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تقييم التربة الملوثة بالنفط الهيدروكربوني بطريقة مسح المقاومة الكهربائية

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الخلاصة

أدى تفجير آبار النفط بالكويت (سنة 1991) إلى تكوين العديد من البحيرات النفطية ،والتي قد جفت ولوثت التربة.

وقد بدأ هذا المشروع البحثي للتحقق من مدى امكانية تحديد نوع التلوث ومدى انتشار التربة الملوثةو ذلك عن طريق مسح المنطقة، باستخدام مسح المقاومة الكهربائية تحديداً في بحيرات نفطية جافة في منطقة بحرة، الصبية. وكان الهدف المحدد للبحث هو تقييم قابلية استخدام مسح المقاومة الكهربائية الصديقة للبيئة في البحيرات النفطية الجافة من اجل المساعدة في تصميم طرق التدابير العلاجية للتربة الملوثة ومدى ملاءمة هذه التقنية للمناخ الصحراوي (مثل مناخ الكويت).

ولقد تم جمع نتائج مسح المقاومة الكهربائية من خلال اختبار شبكة نقاط في المنطقة الملوثة وكذلك في منطقة غير ملوثة. بالإضافة الى ذلك، تم استخدام طرق فحص التربة النمطية عن طريق المجسات لاستكشاف قطاع التربة والتأكد من عمق التلوث في منطقة البحث. وتم عمل فحوصات فيزيائية وكيميائية موقعية ومختبرية على عينات من التربة جمعت من موقع الدراسة لمعرفة نوعية وتركيز المواد الملوثة وكذلك الخواص الفيزيائية والكيميائية لقطاع التربة.

نتائج مسح المقاومة الكهربائيةحددت عمق تلوث في التربة بـــ 1.20 متر من سطح الارض. كما أكدت هذه النتائج من خلال فحوصات التربة. وقد أشارت الفحوصات الكيميائية إلى وجود المركبات الهيدروكربونية في المناطق الملوثة. أثبتت النتائج أن مسح المقاومة الكهربائية يمكن ان يستخدم لإعداد تقييم أولي لمواقع تلوث الهيدروكربون المحتملة وذلك لتحديد عمق و نوع التلوث بدون الحاجة لإجراء فحوصات التربة الحقلية والمختبرية ذات الكلفة العالية والتي تستغرق فترة زمنية طويلة لتطبيقها.

Hydrocarbon oil-contaminated soil assessment using electrical resistivity topography

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ABSTRACT

In Kuwait, oil wells exploded in 1991 have created numerous massive oil lakes, which have subsequently dried and contaminated the soil. A research project was initiated to delineate the type and extent of contaminated soil using an area survey method, namely Electrical Resistivity Topography (ERT), to examine dry oil lakes located in Bahra, Subiya. The specific objective was to assess the applicability of the environmentally friendly ERT to assist in the design of measures to remediate the contaminated land. ERT results were generated by testing a grid in both contaminated and non-contaminated areas. In addition, conventional soil boreholes were used to explore the sub-surface profile and depth of contamination in these areas for comparison with ERT results. In-situ and laboratory physical and chemical tests were performed on soil samples collected from the site to identify the contamination type and concentration as well as variation in the physical properties of the soil profile with depth. Results indicated the contamination depth to be 1.2 m from the ground surface. These results were also confirmed by borehole analyses (chemical and physical). Chemical tests indicated that the contamination consists of hydrocarbons. The findings demonstrate that ERT can be used to establish a baseline in the assessment of potential hydrocarbon-contaminated sites and is applicable for determining the type and depth of contamination without the need for expensive and tedious boreholes and in-situ and laboratory soil testing.

Keywords: Dry oil; contaminated; electrical resistivity topography; hydrocarbons.

INTRODUCTION

During the Desert Storm war in 1991, the largest oil wells in Kuwait were dynamited, causing massive fires that lasted for nearly seven months. These fires led to oil lakes that covered enormous areas of the Kuwaiti desert. A large number of these lakes, although dry, still exist and threaten biological life. Rehabilitation requires comprehensive investigations of the extent and type of soil profile contamination.

It was proposed to use the Electrical Resistivity Topography (ERT) method to establish a baseline and initial data points for developing a comprehensive characterization of hydrocarbon oil-contaminated sites. The objective of this study was to assess the existence and vertical and horizontal extent of hydrocarbon oil-contaminated soil in the Bahra dry oil lake.

ERT was performed by testing grids in a contaminated area s well as a non-contaminated area. Conventional boreholes were used to explore the sub-surface soil profiles and the depth of contamination of the contaminated and non-contaminated areas for comparison with the ERT results. In situ and laboratory physical and chemical tests were conducted on soil samples collected from the site.

Kuwait, lies in the northwestern region of the Arabian Gulf with a total area of 17,800 km2, has 10 oil fields, which include 909 oil wells that are divided into southern and northern wells based on their location. Al-Sarawi *et al*., (1998) and Omar *et al*., (2006) reported that between 613 and 798 oil wells were set on fire during the war in 1991. Seawater was used to fight the fires at an estimated rate of 95,000 m^3 per day (AlSenafy *et al*., 1997). The fire extinguishing process started on March 20 and ended on November 2, 1991.

Omar *et al*., (2006) stated that an estimated two million barrels of oil escaped from the damaged wells daily, and the amount of oil lost due to the fires and oil flows was calculated to be approximately one to one and a half billion barrels. The financial costs were estimated to be approximately 80 billion US dollars (Shaban, 1994).

The accumulated oil spill in the slightly depressed surface area of the Kuwaiti desert formed over 300 distributed large spots, as shown in Figure 1. About 114 km^2 of the Kuwaiti desert (0.65% of the total area of Kuwait) was contaminated with oil, which caused environmental problems affecting the air, land, coast, groundwater, and surrounding life. The oil lakes varied in type, area, volume, penetration depth, and level of contamination. Wet oil lakes are described as a pool of viscous liquid or semi-solid oil sludge overlying oil-contaminated soil and contained in free-flowing state. Dry oil lakes consist of a black, relatively hard, dry surface layer that may contain some contaminated soil, which covers the dark brown oil-contaminated soil without an oily texture.

Fig. 1. Distribution of oil lakes in Kuwait

The depth of soil contamination in the oil lakes varies across different regions of Kuwait. Al-Sarawi *et al*., (1998) noted that the lower hydraulic conductivity and permeability of the Burgan soil layers restricted oil penetration primarily to the upper 25-45 cm layer. In contrast, Massoud *et al*., (2000) claimed that the Aeolian deposits (transported and deposited by wind) of the Al-Ahmadi soil layers, with higher hydraulic conductivity and permeability, allowed the oil to spread over depths of 150-270 cm. In other regions, the contamination analyzed in laboratory studies conducted in 1992 indicated that the infiltration of oil into soil would be confined to approximately 2-3m (AlSenafy *et al*., 1997). Depending on their objectives, other researchers have investigated larger depths of contamination down to 20 m below the surface.

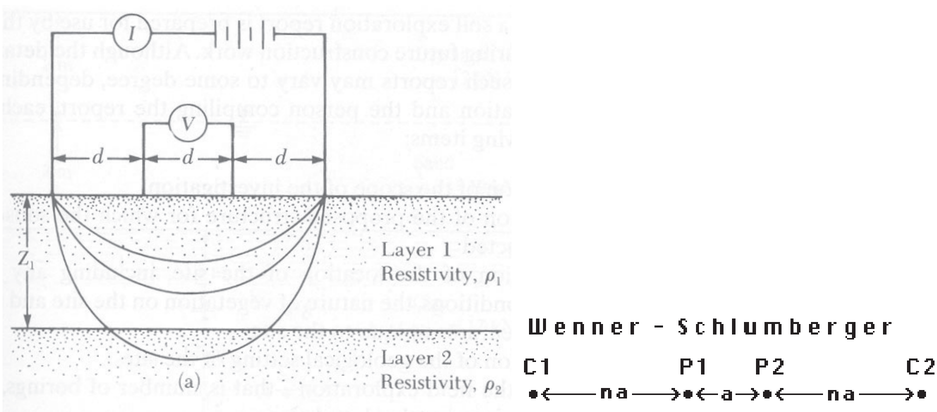
The treatment and rehabilitation of dry oil lake sites for engineering use requires a comprehensive investigation of the horizontal and vertical extents of contamination in the soil profile as well as the soil mechanical and chemical characteristics of the site. This type of subsurface exploration requires specific planning of all investigation processes and close coordination between the geophysical area tests and borehole point tests.

Reconnaissance field studies (Shevin, *et al*., (2005) and Hamzah, *et al*., (2008)) have typically assessed the contamination depth, total petroleum hydrocarbon concentrations and oil contamination concentrations. These parameters have been adopted in situations in which the oil-contaminated sites are large and the mobility necessary to perform conventional investigative methods is restricted. Remote sensing has been the primary tool used for estimating the area, extent of contamination, and changes over time (Al-Fares *et al*. 2010; Al-Fares & Al-Jarallah 2011; Al-Ruwaih 1992; Kwarteng, 1998; Omar *et al*., 2006). Other methods of investigation include using laser-induced fluorescence to examine soil color, soil texture, soil consistency, and site location (Omar *et al*., 2006). Malallah *et al*., (1996) used the reduction in chlorophyll content in certain plants as an indicator of the extent of environmental pollution caused by oil lakes.

In this study, ERT was used as a rapid hydrocarbon oil-contaminated site analysis tool to assess the existence and extent of hydrocarbon oil-contaminated soil. Hamzah *et al*., (2008) reported that ERT measurements in oil-contaminated soil recorded a decrease in conductivity and thus an increase in resistivity, which makes ERT applicable for locating a hydrocarbon plume in the soil if it originated from a particular spill area. Furthermore, Loke (2000) indicated that resistivity values increased with hydrocarbon contamination.

Resistivity measurements are generally made by injecting an electric current into the ground through two outer current electrodes and measuring the resulting voltage difference at two inner potential electrodes, as shown in Figure 2(a). The potential is converted first into apparent resistivity and then to true resistivity by inversion (Loke, 2000).

The standard test method for field measurement, namely, the Wenner-Schlumberger four-electrode method, was used to measure the soil resistivity of in situ soil, as shown in Figure 2(b). In this method, the center point of the electrode array remains fixed between potential electrodes P1 and P2, which remain fixed with a spacing “a”. However, the spacing between electrodes C1-P1 and C2-P2 is increased progressively by a factor “n” to obtain additional information on the deeper layers of the subsurface. The electrodes are inserted into the soil surface to a depth not exceeding 5% of the minimum spacing “a” (ASTM G57, 2006).



(a) **(b)**

Fig. 2. (a) Diagram of electrical poles for ERT measurement; **(b)** Typical layout of electrical poles for ERT measurement (both from Loke, 2000).

Loke (2000) reported that the resulting resistivity measurement represented the average resistivity of a hemisphere of soil with a maximum depth (z) approximated by multiplying the maximum electrode spacing "a", or maximum array length "L", by the appropriate depth factors in Table 1. The array length "L" is the total length of the testing field, which is equal to "2na+a".

Table 1: Maximum depth of investigation (z) by the Wenner-Schlumberger method

"n" factor	z/a	z/L
1	0.519	0.173
2	0.925	0.186
3	1.318	0.189
4	1.706	0.190
5	2.093	0.190
6	2.478	0.191
7	2.863	0.191
8	3.247	0.191
9	3.632	0.191
10	4.015	0.191

PILOT PROJECT: BAHRA DRY OIL LAKE

Among all of the dry oil lakes that were documented and surveyed, none were suitable for conducting the investigation due to the human risk factor posed by the existence of unexploded ordnances. Therefore, attention was directed toward finding another safe, accessible site with similar contamination characteristics.

A project site located in Bahra, Subiya, which is north of Kuwait (Figure 3), was selected. The Bahra site area is uninhabited and has no infrastructure, agricultural areas, or public services. The contamination at the site is due to a leak in an oil pipeline that belongs to the Kuwait Oil Company (KOC). The leak created a contaminated zone with an approximate area of 127,737 m^2. The age, visual appearance, and extent of contamination bore similar characteristics to the dry oil lakes. However, the site was free of unexploded ordnance.

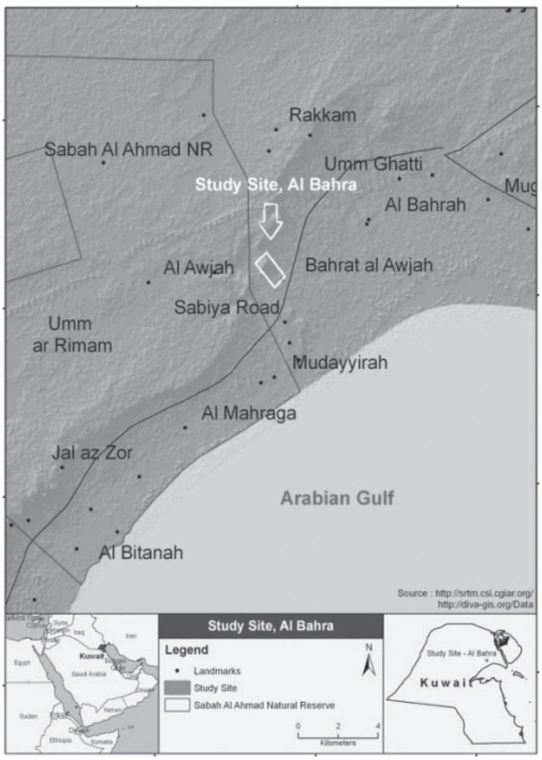


Fig. 3. Location of the Al Bahra study site

A pilot test area was chosen within the Bahra dry oil lake. The requirements considered when selecting the pilot site were: visible surface contamination, feasible area with which to work, accessibility, and adaptability to perform surface testing.

A pilot test area of 3,400 m^2 was chosen near the leak in the oil pipeline that satisfied all of the above requirements. A reference area outside and to the north, which was in the opposite direction of the general flow of the oil leak, was used to calibrate the testing in the contaminated pilot area. Figure 4 presents the location of the pilot test and reference sites.

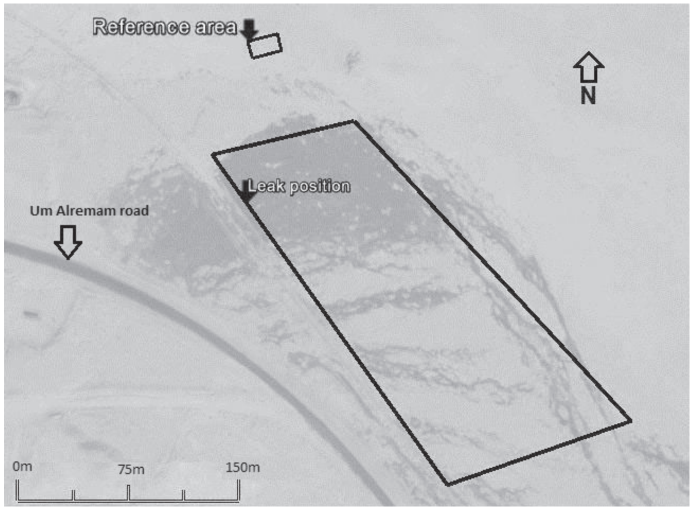


Fig. 4. Pilot site location.

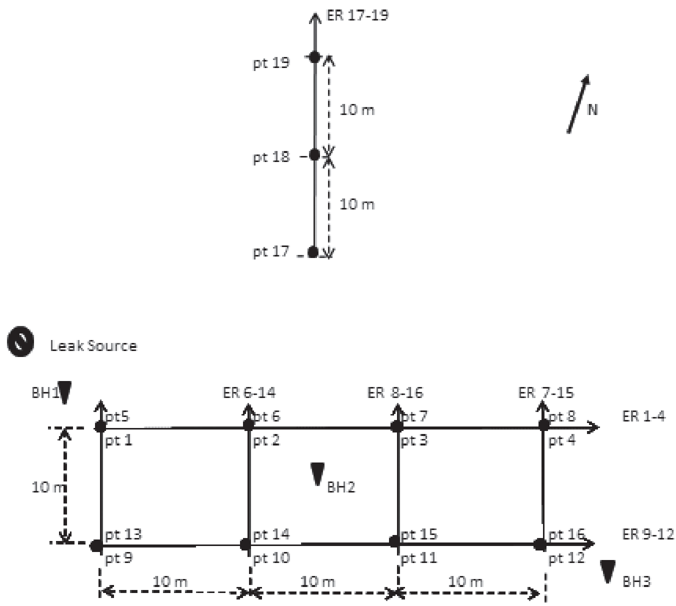
INVESTIGATION

The project team adopted an investigative approach in the pilot test area with emphasis on limiting the disturbance to the contaminated soil surface and subsurface profile due to its weathered and fragile nature.

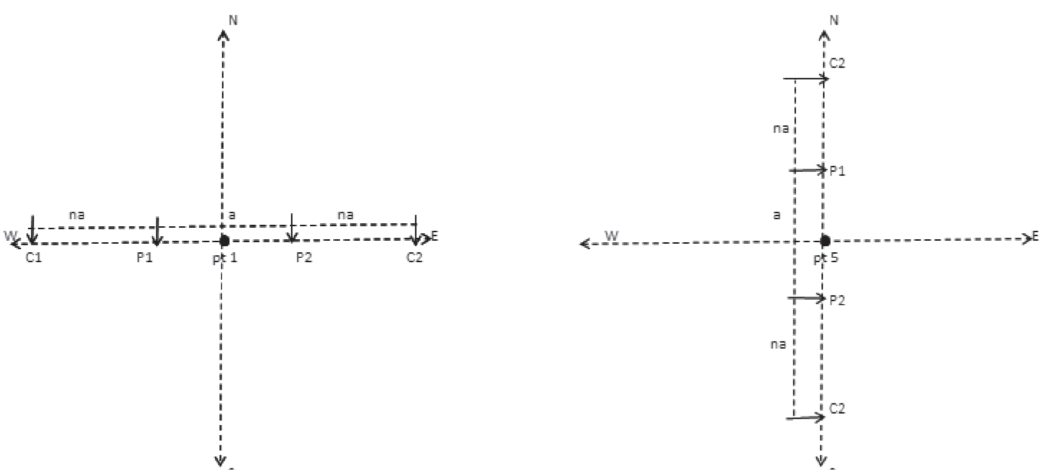
A visual inspection of the dry oil lake was conducted by a walk-through and documentation of the appearance of the location, the surroundings, and size and extent of the contaminated site. Furthermore, soil samples obtained by hand and using shovels from shallow excavations were visually tested for color, smell, and texture.

Topographic surveying was used in the methodology to accurately determine the three-dimensional test points positions and the distances and angles between them. The area chosen for the survey was 400×150 m, with measurements taken at 50×50 m grid points.

ERT was performed by testing grids in the contaminated and non-contaminated areas. Eleven electrical resistivity points were selected for testing; of these 11 points, eight were located in the contaminated area, as shown in Figure 5(a), and three in the uncontaminated area as reference points. The (x, y, z) coordinates were obtained using a handheld GPS to plot on a map as well as for purpose of spatial interpolation. The spacing between the test points was set at 10 m in each direction.



(a)



(b)

Fig. 5. (a) Layout of ERT points in the contaminated area and reference area; (b) Layout of test points along both directions.

The one-dimensional Wenner-Schlumberger survey was used to estimate the vertical and horizontal spread of oil above the ground and below a given test point; the spacing between potential electrodes P1 and P2 remained fixed with pacing (a=0.25 m). The tests were performed at nine spacing intervals between electrodes C1-P1 and C2-P2 (0.25, 0.5, 1, 2, 3, 5, 10, 15 m) in both east-west (EW) and north-south (NS) directions, which resulted in a total of 18 tests at each location in the contaminated area. Each point represents two test points, one in the EW direction and the other in the NS direction. For example, test points 1 and 5 are located at the same coordinates, where test point 1 represents the EW direction and test point 5 represents the NS direction, as shown in Figure 5(b). This pattern was adopted for all eight test points in the contaminated area, resulting in 16 test points. Testing was performed along both directions to create profiles in both directions. In the reference area, test points 17, 18, and 19 were conducted only in the NS direction. Six ERT profiles were produced in the contaminated area, and one profile was produced in the reference area.

Conventional boreholes were used to explore the sub-surface soil profile and contamination depth in the study area as well as the non-contaminated area for comparison with the ERT results. The borehole locations and depths were selected to cover the variation in the sub-surface profile horizontally and vertically. Four boreholes were drilled at the locations shown in Figure 5(a). Three located in the contaminated pilot area were selected to cover different ranges of surface soil contamination. Borehole No.1 was located close to the leak source, which was assumed to be the area of thickest contamination. Nos. 2 & 3 were located along a diagonal axis from the leak source in the direction of the inclination of the surface topography in the SE direction. No. 2, in the center of the study area, was sunk to a depth of 15 m to detect the groundwater table. The other two boreholes were drilled to a depth of 10 m. In the reference area, No. 4 was drilled to a depth of 10 m.

In situ soil testing included the standard penetration test (SPT) as well as the collection of disturbed and undisturbed soil samples for laboratory physical and chemical testing.

Standard Penetration Tests (SPT) were carried out at regular intervals and disturbed samples were obtained for soil classification. SPT was carried out according to ASTM (D-1586) where samplers are driven using a 63.5kg (140 1b) hammer falling freely through a vertical height of 0.76m (30 inches) and the number of blows required to drive the sampler through three successive increments, each of 150mm length, were recorded on the log of borings. The (N) values are calculated as the total number of blows for the last 30cm of penetration.

Laboratory testing on selected disturbed and undisturbed soil samples collected during field investigation included Sieve analysis and Grading (ASTM D-422), Moisture content (ASTM D-4318), Atterberg's Limits (ASTM D-4318), Bulk and

Dry Unit Weight (BS 1377, Part 7, C1 3.5), and Direct Shear Test (BS 1377, Part 7, C1 4.5.4), as well chemical testing for Sulphate, Cholride, Orgainc and Ph (BS 1377, Part 7) , and Total Petroleum Hydrocarbon (EPA METHOD 8015 B).

RESULTS AND DISCUSSION

In general, there is no plant life in the site due to the hard dried oil on the soil surface. However, there were a few small, isolated areas with local plant growth known scientifically as "Rhanterium Epapposum" and locally as "Arfaj" in various places in the site with clean sand lifts, ranged in area between 1 m^2 to 2 m^2, which were deposited on top of the contaminated surface, as shown in Figure 6.

Fig. 6. Surface of contaminated area showing clean sand deposits with "Arfaj" plants.

The surface soil is sandy silt contaminated with hydrocarbons, which have solidified and become a hard layer. The soil is fine sand, ranged in size between 0.5 mm to 0.1 mm, in the uncontaminated areas. The contaminated soil was cemented because the dry oil-contamination has been present for 20 years.

Soils obtained by hand and shovel from the shallow excavations located near Borehole No. 1 (Figure 7) indicated that visible contamination was apparent in the first 10 cm. The depth of contamination however increased to 50 cm in samples that were collected from shallow depths 3 m away from Borehole No. 1 (Figure 7). The results from other soils samples spread in the test area indicated a variation in the depths of contamination in the area. The crust of the contaminated soil was hard, and the contamination of the layer was observed to decrease with depth.

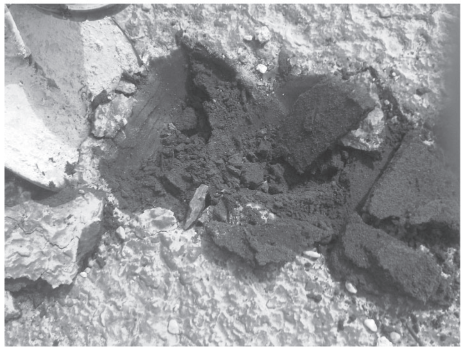


Fig. 7. Hand-dug shallow excavation exhibiting contaminated soil.

Figure 8 presents a three-dimensional profile created for the surface elevation. The leak was located at a high elevation in the northwestern corner of site test area, and the area was inclined in the general southeastern direction toward Kuwait Bay, with a deferential elevation of more than 12m. Furthermore, the ground surface had small slump spots, which created localized ponds of dry, thick oil.

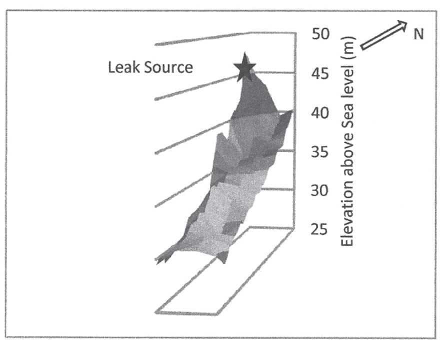
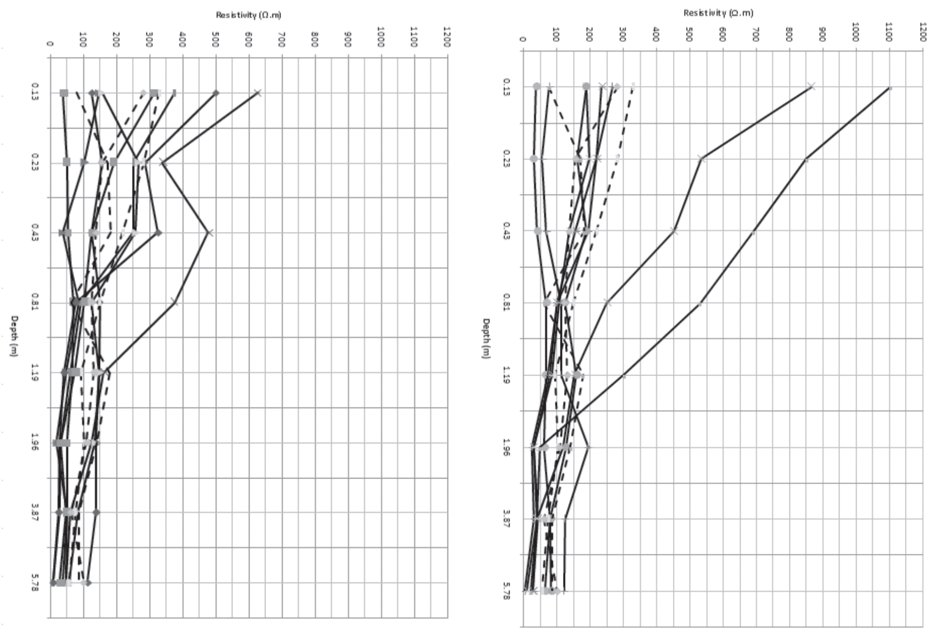


Fig. 8. 3-D plot illustrating an inclination toward the sea

Figure 9 presents plots of the measured ERT values with depths of 0.13-5.8 m below the surface. For ease of comparison, Figure 9(a) plots the ERT measurements at test points in the contaminated area along EW direction (points 1-4 & 9-12) with those at test points in the reference area (points 17-19), and Figure 9(b) plots the ERT measurements at test points in the contaminated area along NS (points 5-8 & 13-16) with those at test points in the reference area (points 17-19).



(a) (b)

Fig. 9. Plots of ERT value versus depth at test points: (a) 1-4, 9-12, and 17-19; (b) 5-8, 13-16 and 17-19.

The ERT values in the contaminated area exhibited variations both vertically and laterally, and variation with depth in the contaminated area tended to exhibit higher values than those in the reference area. In the contaminated area, the values varied between 5.7Ω.m and 1771.5 Ω.m, with an average of 162.8 Ω.m, whereas in the reference area, the ERT values varied between a minimum of 56.5 Ω.m and a maximum of 329.7 Ω.m, with an average of 142.2 Ω.m.

ERT variation with depth, as shown in Figure 9, indicates that at depths of 0.13-1.2 m, the values in the contaminated and reference areas vary considerably. ERT in the contaminated area ranged between 31.1 and 1771.5 Ω.m, with an average of 230.4 Ω.m, whereas in the reference area it ranged between 62.8 and 329.7Ω.m, with an average of 172.5Ω.m. At depths greater than 1.2 m, the variation in ERT in both the contaminated and the reference areas had similar ranges. In the contaminated area ERT ranged between 5.7 and 194.7Ω.m, with an average of 60.3Ω.m, and in the reference area between 56.5 and 141.3Ω.m, with an average of 91.7Ω.m.

At depths greater than 3.94 m, both areas indicate the absence of hydrocarbon oil contamination. In contrast, on the top soil and at depths within the top 1.2 m, there were large differences between the areas, indicating contamination. This result was also confirmed from visual inspection; the depth of contamination was visible down to 50 cm from the ground surface and decreased thereafter.

The results of Loke (2000) in Table 2 support the finding that soils contaminated by hydrocarbons such as xylene (an aromatic compound), typically have higher resistivity than dry silty/clayey sand, as apparent from ERT in the top 1.2 m of the contaminated area. Furthermore, Hamzah *et al*., (2008) reported an increase in the resistivity values in hydrocarbon-contaminated soil compared to sand-silt layers.

Table 2. Resistivity of soils and chemicals (from Loke, 2000).

Material	Resistivity (Ω.m)	Conductivity (S/m)
Soils and Waters		
Clay	1-100	0.01-1
Alluvium	10-800	1.25×10^{-3}-0.1
Groundwater (fresh)	10-100	0.01-0.1
Sea water	0.2	5
Chemicals		
Iron	9.074×10^{-8}	1.102×10^{7}
0.01 M Potassium chloride	0.708	1.413
0.01 M Sodium chloride	0.843	1.185
0.01 M acetic acid	6.13	0.163
Xylene	6.998×10^{16}	1.429×10^{-17}

Lateral variation in contamination is observed by comparing the ERT measurements at several test points (4, 8, 9, 10, and 13) with the remaining test points at depths less than 1.2 m. At these points, ERT measurements have a minimum of 41.5 Ω.m, a maximum of 1771.5 Ω.m, and an average of 455.3 Ω.m. ERT measurements at the other test points have a minimum of 31.1Ω.m,a maximum of 314Ω.m and an average of 128.1Ω.m.

Two-dimensional profiles were generated to investigate the lateral variation in ERT. Four profiles are shown in Figure 10(a-d). They profiles confirm the high values of ERT at test points 4, 8, 9, 10, and 13 at depths closer to the ground surface compared to other tested points within the contaminated area. Oil flows in the direction of test points 4 and 9 due to the general declination of the ground surface profile in the southeastern direction at an average slope of 1.25%. In addition, as shown in Figure 11(a-b), depressions have created localized oil lakes, which explains the increased contamination at those points at shallow depths.

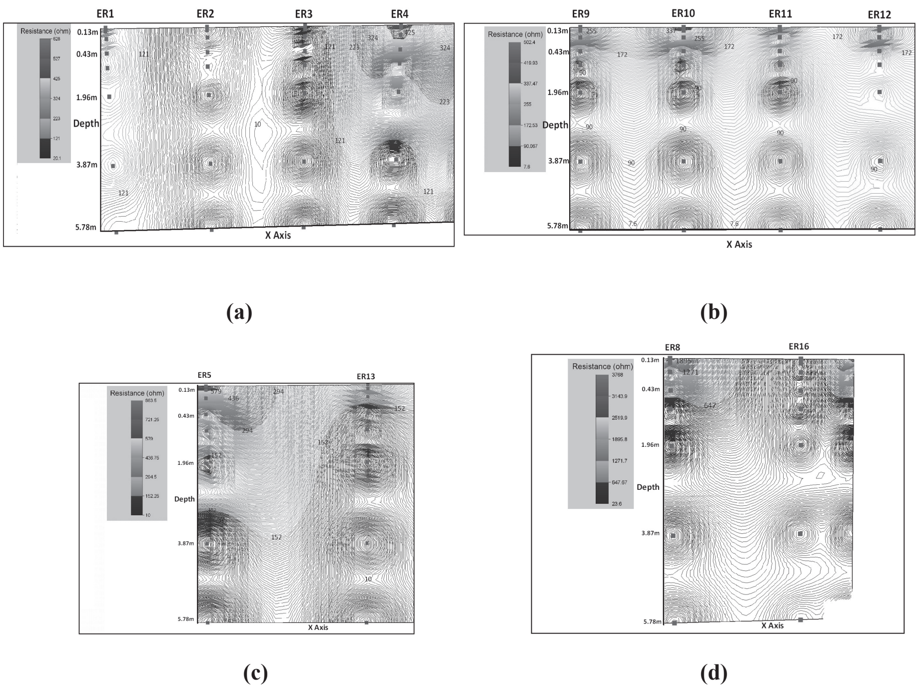
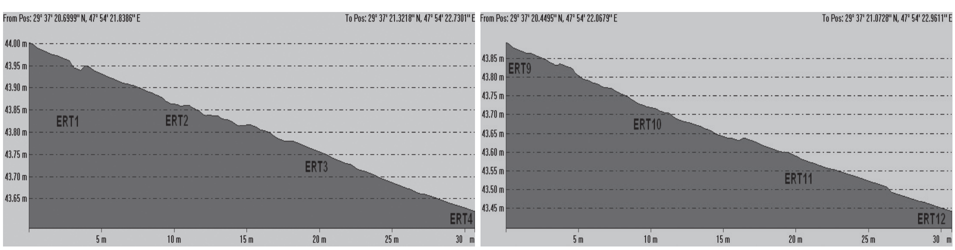


Fig. 10. ERT profile between points: (a) 1-4; (b) 9-12; (c) 5-13; (d) 8-16.



(a) (b)

Fig. 11. General surface profile along: (a) ERT1-ERT4; (b) ERT9-ERT12.

Borehole No. 1 revealed soils that were dark brown at the surface and pale brown at a depth of 6 m. A slight petroleum odor was detected 1 m below the surface. Borehole No. 2 revealed brown-colored soil on the surface, which became pale brown at a depth of 2.5 m and dull white at 3 m. Borehole No. 3 revealed brown soil at the top surface that became pale brown at a depth of 1.5 m. A slight petroleum odor was detected in the top 2.5 m of the soil. Borehole No. 4 in the reference area revealed pale brown soil that changed with depth to very pale brown with no petroleum odor.

The Bahra area consists of surface layers of silty sand to silty/clayey sand. The subsurface profile indicates consistent subsurface conditions, as listed in Table 3, obtained from data from the borehole logs as well as field and laboratory tests. No groundwater table was encountered during the site investigation. The number of SPT blows (N) bore no relation to sludge on the surface. The friction angle displayed no significant variation; it changed from 30˚ for the first 4m to 32˚ below 4 m.

Table 3. Generalized subsurface profiles

Soil layer description	Depth (m)	SPT (N)	Wet density (g/cm³)	Dry density (g/cm³)	Moisture content (%)	Friction (°)	Cohesion (kPa)
Medium dense sand with silt and silty/ clayey sand	0−3.0	20	1.64	1.591	3.1	30	26
Dense to very dense, sand with silt and silty/ clayey sand with silt	3.0−15.0	40−>50	1.720	1.646	4.5	32	26

To validate the ERT and boreholes results, samples from the contaminated and reference areas were tested for Total Petroleum Hydrocarbon (TPH) at different levels (from the surface to 11 m below the surface layer). TPH is a complex mixture composed primarily of saturated hydrocarbon aromatic compounds, and was used as an indicator of soil contamination. The results of the TPH analysis (Figure 12) confirm the results of the ERT and the geotechnical investigation, indicating that the contamination is limited to the surface layer of the polluted site because soils below (1-2 m) the contaminated site are comparable to the reference area.

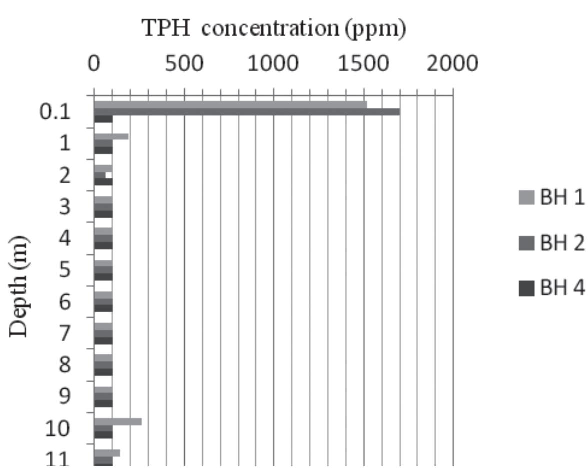


Fig. 12. Total petroleum hydrocarbon concentration (TPH) (ppm)

The presence of TPH in the aged top soil after more than 20 years can be attributed to desorption and biodegradation resistance. Desorption in this case is the slow diffusion of large hydrocarbon molecules into the soil and/or entrapment of the slowly diffused molecules within small pores in the soil (Hatzinger & Alexander, 1995; Torres *et al*., 2005). Entrapment has been shown to be influenced by a number of factors, such as environmental conditions, contaminant properties, and soil properties, including organic content (Al-Zalzaleh & Shabbir 2004; Reeves *et al*., 2001; Scherr *et al*., 2007; Tang *et al*., 2012; Zhao *et al*., 2009). Talley *et al*. (2002), Song et. al. (1990), Hejazi & Husain (2004), Scherr et. al., (2007) have associated the degradation rates of organic hydrocarbons to the abundance and diversity of the microbial community. Several samples were tested for organic content to explore microbial availability. All of the results indicated poor microbial availability with organic matter below 0.025%, which is typical for sandy texture and low organic content (El-Sheikh & Abbadi, 2004; Hejazi & Husain, 2004; Scherr et. al., 2007; Skrbic & Duric-Mladenovic, 2009; Talley *et al*., 2002).

CONCLUSIONS

ERT was performed by testing grids at a pilot site within a contaminated area and a reference non-contaminated area. Visual inspection, topography surveys, and conventional soil investigations using samples collected from shallow depths by hand and from deep soil profiles by boreholes were also used to explore the sub-surface ERT profiles and contamination depths. In situ and laboratory chemical soil tests were conducted on soil samples to quantify the type and extent of contamination.

Visual inspection of soil samples from shallow depths indicated the presence of contaminated soil up to a depth of 0.5 m. Borings indicated the presence of brown-colored soil with a strong petroleum odor in the top 1-2.5 m; then the soil became pale brown and did not have petroleum odor. ERT measurements indicated hydrocarbon -contaminated soil up to a depth of 1-1.2 m from the ground surface.

To confirm the ERT and geotechnical results on contamination, samples from the contaminated area and reference area were tested for TPH at different levels from the surface to a depth of 11 m. The results indicated that contamination is limited to the surface layer of the polluted site because soils below 1-2 m are comparable to those in the reference area.

ERT provides a consistent and reliable assessment of the presence and extent of contaminated soil in the dry oil lakes.

Further studies must be conducted on dry lake sites that contain hydrocarbon-contaminated soil formed from oil well fires to test oil contamination which have been caused by oil well fires. However, these sites are safe and accessible and do not pose a risk to humans due to unexploded ordnance.

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