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CONTENTS

Soil remediation at coastal plains with the help of DC Resistivity Method

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Research Article

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ABSTRACT

The coastline of the Dardanos, a district of Çanakkale, Türkiye, suffers from saltwater intrusion due to excessive extraction of groundwater for domestic usage and also agricultural activities. Thus, the salinity level increased, and much of the land became unusable. The electrokinetic remediation method was employed to reduce the salinity level in the soil samples in laboratory conditions. The sample used in remediation is silty agricultural soil, with pH value and electrical conductivity (EC) of which are 8.33 and 1282 μS/cm respectively. In the lab-scale experiments, three different types of electrodes, aluminum, copper, and galvanized steel, were used in the tests. For each type of metal, electrode pairs were placed in the soil that was filled in a plastic container. Current variation was monitored while 1 VDC/cm was applied to electrodes. Average electrical conductivity reduces to 13.5%. As a side effect, all electrodes suffered from heavy corrosion which may be prevented by using anti-corrosion additives to reduce damage for future applications.

1. Introduction

The coastal areas accommodate the majority (~70%) of the world's population for residential and agricultural activities (Cohen, 2006; Bear and Cheng, 2010). Currently, shoreline settlements are facing a scarcity of water supply due to seawater intrusion (Pulido-Leboeuf, 2004; Abarca Cameo, 2006; Abd-Elaty et al., 2022). Excessive pumping of water from wells due to water needs in industrial activities and residential usage reduces the slope of the water table towards the sea or the water level falls below sea level. In either case, seawater rushes into freshwater aquifers. This invasion reaches a drastic level if the freshwater flow toward the shoreline is interrupted even for a relatively short period. In addition to the replacement of the saltwater and freshwater interface, pumping out of groundwater in coastal areas excessively together with the usage of chemicals (fertilizers, etc.) to increase productivity causes some of the environmental problems and agricultural lands to become redundant.

Various types of soil remediation processes aim to eliminate contaminants from the soil. Traditional and novel soil remediation techniques are subject to various research (Sheoran et al., 1989; Luo et al., 2016; Karaca et al., 2017; 2018; 2022). Electrokinetic soil remediation has attracted increased interest (Acar and Alshawabkeh, 1993; Zelina and Rusling, 1999; Karaca et al., 2019; Bessaim et al., 2020; Özentürk et al., 2021; Karaca et al., 2022*;* Özentürk, 2022; Karaca et al., 2023; Taneja et al., 2023*a*; Taneja et al., 2024; Özentürk et al., 2024). The electrokinetic remediation processes employ the direct current (DC) and create an electric field in the geological unit. This

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is done by placing metal electrodes into the soil to be decontaminated. Then, approximately 50 to 150 V is applied to electrodes to create an adequate current to mobilize the ions in the soil.

Electrokinetic remediation (EKR) works with several different processes. Depending on the specific properties of the pollutants, each process acts individually or in combination to remove the target chemicals from soil. Electromigration, electrophoresis, and electro-osmosis transport the target pollutant to a location for removal (Reddy and Cameselle, 2009; Brusseau and Maier, 2014).

In this study, a bench-scale electrokinetic treatment trial was conducted to reduce soil salinity in the shoreline of the Çanakkale strait. The soil sample was taken from the Çanakkale-Dardanos Campus (CDC), northwest Türkiye (Figure 1). Alluvium stretches along the shoreline and overlays sandstone and mudstone units. Excessive pumping of water from wells with various depths in a relatively small area resulted in saline water intrusion. For testing purposes, we conducted an inter-disciplinary approach; first, we mapped out geological units of the target area and located geological units prone to be polluted by seawater. Then, we conducted a geophysical survey to obtain the resistivity distribution of the area. Based on the result we chose the place to take soil samples, and then an electrokinetic remediation study was carried out.

The outline objectives of this study are as follows;

- Map out possible geological units susceptible to pollution
- Execute a geophysical survey to map out salinization levels in the study area.
- Evaluate the success of electrokinetics for the remediation of salinized soil, and
- Examine the effectiveness of electrode types and configurations.

We recommend the following steps;

- The Direct Current Resistivity (DCR) method shall be used to reveal the geo-electrical image that helps to map the saline-rich geological units.
- Soil samples shall be collected according to resistivity model.
- Multi-electrode system for anodes and cathodes shall be employed for remediation.

Our primary findings indicate that upscaling the application from laboratory to field scale must be solved. Keeping the moisturizing at an adequate level and also removing the pollutants from the system immediately are vital for protecting the electrodes. We will present our results in due course.

In the following sections, we outlined the DCR Method to map out the resistivity distribution of subfurface geology and salty area. This map is used as a reference to locate a sampling point for soil. Then we executed lab experiments. Our findings and discussion follow the experiment section.

2. Methodology

Following our objectives, the local geological map indicates that alluvium stretches along the shoreline and also dominates the CDC area. The unit presents inhomogeneous features. To locate the sampling points, we utilize DCR method that is well known geophysical methods. Note that the electrical conductivity meters are in use for agricultural lands (e.g. McNeill, 1992; Corwin and Lesch, 2005; Kühn et al., 2009; Lech et al., 2016) and target the top-most layer of soil (depth < 1 meter). We employed DCR method to obtain pseudo three-dimensional (3D) resistivity distribution of survey area. In this approach, we are able to map the extension of the saline-rich units in x,y and z (depth) directions, in turn, we can also calculate approximate volume that needs remediation.

2.1. Direct Current Resistivity Method

DCR method is a geophysical method that was first suggested by Schlumberger (1920). Initially, the DCR method was used to delineate the saline and freshwater boundaries and has been subject to research since 1930. Swartz (1937; 1939) pioneered groundwater exploration and used the DCR on the Hawaiian Islands (Fretwell and Stewart, 1981; Ulugergerli, 2017). In simple terms, the DCR method requires injecting electrical current from two electrodes and measuring

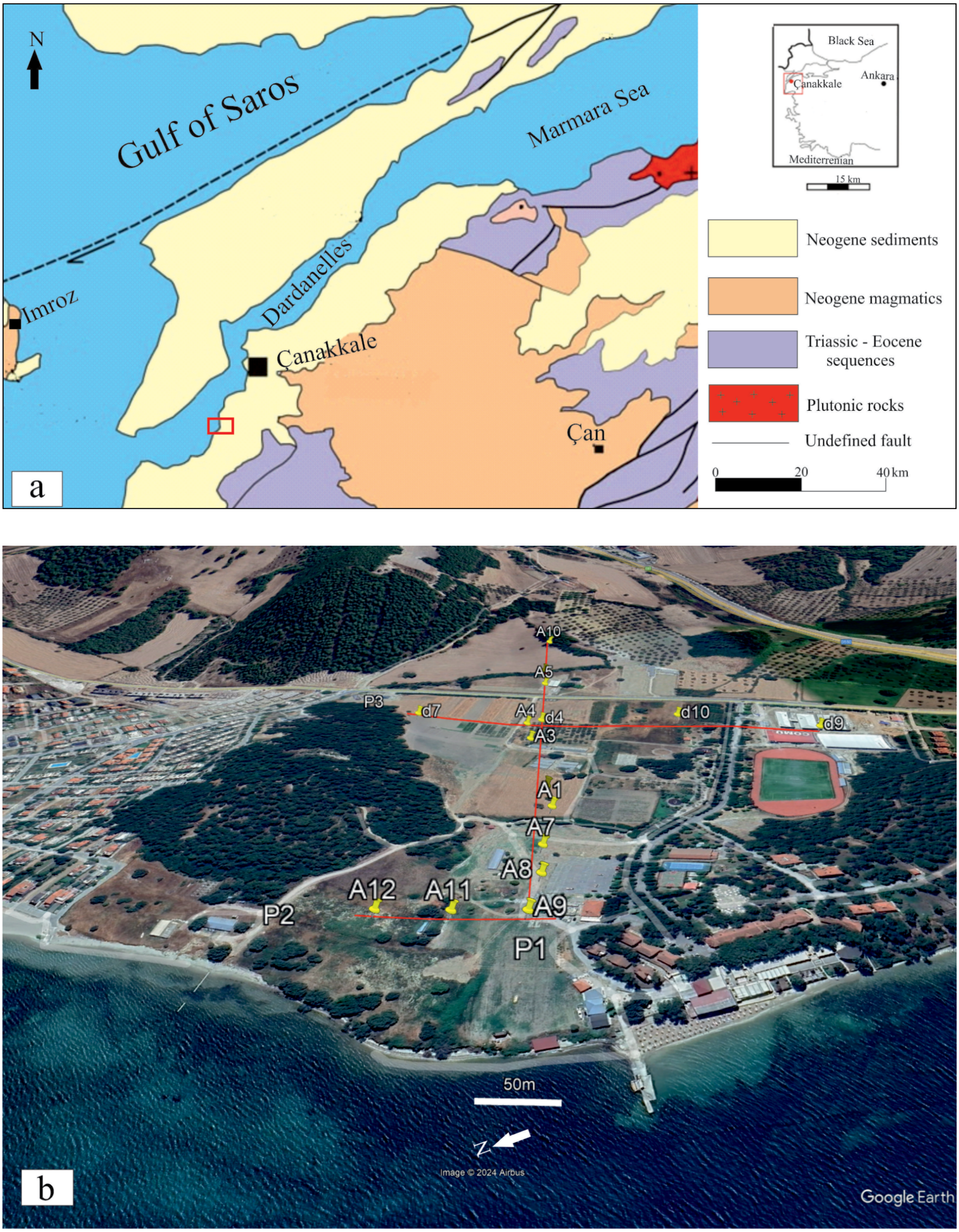

Figure 1- a) Geological setting of Biga peninsula (Okay and Satır, 2000) b) The study area and measurement stations for the DCR method (yellow pins).

voltage difference from the other two electrodes over the ground surface. The difference from EKR is that the duration of injecting current is relatively short, i.e., 10-20 sec.

The injected current and the measured potential difference are used to calculate apparent resistivities for each measurement point along the profiles (Telford et al., 1990). Apparent resistivities are not suitable for image resistivity distribution of geological stratum. Thus, a two-dimensional (2D) inversion scheme was chosen for the current study (Sasaki, 1992). This approach requires all stations to align along a profile and to be spatially dense enough (e.g. Ulugergerli, 2017; Ertekin and Ulugergerli, 2022). Then, an efficient and accurate 2D image of geo-electrical structures beneath the profile could be recovered employing 2D inversion Note that Menke (1989), Meju (1994), Zhdanov (2002), and many other researchers provided details for both inversion and modeling for geophysical methods. Following the technological development, the DCR data can be gathered by using multi-electrode instruments, then this approach is called electrical resistivity tomography (Chambers et al., 2006; Candansayar, 2008; Wilkinson et al., 2012).

2.2. Soil Sampling

We collected the soil sample away from actively used roads. Removed the top dirt and got ~30 kg soil 10-20 cm below the surface. Sieved the soil using a 2 mm sieve and removed pebbles, organic materials, etc. before further steps.

In order to determine physico-chemical parameters, first, natural water content (ASTM D2216) was determined as 19.28%. Then the ratio of 1:5 (Soil: DI water) was used to determine salinity, pH and EC values. The samples were mixed for 6 hours at 180 rpm in the shaking device. At the end of 24 hours, the values measured with the Wtv multi 340i device are given in Table 1. As a result of the sieve analysis, the soil corresponded to the low plasticity clay (CL) class according to the Unified Soil Classification System (USCS).

Table 1- Chemical and physical properties of the sample taken from the study area.

Ground Class (USCS)	Water Content %	pH	Electrical conductivity (EC) µs/cm	Salinity (NaCl equivalent) %
CL	19.28	8.33	1282	0.45

2.3. Electrokinetic Method

During our experiments, a plastic container with dimensions of 40x58x15 cm was used to create a scaled sample for field application. Figure 2 shows the electrode configuration which we used for this study.

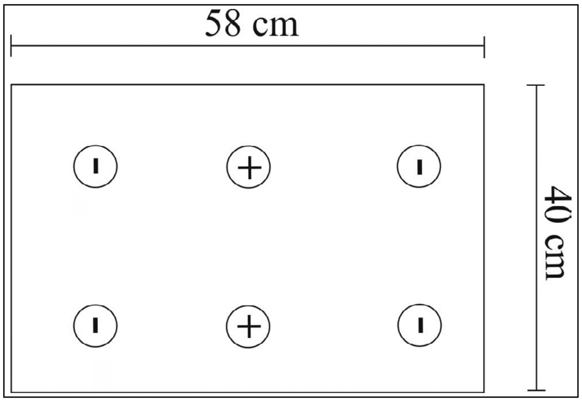

Figure 2- Electrode configuration; (+) anode (-) cathode electrodes.

The mud-cake containing soil and distilled water was placed into a plastic container (Figure 3). A wooden mallet was used to remove the air bubbles, if any, and make it tight. Note that the container must have a lid to prevent drying out during the remediation study.

Parameters such as the type of electrodes, content of electrolytes, and electrical current density affect the electrokinetic enhancement. Voltage set 1 VDC/cm considering the separation of the anode and cathode electrodes. Specifically, 11.6 V was applied because the distance between the electrodes was 11.6 cm. The current values measured during the experiment decreased over time. The experiments were terminated when the current values approached zero due to the displacement of ions in the soil and accumulation around the electrodes. At the end of the tests to determine the physicochemical parameters of the soil, soil samples were taken approximately 1 cm in front of the electrodes.

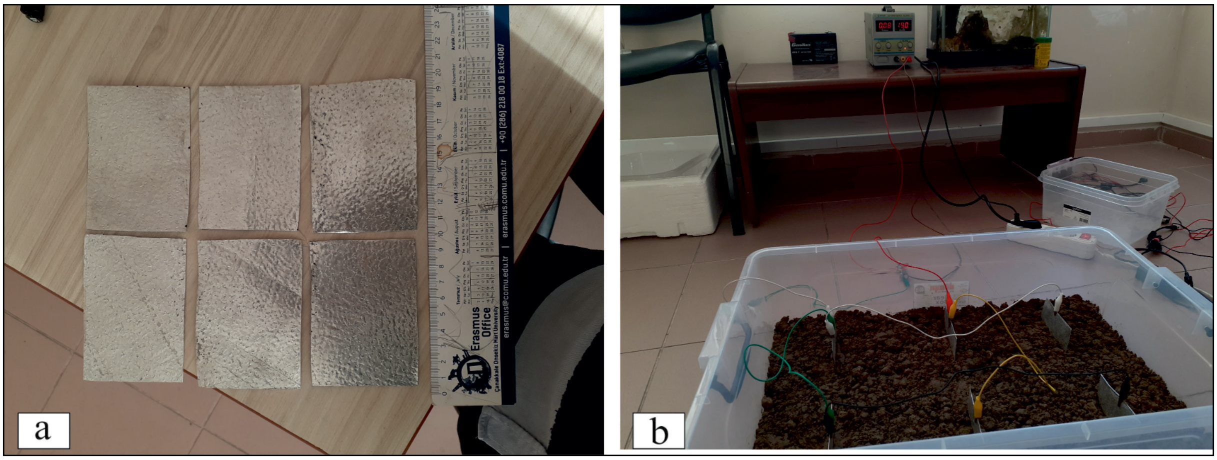

Figure 3- Electrokinetic experimental setup; a) preparation of electrodes, b) placement of electrodes.

3. Result and Discussion

3.1. DCR Survey

Considering the cost of the instruments, we used classical four electrode DCR equipment and we collected data using a vertical electrical sounding technique along lines and we combined and inverted those data sets using a 2D inversion algorithm.

As an example, the 2D resistivity-depth section of Profile 1, obtained from 2D inversion, is given in Figure 4. The agricultural soil (~10 ohm.m) covers the surface along the profile. Then, the existence of a low resistivity (<5 ohm.m) unit points out seawater intrusion. The main geological unit presents discontinuities along the profile (dark blue colored unit).

3.2. DCR Survey Results

In order to define soil sampling location, the 2D resistivity models are combined and the pseudo-3D resistivity model is presented as a fence diagram (Figure 5). While deeper parts let us evaluate the inland limits of seawater intrusion. The shallow part of the fence diagram pointed out the contaminated soils. Considering the low resistivity (<5 ohm.m) zone near the shoreline, we sample the soil between A9 and A11 (see also Figure 1).

A multi-dimensional evaluation of the DCR method pointed out the location requires remediation. Note that, if available, the multi-electrode DCR systems can speed up the survey (Osinowo et al., 2018). Unfortunatelly, the exploration depth and may become insuffcient if the land is surrounded by inaccessible lands. If it is the case electromagnetic method can be employed to map out the saline zones (e.g. Lesch et al., 1995; Çoban et al., 2017).

3.3. EKR Application and Findings

In the soil, the anions Cl^-, $NaNO_3^-$, NaO_3^-, SO^{-2}_4 and cations consisting of Ca^{2+}, K^+, Na^+ and Mg^+ form compounds and cause salinity (Kim et al., 2011). Depending on their charge, the contaminants and mobile ions present carry the electrical current from the anode to the cathode at the beginning of the test, causing a large current density peak after some time. The decrease following this peak is explained by the increase in electrical resistance of precipitates formed as a result of oxidation-reduction, electrolysis, dissolution and precipitation reactions during purification. Calcium ion production around the anode causes the salinity to increase and this value decreases due to calcium hydroxide precipitation at the cathode (Jayasekera and Hall, 2007).

The experiment conducted with copper electrodes was completed at the end of the 6th day when the current decreased to unmeasurable values. The experiment with the galvanized steel electrode was terminated on the 8th day under a 10 V constant current, and the one with the aluminum plate by applying 19 V current on the 15th day (Figure 6).

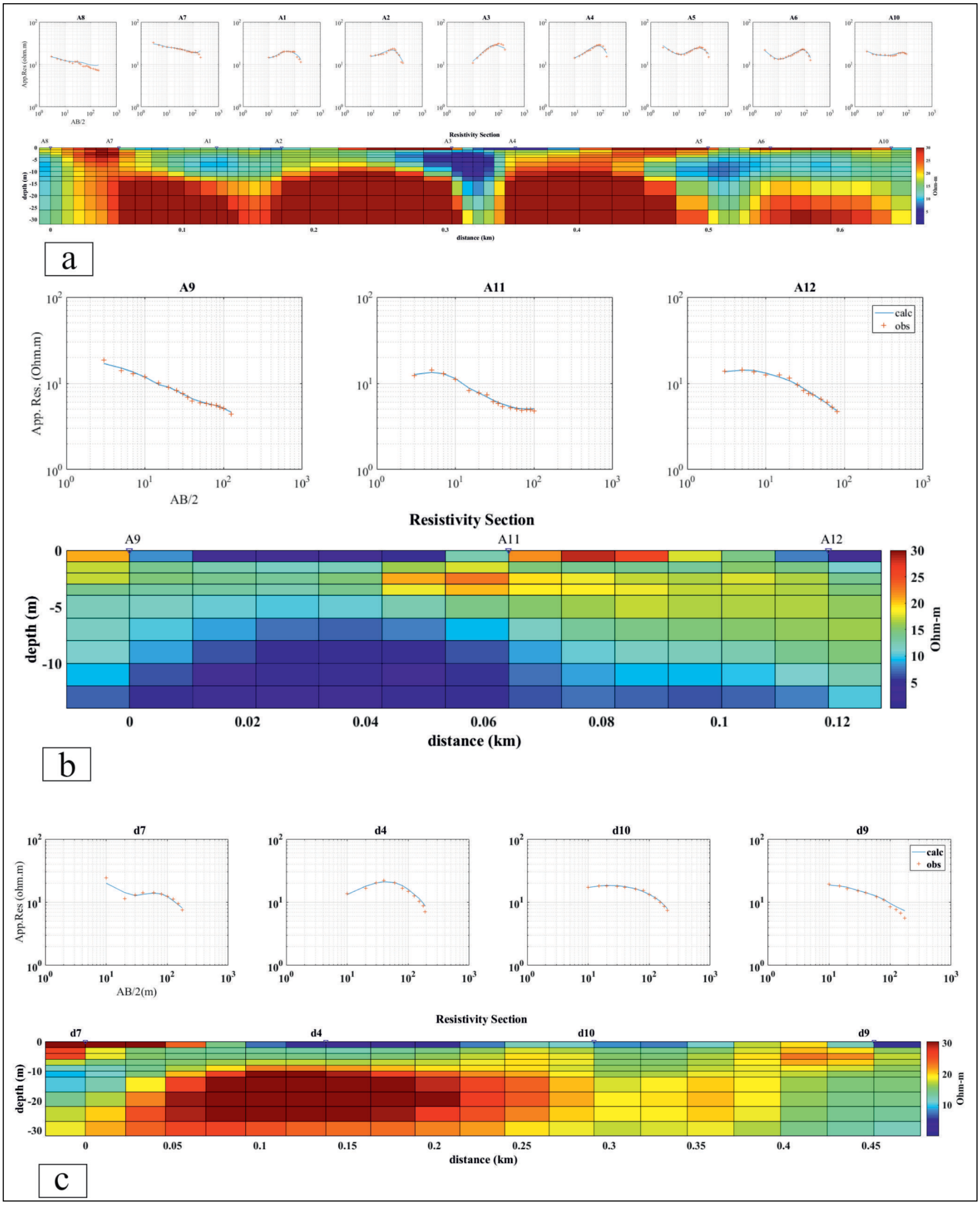

Figure 4- 2D resistivity models obtained from 2D inversion of DCR data. a) Profile 1, b) Profile 2, and c) Profile 3. The top graphs on each panel are apparent resistivity curves of observed (+) and calculated (solid lines) data.

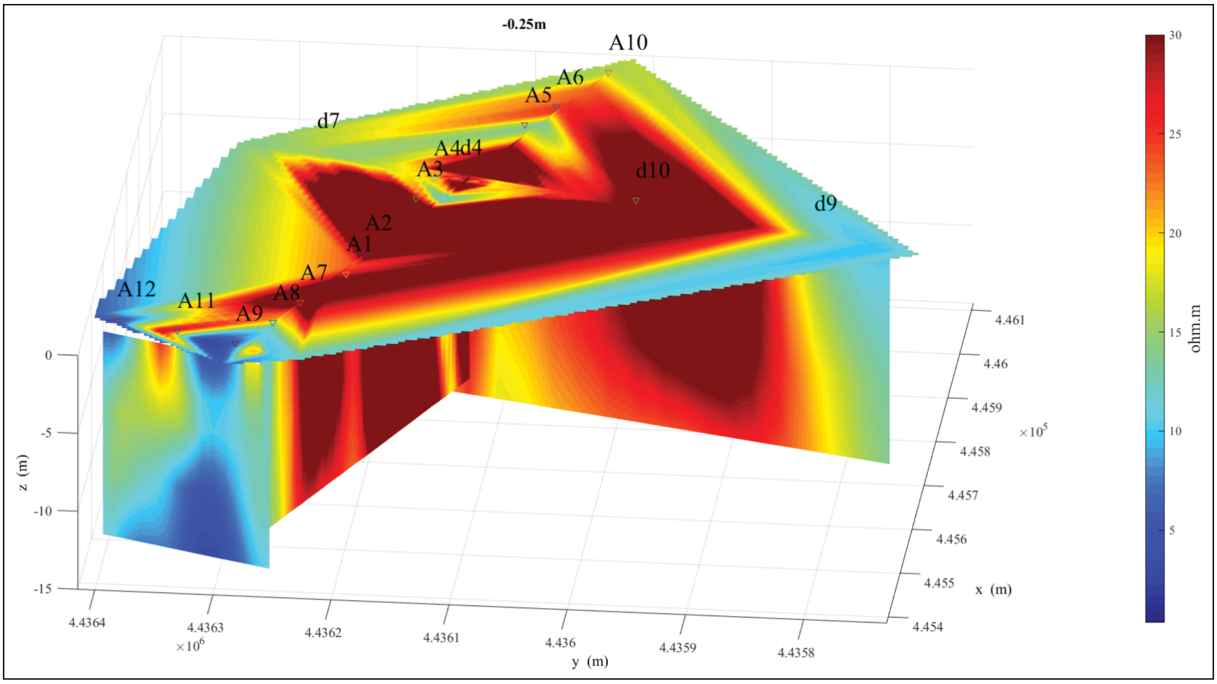

Figure 5- Depth - resistivity distribution at the surface and along the profiles. Resistivity values were extracted from all 2D inversion results.

Table 2 shows the parameters of the soil at the end of the electrokinetic experiments. pH differences at the electrodes are related to the electrolysis of water. By electrolysis of water, it produces O^2 and H^+ ions at the anode and H^2 and OH^- ions at the cathode. Therefore, the pH of the soil near the anode decreases and the pH around the cathode increases. Therefore, acidic pH measurements at the anode and alkaline pH measurements at the cathode are typical. At the same time, electrical conductivity (EC) decreased at the cathode, associated with sodium ion production at the anode. Consequently, it was observed that salinity (NaCl equivalent) was intense, and the EC value was high in the anode region Table 2.

pH differences at the electrodes are related to the electrolysis of water. The oxygen and hydrogen ions produced at the anode create an acidic environment in this region, and the hydrogen and hydroxide ions produced at the cathode create a basic environment. In other words, the pH value is low in the anode region and high in the cathode region. At the same time, the difference in soil moisture content related to the electrolysis of water can be explained. A similar situation can be attributed to the corrosion of anodes

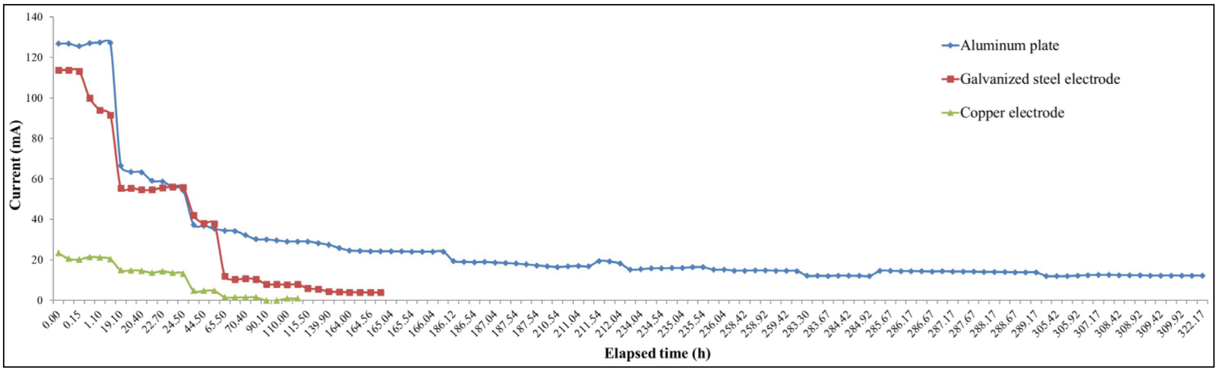

Figure 6- Variation of current intensity during the experiments.

Table 2- Moisture content, pH, EC, and salinity values of the soil after treatment.

End of treatment (average)	Copper electrode		Galvanized steel electrode		Aluminum plate	
	Anode	*Cathode*	*Anode*	*Cathode*	*Anode*	*Cathode*
Moisture content (%)	13.62	17.21	14.28	16.69	12.97	24.58
pH	6.21	9.50	6.53	8.59	6.40	9.78
EC (µS/cm)	328	146	320	178	4050	540
Salinity (%)	0.5	0.2	0.5	0.3	2.8	0.1

by oxidation of water (Barker et al., 2004). In addition, it can be said that other electrochemical reactions during treatment may also be effective. Although salinity removal was achieved in the study, corrosion occurred on the electrodes (Figure 7). In some studies, conducted for the remediation of heavy metals, it has been stated that since graphite oxidizes more easily at higher voltages, stainless steel may be used to conduct electric current at higher voltage with minimum corrosion effect and lower cost (Taneja et al., 2023*b*). Interruptions in the power supply and dryness of the soil affected the efficiency of the method. Thus, the added external liquid (pure water) restores humidity in the soil.

To reduce the electrode damage, pulsed current, instead of constant direct current may be applied. In this approach, the electric current is interrupted at regular intervals during the experiment. Thus, energy savings will also be achieved as an important factor to consider for practical applications of EKR.

4. Conclusion

In this study, the 2D inversion results of DCR data were the keys to locating the polluted area. 2D resistivity models provided information down to 30 m of the study area. Also, the treatment efficiency of the electrodes used in the remediation of polluted soils by the EKR method and the corrosion, which occurred during the experiment, and is one of the important problems of this method, were investigated.

The experiments were conducted on saline soils and 1 V/cm DC voltage was applied to the soil during the experiments. The experiments conducted with copper, galvanized steel electrodes, and aluminum plates were completed after 6, 8, and 15 days, respectively.

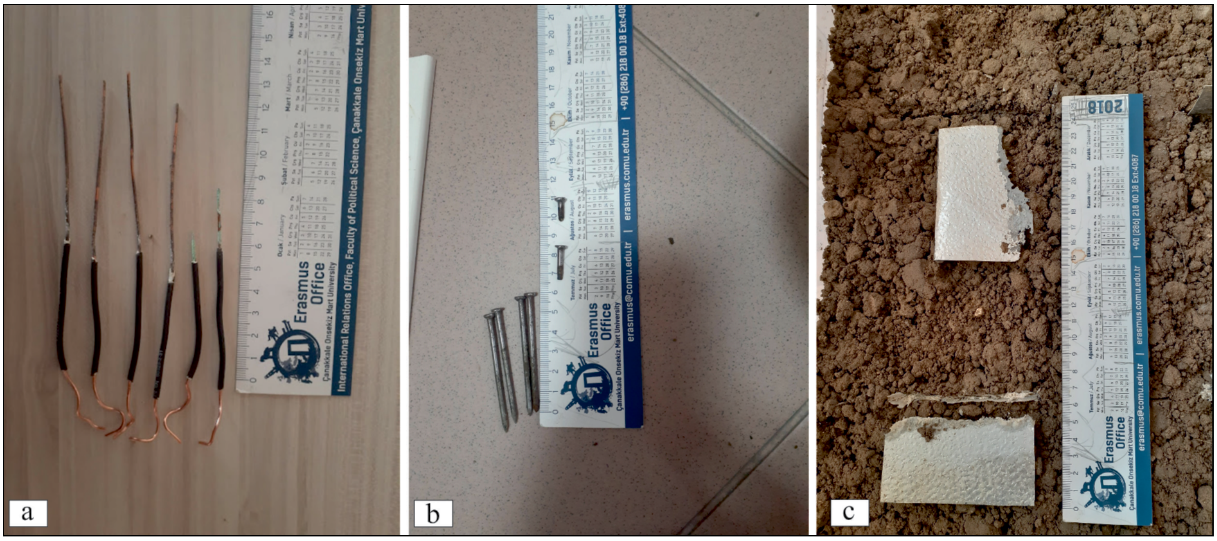

Figure 7- a) Corroded copper electrodes, b) Corroded galvanized steel electrodes, c) Corroded aluminum plate electrodes.

The presence of water controls electrokinetic progress. The electrolysis of water and the ion release in the electrodes, which begins with the application of electric current, continues with the movement of existing and mobile ions in the soil to the electrodes. In the study conducted, this situation, which initially caused the current values to reach the upper values, ended with a decrease in the current values due to the transfer, accumulation and decrease in the concentration of existing ions in the process.

In EKR works, current is transferred to the soil through electrodes. Factors such as pH changes, high heat values due to current and types of contaminants cause corrosion on the electrodes. This causes interruptions in the current and disruptions in the treatment work.

At the end of the EKR, the pH values of the soils decreased slightly at the anode and increased at the cathode in all three experiments. Again, in all experiments, a clear decrease in EC was observed due to the removal of ions by the electrokinetic method, but the decrease at the cathode region was more remarkable due to the alkaline pH recorded.

Electric current applied directly to moist soil results in the electrolysis of water. O_2 and H^+ ions released at the anode result in a decrease in the pH value in this region, and the presence of H_2 and OH^- ions in the cathode results in an increase in the pH value in the region. The change in pH values causes this ion production in the anode region to react with soil components that dissolve carbonates and other basic salts and release metals. Similarly, on the cathode side, hydroxide, which is associated with high pH, provides the environment for the fixation of ionic metals. Therefore, this change in pH values affected the electrical conductivity of the soil, the development of electric current density during the experiment, and the distribution of ionic species in the soil after the electrokinetic treatment.

Since the corrosion of the metallic electrodes used in the study will lead to secondary metallic pollution in the soil due to the damage caused, thus, metal-based electrodes should not be used for treatment. Considering pH values and damage to the electrodes, interrupting the electric current at regular intervals is one of the methods used to reduce high temperature and corrosion intensity in the soil. Using anti-corrosion additives can reduce damage for future applications.

Overall, the outcome indicates that EKR is well-suited to reduce the salinity level in soil. The success of the applicability is site-dependent, thus the electrode material and the current to be applied should be chosen accordingly. In addition, as a further study, before and after the remediation of the area DC resistivity data can be collected to evaluate how successful the remediation is.

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