	m^3
ρ_{EC}	energy consumption	kWh m^{-3}
J_{eo}	electro-osmotic flow	$\text{m}^3 \text{ m}^{-2} \text{ s}^{-1}$
J_{em}	Electromigratory flow	$\text{mg m}^{-2} \text{ s}^{-1}$
ΔT	average temperature variation	$^{\circ}\text{C}$
Δh_w	losses of water through evaporation	mm
m_w/m_w^0	normalized water mass	g g^{-1}

Acronym	Description
2,4-D	2,4-Dichlorophenoxyacetic Acid
CB	Control Borehole

CL	Low Plasticity Clay
EKR	Electrokinetic Remediation
MER	Mock-Up EKR Reactor
PER	Prototype EKR Reactor
PVC	Polyvinyl Chloride
SCADA	Supervisory Control And Data Acquisition
USDA	United States Department Of Agriculture

SUPPLEMENTARY MATERIAL

Data and schemes related to soil characterization, the experimental setups, preparation of soil procedure, and the watertightness tests are compiled in Supplementary material.

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Figure Captions

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

Figure 2. Placement of electrolyte wells in the PER.

Figure 3. Schematic of the instrumentation distribution in the EKR plants: (A) MER and (B) PER.

Figure 4. Control tests of w and ρ_d performed after placing the soil in the EKR reactors used: (A) histogram of ρ_d in MER, (B) histogram of w in MER, (C) histogram of ρ_d in PER, and (D) histogram of w in PER.

Figure 5. Setup procedure of the PER reactor. Dimensions in cm.

Figure 6. Behaviours of I (▲) and ρ_{EC} (■) with time during an EKR process. PER, filled markers; MER, unfilled markers. $E_z = 1 \text{ V cm}^{-1}$

Figure 7. Behaviour of J_{eo} during the EKR process. (●) PER (10.4 m³ of soil); (▲) MER (0.10 m³ of soil). $E_z = 1 \text{ V cm}^{-1}$.

Figure 8. Behaviour of the J_{em} of 2,4-D mobilized towards the anodic wells during the EKR process. (●) PER (10.4 m³ of soil); (▲) MER (0.10 m³ of soil). $E_z = 1 \text{ V cm}^{-1}$.

Figure 9. Behaviour of the average ΔT of the soil during an EKR process. (●) PER (10.4 m³ of soil); (▲) MER (0.10 m³ of soil). $E_z = 1 \text{ V cm}^{-1}$.

Figure Captions (Supplementary material)

Figure S1. Classification of the soil selected based on the Casagrande plasticity chart (ASTM D2487 [22]).

Figure S2. (A) Particle size distribution. (B) Grading curve.

Figure S3. Infiltration test performed with phenolphthalein in basic medium. Sample 1, compacted soil. Sample 2, uncompacted soil.

Figure S4. Study of the influence of E_c on the ρ_d of the soil used. $w = 12.5\%$

Figure S5. Schematic of the setup stages of the soil in the MER reactor. (A) Positioning of the mechanical and drainage support. (B) Compaction of the soil.

Figure S6. Schematic of the watertightness test conducted in the PER.

Figure S7. Behaviour of the normalized mass of water obtained in the watertightness test conducted in the PER. The test was conducted in summer 2015.

Figure S8. Evaporation test. (●) Behaviour of Δh_w in an evaporimeter tank in direct contact with the atmosphere and (●) in an evaporimeter tank covered with an impermeable tarp. The test was conducted in summer 2015.

Supplementary material

for

**Scale-up on Electrokinetic Remediation:
Engineering and Technological parameters**

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(A) Mechanical and drainage support

Coarse-Gravel

Fine-Grained

Sand

(B) Compaction of the soil

Setting layer height

Uncompacted layer

Army-type compaction hammer

Compacted soil

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