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Laboratory and numerical study of the behavior of circular footing resting on sandy soils contaminated with oil under cyclic loading

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Abstract. This research studies the behavior of circular foundations resting on the soils contaminated with gas oil and kerosene oil under cyclic loading. The final objective of this study is to determine the impact level of the foundation of the reservoirs resting on oil-contaminated sand due to their filling and discharging. The contaminated sand layers were mixed with different percentages of contamination from 2% to 6% of kerosene oil and gasoline. The effect of the contamination percentage, the value of the applied load, and the depth and type of contamination were investigated in this study. To validate the numerical studies performed by finite element software, small-scale laboratory tests were carried out. The results showed that the pollutants could affect the amount of final settlement and the number of loading cycles required to achieve this value. An increase in depth, the number of load cycles, and the contaminated content led to an increase in the final settlement. In addition, the number of loading cycles to reach that level increased. Numerical results showed acceptable compatibility in the load-settlement charts with the experimental results.

1. Introduction

Investigating the engineering properties of contaminated soils can facilitate a better understanding and prediction of the behavior of these soils. In recent decades, the number of studies conducted in this area has shown that this issue has become a serious global problem. In some cases, there is no possibility of clearing the contaminated soil, and the necessity to stabilize these soils using the soils themselves involves an accurate determination of the engineering parameters of soils and their changes. One of the most common and most dangerous pollutants is hydrocarbons. There is also a great deal of research on the effects of these pollutants, mostly focusing on the contamination with crude oil. This is probably due to leakage from oil pipelines and unpredicted incidents at oil extraction and exploitation sites. These items are important because of the high volume of contaminants and their concentration. In addition, when the reservoir is under cyclic loading, during its operation under special conditions of filling and discharging, the effect of contamination on the soil is more evident; this issue should be investigated in order to prevent its inappropriate consequences. Therefore, due to the necessity of studies in this field, the main objective of this research

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is to investigate the effect of cyclic loading on the contaminated soil caused by oil leakage in the reservoir.

By studying the published papers and the latest studies, one can observe a great variety in the field of soil pollution and possible changes in the related geotechnical properties. In the past, studies were carried out on the physical and chemical properties of oil-contaminated soils, some of which pertained to the geotechnical parameters of the contaminated soils, and a few addressed the behavior of soils under static and cyclic loads.

Studies on the effects of oil pollution on the bearing capacity of the footings are quite limited, and most of them have investigated the effects of contamination on the geotechnical parameters of soils. In recent decades, several experimental and numerical investigations have been performed to determine the geotechnical parameters of oil-contaminated soils, cyclic loading on footings resting on the uncontaminated soils, and static loading on the contaminated soils. Evgin and Das (1992) carried out a series of triaxial tests on the clean motor oil-contaminated quartz sand. They found that the full saturation of soil with motor oil would result in a significant reduction in the angle of internal friction and a sharp increase in the volumetric strains of dense and loose sands. In addition, their finite element model indicated that the foundation settlement on the contaminated soil increased by increasing the contamination [1]. Das et al. (1993) conducted experiments to predict the settlement of shallow square footings on the geogrid reinforced sand under cyclic loading [2]. Their research showed that the static constant load (q_s) and the number of load frequencies would increase by increasing the cyclic loading amplitude (q_d), and that the maximum produced settlement depends on cyclic and static load amplitudes, geogrid stiffness, and soil degree of compaction.

Das and Shin (1994) implemented a laboratory model to determine the permanent settlement of the strip footings resting on the saturated clay under low-frequency cyclic loading [3]. They showed that the number of periods required to reach permanent settlement (n_{cr}) increased by increasing the initial static load due to the weight of the foundation and its accessories. Meegoda and Ratnaweera (1994) investigated the compressibility of the contaminated fine-grained soils by conducting consolidation tests. They mixed two types of low- and high-plasticity clays with glycerin and propanol. The results showed that there was a significant increase in the compressibility of the contaminated soil, as compared to the uncontaminated soil [4]. Alsanad et al. (1995) and Alsanad and Ismail (1997) conducted a series of experiments to study the effect of oil pollution on the geotechnical properties of a type of sand in Kuwait. The results of the experiments indicated that the soil contaminated with crude oil reduced the permeability and shear strength of the soil. It was also shown in the experiments that 6% of the crude oil contaminated with a relative density of 60% had a lower friction angle (about 2°) than that of dry samples, which reduced the coefficient of bearing capacity (N_γ) from 30.22 to 22.22, resulting in a 25% reduction in the bearing capacity of the foundation resting on the contaminated soil [5,6]. Das and Shin (1996) implemented a laboratory model to determine the permanent settlement of strip footing on the saturated clay soils under low-frequency cyclic loading [7]. They found that for the combined composition of the static load q_s and the dynamic load q_d at a frequency of 1 Hz, a quick initial settlement followed by a slower secondary settlement takes place. The initial settlement occurs due to the dynamic loading during the first load cycle and consists of 60 to 80% of the total settlement. After 1500 to 2000 cycles, the settlement is achieved in a more stable state. For the dynamic load constant values, the total settlement increased by increasing the static load intensity. Aiban (1998) examined the effect of temperature on the characteristics of the sand engineering properties. The results showed that the compressibility and permanent deformation of soil with crude oil contaminated soil increased by increasing the surrounding temperature [8]. Shin et al. (1999) examined the effect of crude oil pollution on the shear strength parameters of a type of sandy soil in Korea [9]. The soil was poorly graded silicate sand (SP). The crude oil was provided from the country of Oman, with a density of 854.0 g per cubic centimeter, a sulfur content of 1.05, and a viscosity of 424 MPa at 24 degrees Celsius; in addition, the pollution content was between 0 and 4.2 percent. They showed that an increase in the percentage of contamination led to a decrease in the internal friction angle of the soil, thereby reducing the load-bearing capacity of the experimental modeling. Shin and Das (2001) carried out studies on the bearing capacity of the unsaturated crude oil contaminated sand. The percentage of pollution in their experiments changed from zero to 6% [10]. The results showed that the increased pollution content contributed to a significant reduction in the bearing capacity of the sand. Ghaly (2001) showed that increasing the percentage of contamination reduced the friction angle of the sand by performing a direct shear test on a number of sand samples contaminated with crude oil [11]. In addition, Shin et al. (2002) reported a significant decrease in the friction angle of the contaminated soil [12]. Olchawa and Kumor (2007) studied the effect of diesel oil on the compressibility of organic soils. The results of their research indicated an increase in compressibility by increasing the pollution percentage [13]. Khamehchiyan et al. (2007) investigated the effect of crude oil pollution on the properties of sandy soil in the southern coast of Iran. According to the results, it was determined that oil contamination could decrease the permeability and shear strength of all samples [14]. Naser (2009) studied the effect of strip foundations' behavior on oil-polluted soils, and showed that by increasing the percentage of the contamination, the bearing capacity decreased and the value of footing settlement increased [15]. In addition, he determined that the thickness of the contaminated layer should be more than 50% of the footing width; therefore, decreasing the bearing capacity would not be acceptable. Olgun and Yildiz (2010) examined the effect of organic fluids on the geotechnical behavior of high-plasticity clay [16]. The results showed that the liquid limit and consolidation parameters decreased by increasing the contamination content. They also showed that the soil electrical constant (conductivity) decreased as the contamination increased. Although the effect of oil pollutants on the soil shear strength is not the same and depends on the type of soil, in all studies, the maximum soil strength tends to decrease by increasing the pollution content. Hataf et al. (2010) investigated the experimental and numerical behavior of the shallow foundation resting on the reinforced sand with geogrid and grid-anchor under cyclic loading [17]. Their research showed that by increasing the cyclic load amplitude, the foundation settlement increased. On the other hand, for constant stress values, the number of loading cycles decreased by increasing the number of reinforcement layers to reach constant settlement. They also revealed that by using the grid-anchor system, the settlement of foundations to reach a constant value decreased up to 17% in comparison with the conventional geogrid and reduced up to 50% in comparison with the unreinforced conditions. These amounts are dependent on the number of reinforcement layers and the value of the applied load. Boushehrian et al. (2011) investigated the experimental and numerical behavior of shallow footing on the reinforced sand with geomesh and geogrid under cyclic loading [18]. They studied the foundation of storage tanks in the condition of frequent filling and discharging such as the cycle loading with amplitude less than the allowable bearing capacity in the field. To carry out experiments, a trench was excavated with a diameter of $5.5 \times 5 \times 4$ m and filled with well-graded sand. At the end of their studies, they proposed practical equations. In these formulas, by determining the load amplitude, width of the foundation (B), and unit weight of the soil, one can predict the permanent settlement (S_d) and the number of loading cycles to reach this settlement (n_{cr}). Abousnina et al. (2015) investigated the effect of the motor oil contamination on the geotechnical parameters of fine-grained sand [19]. He determined that by increasing the percentage of pollution content from zero to 1%, the coefficient of permeability decreased at first, then increased from 1% to 6% and, finally, decrease from 6 to 20%. Nasehi et al. (2016) investigated the effect of gas oil pollution on the geotechnical properties of three different soil types: SP (poorly graded sand), CL (low plasticity clay), and ML (low plasticity silt) [20]. The results of the experiments on CL and ML samples demonstrated that by increasing the percentage of contamination, the liquid limit and plastic limit increased and the plasticity index value decreased. The standard proctor compaction test on all three soil types indicated that by increasing the percentage of contamination, the maximum dry density decreased in all three samples. In addition, the amount of reduction in the sand was less than that in clay. Eissa (2016) investigated the effect of gas oil pollution on the clay soil's geotechnical properties [21]. For this purpose, experiments such as the Atterberg limits tests, the consolidation test, and the unconfined uniaxial test on the two uncontaminated and contaminated clay samples were conducted. In these experiments, soil samples were prepared from dry clay composition with different contamination percentages of 2, 4, 8, 10, and 16. The results of these tests disclosed that diesel oil had a complex condition (even evaporated at room temperature), yet some of its particles remained solid. Therefore, conventional equations cannot be used to determine the moisture content of gas oil contaminated soils. Another researcher performed studies to investigate the load-displacement behavior and bearing capacity of shallow foundation numerically and experimentally [22-25].

Today, due to technological advances and growing industrial expansion, the pollution utilization speed, especially industrial pollution, has increased. Today, the scope of these contaminations has been extended to construction projects such that these pollutants have leaked and penetrated into the soil under the foundation of structures. This issue is not only causing environmental problems, but also making changes in the characteristics of soils and in the bearing capacity of the foundations resting on these soils. In recent decades, most studies have focused on the changes in geotechnical characteristics of contaminated soils; so far, very insignificant amount of information is available on the bearing capacity and the settlement of shallow foundations. Thus, the purpose of this study is to present a laboratory-related and numerical program to determine the effect of contamination on the settlement of the circular foundation resting on sandy soils under cyclic loading. In addition, a comparison is made between the results of contaminated and uncontaminated soils.

2. Loading tests model

2.1. Loading device

The test apparatus used in this study, as shown in

Figures 1 and 2, includes a metal box of $1 \times 1 \times 1$ m and a motor pump, which supports a pneumatic jack to apply the static and dynamic forces to the foundation resting on the soil. The surrounding wall was fixed to prevent the lateral deformation by means of vertical and horizontal stiffeners. The side of the device was made with a glass of 20 mm thick, which contributes to inspecting the soil placed under the foundation. The tank interior wall was polished smoothly. The axial symmetry conditions were established in all the tests. The foundation was made of a steel cylinder with a diameter of 10, a height of 5 cm, and a weight of 405.2 kg. All experiments were conducted such that the bottom of the foundation would be located on the soil surface. The pneumatic jack was attached to a rigid frame to apply the vertical load to the footing. A digital gauge with accuracy of 0.01 mm was placed on the footing to measure its settlement. The gauge was connected to the wall of the apparatus through a magnetic base.

Figure 1. The testing apparatus.

2.2. Test materials

In this study, the SW-SM sand (well graded silty sand) was used according to the unified classification system with the soil grain size distribution curve as depicted in Figure 3 and according to the properties given in Table 1. Table 2 shows the model foundation parameters and specifications. A rough base was provided for the foundation using a thin sandpaper sheet pasted onto the base of foundation using special glue. The soil moisture content utilized during the experiments was kept below 2%. Kerosene oil and gas

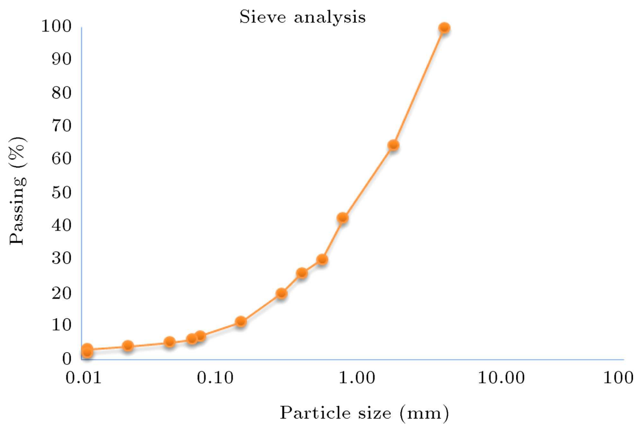

Figure 3. The sand grain size distribution curve.

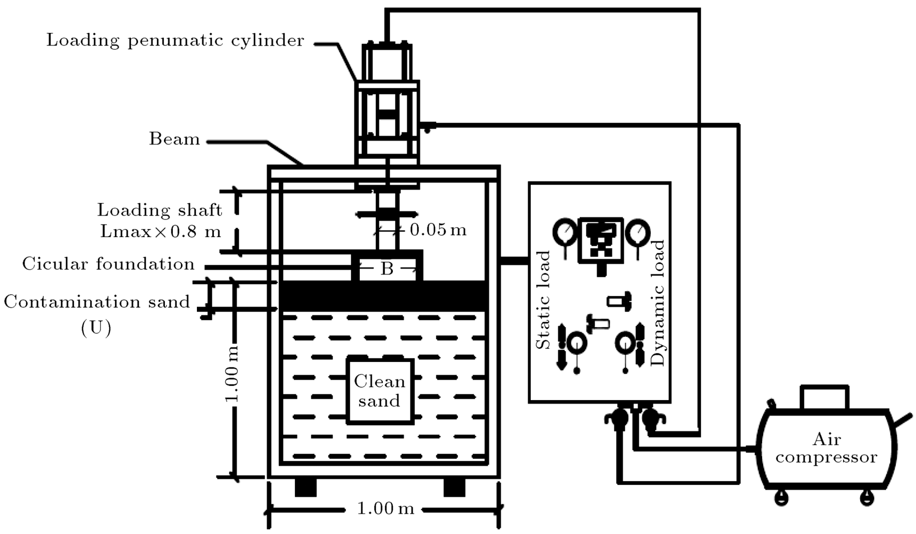

Figure 2. Schematic layout of the testing apparatus.

Table 1. The properties of the sandy soil used in the tests.

Property	Value
Specific gravity, G_s	2.65
Effective particle size, D_{10} (mm)	0.4
Average particle size, D_{50} (mm)	1.2
Uniformity coefficient, C_u	13.84
Coefficient of curvature, C_c	1.53
Average wet unit weight, γ	15.5
Angle of internal friction, ϕ (deg)	31

Table 2. The foundation specifications.

EA (kN/m)	EI (kN.m^2/m)	d (m)	t (m)	ν
7.78e6	7.95e4	0.11	0.035	0.3

oil, according to the specifications given in Tables 3 and 4, were used in order to contaminate the soil. The soil wet density in all experiments was kept between 1.55 to 1.62 g/cm^3. The direct shear test on the soil sample with the same density in the laboratory showed an internal friction angle of 31 degrees.

A knocker of metal with a weight of 65.6 kg and size of 30 cm $\times$ 30 cm was used to compact the soil layers and achieve the desired density. The surface of the prepared layer was precisely leveled immediately after the compaction. This compacting method may cause changes in the state of stress in the soil and, also, changes in the soil, making it different from its status in the normal consolidation state. Since the soil is wet, the raining technique is not suitable for soil placement in the apparatus due to the lack of uniform density. Direct shear tests were carried out to determine the internal friction angle of the soil at different percentages of contamination, and their results are presented in Table 5. Based on the results, because the sand grains were covered with more severe contamination, the internal friction angle showed a smaller number. The utilized circular foundation is made of steel with a diameter of 110 mm and a thickness of 35 mm and a weight of 598.2 kg. In order to perform the test, the device was discharged at a depth of 44 cm (4 times the footing width). The contaminated soil samples were placed on dry soil with different contamination percentages of 2, 3, 4, and 6 in 5-cm layers (the dry weight of approximately 83 kg) and, then, completed by the knocker to achieve the desired density. In this study, in addition to the contamination

Table 3. The kerosene specifications.

Specific Gravity in 60° F (gr/cm^3)	0.856
Density (API in 60° F)	33.76
Viscosity (CP)	22.20
Water and sediment percentage (l b/1000 bbl)	12

Table 4. The gas oil specifications.

Density @ 150°C (kg/L)	0.820-0.860
Sulphur total (mass %)	1.00
Viscosity kinematic @ 37.8°C (mm^2/s)	2.0-5.5
Water and sediment percentage (%vol)	0.05

Table 5. Shear strength parameters of sandy soils contaminated with kerosene oil and diesel oil in different contamination percentages from direct shear test results (for use in software).

Row	Contamination material	Contamination percentage	Cohesion (kPa)	Internal friction angle (deg)
0	Clean sand	0	20.00	31.00
1	Kerosene oil	2	22.30	26.18
2	Kerosene oil	3	26.20	24.80
3	Kerosene oil	4	28.90	22.15
4	Kerosene oil	6	31.45	19.70
5	Gasoline	2	23.90	27.32
6	Gasoline	3	26.80	25.64
7	Gasoline	4	29.70	23.19
8	Gasoline	6	34.30	20.00

Table 6. Summary of tests carried out in laboratory.

Series	Constant parameters	Variable parameters	Variable parameters
CS	Test on clean sand	-	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
CO1	Kerosene oil, 2%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
CO2	Kerosene oil, 3%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
CO3	Kerosene oil, 4%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
CO4	Kerosene oil, 6%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
GO1	Gasoline, 2%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
GO2	Gasoline, 3%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
GO3	Gasoline, 4%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$
GO4	Gasoline, 6%	$U = 0.45B, 0.90B, 1.80B, 2.70B$	$q_d = 0.20q_{ucs}, 0.40q_{ucs}, 0.66q_{ucs}$

percentage, the thickness of the contamination layer varied among 5, 10, 20, and 30 cm. The contaminated soils were subjected to cyclic loading amplitudes, equal to 20, 40, and 66% of the sand failure load. At the beginning of all experiments, the constant load equaled 568.3 kg, and the stress of 619.41 kg/cm^2 was applied statically to simulate the weight of the reservoir and its accessories. A small metal vessel with a given volume was placed randomly in different layers. The prepared surface layer was closely leveled immediately after compaction. The density of both contaminated and uncontaminated soils is always in the same range. This condition was applied by changing the hammer height from 20 to 30 cm, the number of impacts from 3 to 5 beats, and the layer thickness from 5 cm to 3 cm. By beginning the loading with the pneumatic jack, the Linear Variable Displacement Transducer (LVDT) instrument started recording the settlement values. When the settlement reached a constant value after each loading phase, the unloading step was carried out by closing the discharge valve and lifting the pneumatic jack. The soil supported the elasto-plastic behavior due to the small settlement value. The loading-unloading operation took place several times until the settlement did not alter anymore and this amount became constant. At this moment, the permanent settlement occurred.

2.3. Laboratory program

The program of the laboratory tests implemented in the laboratory contained experiments on the loading-unloading of the circular foundation resting on the contaminated and uncontaminated sands. The foundation loading-unloading diagrams include the raw output of the experiments. Based on the loading-unloading curves, the permanent settlement values and the number of loading cycles to reach this settlement can be obtained. The ultimate bearing capacity value of the foundation to determine different values of cyclic load amplitudes was attained by means of a clean sand load-displacement curve. The amount of ultimate bearing capacity was achieved according to Jamick's method based on the punching soil failure mechanism, which was observed in the laboratory [26]. The test program, consisting of 99 cyclic loading tests to study the effect of pollution on the cyclic load-settlement behavior and one load-settlement test to determine the ultimate bearing capacity of the circular footing, is summarized in Table 6. As shown in the table, in the tests, the variable parameters include the percentage of contamination, the type of contamination, the depth of the contaminated layer, and the ratio of cyclic loading amplitude (q_d) to the ultimate bearing capacity of clean sand. To ensure the convenience of expressing and comparing test data, the term settlement ratio is used and described as follows:

$$\mathrm{SR} = \frac{PS_{con}}{PS_{uncon}}, \tag{1}$$

where PS_{uncon} and PS_{con} are the permanent settlements of the contaminated and uncontaminated soils.

3. Results of laboratory tests

Figures 4 and 5 indicate cyclic load-settlement curves for kerosene oil and gas oil with a contamination depth ratio of 0.9 and contamination of 3%, respectively.

3.1. Studying the variation of the contaminated soil layer

Figures 6 and 7 show the load-settlement curves for the circular foundation resting on the soil contaminated

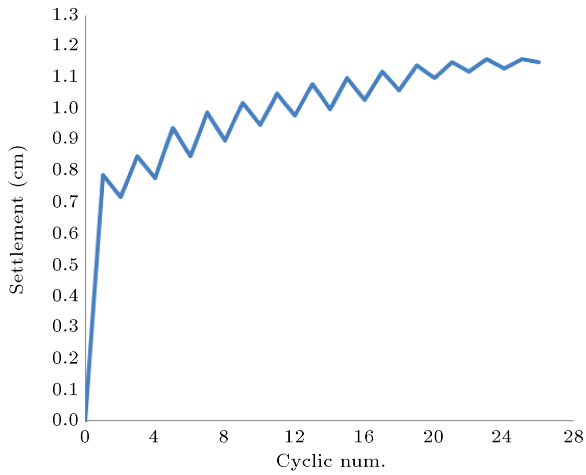

Figure 4. Load cycle-settlement curve of the circular foundation resting on the soil contaminated with kerosene oil with a contamination depth ratio of 0.9 and contamination of 3% for laboratory-related data.

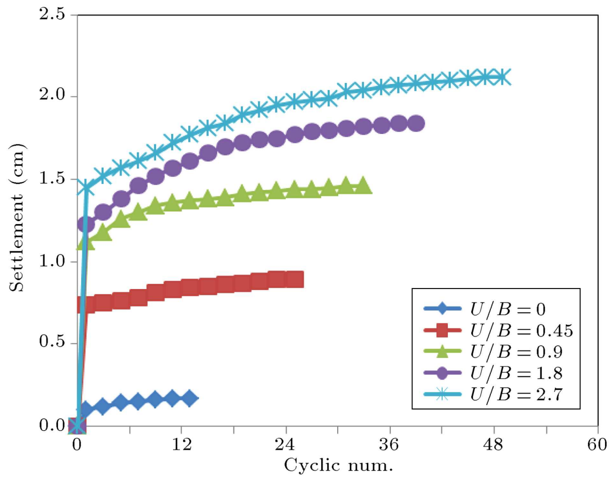

Figure 5. Variation of settlement versus load cycles of sandy soil contaminated with 6% kerosene oil with different contamination depths under 40% of ultimate load resulting from laboratory tests.

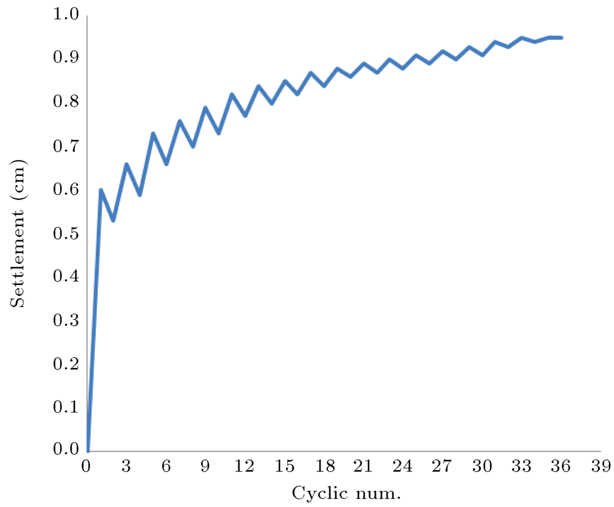

Figure 6. Variation of settlement versus load cycles of sandy soil contaminated with 6% kerosene oil with different contamination depths under 40% of ultimate load resulting from laboratory tests.

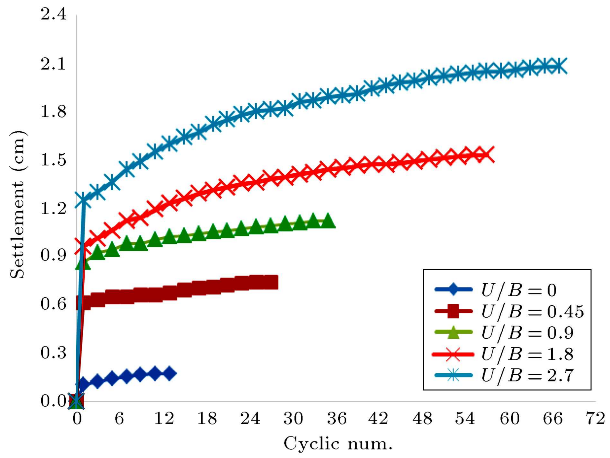

Figure 7. Variation of settlement versus load cycles of sandy soil contaminated with 6% gas oil with different contamination depths under 40% of the ultimate load resulting from laboratory tests.

with gas oil and kerosene oil, obtained from the laboratory results at a constant pollution percentage (6%) at different contamination depth ratios of U/B, i.e., 0, 0.45, 0.9, 1.80, and 2.70. The values of the settlement ratio in this case and for the other pollutant percentages are summarized in Tables 7 and 8. As can be seen, an increase in the thickness of the contaminated layer significantly reduced the bearing capacity of the foundation. This result originated from a reduction in the friction between the soil particles in the foundation influence zone. Based on the results, it can be concluded that the thickness of the contaminated layer significantly affected the sandy soil settlement ratio.

Based on the summarized results of the contaminated layer thickness effect of gas oil and kerosene oil on the parameter SR (Settlement Ratio) shown in Figures 8 and 9, these changes initiated from the low U/B ratios, equal to 0.45 and 0.9. These are due to the encounter between the contaminated soil layers and the failure zone placed under the foundation. At a greater depth ($U/B > 0.9$), SR changes based on U/B significantly increase, indicating that contaminated layer thickness is more than the failure zone depth.

3.2. Studying the variation of the contamination percentage

Figures 10 and 11 show the load cycle-settlement curves for the circular foundation resting on the contaminated soil with diesel oil and kerosene oil, obtained from laboratory results in the case where the ratio of U/B in each graph is constant and equal to 0.9 at different

Table 7. SR for a circular foundation resting on gas oil contaminated sand where the depth of the contamination and cyclic load amplitude are constant and the percentage of contamination is variable (laboratory data).

Series	Contamination material	U/B	Contamination percentage	Cyclic load amplitude	Permanent settlement (cm)	Settlement Ratio (SR)
CS	Clean sand	0	0	$q_d = 0.20q_{ucs}$	0.12	1
CS	Clean sand	0	0	$q_d = 0.40q_{ucs}$	0.17	1
CS	Clean sand	0	0	$q_d = 0.66q_{ucs}$	0.24	1
GO1-1	Gasoline	0.45	2	$q_d = 0.20q_{ucs}$	0.15	1.25
GO1-2	Gasoline	0.45	2	$q_d = 0.40q_{ucs}$	0.29	1.71
GO1-3	Gasoline	0.45	2	$q_d = 0.66q_{ucs}$	0.46	1.92
GO1-4	Gasoline	0.90	2	$q_d = 0.20q_{ucs}$	0.29	2.42
GO1-5	Gasoline	0.90	2	$q_d = 0.40q_{ucs}$	0.52	3.06
GO1-6	Gasoline	0.90	2	$q_d = 0.66q_{ucs}$	0.72	3.00
GO1-7	Gasoline	2.70	2	$q_d = 0.66q_{ucs}$	1.6	6.67
GO2-1	Gasoline	0.45	3	$q_d = 0.20q_{ucs}$	0.21	1.75
GO2-2	Gasoline	0.45	3	$q_d = 0.40q_{ucs}$	0.42	2.47
GO2-3	Gasoline	0.45	3	$q_d = 0.66q_{ucs}$	0.58	2.42
GO2-4	Gasoline	1.80	3	$q_d = 0.66q_{ucs}$	1.43	5.96
GO3-1	Gasoline	0.45	4	$q_d = 0.66q_{ucs}$	0.88	3.67
GO3-2	Gasoline	2.70	4	$q_d = 0.66q_{ucs}$	1.64	6.83
GO3-3	Gasoline	1.80	4	$q_d = 0.66q_{ucs}$	2.07	8.63
GO4-1	Gasoline	0.45	6	$q_d = 0.66q_{ucs}$	0.99	4.13
GO4-2	Gasoline	0.90	6	$q_d = 0.66q_{ucs}$	1.59	6.63
GO4-3	Gasoline	1.80	6	$q_d = 0.66q_{ucS}$	1.96	8.17
GO4-4	Gasoline	2.70	6	$q_d = 0.66q_{ucs}$	2.21	9.21

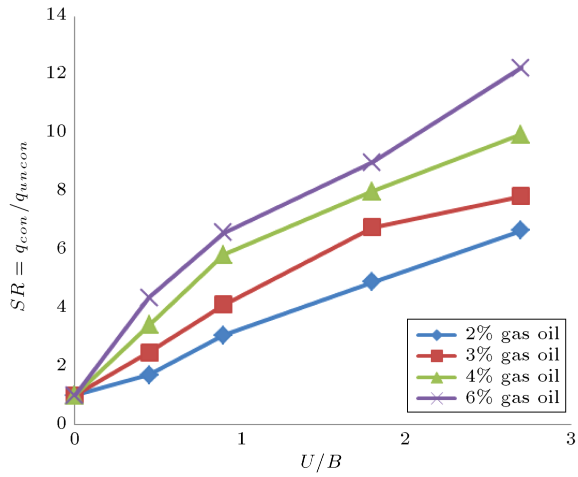

Figure 8. Variations of SR versus U/B for gas oil contaminated soil.

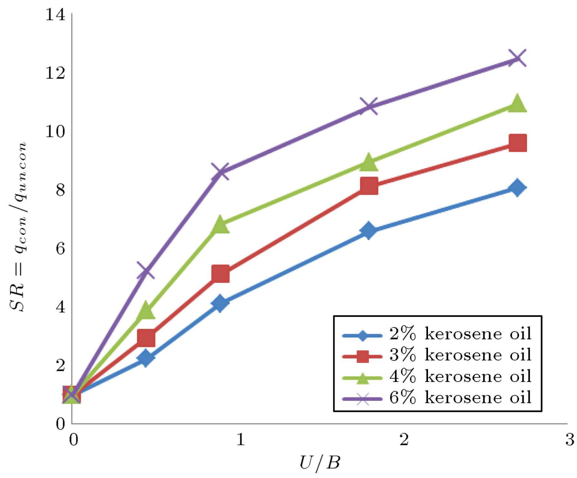

Figure 9. Variation of SR versus U/B for kerosene oil contaminated soil.

percentages of contamination: 0, 2, 4, 3, and 6. In addition, the settlement ratio in this case and for the other contamination ratios is summarized in Tables 7 and 8.

As it was mentioned, an increase in settlement and in the critical load cycle was observed owing to an increase in the contamination percentage.

$$q_u = CN_C S_C + qN_q + 0.5\gamma BN_\gamma S_\gamma. \quad (2)$$

The verification and comparison of laboratory results with analytical methods can be done through the significant relationship between the amounts of load-bearing capacity in the laboratory according to the foundation specifications obtained in the laboratory. Considering the coefficients of the related weight (N_γ) equal to 26.30, the coefficient of adhesion (N_c) equal to 32.88, and the average weight of soil moisture in the laboratory equal to 15.5 kN/m^3, the bearing capacity

Table 8. SR for a circular foundation resting on kerosene oil contaminated sand where the depth of the contamination and cyclic load amplitude are constant and the percentage of contamination is variable (laboratory data).

Series	Contamination material	U/B	Contamination percentage	Cyclic load amplitude	Permanent settlement (cm)	Settlement Ratio (SR)
CS	Clean sand	0.00	0	$q_d = 0.20q_{ucs}$	0.12	1
CS	Clean sand	0.00	0	$q_d = 0.40q_{ucs}$	0.17	1
CS	Clean sand	0.00	0	$q_d = 0.66q_{ucs}$	0.24	1
KO1-1	Kerosene oil	0.45	2	$q_d = 0.20q_{ucs}$	0.18	1.50
KO1-2	Kerosene oil	0.45	2	$q_d = 0.40q_{ucs}$	0.38	2.24
KO1-3	Kerosene oil	0.45	2	$q_d = 0.66q_{ucs}$	0.62	2.58
KO1-4	Kerosene oil	0.90	2	$q_d = 0.20q_{ucs}$	0.32	2.67
KO1-5	Kerosene oil	0.90	2	$q_d = 0.40q_{ucs}$	0.7	4.12
KO1-6	Kerosene oil	0.90	2	$q_d = 0.66q_{ucs}$	1.07	4.46
KO1-7	Kerosene oil	2.70	2	$q_d = 0.66q_{ucs}$	1.83	7.63
KO2-1	Kerosene oil	0.45	3	$q_d = 0.20q_{ucs}$	0.25	2.08
KO2-2	Kerosene oil	0.45	3	$q_d = 0.40q_{ucs}$	0.5	2.94
KO2-3	Kerosene oil	0.45	3	$q_d = 0.66q_{ucs}$	0.75	3.13
KO2-4	Kerosene oil	1.80	3	$q_d = 0.66q_{ucs}$	1.64	6.83
KO3-1	Kerosene oil	0.45	4	$q_d = 0.66q_{ucs}$	1.11	4.63
KO3-2	Kerosene oil	2.70	4	$q_d = 0.66q_{ucs}$	2.16	7.21
KO3-3	Kerosene oil	1.80	4	$q_d = 0.66q_{ucs}$	1.64	9
KO4-1	Kerosene oil	0.45	6	$q_d = 0.66q_{ucs}$	1.31	5.46
KO4-2	Kerosene oil	0.90	6	$q_d = 0.66q_{ucs}$	1.68	7
KO4-3	Kerosene oil	1.80	6	$q_d = 0.66q_{ucs}$	2.22	9.25
KO4-4	Kerosene oil	2.70	6	$q_d = 0.66q_{ucs}$	2.37	9.88

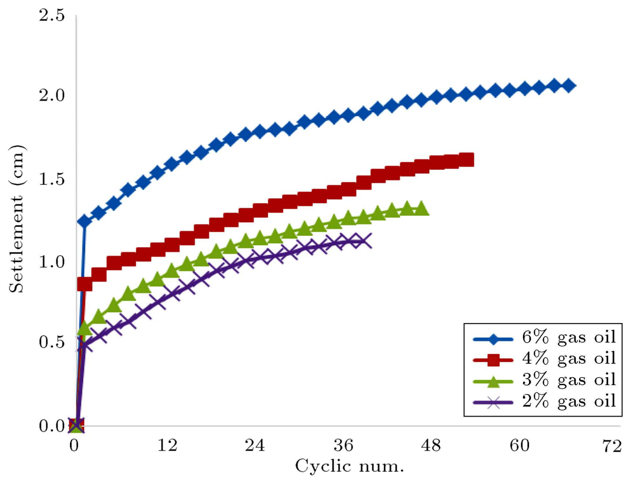

Figure 10. Load cycle-settlement curve of the circular foundation on the gas oil contaminated sand with different contamination depths under 40% of the failure load obtained from laboratory results ($U/B = 2.70$).

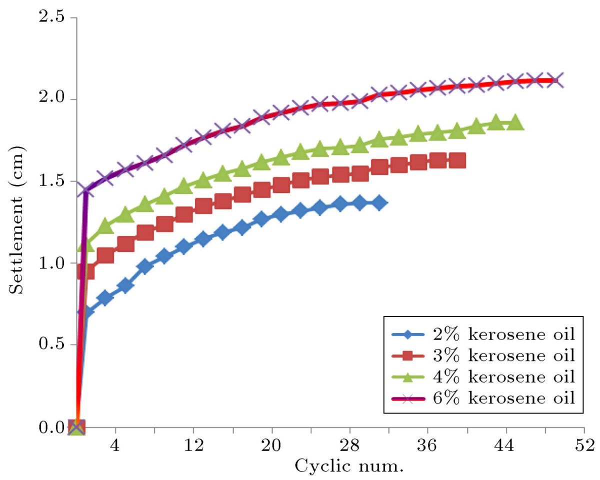

Figure 11. Load cycle-settlement curve of the circular foundation on the kerosene oil contaminated sand with different contamination depths under 40% of the failure load obtained from laboratory results ($U/B = 2.70$).

of a square foundation with a width of 11 cm on the surface of the non-contaminated sand was 691.33 kPa, which had an acceptable difference of about 11% from the amount obtained in the laboratory (619.41 kPa).

3.3. Studying the effect of oil pollution type

By assuming that the other parameters are constant, the effect of the type of pollutants on the foundation behavior can be determined. As shown in Tables 7 and 8, the greatest effect of both pollutants on the Settlement Ratio (SR) occurs at contamination percentage of 6% and the U/B ratio equal to 2.70. In this condition, an increase in SR for gas oil and kerosene oil is 12.2 and 12.5, respectively. On the other hand, an increase in the number of loading and unloading cycles to reach the permanent settlement (n_{cr}) for gas oil and kerosene oil contaminated soils is 13 and 19, respectively. Thus, it can be argued that the increase of permanent settlement and the number of loading and unloading cycles to reach this settlement (so-called critical cycle number) have a direct relationship with the mechanical properties of soils, type of contamination, thickness of the contaminated layer, cyclic load amplitude, and contaminated content. On the other hand, according to other researchers, these parameters also depend on the viscosity of the contaminating material, surrounding temperature, and even chemical properties of the soil, which are not addressed in this research. By comparing the results of the experiments on two types of pollutants, it is determined that kerosene oil has a greater effect on the settlement and critical cycle numbers.

4. Numerical model

A numerical model was created to predict the behavior of the system by a computer program. Additionally, a numerical model validated by actual results could reduce laboratory tests, which can bring about economic benefits. Plaxis2D software, which is two-dimensional finite element software for the static and dynamic stress-strain analyses of soil and rock, was used in this research [27]. This software is able to plot a load-settlement curve and determine the ultimate bearing capacity of the circular foundation. The circular foundation was created based on the axial symmetry modeling software ability. Figure 12 presents one of the models created by Plaxis2D VER8.2 software. To introduce the contaminated soils, their strength parameters were conducted from the direct shear test according to Table 5. In the numerical modeling, the same laboratory tests were carried out as described in Table 6. The strain hardening behavior model was utilized for the analysis. Another required parameter was obtained based on several attempts to match the numerical and laboratory results.

There are many phases in the analyses. One is Phase 0, in which the initial stresses due to soil self-weight are activated. The second one is Phase 1, where the applied load is activated at a certain level (e.g., 20% of the ultimate load). The next one is Phase 2 where the applied load is deactivated and, then, in Phase 3, is activated at the mentioned certain level; this similar process occurs in the next phases. The phases of the analyses continued to reach a reasonably constant settlement amount at the final stage of loading and unloading. Standard fixities, i.e., the horizontal fixity for vertical boundaries and the total fixity for the bottom boundary of the model, were chosen as the boundary conditions for the analyses.

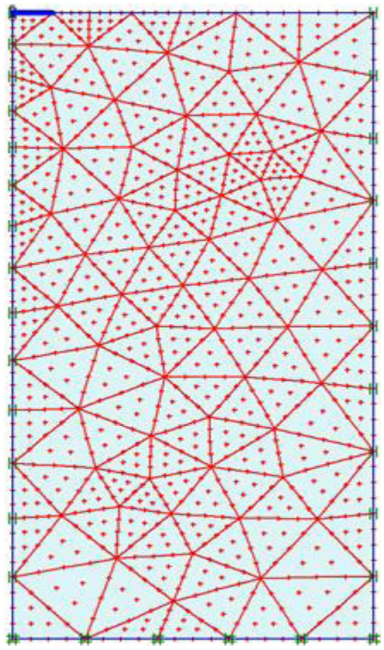

Figure 12. Meshed numerical model.

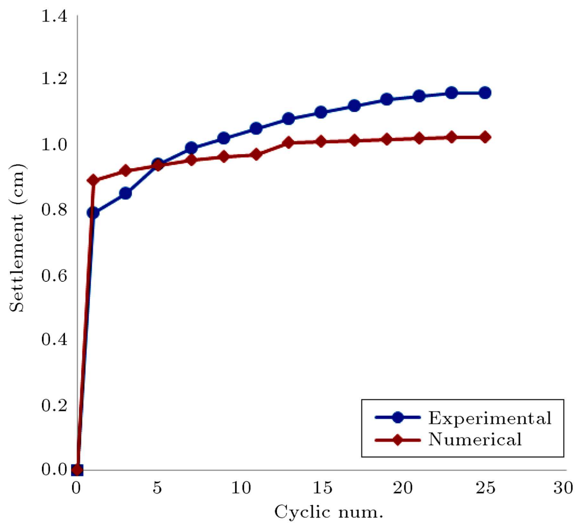

Figure 13. Load cycle-settlement curve of the circular foundation resting on the soil contaminated with kerosene oil with a contamination depth ratio of 0.9 and contamination of 3% for numerical and laboratory-related data.

5. Numerical model results

A sample of the numerical model results for gas oil and kerosene oil in the U/B of 1.8 and 2.7 % of pollution is presented in Figures 13 and 14. At the same time, a

Table 9. SR for the circular foundation resting on the gas oil contaminated sand where the pollution depth and the cyclic load amplitude are constant and the contamination percentage is variable (numerical data).

Series	Contamination material	U/B	Contamination percentage	Cyclic load amplitude	Permanent settlement (cm)	Settlement Ratio (SR)
CS	Clean sand	0	0	$q_d = 0.20q_{ucs}$	0.15	1
CS	Clean sand	0	0	$q_d = 0.40q_{ucs}$	0.37	1
CS	Clean sand	0	0	$q_d = 0.66q_{ucs}$	0.75	1
GO1-1	Gasoline	0.45	2	$q_d = 0.20q_{ucs}$	0.157	1.05
GO1-2	Gasoline	0.45	2	$q_d = 0.40q_{ucs}$	0.396	1.07
GO1-3	Gasoline	0.45	2	$q_d = 0.66q_{ucs}$	0.911	1.21
GO1-4	Gasoline	0.90	2	$q_d = 0.20q_{ucs}$	0.166	1.11
GO1-5	Gasoline	0.90	2	$q_d = 0.40q_{ucs}$	0.413	1.12
GO1-6	Gasoline	0.90	2	$q_d = 0.66q_{ucs}$	0.935	1.25
GO1-7	Gasoline	2.70	2	$q_d = 0.66q_{ucs}$	0.987	1.32
GO2-1	Gasoline	0.45	3	$q_d = 0.20q_{ucs}$	0.161	1.07
GO2-2	Gasoline	0.45	3	$q_d = 0.40q_{ucs}$	0.4	1.08
GO2-3	Gasoline	0.45	3	$q_d = 0.66q_{ucs}$	0.93	1.24
GO2-4	Gasoline	1.80	3	$q_d = 0.66q_{ucs}$	0.97	1.29
GO3-1	Gasoline	0.45	4	$q_d = 0.66q_{ucs}$	0.96	1.28
GO3-2	Gasoline	2.70	4	$q_d = 0.66q_{ucs}$	1.11	1.48
GO3-3	Gasoline	1.80	4	$q_d = 0.66q_{ucs}$	1.16	1.55
GO4-1	Gasoline	0.45	6	$q_d = 0.66q_{ucs}$	0.98	1.31
GO4-2	Gasoline	0.90	6	$q_d = 0.66q_{ucs}$	1.3	1.73
GO4-3	Gasoline	1.80	6	$q_d = 0.66q_{ucS}$	1.38	1.84
GO4-4	Gasoline	2.70	6	$q_d = 0.66q_{ucs}$	1.47	1.96

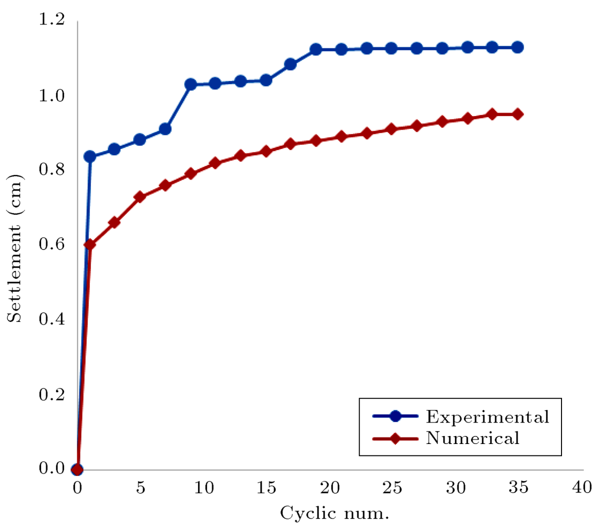

Figure 14. Load cycle-settlement curve of the circular foundation resting on soil contaminated with gas oil with the contamination depth ratio of 0.9 and contamination of 3% for numerical and laboratory data.

comparison between the results of laboratory tests with the same conditions and those of numerical modeling in these figures is presented in these figures. According to these figures, there is acceptable compatibility between the results. Tables 9 and 10 present the complete results of numerical analyses for gas oil and kerosene oil, respectively.

Regarding the amount of the foundation permanent settlement at different percentages, contamination depths, and various load amplitudes, by using Table-Curve software, the following formulas are presented to calculate and predict the amount of permanent settlement and the critical cycle number of circular foundations located on the soil contaminated with gas oil and kerosene oil [28].

a) The relation used for the calculation of the gas oil contaminated soil permanent settlement at a constant thickness of the polluted layer:

$$Z = 8.16\sqrt{Pp} + 0.0831\sqrt{Lp} - 1.31. \quad (3)$$

b) The relation utilized to calculate the critical cycle number of gas oil contaminated soils at a constant thickness of the polluted layer:

$$n_{cr} = 1.70\sqrt{Lp} - \frac{9.85}{\sqrt{Pp}} + 79.20. \quad (4)$$

c) The relation used for kerosene oil contaminated soil at a constant thickness of the polluted layer:

$$Z = 7.32\sqrt{Pp} + 0.077\sqrt{Lp} - 0.85. \quad (5)$$

Table 10. SR for the circular foundation resting on the kerosene oil contaminated sand where the depth of pollution and the cyclic load amplitude are constant and the percentage of contamination is variable (numerical data).

Series	Contamination material	U/B	Contamination percentage	Cyclic load amplitude	Permanent settlement (cm)	Settlement Ratio (SR)
CS	Clean sand	0	0	$q_d = 0.20q_{ucs}$	0.15	1
CS	Clean sand	0	0	$q_d = 0.40q_{ucs}$	0.37	1
CS	Clean sand	0	0	$q_d = 0.66q_{ucs}$	0.75	1
KO1-1	Kerosene oil	0.45	2	$q_d = 0.20q_{ucs}$	0.162	1.08
KO1-2	Kerosene oil	0.45	2	$q_d = 0.40q_{ucs}$	0.393	1.06
KO1-3	Kerosene oil	0.45	2	$q_d = 0.66q_{ucs}$	0.857	1.14
KO1-4	Kerosene oil	0.90	2	$q_d = 0.20q_{ucs}$	0.171	1.14
KO1-5	Kerosene oil	0.90	2	$q_d = 0.40q_{ucs}$	0.436	1.18
KO1-6	Kerosene oil	0.90	2	$q_d = 0.66q_{ucs}$	1.09	1.43
KO1-7	Kerosene oil	2.70	2	$q_d = 0.66q_{ucs}$	1.22	1.63
KO2-1	Kerosene oil	0.45	3	$q_d = 0.20q_{ucs}$	0.167	1.11
KO2-2	Kerosene oil	0.45	3	$q_d = 0.40q_{ucs}$	0.4	1.08
KO2-3	Kerosene oil	0.45	3	$q_d = 0.66q_{ucs}$	0.9	1.20
KO2-4	Kerosene oil	1.80	3	$q_d = 0.66q_{ucs}$	1.153	1.54
KO3-1	Kerosene oil	0.45	4	$q_d = 0.66q_{ucs}$	0.91	1.21
KO3-2	Kerosene oil	2.70	4	$q_d = 0.66q_{ucs}$	1.26	1.68
KO3-3	Kerosene oil	1.80	4	$q_d = 0.66q_{ucs}$	1.32	1.76
KO4-1	Kerosene oil	0.45	6	$q_d = 0.66q_{ucs}$	0.972	1.30
KO4-2	Kerosene oil	0.90	6	$q_d = 0.66q_{ucs}$	1.373	1.83
KO4-3	Kerosene oil	1.80	6	$q_d = 0.66q_{ucs}$	1.52	2.03
KO4-4	Kerosene oil	2.70	6	$q_d = 0.66q_{ucs}$	1.48	1.97

d) The relation used to calculate the critical cycle number of kerosene oil contaminated soil at a constant thickness of the polluted layer:

$$n_{cr} = 34.54 - \frac{0.65}{Pp} + 1.38\sqrt{Lp}, \tag{6}$$

where:

Z Permanent settlement (cm)

Pp Pollution percentage (%)

Lp Cyclic loading (kN/m^2)

n_{cr} Critical cycle number

6. Conclusion

In this research, by using a pneumatic loading apparatus, at first, the bearing capacity of the shallow circular footing resting on the sandy soil was investigated in unpolluted conditions. Then, by using the device capability, the cyclic load was applied as percentages of the foundation ultimate bearing capacity. The footing was loaded and unloaded on clean and contaminated sands with different thicknesses for the contaminated layer and different pollutants. The experimental results were compared by finite element software, and the following results were obtained.

The results of the laboratory and numerical modeling showed that increasing the percentage and depth of the polluted layer with both kerosene and gas oil contamination contributed to an increase in the critical cycle number and the permanent settlement.

In clean sand, 13 loading cycles were required to reach the permanent settlement equal to 0.24 cm. However, in kerosene oil contaminated sand, 53 load cycles were needed to achieve 2.37-cm permanent settlement. In gas oil contaminated sand, the critical load cycles and the related permanent settlement increased up to 73 stages and 2.22 cm.

Based on the comparison of the results, it is seen that the pollution of sandy soils with gas oil has less effect on the increasing settlement and decreasing critical cycle number against kerosene oil.

The mean value of Settlement Ratio (SR) for the sand contaminated with gas oil was about 1.22 times more than that for kerosene oil contaminated sand. The comparison of numerical and laboratory-related results indicated that the results of experimental and numerical models were compatible.

The correlation relationships were presented at the end of the research. Having considered these equations and determined the type, depth, and percentage of contamination, one can predict the critical cycle number and permanent settlement of a circle foundation. This final conclusion and the provided relationships have made it possible to avoid time-consuming calculations and expensive tests.

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