Original Research Paper

Grain Size Distribution Characteristics Variation in Oily Contaminated Sandy Soils Due to Long Term Aging Effect in Al-Ahmadi Field at Kuwait

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Abstract: Almost three decades on, the negative environmental impacts arising from the burning of over 600 oil wells in Kuwait following the 1991 Gulf War are still evident. At the time of the incident, the Kuwaiti desert region became polluted with hydrocarbon, with a number of 'oil lakes' forming, causing critical harm to local land. This paper discusses the shifts in particle size distribution (PSD) found in soil taken from Kuwait's Al-Ahmadi oil field, caused by aging sandy soil polluted with hydrocarbon. The analysis of changes in PSD was achieved using 16 contaminated and uncontaminated soil samples, with the samples undergoing PSD analysis along with Unified Classification Soil System (UCSS), Scanning Electronic Microscopy (SEM) and Gas Chromatograph Mass Spectrometer (GC-MS) analyses.The analyses revealed a significant reduction in the mean values of both sand and silty/clay particles, which fell from 44.6% to 9.0% and 7.8% to 3.4%, respectively. The analyses also showed a significant increase in the mean values of gravel particles, rising to 44.6% from 6.1%. These results obviously clarify that the overall outcome of the alteration in soil gradation was a poorer one, which may be due to bigger particles forming out of fine particles as a result of oil contamination. The results presented in this paper are intended to support the treatment (soil washing and cement stabilisation) of contaminated sandy soil based on the insights gained into how soil grain size distribution is impacted by oil contamination.

Keywords: Oil Contaminated Sand, Al-Ahmadi Oil Field, Aging Effect, Particle Size Distribution

Introduction

Kuwait is situated at the northwest edge of the Arabian Gulf and is nearly 18,000 km^2 in size. As Al-Duwaisan and Al-Naseem (2011) explain, Kuwait's 10 oil fields - Greater Burgan (containing the Ahmedi, Burgan and Magwa fields) along with Bahra, Minagish, Ratga, Raudhtain, Sabriay, Umm Gudair and Wafra - contain over 909 oil wells. As shown in Fig. 1, Kuwait's oil fields are typically categorized based on their northern/southern location:

As illustrated in Fig. 2, it is reported that a total of 565 of Kuwait's oil wells were set alight after the 1991 Gulf War, with an additional 74 oil wells overflowing following their demolition. This resulted in critical oil spillages across the Kuwaiti desert (Al-Besharah, 1991),

with Al-Awadhi *et al*. (1996) also noting that this resulted in the formation of over 300 oil lakes, spanning an area greater than 49 km^2 over both the northern and southern Kuwait oil fields. As Fig. 2 also illustrates, whilst the oil lakes were 0.3m deep on average, a number of them were as much as 1.2m deep (Al-Awadhi *et al*., 1992; 1993). Kwarteng (1998) and Omar *et al*. (2000) additionally report that both dry and wet oil lakes were present. These oil lakes, combined with hydrocarbon contamination, have resulted in significant environmental damage in Kuwait (Aldaihani, 2017).

It is acknowledged in the literature that the geotechnical attributes of soil can be altered by the presence of significant oil contamination (Asem *et al*., 2016), causing any constructions housed on the soil to become compromised (Karkushaand Abdul Kareemb, 2017).

Fig. 1: Kuwait's oil fields (Ministry of oil - state of Kuwait, 2018).

Fig. 2: Environmental damage in Kuwait as a result of oil wellfires and spills (Kuwait Oil Field Restoration, 2018)

Numerous researchers have investigated the changes occurring in cohesive soil's Particle Size Distribution (PSD) following the introduction of crude oil at various levels (i.e., Al-Otaibi *et al.*, 2012; Al-OtaibiandWegian, 2012; Caravacaand Roldan, 2003; Karkusha and Kareem, 2017; Ijimdiya, 2013; MeegodaandRatnaweera, 1995; Taqieddin, 2017). The results of these studies indicate that the more significant the level of contamination from

crude oil, the greater the proportion of large particles (and lower the proportion of fine particles) in the soil. Another study focused specifically on the impacts of dry oil lakes (i.e., hydrocarbon contamination) on soil properties following the 1990 Iraqi attacks. The researcher obtained soil samples from dry oil lakes at the Al-Magwa site, representing six different oil lake depths (0.25 m increments from 0.0 m to 2.0 m). It is worth noting that Al-Magwa is around 15 km from Al-Ahmadi, the location selected in the current study. The results showed that hydrocarbon contamination appeared to lead to an increase in the proportion of both gravel-size (>2.0 mm) and fine (<0.063 mm) particles (Aldaihani, 2017).

At the time of writing, there does not appear to be any other paper published since 1990 that specifically analyses the long-term ageing effect of PSD in soil samples contaminated by wet oil lakes in Kuwait's hot arid region. The only similar recent study was an exploration of PSD in soil contaminated by a dry oil lake, conducted by Aldaihani (2017). The current paper specifically explores PSD through a comparison of wet oil lake contaminated and uncontaminated soil samples from the Al-Ahmadi site.

It is crucial to analyze grain size distribution and other geotechnical characteristics of soil in order to effectively treat contaminated soil with the soil washing and cement stabilization techniques. It is therefore intended that the results of this study provide valuable insights that will help to create solutions for oil-contaminated soil.

Site Location and Samples Collection

The southern Al-Ahmadi oil field was selected as the site from which to obtain soil samples for this study for a number of reasons, including the discussion of the region presented in Aldaihani's (2017) recent work. Furthermore, the Al-Ahmadi oil field houses Kuwait's largest oil lake, representing a soil volume of 14,520,000 m^3 and total area of 25.6 km^2. Another reason for the selection of this site is that it is one of the seven oil fields known to still contain oil lakes and hydrocarbon-contaminated soil. Additionally, the Al-Ahmadi oil field is located in an area highlighted for major urban construction over the coming years, on account of its close proximity to densely-populated areas such as Al-Ahmadi, Jaber Al-Ali, Jeleeb Al-Shuyoukh and Sabah Al-Salam.
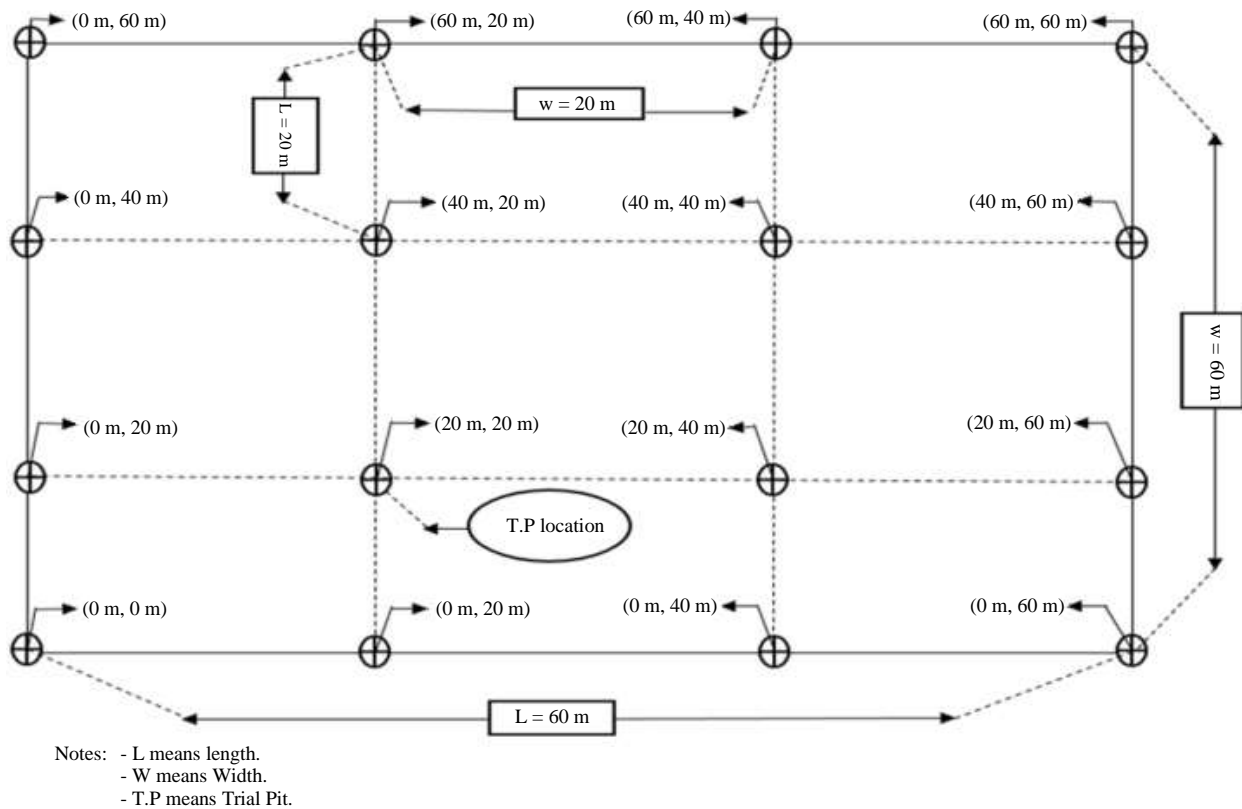

Notes: - L means length.
       - W means Width.
       - T.P means Trial Pit.

Fig. 3: T.P.Cs Locations for contaminated and uncontaminated soil samples

Fig. 4: Contaminated site (A), uncontaminated site (B) and disturbed samples (C)

As shown in Fig. 3, due to the lack of data available on the chosen site, contaminated and uncontaminated samples were taken from a 60×60 m gridded plots with gridlines crossing every 20 m. Each site produced a total of 16 Trial Pits (TPs) at 20 cm deep. Chemical and physical analyses were performed on the 16 samples after extraction, with each sample weighing 2.5 kg (Fig. 4). The sampling preservation guidelines outlined in Landon (2007) and ASTM (2000) were followed when storing the samples taken from the sampling plots to the laboratory tests.

Experiments

The testing procedure for the contaminated and uncontaminated soil samples included UCSS and SEM, with the samples analyzed for petroleum hydrocarbon and PSD.

Crude Oil Test

The contaminated soil samples were converted from solid to liquid phase and analyzed for Total Petroleum Hydrocarbon (TPH) concentrations using various tests, including Accelerated Solvent Extraction (ASE) and GC-MS. The following sections describe the specifics of each of the tests performed.

Crude Oil Extraction Test

Dry weight analysis was performed with 3 grams' samples of contaminated and uncontaminated soil. The samples were combined with 3 grams of drying agent Diatomaceous Earth (Thermo Scientific, USA) and placed between acid-washed sand (BDH, USA) and cellulose filters (Dionex, UK) in an extraction cell. Hydrocarbon was then extracted from the contaminated sample using the Dionex ASE 350 under Dionex (2011) Method 324.

In order to avoid contamination of the GC column, each sample was then combined with 3 grams of activated silica gel and placed in a 50 mL volumetric flask. To ensure that the GC column remained clear of obstruction-causing particles, the soil samples were stripped of polar compounds before filtering the extracted substance using 0.45 μm Chromacol filters. A 3h resting period was then implemented, allowing the silica gel to smooth out before removing the liquid layer and moving it into a separate beaker. The last step in the process was to apply nitrogen and heat through a Turbo Evaporator (EQP-11, Athena technology) to reduce the samples to 1 mL. This allowed the samples to be moved into the GC vial for the GC-MS test outlined in the following section.

Gas Chromatography Mass Spectrometry (GC-MS) Test

In line with Aldaihani's (2017) work, GC-MS analysis was carried out in order to quantify the level of TPH in the contaminated soil sample. The following equations were used for this person, with TPH expressed in mg/g:

- *x 100 = Dm*
- *= Dws.*
- *X 1000= TPHdds.*

Where:
Dw: Dry weight (%)
Ww: Wet weight (%)
Dm: Dry mass (%)
Dws: Dry weight of soil (%) (i.e., actual used in ASE)
TPHI: TPH obtained from the integration (µg/ml)
TPHdds: TPH dry of dry soil (mg/g)

Particle Size Distribution (PSD)

The ASTM (1998) method was followed to carry out the PSD analysis for each soil sample.

Unified Classification Soil System (UCSS)

As per the following equations, Casagrande's (1948) UCSS asserts that the Coefficient of uniformity (Cu) and Coefficient of curvature (Cc) can be used to classify grain-size soil samples:

$$Cu = D60 / D10 \qquad (1)$$

$$Cc = (D30)2 / (D10)*(D60) \qquad (2)$$

Here, well-graded soil is given by a Cu value greater than 6.00 and Cc value between 1.0 and 3.0.

Scanning Electron Microscope (SEM)

In order to examine the way in which surface grain shape is influenced by contamination from a wet oil lake, PSD was analyzed using high resolution images obtained through SEM tests. Only one of each sample type (contaminated and uncontaminated) was analyzed using this method, since it is an expensive and time-consuming form of analysis. The testing process involved the use of a carbon adhesive disk to attach grains from the soil samples to an aluminum pin stub. As per the work of Aldaihani (2017), a Sputter Coater was then used to manually apply a fine Gold/Palladium outer layer.

Results and Analysis

Gas Chromatography Mass Spectrometry (GC-MS) Result

Table 1 outlines the findings from the GC-MS tests, which illustrate the TPH concentrations (mg/kg) detected in 16 contaminated and uncontaminated samples. The results in this table were obtained from an analysis of chromatogram curves via a GC-MS instrument (as shown in Fig. 5). This chromatogram shows results for one of the detected samples in the contaminated site. Table 1 shows that TPH was not detected at the uncontaminated site, which confirms that this site was not contaminated with hydrocarbon and can be considered a reference site for comparison. Based on the table, it is noted that the TPH concentration was 8,670.3 mg/kg.

Table 1: TPH analysis of contaminated and uncontaminated soil samples

TPCs	Oil lake contaminated area			Uncontaminated area		
	Number of sample	Mass of sample (g)	TPH content (mg/kg)	Number of sample	Mass of sample (g)	TPH content (mg/kg)
(0 m, 0 m)	1	9.97	7543	1	10.00	*N.D
(0 m, 20 m)	1	10.02	7002	1	10.00	
(0 m, 40 m)	1	10.02	8200	1	9.96	
(0 m, 60 m)	1	10.03	8180	1	10.04	
(20 m, 0 m)	1	10.01	8500	1	10.03	
(20 m, 20m)	1	10.00	7800	1	10.02	
(20 m, 40m)	1	10.02	7850	1	10.01	
(20 m, 60m)	1	10.04	9000	1	9.99	
(40 m, 0m)	1	10.02	9300	1	10.02	
(40 m, 20m)	1	10.02	9500	1	10.01	
(40 m, 40m)	1	10.03	9520	1	10.04	
(40 m, 60m)	1	10.01	9530	1	10.03	
(60 m, 0m)	1	9.98	8700	1	10.05	
(60 m, 20m)	1	10.03	8900	1	10.01	
(60 m, 40m)	1	10.02	9800	1	10.01	
(60 m, 60m)	1	9.99	9400	1	10.01	
TPH content average (mg/kg)		8670.30			*N.D	

*N.D means non detected with TPH

Table 2: Mean values of soil classification constituents for contaminated and uncontaminated samples at depth (20 cm)

TPCs	Silty clay	Fine sand	Medium sand	Coarse sand	Fine gravel	Coarse gravel	Exact soil	S.G*
Classification of soil (%) at contaminated area								
(0 m, 0 m)	3.0	11.0	24.0	21.0	41.0	0	3.0	Poorly graded sand
(0 m, 20 m)	4.0	8.0	27.0	16.0	45.0	0	4.3	
(0 m, 40 m)	4.0	11.0	25.0	18.0	43.0	0	3.5	
(0 m, 60 m)	3.0	9.0	27.0	19.0	44.0	0	2.5	
(20 m, 0m)	4.0	7.0	28.0	17.0	44.0	0	3.8	
(20 m, 20m)	3.0	8.0	27.0	18.0	46.0	0	2.7	
(20 m, 40m)	3.0	9.0	25.0	18.0	45.0	0	3.2	
(20 m, 60m)	4.0	9.0	26.0	19.0	42.0	0	4.2	
(40 m, 0m)	3.0	10.0	24.0	21.0	43.0	0	2.8	
(40 m, 20m)	3.0	8.0	25.0	18.0	45.0	0	3.3	
(40 m, 40m)	4.0	6.0	27.0	18.0	45.0	0	4.2	
(40 m, 60m)	2.0	12.0	26.0	18.0	43.0	0	1.9	
(60 m, 0m)	4.0	8.0	26.0	16.0	46.0	0	4.2	
(60 m, 20m)	4.0	10.0	23.0	19.0	44.0	0	3.7	
(60 m, 40m)	3.0	9.0	25.0	20.0	44.0	0	2.6	
(60 m, 60m)	3.0	9.0	24.0	19.0	45.0	0	3.4	
Mean value (%)	3.4	9.0	25.6	18.4	44.1	0	3.3	
Classification of soil (%) at uncontaminated area								
(0 m, 0 m)	7.0	44.0	37.0	10.0	3.0	0	6.5	Sand with silt
(0 m, 20 m)	8.0	44.0	29.0	12.0	7.0	0	8.1	
(0 m, 40 m)	8.0	45.0	35.0	10.0	2.0	0	8.4	
(0 m, 60 m)	10.0	42.0	28.0	13.0	7.0	0	9.5	
(20 m, 0m)	9.0	41.0	30.0	13.0	7.0	0	9.2	
(20 m, 20m)	8.0	42.0	31.0	9.0	10.0	0	7.5	
(20 m, 40m)	7.0	41.0	29.0	17.0	6.0	0	7.1	
(20 m, 60m)	7.0	42.0	30.0	17.0	4.0	0	6.8	
(40 m, 0m)	6.0	46.0	29.0	15.0	4.0	0	6.2	
(40 m, 20m)	8.0	45.0	26.0	13.0	9.0	0	8.3	
(40 m, 40m)	9.0	46.0	29.0	10.0	7.0	0	8.8	
(40 m, 60m)	7.0	44.0	30.0	10.0	8.0	0	7.2	
(60 m, 0m)	8.0	46.0	27.0	16.0	4.0	0	7.5	
(60 m, 20m)	7.0	45.0	29.0	10.0	9.0	0	7.4	
(60 m, 40m)	9.0	54.0	20.0	11.0	7.0	0	8.5	
(60 m, 60m)	7.0	46.0	30.0	13.0	4.0	0	6.7	
Mean Value (%)	7.8	44.6	29.3	12.4	6.1	0	7.7	

*S.G means soil symbol group in accordance with (ASTM, 1998)

Table 3: Comparing the UCSS factors (i.e., Cu and Cc) for the soil at contaminated and uncontaminated site

	Analysis of grading (Casagrande, 1948)			
	Contaminated site		Uncontaminated site	
TPCs	Uniformity coefficient (Cu)	Coefficient of curvature (Cc)	Uniformity coefficient (Cu)	Coefficient of curvature (Cc)
(0 m, 0 m)	21.25	1.600	6.10	0.545
(0 m, 20 m)	19.67	1.030	6.04	0.493
(0 m, 40 m)	17.18	1.270	6.10	0.580
(0 m, 60 m)	18.43	1.350	6.30	0.632
(20 m, 0m)	19.06	1.310	6.37	0.551
(20 m, 20 m)	14.44	1.000	6.09	0.536
(20 m, 40 m)	16.31	0.950	6.22	0.600
(20 m, 60 m)	18.33	1.180	6.14	0.590
(40 m, 0m)	15.40	0.940	6.17	0.483
(40 m, 20 m)	16.00	1.000	6.25	0.562
(40 m, 40 m)	14.87	1.020	6.20	0.581
(40 m, 60 m)	19.65	1.548	6.14	0.463
(60 m, 0m)	16.57	1.070	6.17	0.469
(60 m, 20 m)	20.00	1.330	6.10	0.630
(60 m, 40 m)	15.00	0.940	5.06	0.440
(60 m, 60 m)	20.33	1.070	6.05	0.493
Mean Value	17.65	1.160	6.10	0.540

Particle Size Distribution (PSD)

Figure 6-9, below, illustrate the PSD of contaminated and uncontaminated soil samples. Because the curves were difficult to read as a result of overlapping due to the high number of Trial Pit Coordinates (TPCs) used to obtain the samples, Figure 8 can be observed for the clearest representation of high PSD levels. It is evident that the

gradation of contaminated soil samples obtained from different TPCs of the same depth showed minimal range, based on the PSD curves; with a greater gradation range shown in the case of the uncontaminated soil samples (Fig. 6-9). This could be due to oil adsorption, causing soil particles to clump together at the contaminated site.
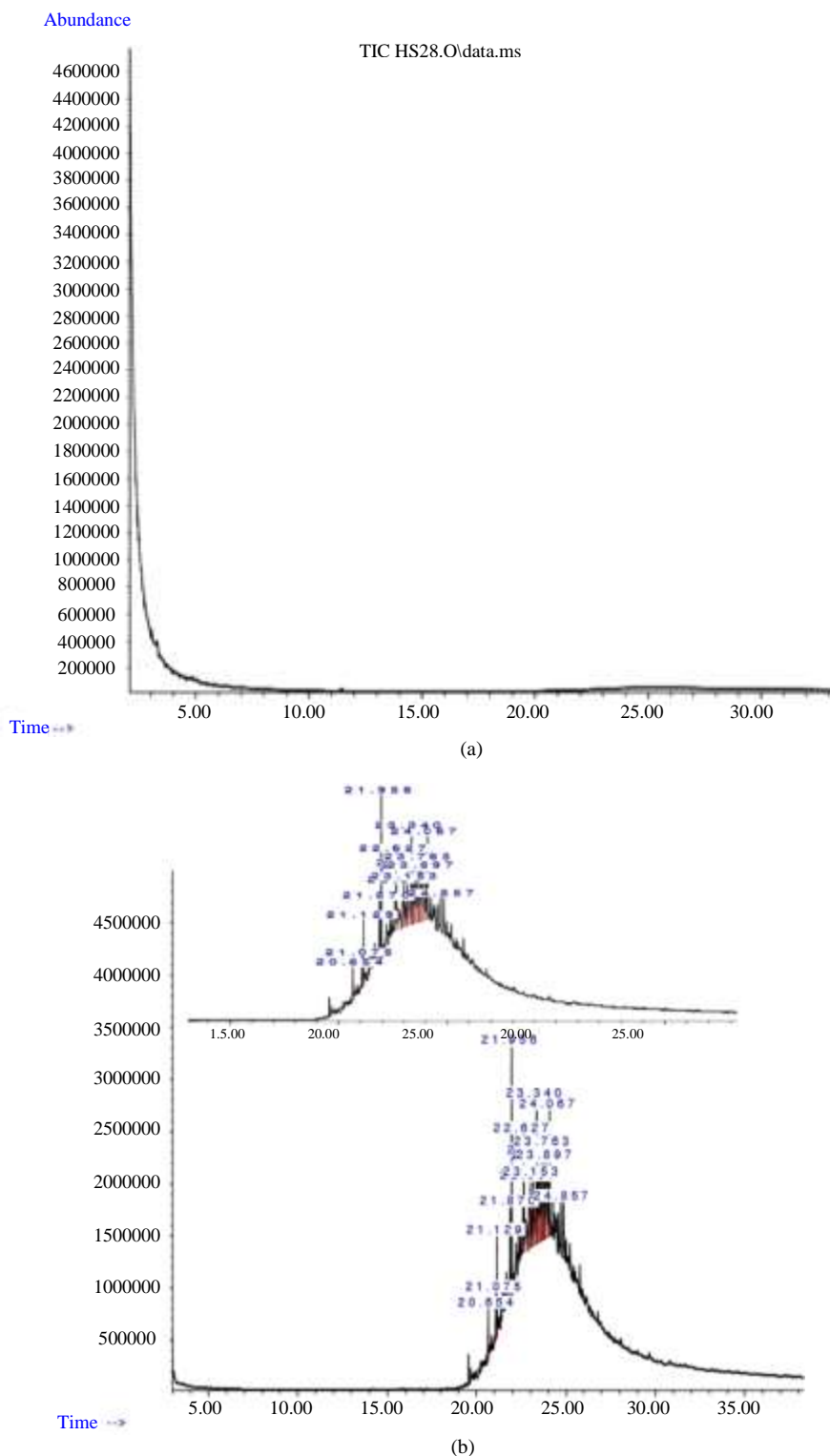

(a)

(b)

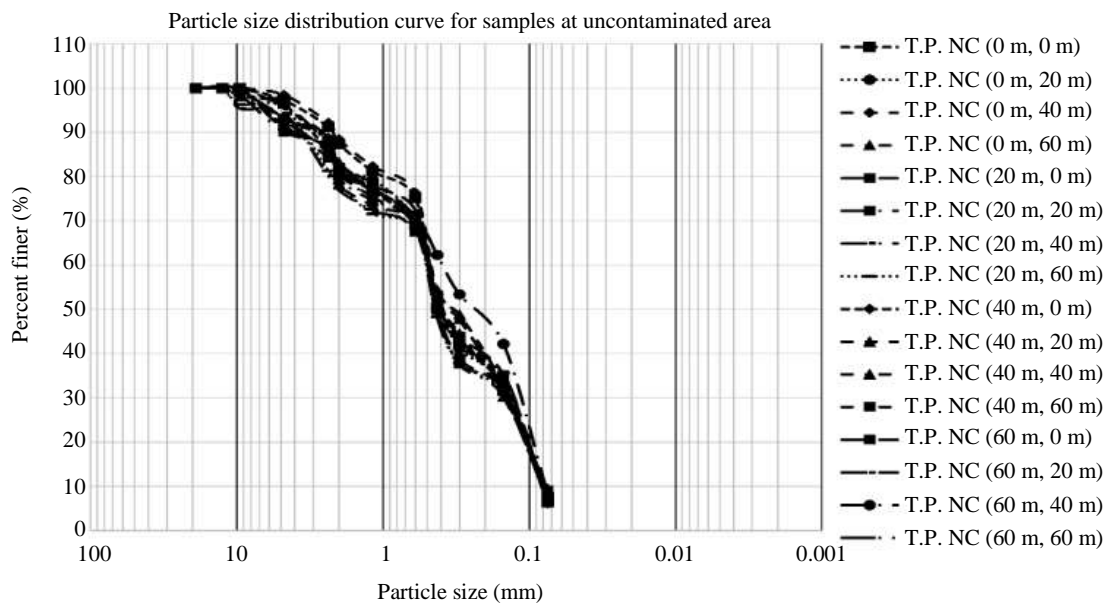**Fig. 5:** Chromatogram curve analysis for (a) uncontaminated and (b) contaminated sample
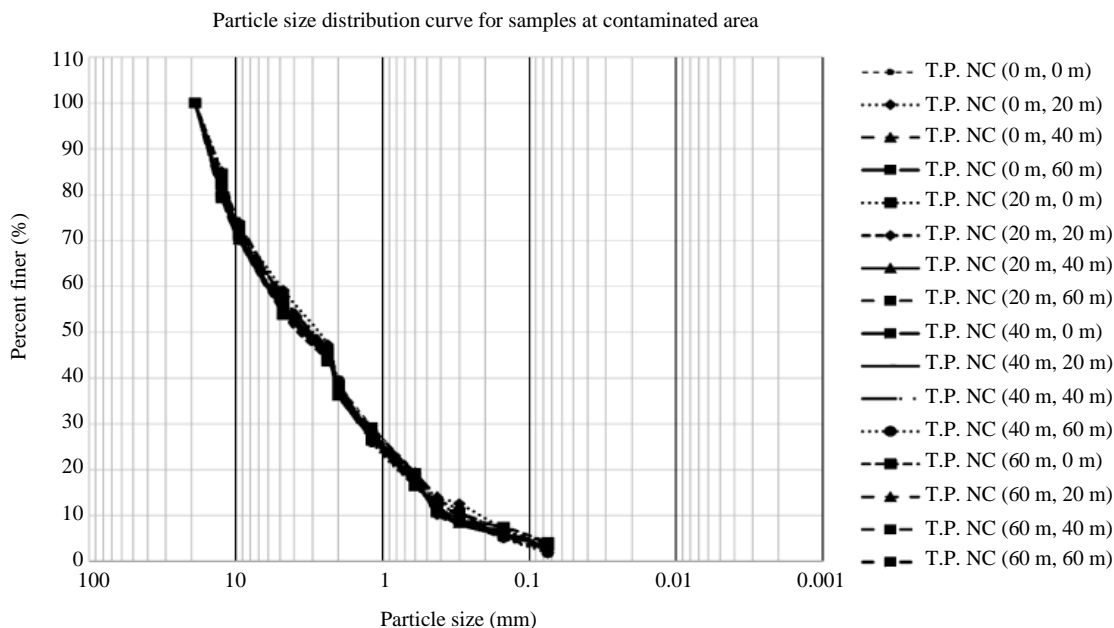
Fig. 6: PSD curves for contaminated samples

Fig. 7: PSD curves for uncontaminated samples

The mean percentage of each soil class in both the contaminated and uncontaminated soil samples (extracted at a top soil level of 20 cm deep) is shown in Table 2. Gravel-size particles (Sieve No. 4) can be seen to represent 44.1% of the contaminated soil sample, but just 6.1% of the uncontaminated soil sample. This may be due to the effects of hydrocarbon contamination from the wet oil lake, resulting in particles clumping together to create larger particles. In line with the rise in large particles, small grain-size (Passing No. 200) and fine particles can be seen to represent 3.4% and 9.0% of the contaminated soil sample and 7.8% and 44.6% of the uncontaminated soil samples, respectively. Whilst these results concur with the results of other studies (e.g., Taqieddin, 2017), they oppose those of Aldaihani's (2017) study. Given that the current study examines the wet oil lake effects, whilst Aldaihani's study examined dry oil lake effects, this difference in results is not unexpected. In Aldaihani's research, the percentage of fine particles was found to increase, due to

the formation of asphaltene particles in the soil, caused by hydrocarbon drying.

Unified Classification Soil System (UCSS)

The results of the UCSS analysis illustrate a noticeable difference between the two types of soil samples in terms of Cu and Cc values (Table 3). In samples taken from surface level soil (20 cm depth), Cu values were greater than 6.0 in both the contaminated and uncontaminated cases, whilst Cc values were more than 1.0 in the contaminated samples and lower than 1.0 in the uncontaminated samples. The results indicate that

at the top soil level (up to 30 cm, at the silty sand level), weaker PSD can be found. Additionally, the contaminated soil samples were found to be well-graded, whilst the uncontaminated samples were poorly-graded; demonstrating that hydrocarbon contamination results in a greater proportion of gravel-size particles due to fine particle clumping. Thus, poorly-graded fine silty sand becomes well-graded, with a larger particle size, due to wet oil lake contamination. This is an important result for the purpose of forming effective treatment strategies for contaminated soil, highlighting the benefits of measuring changes in soil PSD.
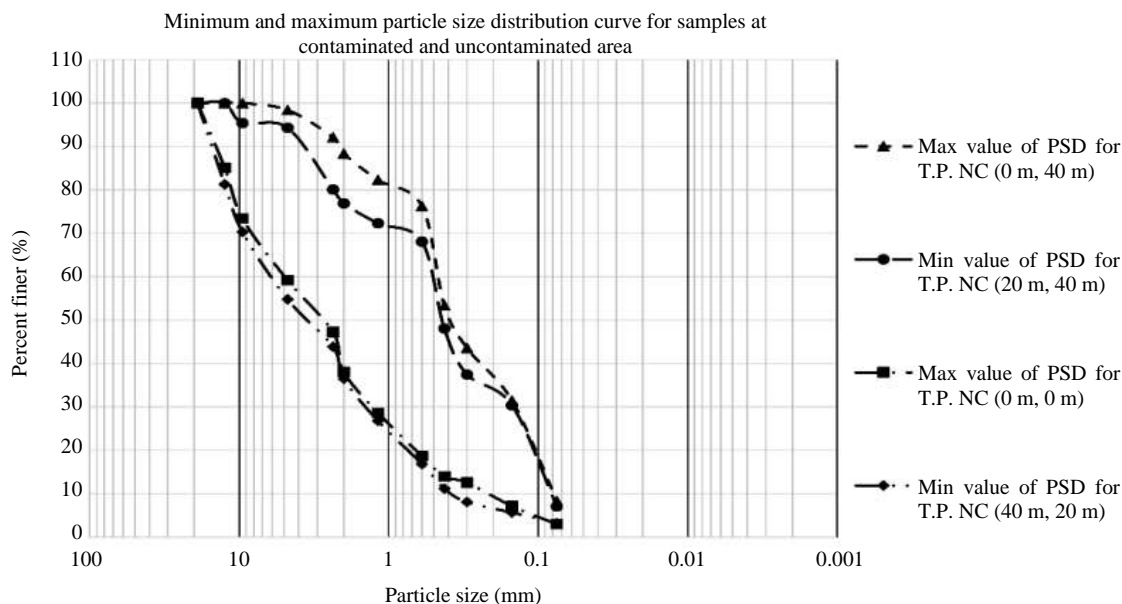

Fig. 8: Maximum and minimum value of PSD for uncontaminated and contaminated samples
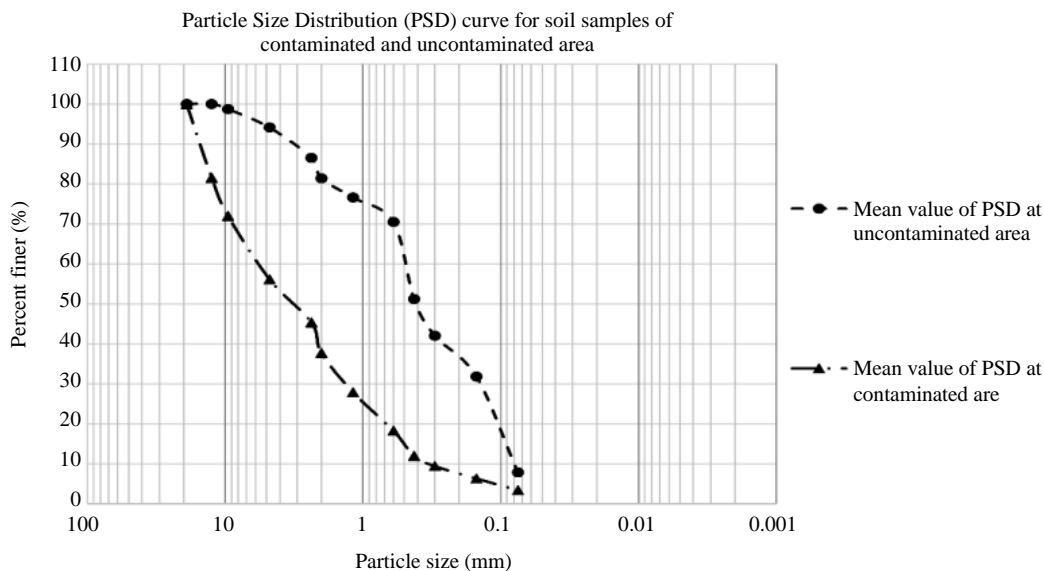

Fig. 9: Mean value of PSD for uncontaminated and contaminated samples
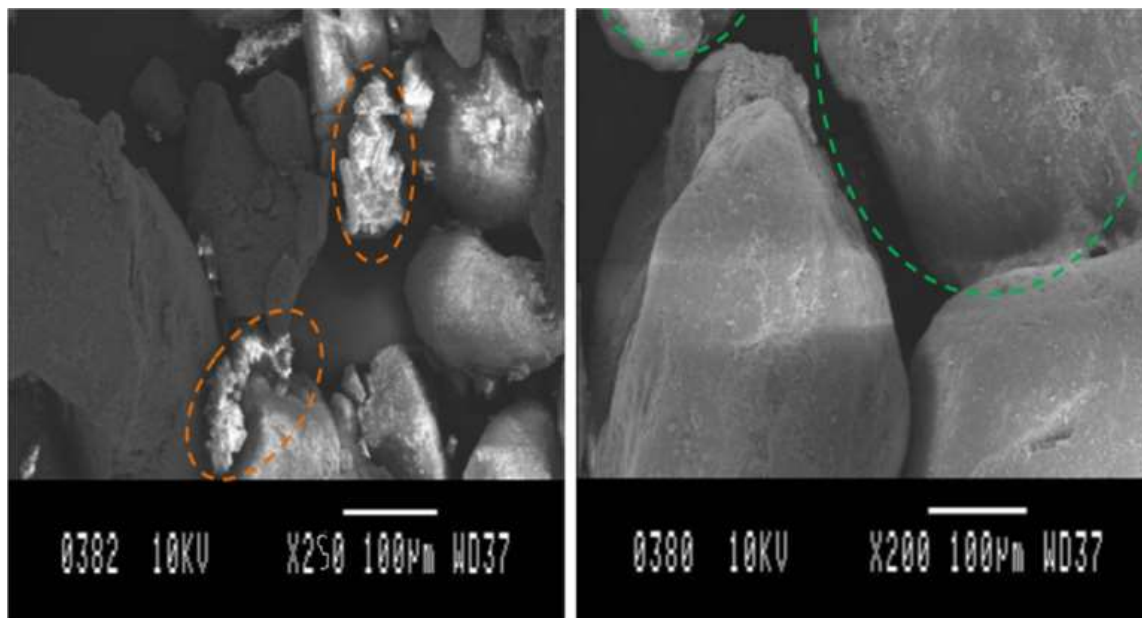
Fig. 10: Indicate to the binding in soil particles forming large grain for T.P.C (0 m, 20 m) at contaminated site (A). Also, to the soil particles without any binding for the T.P.C (0 m, 20 m) at uncontaminated site (B)

Scanning Electron Microscope (SEM)

SEM testing with a single soil sample of each type (contaminated and uncontaminated) was performed in order to validate the results of the previous PSD analyses. The samples were extracted at surface level (i.e., 20 cm) and did not undergo treatment or washing before SEM analysis. The tests indicated that contamination of the soil from the wet oil lake resulted in the formation of large aggregated particles, with a single clumped particle forming as the contaminated soil sample was run through the sieve (Fig. 10).

Conclusion

This study has analyzed contaminated and uncontaminated soil samples from the Al-Ahmadi site in Kuwait using PSD, UCSS, SEM and petroleum hydrocarbon tests. The aim of these analyses was to understand the long-term ageing effect of hydrocarbon contamination from wet oil lakes on soil PSD. The key findings are as follows.

TPH-Contaminated Soil

Whilst testing of the uncontaminated soil sample found no TPH to be present in the soil, the TPH concentration of the contaminated sample was found to be 8,670.3 mg/kg. The findings indicate a clear long-term ageing effect of oil, with 27 years having passed between the year of contamination (1991) and the year of study (2018).

PSD

The contaminated soil samples were found to have mean average percentages of 44.1% for gravel-size (> 4.75 mm) particles, 3.4% for fine (0.075 mm) particles and 9.0% for fine sand particles. Conversely, the uncontaminated samples had mean average percentages of just 6.1% for gravel-size particles, 7.8% for fine particles and 44.6% for fine sand particles. The results therefore showed that oil contamination resulted in a poorer change in soil gradation.

UCSS

Both types of soil (contaminated and uncontaminated) were found to have a Cu value of above 6.0, with a Cc value of above 1.0 in the contaminated soil and below 1.0 in the uncontaminated soil. Therefore, the results indicate that whilst uncontaminated top soil is classed as silty sand, PSD changes in contaminated soil result in a poorer classification, with contaminated soil becoming well-graded. These results demonstrate that hydrocarbon contamination leads fine particles to clump together, forming larger particles.

SEM

The SEM tests confirmed that wet oil lake contamination leads particles to clump together, creating larger particles. A single large particle was formed in the contaminated sample during sieving. This is due to the viscosity of oil from wet oil lakes.

Treatment

The insights into PSD changes outlined in this paper will help to support the creation of effective soil treatment strategies such as soil washing and cement stabilization.

Future Works

A number of recommendations can be made for further research in this area. Firstly,the increased in the coarse soil particles due to agglomeration under the effect of the hydrocarbon (6.1% to 44.6%) is paramount importance to be under consideration for engineering works. In the other words, designers of civil engineering works should be aware of the behavior of this contaminated soil and must therefore make arrangements before the use of this material in the design of structures.

Secondly, because the specific attributes of soil contamination in Kuwait vary greatly, it is suggested that future research examines alternative geotechnical characteristics, such as compressibility, consolidation, compaction and permeability. This will help to better understand the nature of the changes occurring in soil over a long period following contamination due to oil spillages.

Furthermore, future research into specific soil treatment options, including cement stabilization and soil washing, would be beneficial.These treatments should be consisting in determining the mechanical characteristics such as the hardness of the grains of this soil via Los Angels, Devaltests etc. These tests will make it possible to better appreciate the behavior of these agglomerations of fine particles and their probable use as concrete aggregates. Such studies would help to bring insight into the ways in which such treatments can alter the geotechnical attributes of contaminated soil, supporting Kuwait's upcoming urban construction and growth plans in the area of study.

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Author's Contributions

Humoud Melfi Aldaihani: Conducted the soil samples collection, experimental setup, samples testing and prepared the original manuscript.

Fahad A. Alotaibi: Inspect samples in laboratory, design the results analysis and writing the manuscript.

Farraj F. Al-Ajmi: Prepared the literature review and writing the manuscript.

Ethics

This article is original and contains unpublished material. It is confirmed that all authors have read and approved the manuscript and there are no ethical issues involved.

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