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A Correlation between the Effect of Homogenous and Non-Homogenous Oil Contamination Dispersions on the Ultimate Load-Bearing Capacity of Pile Foundations Buried in Silty Sand

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ABSTRACT

In recent years, hydrocarbon contaminants have immensely influenced their surrounding environments, especially in soil mediums. The crude oil contaminations have also had a significant share of these impacts. The contaminations caused by the dispersion of hydrocarbon contaminants in soil mediums not only influence the chemical and geotechnical properties of soils, but also affect the strength of structures associated with the contaminated soil such as the deep foundations. In this research, besides analyzing the geotechnical properties of the oil-contaminated silty sand specimens under homogenous and non-homogenous oil dispersion conditions, the PLAXIS 2D finite element software was used to model the research problem and analyze the load-bearing capacity of the buried pile foundations. A relation was also proposed to establish a satisfactory correlation between the results from both contamination conditions using a suitable determination coefficient. The results from this research showed a considerable decrease in the load-settlement values tolerated by the buried pile under both soil contamination conditions. This decrease revealed a satisfactory correlation between the results from the one-dimensional contamination dispersion and the maximum homogenous soil contamination.

Keywords
Hydrocarbon contaminant, Homogenous and non-homogenous oil dispersion, PLAXIS 2D, Buried pile, One-dimensional contamination dispersion

Introduction

The air and water resources as well as soils and their surrounding environments have undergone irreversible damages as a result of human activities. Among the existing pollutants, hydrocarbon contaminants have had a large role in the production of environmental pollutions (Mohamadi et al. 2010). These pollutions are extremely common in petroleum-rich countries due to the contamination of soil with petroleum products in the course of refining and transportation processes (Zomorodian et al. 2018). Hydrocarbon compounds, especially crude oil, have considerably influenced the physical properties of soils as well as their chemical properties. The changes in the geotechnical properties and strength of soils have been significant in geotechnical engineering. They also manifest as the variations of the physical properties of granular soils and textural and structural changes in cohesive soils (Mohamadi et al. 2010; Zomorodian et al. 2018). These changes can also affect the strength and geotechnical properties of soil-related structures such as buried foundations and piles. To wit, any alteration of one of the aforesaid parameters changes the maximum load-bearing capacity of the soil or the foundation. Moreover, although methods such as adding plain Portland cement, nanomaterials, and nanosilica can improve the geotechnical properties of soil and reduce its permeability and adverse environmental impacts, this method is quite expensive (Zomorodian et al. 2018; Saberian and Kaberian 2018).

The research and studies carried out in recent years have only been limited to the effects of hydrocarbons such as crude oil on the strength and geotechnical parameters of soils. In other words, these studies have only explored the effect of hydrocarbon contamination percentage on the physical, chemical, and geotechnical parameters. Hence, the effect of this phenomenon has not been studied using contaminant dispersion equations, and no sensitivity analysis has determined the effects of contaminant dispersion on the load-bearing capacity of deep foundations. These issues were, therefore, the advantages and innovations of this research.

In general, studies conducted on this topic can be classified into the following 3 categories.

1- Studies on the effect of hydrocarbons dispersion on the strength and geotechnical soil properties

2- Studies on the transport of hydrocarbon contaminants in soil
3- Studies on the load-bearing capacity of foundations buried in hydrocarbon-contaminated soils

The first group of studies included the research by Evgin and Das (1992), who studied the oil-contaminated quartz specimens and uncontaminated specimens. Their findings mirrored a relatively drastic decrease in the internal angle of friction in the compact and uncompact specimens saturated with oil. The drastic increase in the volume strain and the increased foundation settlement due to oil contamination were the other advantages of their research.

Aiban (1996) studied the effect of temperature on the strength, permeability, and compressibility of an oil-contaminated sand specimen and concluded that at temperatures higher than the room temperature, the variations of compressibility of oil-contaminated soil increased, whereas the shear strength parameters of the compressed specimen did not vary considerably by temperature.

Ismael and Al-Sanad (1997) explored the effect of time on the strength parameters of oil-contaminated sandy soils. Their experimental findings revealed that the hydrocarbon contamination decreased gradually over time, resulting in an increase in the internal angle of friction. They also carried out a series of experiments such as the Marshal test to analyze the porosity (%) of the mentioned sandy specimens with 5% bitumen. They reported that these materials can be used in asphalt concrete due to their significant contribution to the improvements in contaminated soils.

Puri (2000) assessed the geotechnical properties of oil-contaminated soils by conducting experiments on the sand and gravel specimens. Their findings revealed the effects of oil and gas contamination on soil compressibility. Moreover, it was found out that the internal angle of friction of sand and gravel decreases under the overall stress conditions despite the presence of oil in the pores.

Ratnaweera and Meegoda (2006) carried out a series of unconfined compression tests on fine-grained soil specimens contaminated with varying amounts of chemicals. They used glycerol, propanol, and acetone as contaminants, and the test results were indicative of a decrease in the shear strength and the stress-strain behavior of the soil specimens.

The research carried out by Khamehchian et al. (2007) on three soil specimens, namely SM (sitly sand), SP (poorly graded sand), and CL (lean clay) specimens, to identify the effects of oil contamination on the geotechnical properties of the mentioned specimens is another example of research on this topic. Their experimental findings reflected a decrease in the permeability and the maximum shear strength of all three specimens, a decrease in the maximum dry density, and a decrease in the optimal humidity (%).

Olchawa and Kumor (2007) analyzed the effect of diesel on the compressibility of organic soils. They reported an increase in soil compressibility with an increase in the diesel volume.

Jia et al. (2011) carried out an in-situ experiment to determine the effect of contamination with crude oil on the geotechnical properties of soil. Their findings indicated that the number of clay particles (smaller than 0.005mm) was higher in the specimens with severe contamination, but the Atterberg limits increased with oil contamination.

Khosravi et al. (2013) studied the effect of oil and gas contamination on the geotechnical properties of kaolinite. Their findings showed an increase in cohesion and a decrease in the internal angle of friction and compressibility of kaolinite soils with an increase in the oil and gas content.

Nasehi et al. (2016) investigated the effect of oil and gas contamination on the geotechnical properties of some soil specimens such as poorly-graded sand specimens (SP) and clay and silty specimens with low plasticity (CL, ML). The uncontaminated specimens were examined experimentally by the plasticity, compression, unconfined compressive strength, and direct shear tests. The specimens were artificially contaminated with oil and gas contaminants 3, 6, and 9% by their dry weight. The experimental results indicated that an increase in the concentrations of oil and gas reduces the internal angle of friction and soil cohesion. Moreover, a decrease in the maximum specific dry weight and optimal humidity was observed in the compression test. The investigation results indicated that an increase in the concentrations of oil and gas directly affects the fluidity and plasticity of clay and silty soils. On the other hand, an increase in the concentration of oil and gas has an inverse effect on the compressive strength of unconfined soils.

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Ghasemzadeh and Tabaiyan (2017) studied the effect of different additives such as lime, cement, rice husk ash and RRP-235 Special on the geotechnical properties of a diesel fuel contaminated kaolinite. Results showed that an increase in diesel fuel as contaminant up to 10% by dry weight of the soil, had adverse effects on lime and rice husk ash stabilized soil strength and cohesion, while it increased the strength and cohesion of cement stabilized soil. The friction angle of all the lime, cement and rice husk ash stabilized specimens also decreased with an increase in the contaminant.

Safehian et al. (2018) studied an illite clay soil specimen polluted by different amounts of diesel (0 to 20% by soil dry weight). In this paper, the geotechnical properties of clean and contaminated illite specimens including the compaction characteristics, compressibility, shear strength parameters and unconfined compression strength were evaluated through compaction, consolidation, direct shear and unconfined compression tests, respectively. Additionally, the effect of diesel on the microscopic properties of the illite was studied by scanning electron and atomic force microscopes. The findings from the study indicated a decline in the maximum dry density and an increase in the optimum fluid content in the presence of diesel. The compressibility of the soil increased when it was exposed to the organic fluid. Adding diesel reduced cohesion, internal friction angle and unconfined compressive strength of the soil.

The second group of studies included studies such as the research by Van der Warder et al. (1971), who used an experimental model and glass particles without absorption properties to analyze the transportation of hydrocarbon contaminations such as oil contamination from an oily waste region to a water-carrying soil region. The results from these studies revealed that the components of leakage at the source of contamination could be calculated using the water flow and the velocity obtained using the diffusivity coefficient of the components. The research by Meegoda et al. (1993) on the short- and long-term permeability of clay specimens was another study conducted on this topic. In fact, their research results revealed that the variations of the hydraulic conductivity coefficient result from the fluid viscosity variations while the intrinsic permeability remains constant.

In 1994, Zhou conducted experiments to analyze the transport of diesel and JP-5 fuel in sandy soil and regular soil mediums. He also studied the transportation of these contaminants in the mentioned soil mediums through long-term large-scale three-dimensional tests. The test results indicated that the transport of diesel in a sandy medium occurs at a lower speed than the transport of JP-5 fuels in these mediums, and both forms of transport occur along the horizontal and vertical directions. In addition, the transport of fuel in regular soils is more limited than the transport of fuel in sandy soild, while the measured concentrations in soil also exceeded the measurements in sand.

Lee et al. (2001) conducted studies on the determinants of the diffusivity of hydrocarbon contaminants in relatively narrow sandy aquifers. Conducting chemical tests on groundwater resources and collecting samples from different depths in a sandy medium by drilling observation wells and installing piezometers in the wells were among the actions taken in their research. The findings from this research revealed the determinants of oil decontamination such as the fluctuations of water level, decontamination efficiency, underground water conditions, and the biological analysis of contaminants.

Qin et al. (2009) proposed a suitable method of modeling and optimizing the hydrocarbon waste management methods and controlling hydrocarbon decontamination solutions to develop a hybrid model for estimating the dispersion behavior of contaminants in the vicinity of water and soil mediums. They also introduced the best and most effective contaminant management method and described the application of various efficient methods to oil decontamination and remediation under different environmental and actual conditions.

Hulagabali et al. (2014) proposed a two-dimensional model for the transport of pollutants dissolved in a saturated porous medium. Their model offered a numerical method for the two-dimensional transport of contaminants in saturated porous mediums using the finite difference method. The results from this model were compared to the output of CTRAN, which is a software solution for solving the contaminant transport and dispersion equations using the finite element method.

Komeili and Akhtarpour (2017) carried out a numerical analysis of the dispersion of oil contamination in unsaturated soils to conclude that the penetration depth of contaminants decreases significantly with a decrease in the soil grain size.

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
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The third group of studies included the research by Shin et al. (1999), who examined the load-bearing capacity of foundations in sandy soils contaminated with crude oil. Their findings not only changed the amount of the oil contaminant from 0 to 4.2%, but also indicated that the decrease in the angle of friction following the increase in the oil concentration reduced the load-bearing capacity. Their findings also indicated that the results from the direct shear tests represent the actual medium conditions, and a higher than 1.3-percent increase in contamination does not considerably influence the ultimate load-bearing capacity. The research by Nasr (2009), which was carried out for numerically and experimentally investigation of the effect of hydrocarbon contaminants on the ultimate load-bearing capacity and strip foundations, is another study in this category. Their findings indicated that the decrease in the load-bearing capacity is determined by the mechanical properties of oil contaminants, soil type, medium temperature, and humidity. In fact, the decrease in the load-bearing capacity and the increase in the settlement of foundations in contaminated soils are extremely higher with a heavy contaminant than the decrease obtained using the same foundation in a soil contaminated with a lighter oil contaminant.

Pousti and Jalali (2014) numerically analyzed the effect of crude oil contamination on the load-bearing capacity of strip foundations using the capacity ration (f). They studied the effects of contamination depth and foundation burial depth by defining the ratio of decreased contaminated oil strength to the load-bearing capacity of the same foundation in uncontaminated soil. Their studies revealed that contamination with crude oil often reduces the load-bearing capacity and the load-bearing capacity only escalates in poorly graded sandy soils. This is caused by the increase in the cohesion of soil due to oil viscosity. They also used the Ordinary Least Squares (OLS) method to propose the experimental equations in relation to the oil contamination level and utilized foundation burial depth to calculate the strength reduction factor in three types of sandy soils, namely poorly-graded sandy soil, low-activity clay, and silty sand.

In 2012, Forouk and Shaien studied the behavior of foundations in delta soils. Their experiments indicated that with an increase in the contaminant viscosity, the reduction in the friction resistance increases. Moreover, the angle of friction decreases with an increase in the fine grains. These experiments revealed three types of behavior in the load-settlement curves. One behavior showed overall failure and the other two showed local failure. In the specimens experiencing local failure, the compressibility was higher in the upper contaminated layers than the clean lower layers. The analysis of the load-bearing capacity also showed a trend similar to the effect of contamination on the soil shear strength. The results from the bed modulus measurements in this study mirrored a decrease in this modulus with an increase in the fine grains and an increase in the contamination-induced settlement.

Frances (2013) carried out a case study on the relationship between the load-bearing capacity and contamination percentage. He used intact specimens to measure the strength and bulk density of clean soils. He also built simulated specimens to measure this parameter with varying degrees of contamination. In this research, the load-bearing capacity of strip and square foundations buried in contaminated soil with different contamination percentages was calculated, and the data analysis in SPSS (Statistical Package for Social Sciences) revealed the linear relationship between contamination percentage and load-bearing capacity reduction.

The present research was an attempt for calculating and studying the load-bearing capacity of deep foundations under the effect of homogenous oil contamination and non-homogenous oil dispersion using a one-dimensional dispersion equation and the strength and geotechnical parameters of specimens contaminated with hydrocarbons. Afterwards, the satisfactory correlation between the results from both analyses was formulated using the maximum homogenous contamination and one-dimensional oil dispersion conditions. Hence, first, the soil specimen was described along with the strength and geotechnical parameters for different percentages of homogenous contamination. Next, the one-dimensional dispersion equation for contaminants in soil was introduced and applied to the study`s problem. The software solution used in this research was also introduced along with the problem modeling process. Afterwards, the load-settlement behavior of the pile foundation and the correlation between the results from both analyses were studied by analyzing the results from the exact modeling process. One of the most important applications of this method is in the design of off-coast oil platforms and platforms in oil fields, which are prone to hydrocarbon contaminations.

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
Received 25 April 2021; Accepted 08 May 2021.

Materials and Methods

Studied Soil Specimen

In this study, the silty sand specimen used by Khamehchian et al. in their 2007 research and experiments was employed based on the joint research carried out by Tarbiat Modares University and the Soil Conservation and Watershed Management Research Institute on the coastal soil of Bushehr. The gradation curve of this silty sand has been presented in Figure (1). After classifying the specimens by grain size, the specimens were grouped into five categories and were dehydrated completely at 105 $^{\circ}C$ in an oven. Next, each specimen was mixed with 0, 4, 8, 12, and 16% of crude oil by their dry weight and were tested. The geotechnical characteristics of the silty sand specimen have been listed in Table (1).

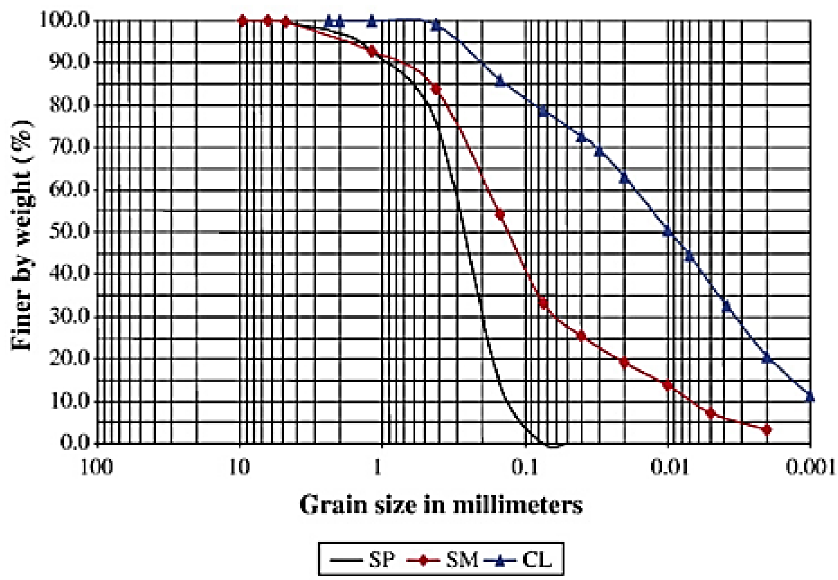

Figure 1. Gradation curve of the silty sand (Khamehchian et al. 2007)

Table 1. Geotechnical properties of oil contaminated silty sand (Khamehchian et al. 2007)

Modulus of elasticity (kg/cm^2)	**Apparent specific gravity(gr/cm^3)**	**Saturated specific weight (gr/cm^3)**	**Dry specific weight (gr/cm^3)**	**Water content (%)**	**Dilation angle**	**Internal angle of friction**	**Apparent cohesion(kg/cm^2)**	**Oil content (%)**
49/821	2/156	2/160	1/9	13/5	3/517	33	0/272	0
44/643	2/046	2/142	1/87	9/43	3/398	32/9	0/195	4
48/153	1/998	2/124	1/84	8/57	2/332	32	0/227	8
39/811	1/942	2/124	1/84	5/55	0	26/2	0/210	12
21/128	1/860	2/112	1/84	5/55	0	26/2	0/21	16

It is worth noting that in the above table, the lateral dilation angle was obtained using relation (1), which was introduced by Schanz and Vermeer (1996).

$$\sin\psi = \frac{\sin\phi - 0.5}{1 - 0.5\sin\phi} \quad (1)$$

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
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Equation and theory of contamination dispersion

The contamination dispersion in soil mediums with the weakening parameters (surface absorption and radioactive decomposition) has been defined as the following basic differential equation (Sabzipour et al. 2016a; Fetter 1999).

$$(\theta + \rho_d \frac{\partial s}{\partial c})\frac{\partial c}{\partial t} = \theta D\frac{\partial^2 c}{\partial x^2} - V\frac{\partial c}{\partial x} - \lambda\theta C - \lambda S\rho_d \quad (2)$$

Where C is the soil contamination concentration, S is the surface absorption equal to the oil mass stuck on soil particles due to the separation from the contaminator particles (by weight of the soil mass), θ is the water volume in saturated and unsaturated soils, λ is the decomposition coefficient, D is diffusion coefficient in contamination dispersion, V is the apparent velocity of contamination flow in soil, ρd is the soil dry density, and x and t are the location and time variables, respectively (Sabzipour et al. 2016a).

It should also be noted that in the weakening part of the equation, the displacement and spreading processes are shown respectively by parameters S and λ.

Since the surface absorption and radioactive decomposition processes have been negligible in many studies, in this study, the S and λ terms in Relation 2 were also assumed to be equal to 0 for the purposes of simplification and development of the equation for the one-dimension dispersion conditions. Hence, the above Relation has been revised as follows (Ogata and Banks 19961).

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - V\frac{\partial c}{\partial x} \quad (3)$$

To solve the aforesaid equation, the appropriate boundary conditions were applied as described by Ogata and Banks (1961) and the equation was solved through relation (4), (Ogata and Banks 1996).

$$C(x,t) = \frac{C_0}{2}\left[erfc\left(\frac{x - V_s t}{2\sqrt{D_L t}}\right) + \exp\left(\frac{V_s x}{D_L}\right) erfc\left(\frac{x + V_s t}{2\sqrt{D_L t}}\right)\right] \quad (4)$$

It is also worth mentioning that for calculation of simplification purposes in practical applications, the second part of Relation 5 was assumed to be negligible and it was rewritten as follows (Sabzipour Hajianinia and Eslamian 2017a).

$$C(x,t) = \frac{C_0}{2}\left[erfc\left(\frac{x - V_s t}{2\sqrt{D_L t}}\right)\right] \quad (5)$$

Where Vs is the real linear mean velocity of the fluid flow in soil, DL is the coefficient of 1D diffusion of oil contamination along the depth, and x and t are the location and time variables, respectively. Moreover, Co is the contaminator concentration in soil, and erfc is a function of the value of which, as regards the subject of contaminator dispersion in soil mediums, is found via relations 6, 7 and 8. (Sabzipour et al. 2016a; Sharma and Krishna 2003).

$$erfc(u) = 1.0199 - 0.0878u^3 + 0.6064u^2 - 1.3724u \quad 0 \le u \le 3 \quad (6)$$

$$erfc(-u) = 1 + erf(u) \quad -3 \le u \le 0 \quad (7)$$

$$erf(u) = 0.878u^3 - 0.6064u^2 + 1.3724u - 0.0199 \quad 0 \le u \le 3 \quad (8)$$

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
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In the above Relation, parameter u, which is equal to the terms of arc erfc in the contamination displacement relations, has been calculated as follows (Sabzipour et al. 2016a).

$$u = \frac{x - V_s t}{2\sqrt{D_L t}} \quad (9)$$

Furthermore, to find Vs, Relation 10 (below) has been used with Darcy Law, which yields the water flow velocity in saturated soils (Das and Tahooni 2012).

$$V_s = \frac{K}{n} \quad (10)$$

In this research, to extend the resulting dispersion equation (relation 5) for a dispersion duration of 30 days, the dispersion equation for the study specimen under one-dimensional dispersion conditions (non-homogenous dispersion) has been expressed as follows (relation11) based on the permeability, equivalent porosity, contamination diffusion coefficient values listed in Table (2).

Table 2. Equivalent permeability, diffusion coefficient, and porosity.

Parameter	Unit	Value
Permeability (K)	m/s	3.62E-6
Coefficient of longitudinal diffusion (DL)	m2/s	1E-7
Porosity (n)	-	0.28

$$C(x,30) = \frac{16}{2}\left[erfc\left(\frac{x-33.51}{1.018}\right)\right] \quad (11)$$

Based on relation (11), the oil contamination variations` curve for the silty sand specimen under one-dimensional dispersion conditions was depicted in Figure (2).

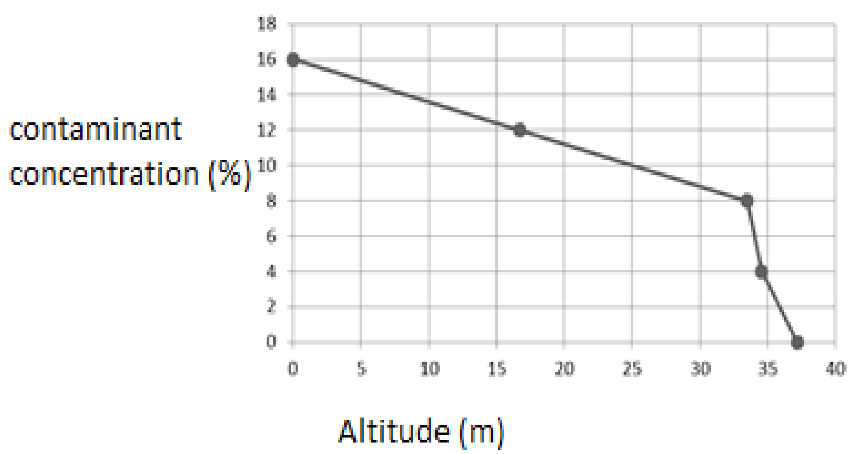

Figure 2. Oil contaminator concentration variations in deep soil (Sabzipour et al. 2016a).

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
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Introduction of the software and modeling process

PLAXIS Software

PLAXIS is one of the most commonly used software for civil engineering, especially in the fields of geotechnical engineering. This software is used in almost all geotechnical projects. In fact, this software is a package of engineering modeling based on finite element method that allows the analysis of deformation and stability in geotechnical engineering projects. (Sabzipour et al. 2016b).

Hence, the two-dimensional version of this software was used in this research to model the study`s problem.

Validation of Software Results

Now, in order to validate the results from PLAXIS 2D, which was used in this study, an experimental model developed for estimating the load-bearing capacity of the pile foundations has been selected and it was then modeled and analyzed in PLAXIS 2D. At the end, the results from the software analysis were compared to the measurements by the experimental model to gain a good estimate of the validity of the model results. Therefore, the research by Shooshpasha and Sharafkhah (2013), who carried out an experimental and analytical study of settlement in in-situ concrete piles in sandy soil, was selected. The specifications of the selected sandy soil specimen and the pile foundation derived from their research have been also presented in Tables (3) and (4).

Table 3. Specifications of the sand specimen (Shooshpasha and Sharafkhah 2013).

Parameter	***Unit***	***Value***
Apparent cohesion	kg/cm^2	0/006
Internal angle of friction	deg	33
Elasticity modulus	kg/cm^2	120
Apparent specific weight	gr/cm^3	1/706
Saturated specific weight	gr/cm^3	2/126
Lateral dilation angle	deg	3/517

Table 4. Apparent specifications and load-bearing capacity of the pile (Shooshpasha and Sharafkhah 2013).

Pile specifications	**Unit**	**Value**
Pile geometry	-	Spherical
Pile type	-	In-situ concrete pile
Pile length	Cm	1000
Pile diameter	Cm	100
Length/diameter ratio	-	10
Ultimate load-bearing capacity	kN	35/6

Using the values presented in the above tables, the research problem was modeled and the load-settlement curve resulting from the software analyses was presented along with the load-settlement curve resulting from the experiments (Figure 3).

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
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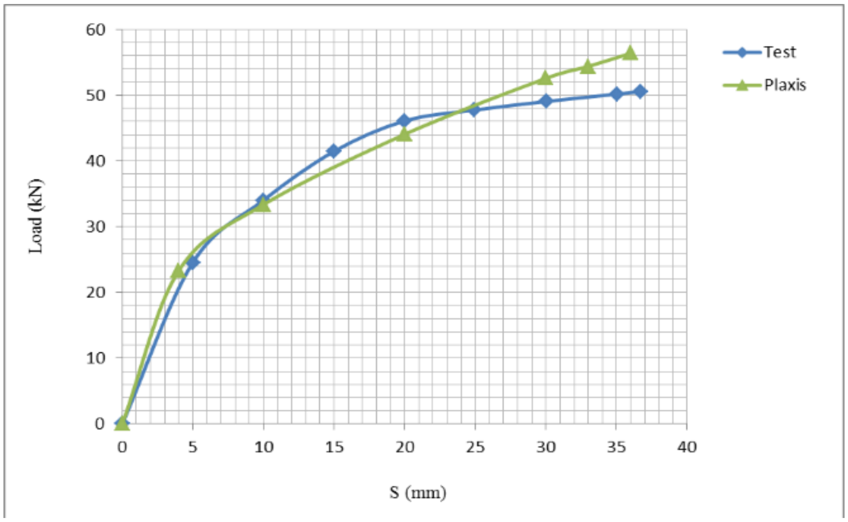

Figure 3. The load-displacement curves resulting from the software modeling and experiments for the validation analysis.

As seen in Figure (3), the difference between both curves was almost insignificant and below 20%. Table (5) presents the clear numerical results for the ultimate load-bearing capacity derived from the curves using Terzaghi's method(Terzaghi 1942). However, in Terzaghi's method, the ultimate load-bearing capacity of the pile equaled the load corresponding to a settlement , which equaled to 10% of the pile diameter.

Table 5. The ultimate load-bearing capacity calculated using Terzagh's method in the validation analysis.

Analysis type	*Ultimate load-bearing capacity from Terzaghi's method*
Experimental	6.35
Software	34.2

The ultimate load-bearing capacities presented in the above table were, in fact, indicative of the extremely satisfactory conformity between the software results and the experimental results with an approximately 4% difference. These values also reflected the high validity of the developed model as compared to actual conditions.

Modeling Process and Limits

Since the piles had axial symmetry and there was no need to fully model the medium, half of the pile dimension (i.e. D/2) was modeled in this research in the pile foundation modeling phase. Moreover, the distance of the boundaries from the pile was enough for neglecting the loading-induced stresses and deformations (Shooshpasha and Sharafkhah 2013).

The other specifications required for modeling the problem were the same as Tables` (6 and 7) data.

Table 6. Apparent specifications of the studied pile (Sabzipour et al. 2016a)

Pile specifications	***Description and values***
Geometry	Spherical
Type	In-situ concrete
Length (cm)	1000
Diameter (cm)	100
Length/Diameter ratio	10

Table 7. Specifications of the concrete used in pile modeling (Sabzipour et al. 2017b)

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
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Pile specifications	Unit	Value
Concrete Poisson's ratio	-	0/15
Young's modulus	Gpa	21
Pile foundation specific weight	Kn/m^3	25

Evaluating the Results and Outputs

Since the load-settlement curves are substantially important outputs, PLAXIS can be used to obtain the load-settlement curves of the soil mass or structure under study. Hence, using the process described in the previous sections, the results from modeling the study problem in the homogenous dispersion and non-homogenous one-dimensional dispersion conditions have been presented in the following as load-settlement curves.

The Load-Settlement Curves of the Studied Pile Foundation under Homogenous Oil Contamination Dispersion Conditions

In this section, based on the specifications of the oil-contaminated specimens (Table 1) and the other modeling conditions (Tables 2 and 3), the homogenous oil contamination dispersion conditions were modeled and studied with 0, 4, 8, 12 and 16 volume percent contaminations. Hence, the load-settlement curves of the pile buried in the soil specimens with certain percentages of homogenous contamination have been illustrated in Figure (4).

Moreover, in this section, the load-displacement curves for base piles buried in soils with 0, 4, 8, 12, and 16% oil contamination have been shown as P0, P4, etc., in Figure 4.

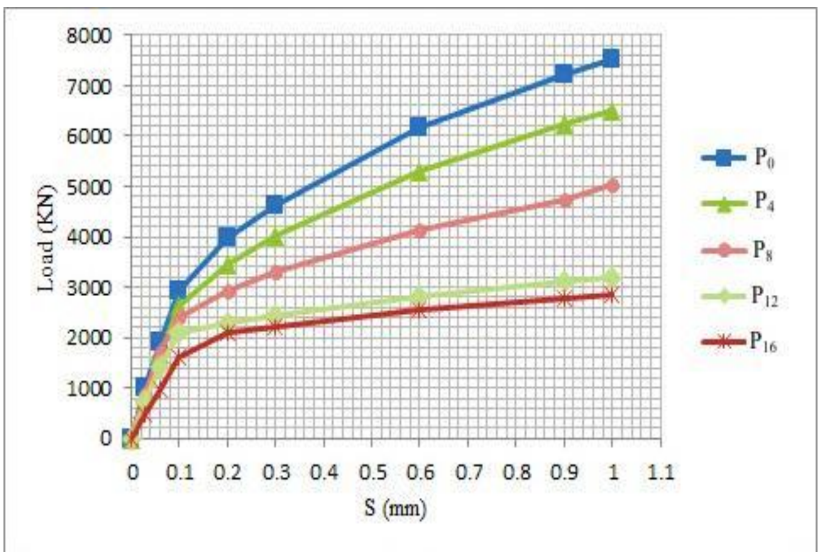

Figure 4. Piles' load-displacement curves (Sabzipour et al. 2017b)

As seen in the above figure, the load-settlement curve of the pile buried in the uncontaminated soil specimen (P0) had a higher level than the stress curve as compared to the other buried foundation curves in soil specimens for varying percentages of homogenous contamination. This difference became more evident as the percentage of soil contamination increased. In other words, the load-settlement curve level rised with an increase in the soil contamination percentage. In other words, as the hydrocarbon contamination increased in the soil specimen, the buried pile foundation lost its strength, leading to a decrease in the maximum load bearable by the pile foundation buried in this soil specimen.

Annals of R.S.C.B., ISSN:1583-6258, Vol. 25, Issue 6, 2021, Pages. 3571 - 3584
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Load-Settlement Curves of the Study Pile Foundation under One-Dimensional Oil Contamination Dispersion Conditions

Similar to the previous section, the non-homogenous oil contamination dispersion condition has been studied in this section using the one-dimensional contaminant dispersion equation, the oil-contaminated soil specimens, and the studied pile foundation specifications (relation 11). Hence, the load-settlement curves of the pile foundation buried in the contaminated soil specimen under one-dimensional contamination dispersion and uncontaminated conditions have been depicted in Figure (5).

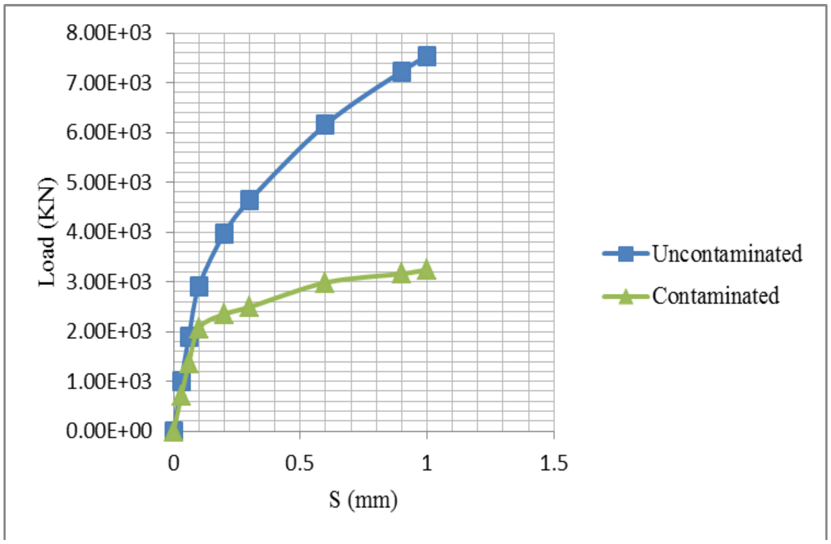

Figure 5. Load-displacement curves of piles buried in uncontaminated and oil-contaminated soils (Sabzipour et al. 2016a)

In the above diagram, the uncontaminated and contaminated curves represented the load-displacement curve of the pile foundation buried in the uncontaminated and oil-contaminated specimens, respectively.

The above curves suggested that considering the oil contamination dispersion in the study soil specimen, the load-settlement curve for the pile buried in the soil was on a lower level than the curve for the uncontaminated conditions similar to the previous case (homogenous dispersion).

The Correlation between the Results from Analyses under Homogenous and Non-homogenous Oil Contamination Dispersion Conditions

In this section, to attain one of the primary objectives and innovations of this research, an appropriate correlation relation was introduced to convert the results from the homogenous contamination analysis into non-homogenous hydrocarbon contamination results (i.e. one-dimensional dispersion). To this end, the load-settlement curves of the minimum and maximum homogenous oil contamination percentages and the load-settlement curves of the non-homogenous hydrocarbon contamination have been presented in Figure (6).

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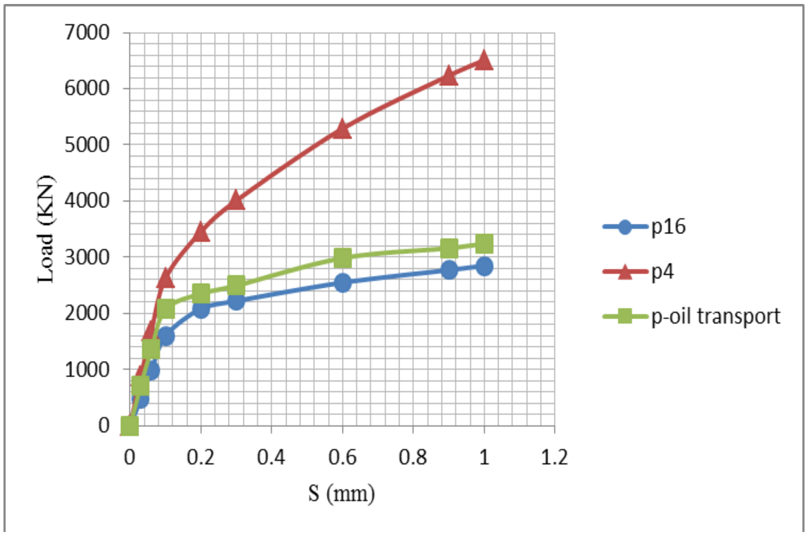

Figure 6. The load-settlement curves of the minimum and maximum percentages of homogeneous and non-homogenous oil contamination.

In the above figure, P16, P4, and P-oil transport represented the load-settlement curves of the foundation buried in the specimen with 16% homogenous contamination, the specimen with 4% homogenous contamination, and the specimen with the non-homogenous dispersion of hydrocarbon contamination. As seen in Figure (6), since the load-settlement variations for the 16% homogenous oil contamination were closer to the non-homogenous oil contamination dispersion conditions, a good correlation between the results from the maximum homogenous oil contamination (16%) and non-homogenous oil contamination (one-dimensional dispersion) conditions was obtained in accordance with relation (12) with an appropriate determination coefficient.

$$R^2 = 0.9936 \; g(S) = -3.4247S^4 8.7974S^3 - 7.7449S^2 + 2.666S + 0.5847 \qquad (12)$$

In fact, for settlements higher than 0.3mm, relation (12) provided an excellent correlation for converting the results from the analysis of the loads bearable by the buried foundation under the maximum homogenous oil contamination conditions (16%) and the results from the non-homogenous oil contamination conditions.

Conclusions

In this research, based on the geotechnical values of the silty sand specimens contaminated with different percentages of oil and the pile foundation specifications, the research problem was modeled in the PLAXIS 2D software under homogenous dispersion and one-dimensional dispersion (non-homogenous) conditions. The results from this research were assessed using the corresponding load-settlement curves. In fact, the research results revealed that the presence of hydrocarbons in the soil specimen reduced the load-bearing capacity of the buried pile foundations, which reflected the excellent conformity between the load-settlement behavior of the pile behavior curve under one-dimensional dispersion conditions and the maximum homogenous contamination conditions (16% contamination). Hence, a highly suitable correlation was observed between the results from the non-homogenous and homogenous hydrocarbon dispersion conditions. In fact, it is possible to access the results from the one-dimensional dispersion conditions within a 1-month period through the 16% homogenous oil contamination dispersion results and the correlation proposed in this research. This was, therefore, the advantage of the present research.

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