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Contamination Effects on the Bearing Capacity of Circular Shallow Foundation Rested on Sand

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ABSTRACT

The growth and development of industries have led to expanding suburban factories, complexes, refineries, and oil product transportation lines, causing environmental concerns and repercussions due to the leakage and discharge of pollutions into potable water resources. These contaminations can change the geotechnical characteristics and bearing capacity of soils. This study determined the behavior of circular footings rested on the gasoil and kerosene-contaminated soil. In addition, the obtained results comprised those collected from the uncontaminated soil. The study mainly attempted to determine the effect of oil contamination on the bearing capacity of oil-contaminated sand based on the numerical model created in the PLAXIS. The contaminated sand layers were mixed with varying gasoil and kerosene contaminations levels (1%-4%). Direct shear tests were conducted on the contaminated soil samples to determine the shear strength parameter utilized in numerical analysis. The influences of the contamination depth and type were examined. The numerical model results indicated the negative relationship between the percentage and the depth of contamination with gasoil and Kerosene and the circular foundation bearing capacities; an increase in the first two criteria reduced the later property in the soil. This paper proposed several equations to predict the bearing capacity of a circular foundation based on depth and percentage of contamination. The numerical model used had been verified by recent experimental results.

1. Introduction

Relevant studies have addressed the load-settlement behavior of foundations rested on clean soils in various conditions (Azarafza et al., 2014; Alemyparvin, 2020; Hajiani Boushehrian, 2020). In some contexts, such as petrochemical tanks, railroads, and subways on contaminated embankments, footings are located on contaminated soils. These sites are probably contaminated due to the oil leakage from oil pipelines, oil wells, and unpredicted incidents at oil extraction and exploitation sites. Most recent studies in this field reveal a great variety in soil pollution and the changes in the related geotechnical properties. Former studies dealt with the physical and chemical properties of oil-contaminated soils, some of which pertained to the geotechnical parameters, and several others addressed the behavior of shallow foundations rested on these soils. For instance; Meegoda and Ratnaweera (1994) investigated factors controlling the compression index of contaminated, fine-grained soils with the consolidation test. Similarly, Al-sanad et al. (1995) and Al-sanad and Ismael (1997) conducted several tests to examine the influence of crude oil contamination on the

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geotechnical properties of a specific sand type in Kuwait. The results showed that soil contamination with crude oil reduced the permeability and shear strength of the soil. Aiban (1998) studied the effect of temperature on the strength, permeability, and compressibility of the contaminated sand. Shin and Das (2001) evaluated the variation of the shear strength of sand contaminated with three different types of oils with varying kinematic viscosities and thus the ultimate bearing capacity of shallow foundations. The percentage of pollution in their experiments changed from 0% to 6%. Accordingly, this paper discussed e effect of oil contamination in drastically reducing the bearing capacity based on these experiments.

Ghaly (2001) conducted a direct shear test on some sand samples contaminated with crude oil to show that increasing the contamination percentage could reduce the friction angle of the sand. Shin et al. (2002) showed a considerable decrease in the friction angle of the contaminated soil. Ratnaweera and Meegoda (2006) conducted some unconfined compression tests on fine-grained soils contaminated with different concentrations of glycerin and propane and acetone chemicals. The experiments were associated with a decrease in the soil shear strength and changes in soil stress-strain behavior samples. In addition, 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. Mashalah et al. (2007) studied the effects of crude oil on the sandy soils of Bushehr in the south of Iran. The results indicated that oil contamination leads to a reduction in all the samples' permeability and shear strength. 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 decreases, and the value of footing settlement increases. Furthermore, Naser determined that the thickness of the contaminated layer should be more than 50% of the footing width, decreasing the bearing capacity will not be appreciable.

Olgun and Yildiz (2010) examined the effect of organic fluids on the geotechnical behavior of high-plasticity clay. The results showed that the liquid limit and consolidation parameters decreased by increasing the contamination content, and the soil electrical constant (conductivity) decreased as the contamination increased. Although oil pollutants affect soil shear strength differently depending on the soil type, the maximum soil strength tends to decrease by increasing the pollution content in all studies. Khamehchiyan et al. (2007) studied the effects of the geotechnical properties of the contaminated and uncontaminated clay and sandy soil samples by performing the Atterberg limits, compaction, direct shear, unconfined compression strength, and permeability tests. The results revealed that when the contamination increased, the maximum dry density and optimum moisture content decrease, and this reduction in the SM and CL types was faster than that in the SP type. The pollution reduced the amount of water needed to achieve the maximum dry density. The studies showed an increase in the contamination percentage decreased the SM and CL samples' compressive strengths. Naser (2014) investigated the strength behavior of oil-contaminated sand stabilized with cement kiln dust (CKD) to assess the engineering properties of the stabilized soil for application in rural road construction. They showed that adding CKD increased the unconfined compressive strength (UCS) and California bearing ratio (CBR) values of oil-contaminated sand. The strength of stabilized contaminated sand decreased as the percentage of oil increased. Adding 10% CKD to the sand contaminated with 6% oil content gave the optimum UCS and CBR values.

Harsh et al. (2016) studied the influence of crude oil contamination on the geotechnical properties of the soils by performing different tests on the contaminated fine sand and Kaolinite clay. The tests showed that when the contamination increased, the liquid limit and the density of the grains of both types of soil decreased while the plastic limit, the shrinkage limit, and the swelling coefficient of Kaolinite clay increased. Mohammadi et al. (2016) investigated the interface behavior of crude oil-contaminated sand-concrete using a direct shear apparatus for interface tests. The experimental results showed that the concrete surface texture, the normal stress, and the crude oil content played important roles in interface shear strength. Moreover, the friction angle decreased with increasing crude oil content due to increased oil concentration in soil and increased interface roughness. Ghasemzadeh and Tabaiyan (2017) investigated the effect of various additives, such as lime, cement, rice husk ash, and RRP-235 Special, on the geotechnical properties of a diesel fuel contaminated Kaolinite. Results indicated that an increase in diesel fuel as a contaminant up to 10% by dry weight of the soil negatively affected the strength and cohesion of lime and rice husk ash stabilized soil while improving the strength and cohesion of cement stabilized soil. The friction angle of all the lime, cement, and rice husk ash stabilized samples decreased with increased contaminant concentrations. An increase in RRP-235 Special did not affect the soil's shear strength characteristics. Hosseini and Hajiani Busherian (2019) studied the behavior of circular footings on oil-contaminated sand under cyclic loading. Their experimental and numerical analysis results presented equations that predicted overall settlement and the number of loading periods to reach the desired settlement. The equations were based on contamination percentage, contaminated-layer thickness, loading frequency, and cyclic load frequency. Recent studies have also reported that the accumulated contaminants in the subsoil affect the changes in the shearing strength properties of the soil, and accordingly, the bearing capacity of foundations rested on them (Nezhad et al., 2021; Ostovar et al., 2021; Ahmadi et al., 2021; Hanaei et al., 2021; Portelinha et al., 2021; Li et al., 2020; Kererat, 2019; Fazeli et al., 2021).

Today, the domain of oil pollutants has been extended to construction projects so that by leaking and penetrating these contaminations into the soil under the structure's foundation. As shown above, previous studies have dealt with oil and petroleum-contaminated soils physical properties and behavior, although little data is available concerning the effect of soil oil contamination on the bearing capacity and settlement of shallow foundations. Thus, this study provided a numerical program to determine the effect of sandy soil contamination on the bearing capacity of circular foundations. Furthermore, the results covered those collected from the uncontaminated soil.

2. Materials and Methods

Abtahi and Hajiani Boushehrian (2020) studied the experimental behavior of circular foundation on oil contaminated sand. Based on that study, a numerical model has been created and verified in this paper. After verification, a parametric study has been done. The effect of different variables has been studied in numerical model. According to the unified classification system; type of soil used in this study is SP. The soil grain size distribution curve has been shown in Fig. 1. The soil moisture content used during testing was kept below 1 percent. Kerosene and gas oil were utilized in order to contaminate the soil. Table 1 is a summary of the basic oil properties. The soil wet density was kept between 1.75 to 1.80 grams per cubic centimeter. The direct shear test was conducted on a soil sample with the same laboratory compaction, showing an internal friction angle of 32 degrees. Some of the sandy soil characteristics have been presented in Table 2. Another Direct shear tests were conducted to determine the angle of internal friction on different percentages of soil contamination and the results have been presented in Table 3. The output curves of direct shear test are presented in Figs. 2 and 3. The reported friction angel was measured at peak. As can be seen from the results, because the sand grains are covered with more contamination, the internal friction angle shows smaller values.

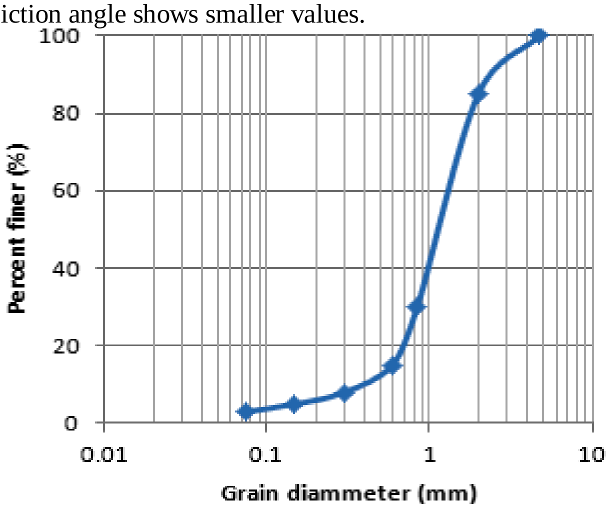

Figure 1. The grain size distribution curve of the sand

Table 1. The oil properties

Oil type	Density max (kg/l)	Viscosity Kinematic (m²/s)
Kerosene	0.820 @ 15ºc	$2.71*10^{-6}$ @ 37.8ºc
Gas oil	0.86 @ 15ºc	$200.0*10^{-6}$ mm²/s @ 37.8ºc

Table 2. Properties of reinforcement

No.	Property	Unit	Value
1	Specific gravity	G_s	2.65
2	Effective particle size	mm	0.4
3	Average particle size	mm	1.20
4	Uniformity coefficient	-	3.26
5	Coefficient of curvature	-	1.36
6	Average wet unit weight	kN/m³	17.75
7	Angle of internal friction	degree	32

Table 3. Shear strength parameters of sandy soil contaminated with gasoil and kerosene at different percentages of contamination

Row	Contamination Material	Contamination (%)	Cohesion (kPa)	Friction (º)
0	Clean Sand	0	5.90	33.00
1	Gas Oil	1	7.00	28.00
2	Gas Oil	2	7.24	27.38
3	Gas Oil	3	7.24	26.95
4	Gas Oil	4	6.70	26.00
5	Kerosene Oil	5	6.71	27.40
6	Kerosene Oil	6	6.71	26.50
7	Kerosene Oil	7	6.71	26.10
8	Kerosene Oil	8	6.71	25.60

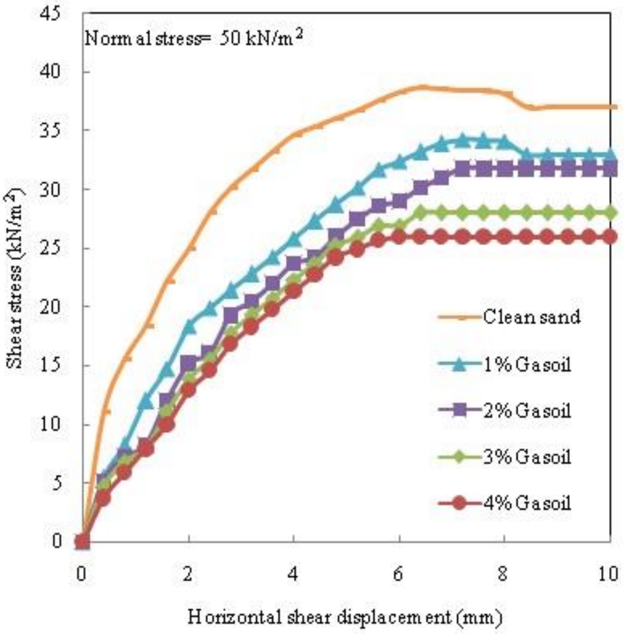

Figure 2. Shear stress variations against horizontal displacement for gas oil contaminated sand

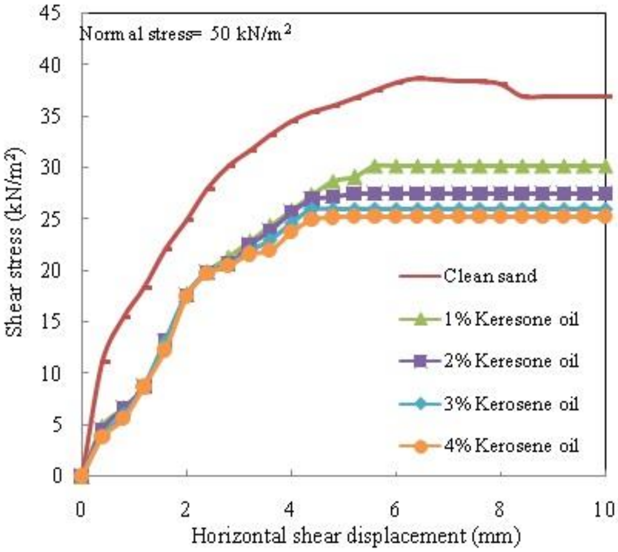

Figure 3. Shear stress variations against horizontal displacement for kerosene oil contaminated sand

A numerical model was created by a computer program to predict the different conditions behavior. In addition, the numerical model validated by the experimental results can decrease the laboratory tests with different conditions, which can have economic benefits. Plaxis2D, which is two-dimensional finite element software for the static and dynamic stress-strain analysis of soil and rock, has been used in this research. This software is able to prepare load-settlement curves and determine the ultimate bearing capacity of circular foundations. The circular foundation has been created based on the software ability of axial symmetry modeling. Fig. 4 shows one of the models created by Plaxis2D software. The model was created with the dimension 1(m) x 0.5(m) (half actual experimental model). The foundation is also modeled as a steel plate with a circular shape of 10 cm in diameter and 5 cm thick. The depth of soil contamination used in the software is defined as a separate layer with different specifications

To introduce the contaminated soils, their strength parameters have been conducted from the direct shear test according to Table 2. Load diagrams are plotted from the output results of the software. The bearing capacity of the foundation is calculated from these graphs. The bearing capacity of the foundation is considered to be the point of the load-settlement diagram, which corresponds to 10% of the foundation diameter. For a better investigation and comparison of the parameters, the BCR bearing capacity ratio is defined as follows.

$$BCR = \frac{q_{con}}{q_{uncon}} \tag{1}$$

where q_{con} and q_{uncon} are the ultimate bearing capacity of the contaminated and uncontaminated soil, respectively. In the numerical modeling, the same laboratory tests as described in Table 3 were carried out. The Mohr-Coulomb behavior model was utilized for analysis. Other required parameters were obtained based on multiple attempts in order to match the numerical and experimental results. U/B ratio has also been used to investigate changes in the bearing capacity with the depth of contamination. Where U is the depth of pollution and B is the diameter of the foundation.

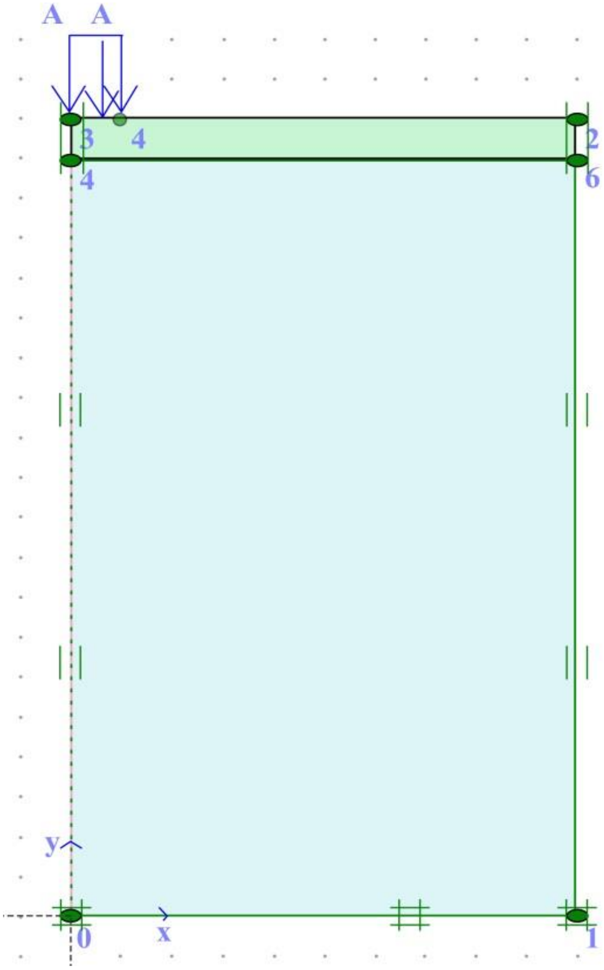

Figure 4. Numerical model sample

3. Results and Discussions

3.1. Verification of Finite Element Model

For verification the initial created model in the software, the results of experimental and numerical load-settlement of circular footing on contaminated sand with 2 percent kerosene and gasoil contamination have been studied in Figures 5 and 6.Experimental results have been extracted from Abtahi and Hajiani Boushehrian (2020) study. In all these cases, U/B=1.5. As the results, the maximum difference between experimental and numerical load carrying capacity was up to 10 percent. As is clear, there is a good agreement between experimental and numerical results.

3.2. Studying the variation of contamination layer thickness

Figures 7 and 8 are the load-settlement curves for circular footing rested on kerosene and gas oil contaminated sand extract from the software output in the case of 2 percent pollution and in the U/B equal to 0.5, 1.0, 1.5, and 2. The bearing capacities for all percent and depth of pollutant have been shown in Tables 4 and 5. As it can be seen, by increasing the contaminated layer thickness, the bearing capacity of foundation dramatically decreases. The main cause of this fact is decrease the friction between soil particles in foundation effective zone. Based on the results, one can say that the contamination layer is considerably influence the bearing capacity of the foundation. According to Figs. 9 and 10 for values of U/B greater than 1, the slope of BCR changes versus U/B is significantly reduced. This can be explained by the fact that the contaminated area is out of the failure zone under the foundation.

3.3. Studying the variation of contamination percent

Figures 10 and 11 show the load-settlement curve for circular foundation rested on gas oil and kerosene oil in the case of U/B=0.5 and pollution percent equal to 0, 1, 2 and 3. The BCR for this condition and any other pollution depth have been indicated in tables 4 and 5. As it can be seen, the bearing capacity decreases by increasing the pollution percent. The main cause of this reduction is the decrease of N_c and N_γ factors in bearing capacity formula.

In order to compare the results extracted from numerical model and analytical methods, by considering $N_\gamma = 36.5$, $N_c=52.6$ and average soil unit weight equal to 17.75 KN/m3, the bearing capacity of circular foundation with 10 cm diameter on the clean sand, based on the Terzaghi’s method, is 440 kPa. This value has just 9 percent different with numerical modeling. In soils contaminated with kerosene and gas oil, an increase in the percentage of contamination resulted in changes in cohesion and internal friction angle. Therefore in order to calculate the bearing capacity of contaminated sand soils, it is necessary to consider the N_c and N_γ coefficients based on the percentage of contamination and the thickness of the contaminated layer.

3.4. Studying the type of contamination percent

As shown in Tables 4 and 5, in all percentages and depths of pollution, the effect of kerosene oil on reducing the bearing capacity is greater than that of gas oil. In such a way, kerosene oil can reduce bearing capacity up to 47 percent and gas oil decreases it up to 45 percent. Based on the obtained numerical results in percentages and depths of different contamination, using the Table Curve software, the following equations are derived to calculate the bearing capacity of a circular foundation on sandy soils contaminated with gas oil and kerosene oil.

a) The relations used for kerosene oil:

$$q_{\text{ult}}\,(\text{kPa}) = (7242 + \frac{1770.23}{X} + \frac{1770.23}{Y}) \tag{2}$$

b) The relations used for gas oil:

$$q_{\text{ult}}\,(\text{kPa}) = (15771 - 2575X - 643.7Y) \tag{3}$$

where q_{ult} is the ultimate bearing capacity, X is the percentage of contamination and Y is the thickness of the contaminated layer.

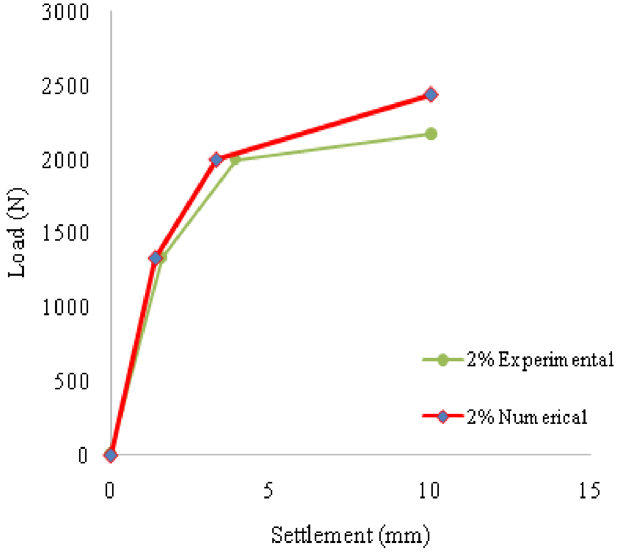

Figure 5. Load-settlement curve of the circular foundation rested on the soil contaminated with gas oil with the contamination depth ratio of 1.5 and contamination of 2%

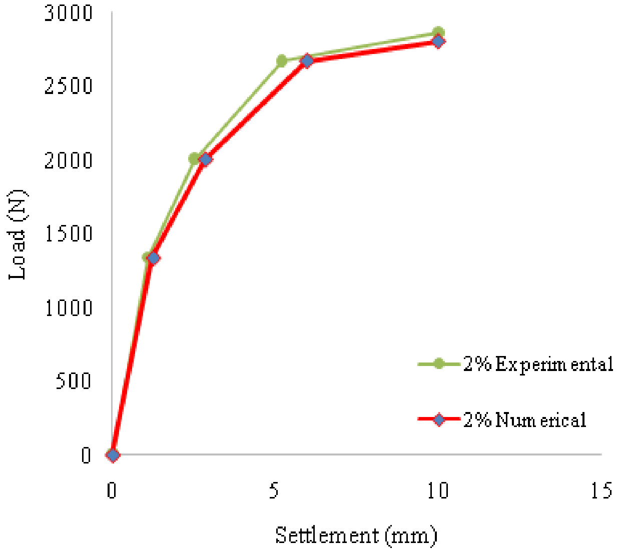

Figure 6. Load-settlement curve of the circular foundation rested on the soil contaminated with kerosene oil with the contamination depth ratio of 1.5 and contamination of 2%

Table 4. BCR for the circular foundation placed on sandy soil contaminated with gas-oil

Series	Contamination material	U/B	Contamination (%)	Bearing capacity (KPa)	BCR
CS	Clean Sand	0.0	0	482.80	1.00
GO1-1	Gas Oil	0.5	1	432.68	0.90
GO2-1	Gas Oil	0.5	2	422.68	0.88
GO3-1	Gas Oil	0.5	3	407.23	0.84
GO4-1	Gas Oil	0.5	4	381.78	0.79
GO1-2	Gas Oil	1.0	1	376.69	0.78
GO2-2	Gas Oil	1.0	2	361.42	0.75
GO3-2	Gas Oil	1.0	3	351.24	0.73
GO4-2	Gas Oil	1.0	4	320.70	0.66
GO1-3	Gas Oil	1.5	1	371.60	0.77
GO2-3	Gas Oil	1.5	2	356.33	0.74
GO3-3	Gas Oil	1.5	3	346.15	0.72
GO4-3	Gas Oil	1.5	4	315.20	0.65
GO1-4	Gas Oil	2.0	1	361.42	0.75
GO2-4	Gas Oil	2.0	2	346.15	0.72
GO3-4	Gas Oil	2.0	3	335.97	0.70
GO4-4	Gas Oil	2.0	4	310.51	0.64

Table 5. BCR for the circular foundation placed on the sandy soil contaminated with Kerosene

Series	Contamination material	U/B	Contamination (%)	Bearing capacity (KPa)	BCR
CS	Clean Sand	0.0	0	482.80	1.00
KO1-1	Kerosene Oil	0.5	1	357.90	0.74
KO2-1	Kerosene Oil	0.5	2	350.80	0.73
KO3-1	Kerosene Oil	0.5	3	340.80	0.71
KO4-1	Kerosene Oil	0.5	4	327.39	0.68
KO1-2	Kerosene Oil	1.0	1	339.36	0.70
KO2-2	Kerosene Oil	1.0	2	299.20	0.62
KO3-2	Kerosene Oil	1.0	3	284.40	0.59
KO4-2	Kerosene Oil	1.0	4	280.60	0.58
KO1-3	Kerosene Oil	1.5	1	311.20	0.64
KO2-3	Kerosene Oil	1.5	2	276.90	0.57
KO3-3	Kerosene Oil	1.5	3	270.30	0.56
KO4-3	Kerosene Oil	1.5	4	254.52	0.53
KO1-4	Kerosene Oil	2.0	1	286.00	0.59
KO2-4	Kerosene Oil	2.0	2	274.80	0.57
KO3-4	Kerosene Oil	2.0	3	268.70	0.56
KO4-4	Kerosene Oil	2.0	4	254.52	0.53

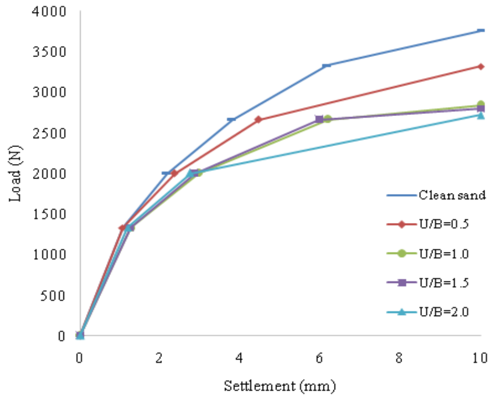

Figure 7. The load-settlement curves for circular foundation placed on a sandy soil with gasoil

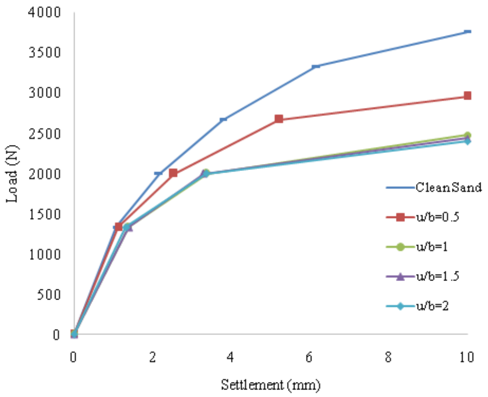

Figure 8. The load-settlement curves for circular foundation placed on a sandy soil with kerosene

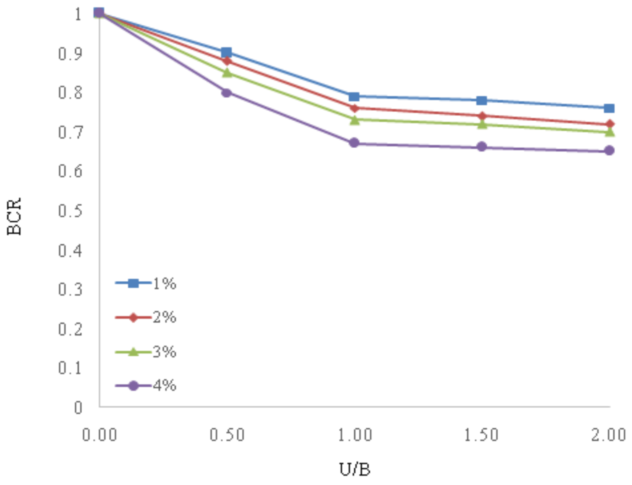

Figure 9. BCR changes with U/B for soils contaminated with gasoil

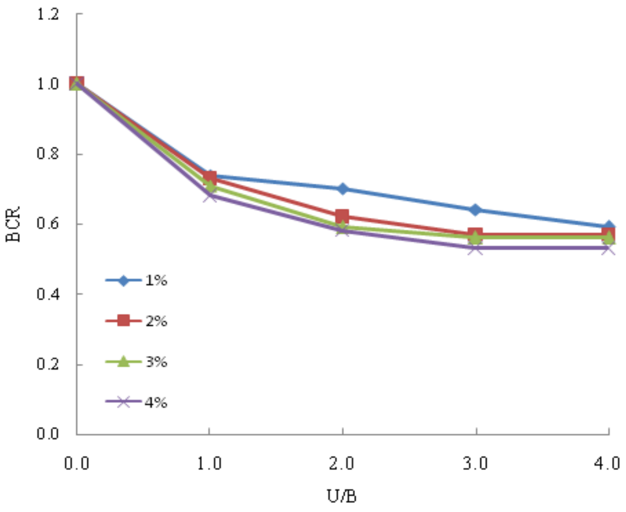

Figure 10. BCR changes with U/B for soils contaminated with Kerosene

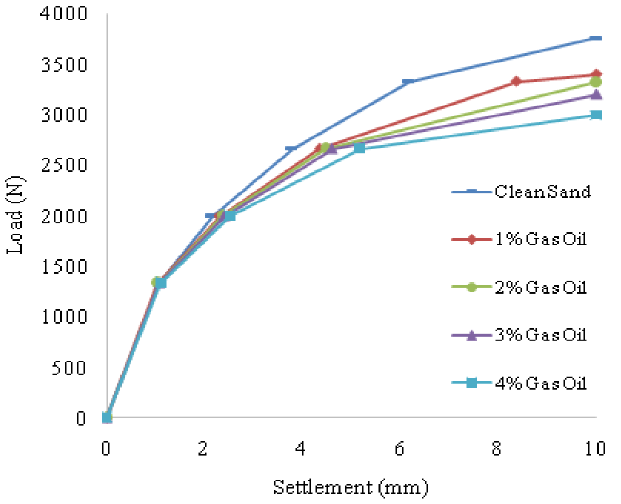

Figure 11. Load- settlement curves of the circular foundation placed on the sandy soil contaminated with gasoil (U/B = 0.5)

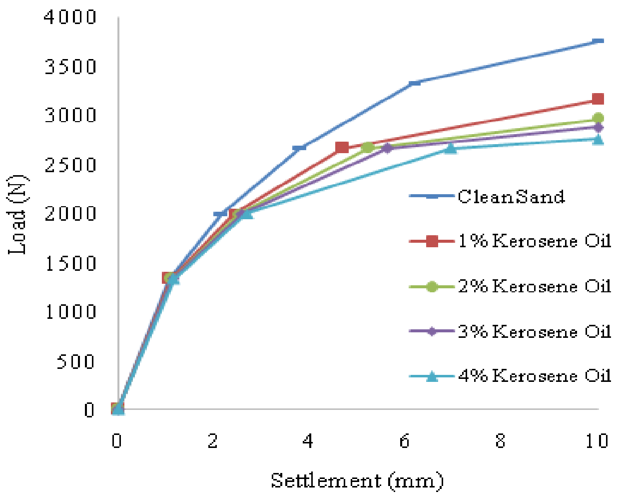

Figure 12. Load- settlement curves of the circular foundation placed on the sandy soil contaminated with kerosene (U/B = 0.5)

4. Conclusion

The researcher in this paper used finite element software to investigate the bearing capacity of a circular foundation on sandy soil in non-polluted and contaminated conditions with two pollutants of kerosene oil and gas oil (in different percentages and depths of contamination), reported the following results:

Increasing the percentage and depth of pollution in contaminated sand with both kerosene oil and gas oil contaminants reduced the bearing capacity of the circular foundation. However, the reduction rate was no significant for pollution percentages above 2% and the depth of pollution greater than the footing width (U> B).

Kerosene oil could reduce the bearing capacity up to 47% and gas oil up to 45%.

Bearing capacity ratios (BCRs) showed that increasing the depth of contamination reduced the bearing capacity more significantly than increased contamination.

Comparing the data on kerosene oil and gas oil indicated that the pollution of sandy soils with kerosene oil reduced the bearing capacity more significantly than oil gas pollution.

In all percentages of contamination, increasing the depth ratio (U/B) of pollution from zero to 0.5 would significantly reduce the bearing capacity. However, for depths with U/B>1, the reduction in bearing capacity decreases attributable to the fact that the contaminated layer can be removed from the failure zone under the footing.

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