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INVESTIGATION OF PERMEABILITY BEHAVIOR OF WET OIL LAKE CONTAMINATED SANDY SOIL AT AL-AHMADI FIELD IN KUWAIT

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ABSTRACT: The 1991 Gulf War saw the tragic burning of more than 600 oil wells which formed several oil lakes that polluted Kuwaiti soils. The main aim of this paper is to discuss the apparent shift seen in the permeability coefficient characteristics of the soil collected from Kuwait's Al-Ahmadi oil field, likely to be due as result of the aging sandy soil polluted with crude oil. The variations in coefficients of permeability were analyzed using five uncontaminated and contaminated soil samples. In addition, alongside the permeability coefficient analysis, grain size distribution, unified soil classification system analysis and Atterberg limit testing were undertaken. The analysis of grain size distribution revealed a substantial decrease in the mean value of different soil particles, where the overall outcome of variation in soil gradation was a poorer one. This might occur because larger particles are forming out from fine particles, due to oil contamination. The unified soil classification system shows that the contaminated samples were indeed well-graded, when compared to the poorly graded in uncontaminated samples. The observed decrease in permeability values could be attributed to the fact that the presence of oil is clogging the inter-particular spaces reducing water permeability. The arguments and findings presented in this paper propose to support the treatment of contaminated soil, and are based upon arguments on how oil contamination can affect grain size distribution and permeability.

Keywords: Wet oil lake contamination, Physical properties, Permeability coefficient properties, Sandy soil.

1. INTRODUCTION

Kuwait is a country located along the north-western border of the Arabian Gulf, with an area of approximately 18,000 sq. km. Like most Gulf countries, Kuwait has 10 major oil fields: Greater Burgan (comprising of the Ahmedi, Burgan, and Magwa fields), along with Bahra, Minagish, Ratga, Raudhtain, Sabriay, Umm Gudair and Wafra fields have approximately 909 oil wells in total. The Kuwaiti oil fields are categorized according to their location, as shown in Fig. 1.

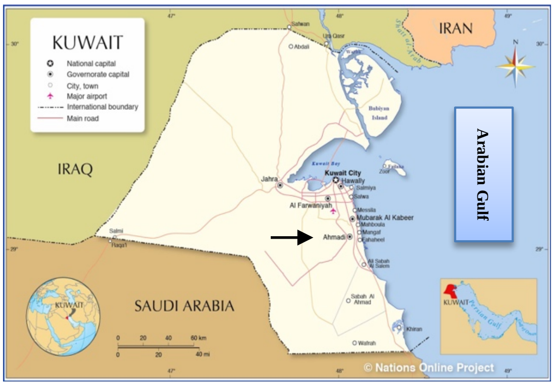

Fig 1. Kuwait oil field areas [1].

Amongst other things, the 1991 Gulf war caused the burning of over 565 Kuwait's oil wells and the demolition of 74 more. This led to their oil over spilling into the surrounding area. Al-Besharah and Al-Awadhi et. al. [3, 4] postulate that this event could be identified as the root cause for the formation of more than 300 oil lakes, spread over a total area of 49 sq. km within the northern and the southern regions. While the majority of the lakes had a depth of around 0.3 m, a few were up to 1.2 m deep [5, 6]. Furthermore, the presence of dry and wet oil lakes has been confirmed by [7, 8]. In addition, Aldaihani [2] hypothesizes that both oil lakes and hydrocarbon pollution played a key role in the degradation of Kuwait's environment quality.

Recent literature presents various proofs that substantial oil contamination possesses the ability to alter the soil geotechnical characteristics [9-11]. This results in compromising the structural integrity of any construction done of such soil [12].

The manner in which the introduction of crude oil into the sandy soil affects the sample permeability coefficient has been subject of extensive studies by numerous scientists [13-19].

These investigations conclude that the level and degree of soil contamination by crude oil is inversely proportional to the soil permeability coefficient.

There are a few other studies that deal specifically with hydrocarbon soil contamination, or with the effects of the dry oil lakes following Iraqi attacks on Kuwait. Detailed soil samples representing six different oil lake depths (up to 2 m), with an increment of 0.25 m, were collected from dry oil lakes at the Al-Magwa site, located 15 km from Al-Ahmadi. This is the location of the current study site (as shown in Fig. 2). From the attained results, it can be concluded that both the permeability coefficient and the hydrocarbon contamination levels were higher in the top layers and lower in the deeper layers [2].

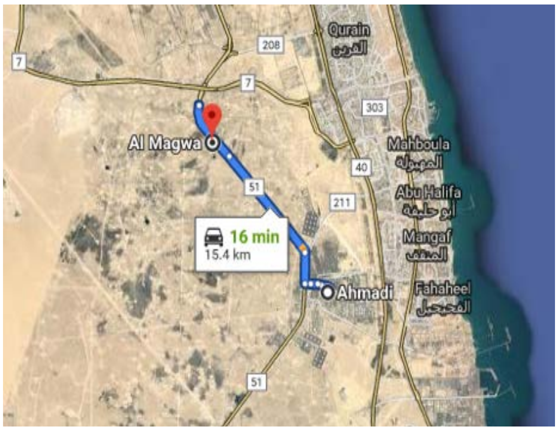

Fig 2. The distance between Al-Ahmadi and Al-Magwa Locations.

Over the past three decades, since 1990, there has been a scarcity of papers analyzing the prolonged effect excercized by the alteration of the permeability coefficient on soil samples from the Kuwait's hot arid region contaminated by the presence of wet oil lakes. Furthermore, the studies conducted to date have analyzed soil samples that have been contaminated by hydrocarbons for a short period time. On the other hand, this study utilizes soil samples that contains contamination that is more than two decades old. The most recent study in the same field conducted by [2] analyzes the changes in the soil permeability coefficient brought about by contamination from dry oil lakes. He then progressed to study the effect of wet oil lake on the soil shear strength and the particle size distribution (PSD), but not the effect on permeability [20, 21].

Therefore, the purpose of this study lays in the aim to shed light and discuss in details the effect of wet oil lake contamination on the permeability coefficient of the contaminated soil sample by comparison with a uncontaminate soil sample from the Al-Ahmadi site.

Analyzing the soil permeability coefficient and other geotechnical characteristics is essential, in order to devise the most suitable method to treat and stabilize the contaminated soil. This study aims to show results that could contribute significantly in providing a further detailed picture of the present situation. This should assist the design of a solution for oil-contaminated soil treatment.

2. SELECTED LOCATION AND SAMPLES COLLECTION

For the benefit of this study, the author decided to collect samples from the southern Al-Ahmadi oil field following previous experience [2, 20, 21].

The lack of genuine data from the test site led to the collection of contaminated and uncontaminated samples, approximately 20 cm deep from five trial pits (TPs): every spot was situated 20 m apart in a site measuring 60 m by 60 m in area. The sizes were selected based on statistical studies from recent literature [2, 21, 20]. Sampling process was carried out on November 18, 2018 in accordance with Kuwait Oil Company (KOC) field staff. From every site, the five samples, weighing approximately 2.5 kgs, were analyzed to determine the Atterberg Limit, Grain Size Distribution (GSD), and Unified Soil Classification System (USCS), as shown in Fig. 3.

To conduct the permeability test, five undistributed soil samples measuring 50 mm in height and 50 mm in diameter were collected from the site using a steel sampler ring inserted into the ground to extract cylindrical samples and extracting the excess oil from each end [22].

The samples were then rubber-sealed at each end, before being packed in individual bags and sealed with plaster, as shown in Fig. 4. Samples storage and preservation was done according to the guidelines previously outlined [23, 24]. Later, the permeability test was conducted with the sample encased in the ring.

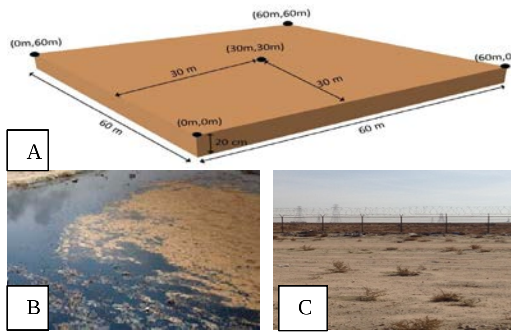

Fig. 3. Site View Plan of T.P.Cs Locations (A) for contaminated (B) and uncontaminated (C) soil samples.

Fig. 4. Indicating to undisturbed (A) and disturbed (B) soil samples.

3. LABORATORY TESTING PROGRAM

With regards of tests conducted on contaminated and uncontaminated samples, the main areas of interest included grain size distribution, plasticity, permeability coefficient assessment and unified soil system.

3.1 Atterberg Limit

The methods outlined in [25] was implemented to conduct the Atterberg limit test ascertaining the liquid and plastic limits of the soil samples.

3.2 Grain Size Distribution (GSD)

The GSD analysis of the soil sample was based on the methods outlined in [26].

3.3 Unified Soil Classification System (USCS)

USCS claims that the Coefficient of uniformity (Cu) and the Coefficient of curvature (Cc) can be used to classify soil samples grain-size [27].

As per the aforementioned conditions in accordance with Casagrande [27], a well-graded sample has a Cu value of more than 6.00 and Cc value ranging from 1.0 to 3.0.

3.4 Permeability Coefficient (Constant Head)

We adhered to the guidelines and procedures presented in ISO/TS 17892-11: 2013 while performing the permeability coefficient test, with constant-head conditions.

4. RESULTS AND ANALYSIS

4.1 Atterberg Limit

As expected, the Atterberg limit is not subjected to the level of hydrocarbon contamination in the sample because the soil sandy characteristic renders it non-plastic. Furthermore, any form of petroleum-based contaminants are hydrophobic and do not have any effect on the level of plasticity of the soil sample.

Plasticity soil behavior results confirm those from studies conducted analyzing the impact of oil contamination on sandy soil, concerning the Atterberg limit [21, 13].

4.2 Grain Size Distribution (GSD)

The GSD of both contaminated and uncontaminated samples have been presented with detail in Figures 5, 6, and 7. From observing the GSD curves, it can be concluded that there exists minimum gradation within the contaminated soil samples collected from various TPCs with the same depth. However, a larger range of gradation can be observed in uncontaminated samples, as shown in Figure 5, 6, and 7. This outcome can be attributed to the agglutination of soil particles within the contaminated site due to oil absorption.

Table 1 presents a detailed illustration of the mean percentage in each soil class in both contaminated and uncontaminated soil samples with a depth of 20 cm from the topsoil. Approximately 40.4% of the contaminated soil sample is composed of gravel-sized particles (sieve no. 4). However, these constitute only 3.6% of the uncontaminated soil sample. This can be attributed to hydrocarbon contamination from wet oil lakes that causes soil particles to clump together, therefore creating larger particles. The smaller particles (Passing No. 200) and fine sized particles constitute 2.6% and 7.0% of the contaminated, and 8.3% and 49.0% of the uncontaminated soil samples, respectively. These findings conform to the results presented from other studies [21, 28]. However, they contradict those reported by [2]. Nevertheless, this difference can be attributed to a significant difference: while this study analysis is conducted with wet oil lakes, Aldaihani assessed dry oil lakes. In his study, hydrocarbon drying resulted in the formation of asphaltene particles, thus increasing the percentage of fine particles in the soil.

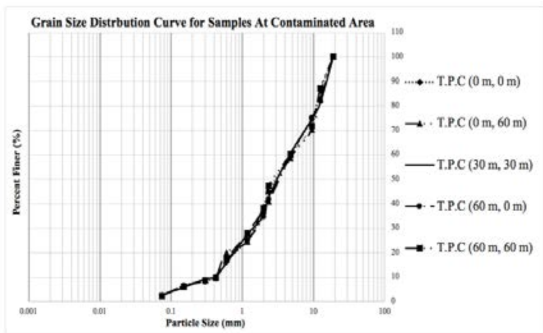

Fig.5. GSD curves for contaminated samples.

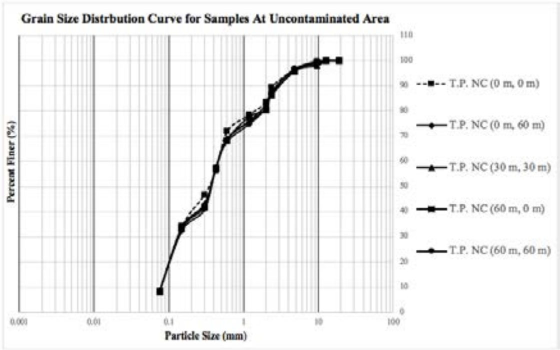

Fig. 6. GSD curves for uncontaminated samples.

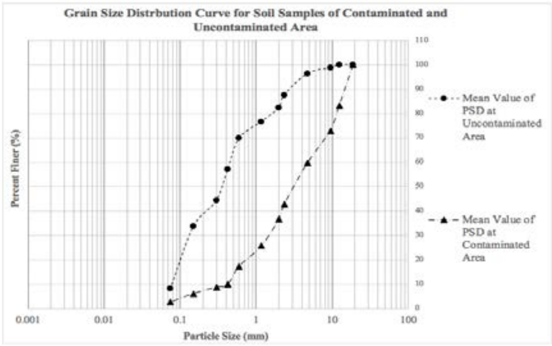

Fig.7. Mean value of GSD for uncontaminated and contaminated samples.

Table 1. 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	7	27	24	40	0	2.6	Poorly graded sand
(0 m, 60 m)	3	7	29	20	41	0	2.7	
(30 m, 30 m)	3	7	25	25	40	0	2.8	
(60 m, 0 m)	2	7	25	25	41	0	2.3	
(60 m, 60 m)	2	7	29	22	40	0	2.4	
Mean value (%)	2.6	7.0	27.0	23.2	40.4	0	2.6	
	Classification of soil (%) at uncontaminated area							
(0 m, 0 m)	8	48	27	13	4	0	8.3	Sand with silt
(0 m, 60 m)	8	49	24	16	3	0	8.2	
(30 m, 30 m)	8	50	25	14	4	0	8.1	
(60 m, 0 m)	8	49	23	15	4	0	8.4	
(60 m, 60 m)	8	49	24	15	3	0	8.3	
Mean Value (%)	8.0	49.0	24.6	14.6	3.6	0	8.3	

4.3 Unified Soil Classification System (USCS)

Table 2 presents a detailed picture of the significant differences detected in the two soil samples after assessing Cu and Cc values, obtained as a result of the USCS analysis. Cu values of more than 6.0 were recorded for both contaminated and uncontaminated soil samples (20 cm depth). On the other hand, the Cc values were found to be greater than 1.0 in contaminated and less than 1.0 in uncontaminated samples.

Therefore, it can be concluded that the topsoil level (up to 20 cm deep) has a lower GSD. Furthermore, hydrocarbon contamination gives rise to a higher percentage of gravel-size particles due to fine particle agglutination, as observed in the well-graded contaminated soil sample and poorly-graded uncontaminated soil sample. Hence, wet oil lake contamination gives rise to the poorly-graded fine silty sand that becomes well-graded with larger particle sizes.

This is a significant finding that could contribute to the design of robust treatment procedures for contaminated soil, therefore emphasizing the benefits of measuring changes in soil GSD.

Table 2. Comparing the USCS factors (i.e. Cu & Cc) for the soil at contaminated and uncontaminated sites.

TPCs	Analysis of grading (Casagrande, 1948)			
	Contaminated site		Uncontaminated site	
	Uniformity coefficient (Cu)	Coefficient of curvature (Cc)	Uniformity coefficient (Cu)	Coefficient of curvature (Cc)
(0m, 0m)	14.6	1.45	7.03	0.42
(0m, 60m)	18.57	1.12	6.12	0.56
(30 m, 30 m)	14.10	1.19	6.05	0.50
(60 m, 0 m)	17.87	1.49	6.02	0.47
(60 m, 60 m)	16.66	1.16	6.02	0.54
Mean Value	16.36	1.28	6.10	0.540

4.4 Permeability Coefficient (Constant Head)

At 20 cm of depth, the permeability coefficient values of contaminated and uncontaminated samples have been presented in Table 3 and Figure 8. In Table 3, it can be observed that the mean value of the permeability coefficient (3.53×10^{-6}) for contaminated samples is 85% lower than that of uncontaminated samples at (2.28×10^{-5}). This could be attributed to oil clogs in inter particular spaces. Furthermore, it was discussed in the previous section that the contaminated samples displayed well-graded USCS results due to the hydrocarbon present in inter-particle spaces acting as an obstacle for water permeability. This is the opposite of what is observed in the analysis of the wide inter-particle spaces present in the uncontaminated samples.

These conclusions confirm the findings from other studies [10, 13, 11, 17]. However, it must be reported that they contradict those of Aldaihani [2]. This difference may be attributed to different samples sources: for this study we analyze wet oil lakes, while Aldaihani [2] studied dry oil lakes. In his study, hydrocarbon drying for over two decades resulted in the formation of asphaltene particles, changing the GSD and increasing the inter-particle spaces, resulting in increased permeability.

Table 3. Comparing the Permeability Coefficient values for the soil at contaminated and uncontaminated sites.

Trial Pits Coordinates (T.P.Cs)	Permeability Coefficient (m/s)		The Variation (reduction) of Permeability Coefficient Between Two Sites
	Contaminated Site	Uncontaminated Site	
(0 m, 0 m)	3.17×10^{-6}	2.31×10^{-5}	-86
(0 m, 60 m)	3.85×10^{-6}	2.38×10^{-5}	-84
(30 m, 30 m)	2.9×10^{-6}	2.33×10^{-5}	-88
(60 m, 0 m)	4.32×10^{-6}	2.12×10^{-5}	-80
(60 m, 60 m)	3.44×10^{-6}	2.28×10^{-5}	-85
Mean Value	3.53×10^{-6}	2.28×10^{-5}	-85

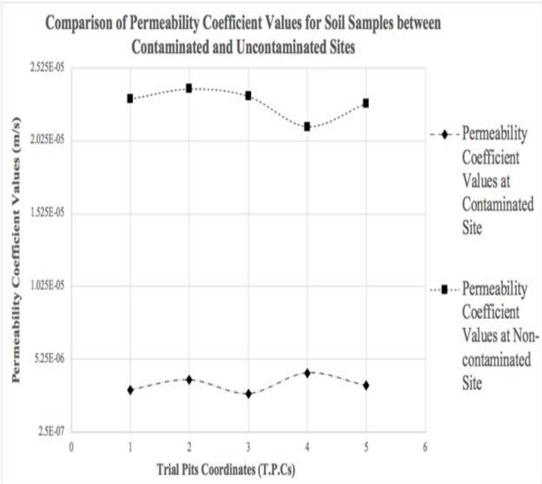

Fig.8. Comparison of the mean values of the permeability coefficient for contaminated and uncontaminated samples.

5. CONCLUSION

In this study, contaminated and uncontaminated soil samples from Kuwait's Al-Ahmadi site were analyzed using the Atterberg limit, PSD, USCS and permeability coefficient tests. The fundamental aim of the study was to ascertain how soil permeability is affected by the wet hydrocarbon pollutants left since the Gulf war of 1991.

- Atterberg limit: it was concluded that both contaminated and uncontaminated soil samples were non-plastic courtesy of the soil sand-like quality that underpin this characteristic.

- GSD: the mean average percentage for gravel-size (> 4.75 mm) particles in the contaminated soil samples was found to be 40.4%, while for fine (0.075 mm) particles it was 2.6% and for fine sand particles it was 7.0%. On the other hand, the average percentage of gravel-size particles for uncontaminated samples was 3.6%, fine particles at 8.0% and fine sand particles at 49.0%. In conclusion, oil contamination led to poor changes in soil gradation.
- USCS: both soil samples had a Cu value of more than 6.0. On the other hand, a Cc value of more than 1.0 was observed in contaminated and less than 1.0 in uncontaminated soil samples. Therefore, uncontaminated soils have silty-sand topsoil, while the PSD changes in contaminated soil lead to poorer classification and a well-graded soil sample. In conclusion, hydrocarbon contamination leads to agglutination of finer particles leading to the formation of larger particles.

- Permeability Coefficient (Constant Head): the contaminated samples showed an average of 85% reduction in permeability, due to oil clogs in inter-particle spaces that create a barrier for water permeability.

- Soil Remediation: the comprehensive knowledge of GSD, USCS and permeability changes presented in this paper could play a key role in designing robust and successful soil treatment procedures, such as soil washing and cement stabilization.

6. FURTHER WORK

There is significant scope for further research in this area. It must be noted that since the soil contamination specific characteristics in Kuwait show great variation from place to place, further research could analyze other geotechnical attributes, such as compressibility, consolidation, and compaction, to name a few. This will improve the comprehensive understanding of the changes occurring in the soil following oil spillages over long periods. In addition, alternative soil treatment options may be evaluated in future research to disclose a further detailed picture of the effects such procedure exercises on the geotechnical characteristic of contaminated soil samples. In turn this could be crucial for aiding Kuwait's efforts towards urban infrastructure developments.

7. ACKNOWLEDGEMENT

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