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Article · April 2016

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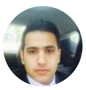

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ABSTRACT

Many research studies have been done on the effects of hydrocarbon (especially oil) contamination on such soil strength and geotechnical indices as cohesion, angle of internal friction, shear strength, permeability, dry density, and so on. In studying this phenomenon, it can be stated that the dispersion of hydrocarbon materials (such as oil) not only considerably affects the soil strength properties, but it also highly influences the maximum tolerable load or, in other words, the maximum bearing capacity of subsurface structures such as foundations. In this research, effort has been made to software model a buried concrete pile with specified dimensions using the results of the previous researches, geotechnical properties of the SM soil contaminated with hydrocarbon materials, and the PLAXIS 2D Software, and show precisely how 1D oil contamination dispersion in soil mediums affects the bearing capacity of the pile. Results of this research have revealed that the ultimate bearing capacity of piles buried in oil contaminated soils is reduced; the reduction for the pile studied in this research was 30%. In fact, 1D oil contamination dispersion in soil mediums highly affects the behavior and ultimate bearing capacity of buried piles.

KEYWORDS: strength indices, hydrocarbon contamination, mechanism of contaminator dispersion, bearing capacity, pile foundation.

INTRODUCTION

Nowadays, not only the air and water, but also soil and its surroundings are experiencing irrecoverable changes and contaminations due to human activities. In this regard, hydrocarbon compounds have a considerable share in contaminating the soil. This contamination (especially that with the crude oil) occurs through various sources among which leakage from oil transfer pipes, natural oil leakage, oil discharge from sea/land establishments, dust from oil-associated gas burning, and oil transportation or storage are very important and play vital role in spreading and dispersion of hydrocarbon contaminators in the soil medium and its surrounding aquifers. Hydrocarbon compounds (specifically crude oil) considerably affect not only the physical and apparent, but also the chemical properties of soils; in civil engineering, changes in the strength and geotechnical parameters of soil are quite serious. In granular soils, the changes are in the physical properties while in cohesive ones, the texture and structure are affected (Mohammadi Akbarabadi et al., 2010). Changes in physical properties (apparent cohesion, angle of internal friction, percent optimum moisture content, maximum dry density, and Atterberg limits) affect slope stability, foundation load bearing capacity, and the like. A change in any of the mentioned parameters, can lead to a change in the maximum load tolerated by the soil or its surrounding foundations. Oil leakages in Kuwait (during the Persian Gulf War), in Valdez, Alaska (due to tankers' crashes), and from oil transfer pipes in Saudi Arabia are among the very serious oil contaminations in the respective area soil.

Researches on the effects of oil contamination on the strength and geotechnical parameters of soil are numerous. Das and Evgin (1992) concluded, through their triaxial tests on contaminated and uncontaminated quartz samples that the angle of internal friction in fully oil saturated samples (both compacted and non-compacted) was considerably reduced. Al Sanad et al. (1995 and 1997) have done their studies on Kuwaiti sandstone samples aiming at determining the effects of oil contamination on their strength properties, permeability, and compactibility. Khamehchian et al. (2007) have performed their laboratory studies on the SM, SP, and CL soil samples aiming at determining the effects of crude oil contamination on their geotechnical properties. Pandey and Bind (2014) concluded, through their tests on alluvial soil soaked with motor oil, that the reason for the changes in geotechnical properties of oil contaminated soils is the entrapment of hydrocarbon materials in the pores and voids of the contaminated medium. In addition to the above mentioned studies, those of Aiban's (1996), Sheen's (1999), Kermani and Ebadi's (2012), Zulfahmi et al.'s (2010), etc are noteworthy.

In this research, effort has been made to determine the elasticity modulus of oil contaminated soil samples using their stress-strain curves, and calculate the bearing capacity of deep foundations affected by oil dispersion using the necessary parameters. Among the important applications of the results of this research, is their use in the design of coastal oil platforms that are facing hydrocarbon contamination problems.

In this research, we will first introduce the tested soil sample and its strength and geotechnical parameters under different percent contaminations. Then, we will discuss the principal equation of the dispersion of contaminators in soil mediums and develop it for the conditions of 1D dispersion. Next, we will address the dimensions and limits of the problem, the related software, and the modeling process. Finally, we will determine the ultimate bearing capacity of a deep foundation buried in the soil sample contaminated with hydrocarbon materials.

SPECIFICATIONS OF THE TESTED SOIL

In the present research, use has been made of SM soil samples adapted from the work of Khamehchian et al., (2007) with a gradation curve as in Fig. 1. The samples were tested and evaluated under oil contaminations of 0, 4, 8, 12, and 16% (by volume) and a constant solid particle density of 2.57. The after-test strength and geotechnical properties of the samples are shown in Table 1.

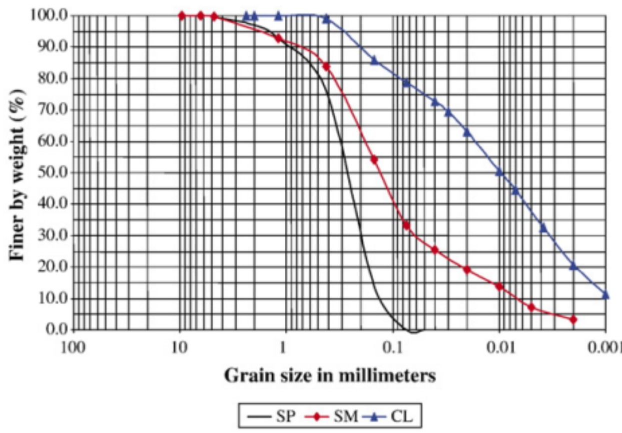

Fig. 1- Gradation curve of the soil used by Khamehchian et al., (2007)

Table 1- Geotechnical properties of oil contaminated SM soils (Khamehchian et al., 2007)

Oil Content	*C (kN/m2)*	*φ (deg)*	*ψ (deg)*	*n*	*K (m/s)*	*γ (kN/m3)*	*γsat (kN/m3)*	*E(kN/m2)*
0	27.2	33	3.517	0.26	1E-5	21.56	21.60	**4982.1**
4	19.5	32.9	3.398	0.27	4.36E-6	20.46	21.42	**4464.3**
8	22.7	32	2.332	0.28	3.16E-6	19.98	21.24	**4815.3**
12	21	26.2	0	0.28	5.21E-7	19.42	21.24	**3981.1**
16	33.6	26	0	0.29	6.95E-8	18.60	21.12	**2112.8**

It is to be noted, of course, that values of the elasticity moduli of the samples in the above table have been found using the secant method and the stress-strain curves of the oil contaminated SM soil samples (Khamehchian et al., 2007), and values related to the samples' angles of lateral dilation have been found using the relation proposed by Schanz and Vermeer (1996) (Relation 1).

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

EQUATION AND THEORY OF CONTAMINATION DISPERSION

Mechanism of contaminator dispersion

Dispersion and weakening are two principal factors that affect contamination dispersion in soil mediums. Dispersion is shown with equations that are based on the laws of fluid flow. These equations can associate with some mass equilibrium equations (which state the weakening factor in the dispersion of contamination in soil) and finally form the main dispersion equation.

Basic contamination dispersion equation and developing it for conditions of 1D dispersion

The basic differential equation of contamination dispersion in soil mediums with the weakening parameters (surface absorption and radioactive decomposition) based on the mechanism mentioned in the previous section is as follows (Pousti et al., 2014; Fetter, 1999):

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

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. Also, λ is the decomposition coefficient, D is diffusion coefficient in contamination dispersion, V is the apparent velocity of contamination flow in soil, ρ_d is the soil dry density, and x and t are the location and time variables, respectively.

It is to be noted that in the weakening part of the equation, the displacement and spreading processes are shown respectively by parameters S and λ, but in the dispersion part, they are shown by D and V respectively. Since surface absorption and radioactive decomposition processes have been negligible in many researches, in this research too the S and λ terms in Relation 2 have been assumed equal to 0 for the purposes of simplification and development of the equation for the conditions of 1D dispersion, and the above Relation has taken the following form (Pousti, 2014):

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

In fact, Relation 3 is the principal equation of 1D contamination dispersion in soil mediums for the solution of which we need some initial and boundary conditions appropriate to the subject of dispersion; Relations 4 to 6 provide these conditions.

$$C(x,0)=0 \quad x\geq 0$$ initial condition (4)

$$C(0,t)=C_0 \quad t\geq 0$$ boundary condition (5)

$$\frac{\partial C(L,t)}{\partial x}=0 \quad t\geq$$ boundary condition (6)

Applying the proposed boundary conditions to Relation 3, we will have the following solution (Ogata and Banks, 1961) [10]:

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

(7)

where V_s is the real linear mean velocity of the fluid flow in soil, D_L is the coefficient of 1D diffusion of oil contamination along the depth, x and t are the location and time variables respectively, C_o is the contaminator concentration in soil (assumed the highest in this research), and *erfc* is a function the value of which, as regards the subject of contaminator dispersion in soil mediums, is found using the information in Table 2 or Relations 8, 9, and 10 which are the regressions of the values proposed for this function in the related Table (Sharma and Krishna, 2004).

Table 2: Values related to erf and erfc functions

u	***erf***	***erfc***	***u***	***Erf***	***erfc***
0	0	1	**1.1**	0.880205	0.119795
0.05	0.0563720	0.9436280	**1.2**	0.910314	0.089686
0.1	0.1124629	0.8875371	**1.3**	0.934008	0.065992
0.15	0.1679960	0.8320040	**1.4**	0.952285	0.047715
0.2	0.2227026	0.7772974	**1.5**	0.966105	0.033895
0.25	0.2763264	0.7236736	**1.6**	0.976348	0.023652
0.3	0.3286268	0.6713732	**1.7**	0.983791	0.01621
0.35	0.3793821	0.6206179	**1.8**	0.989091	0.01091
0.4	0.4283924	0.5716076	**1.9**	0.99279	0.00721
0.45	0.4754817	0.5245183	**2**	0.995322	0.004678
0.5	0.5204999	0.4795001	**2.1**	0.997021	0.00298
0.55	0.5633234	0.4366766	**2.2**	0.998137	0.001863
0.6	0.6038561	0.3961439	**2.3**	0.998857	0.001143
0.65	0.6420293	0.3579707	**2.4**	0.999312	0.000689
0.7	0.6778012	0.3221988	**2.5**	0.999593	0.000407
0.75	0.7111554	0.2888446	**2.6**	0.999764	0.000236
0.8	0.7421008	0.2578992	**2.7**	0.999866	0.000134
0.85	0.7706679	0.2293321	**2.8**	0.999925	0.000075
0.9	0.7969081	0.2030919	**2.9**	0.999959	4.11E-05
0.95	0.8208907	0.1791093	**3**	0.999978	2.21E-05
1	0.8427007	0.1572993	**>3**	-	-

$$erfc(u) = 1.0199 - 0.0878u^3 + 0.6064u^2 - 1.3724u \qquad 0 \le u \le 3 \tag{8}$$

$$erfc(-u) = 1 + erf(u) \qquad -3 \le u \le 0 \tag{9}$$

$$erf(u) = 0.878u^3 - 0.6064u^2 + 1.3724u - 0.0199 \qquad 0 \le u \le 3 \tag{10}$$

It is worth mentioning that in the above Relation, parameter u, which is equal to the terms of arc *erfc* in the contamination displacement relations, is found as follows:

$$u = \frac{x - V_s t}{2\sqrt{D_L t}}$$

(11)

It is also worth mentioning that for calculation simplification purposes in practical applications, the second part of Relation 7 is assumed negligible reforming as follows:

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

(12)

To find V_s, use is made of Relation 13 (below) using Darcy Law that contains water flow velocity in saturated soil:

$$V_s = \frac{K}{n} \quad (13)$$

where Vs is the real velocity of flow in soil (leakage velocity), K is the coefficient of soil sample permeability, and n is its porosity. To find the values of Vs and D_L, we should first find the permeability coefficient of the SM soil sample, its porosity, and the coefficient of diffusion of the contaminator (crude oil). Table 3 shows the values of each of the above parameters in the form of average values of numbers related to the contaminated samples [46].

Table 3: 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

Using Relation 13 and Table 3, V_s is found as follows:

$$V_s = 12.93 * 10^{-6} m/s \quad (14)$$

On the other hand, since the data related to the SM soil sample used in this research for a 30-day period of stable conditions, the value of parameter t in Relation 11 has been taken equal to 30 days as follows:

$$t = 30 days = 2592 * 10^3 s \quad (15)$$

Substituting Relations 14 and 15 in Relation 12, we will have the dispersion equation as follows:

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

Contaminator concentration variations in the soil depth

Using Relation 13, the height (vertical) values of the crude oil permeation depth, based on 0, 4, 8, 12, and 16% concentration, have been found according to Fig. 2 which shows that with an increase in the soil permeation depth, the oil contaminator concentration in soil gradually decreases until it becomes 0 at a depth of 37.20 m. According to the data related to the oil contaminated SM soil samples, and as shown in Fig. 2, the maximum concentration (C0) at the ground surface level has been assumed equal to 16% in this research. With an increase in the permeation depth in soil, this concentration decreases and becomes 0 according to the mentioned dispersion equation. Next, since the oil contaminator concentration variations are now specified, and to simplify the software modeling process, the soil sample being studied has been divided into 5 layers corresponding to different percents of oil contamination that will lead to different specific strength and geotechnical parameters for each layer.

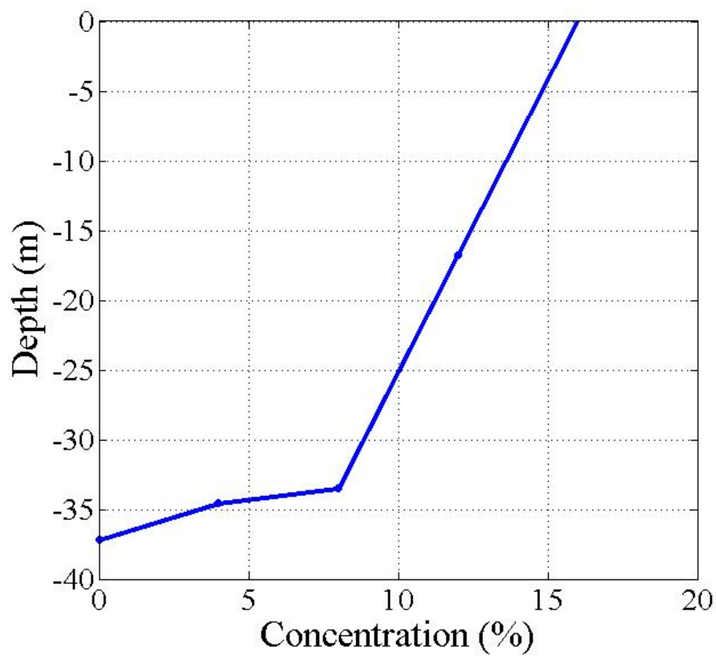

Figure 2: Oil contaminator concentration variations in deep soil

INTRODUCTION OF THE SOFTWARE AND MODELING PROCESS

PLAXIS Software

PLAXIS is a numerical analysis software program that analyzes and models geotechnical problems through finite element method and is used to determine the stability and deformations in geotechnical structures. One can model elastoplastic deformations, static analyses, consolidation analyses, and ground water problems through the 2D finite element and advanced soil modeling programs integrated in its 2D software package. The program is also capable of modeling soil, individual structural elements, soil-structure interaction, and such geotechnical structures as foundations and so on. In this research, use has been of the PLAXIS 2D program that is used in 2D finite element analyses. A very important parameter that is easily calculated from the program outputs is the maximum tolerable load or the ultimate bearing capacity of the modeled structure (e.g. a buried foundation) (Fathollahzadeh, 2014).

Setting the conditions and specifications of the layering of the soil being studied

Before proceeding towards the modeling process, it is to be emphasized (as was earlier) that it is required to calculate and extract the values of the strength and geotechnical parameters (coefficient of apparent cohesion, angle of internal friction, modulus of elasticity, apparent and saturated soil specific weights, and angle of lateral dilation) related to each layer of the soil separately to prepare the necessary conditions for the software modeling. Fig. 3 shows the values of each of these parameters found by the average weight method separately for each layer and used in this research.

		C KN/m²	ϕ Degree	E KN/m²	γ KN/m³	γ_{sat} KN/m³	K m/s	ψ Degree
16.75	Layer1	22.359	26.17	3642.385	18.90	20.80	4.6e-7	0
16.75	Layer2	21.967	30.84	4558.621	19.40	20.80	2.63e-6	1.866
1.06	Layer3	20.201	32.60	4492.622	19.90	20.90	3.96e-6	3.043
4.99	Layer4	19.123	32.90	4377.982	20.00	21.0	4.36e-6	3.398
20.45	Layer5	26.674	33.00	4885.771	21.10	21.20	1e-5	3.517

Figure 3: Geotechnical specifications of the SM layering

Process and limits of the problem modeling

To model a deep foundation, use has been made, in this research, of an insitu concrete pile with the apparent specifications given in Table 4. Since a single pile is axisymmetric, the soil medium has been modeled accordingly. The end boundaries should be so far away from the pile as to make the loading stresses and deformations in them insignificant and negligible. This is why in this research the horizontal distance from the pile axis of symmetry has been taken more than 30 m (3 times the pile length) and the vertical distance from the ground surface level is 60 m (6 times the pile length) deep inside the soil. Fig. 4 shows the modeling process.

Table 4: Apparent specifications of the pile being studied

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

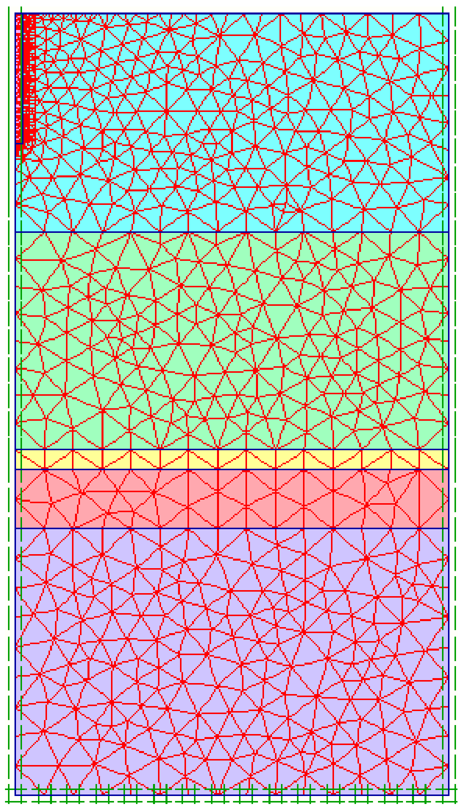

Figure 4: Limits and dimensions of the problem modeling

It is worth mentioning that since the soil studied in this research is of SM genus, its Poisson coefficient has been assumed equal to 0.333, and to take into account the effects of slippage on the pile surface or its top, the boundary regions around it have been defined by the program's Interface choice. In this research, the piles have been assumed as linear elastic with no pores, and the meshing is very fine. Since the friction angle of the soil-pile interface boundary region has been proposed (by different researchers) equal to 0.7 to 1 time that of the soil angle of friction for insitu concrete piles, the reduction coefficient has been taken equal to 0.8 in the Rint Software, and the soil behavior has been modeled using Mohr-Coulomb's full elasto-plastic model. The pile specifications can be defined using its Young modulus, Poisson ratio and specific weight; here, they have been assumed equal to 21 GPa, 0.15, and 25 kN/m^3 respectively (Shooshpasha and Sharafkhah, 2013). Using the above values and those in Fig. 4 for the geotechnical parameters of the soil layers, the pile was modeled and then the results of the software analyses were compared with those of the no-contamination modeling.

EVALUATION OF THE RESULTS AND OUTPUTS

An important result and output of the modeling and analytical processes in the PLAXIS 2D Software is the load-displacement curves for the model introduced to the software for the purpose of observing the behavior of the elements, and even estimating the maximum load carried by the modeled element. Fig. 5 shows the load-displacement curves related to the modeling of the pile buried in uncontaminated and oil-contaminated soils.

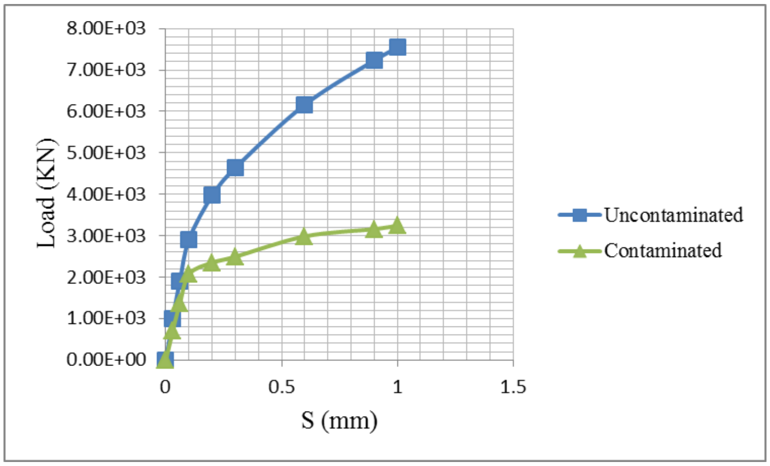

Figure 5: Load-displacement curves of piles buried in uncontaminated and oil-contaminated soils

As regards the bearing capacity, Fig 5 shows that the curve of the uncontaminated case stands higher than that of the oil-contaminated soil; in other words, hydrocarbon contamination dispersion in soil reduces the stress tolerated by the buried pile.

In this research, use has been made of Terzaghi (1942) method to find the ultimate bearing capacity of the pile under investigation; in fact, the ultimate bearing capacity in this method is equal to the load corresponding to a settlement equal to 10% of the pile diameter. Fig. 6 shows the ultimate bearing capacity found according to Terzaghi (1942) method.

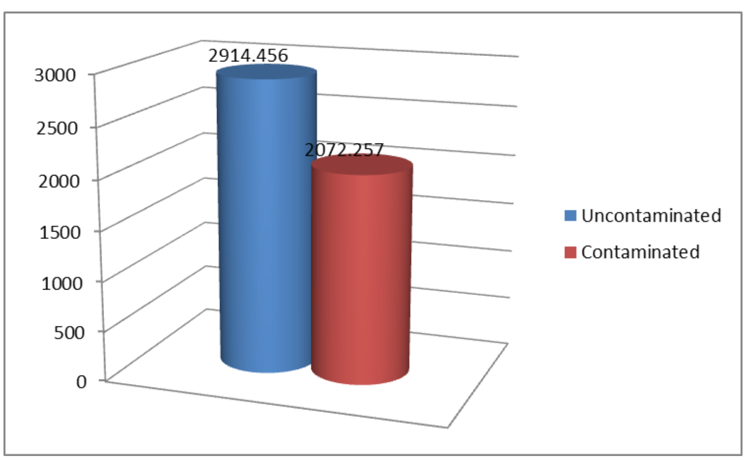

Figure 6: A comparison of the ultimate bearing capacity under both uncontaminated and contaminated conditions

Results of Fig. 6 show that oil-contamination dispersion in soil reduces the maximum tolerable load (or the ultimate bearing capacity) of deep piles buried in soil. This reduction, under the conditions of this research, has been almost 30%.

CONCLUSIONS

In this research, the maximum load tolerated by a pile buried in soil was evaluated using the strength and geotechnical parameters of oil-contaminated SM soil samples, 1D equation of contamination dispersion, and analyses of the results and outputs of the PLAXIS 2D Software. Results of this research have shown that oil-contamination dispersion in soil considerably reduces the ultimate bearing capacity of buried deep piles; this reduction has been almost 30% for a maximum soil contamination of 16%. Therefore, it can be concluded that since the strength and geotechnical properties of soil (apparent cohesion, angle of internal friction, percent optimum moisture content, maximum dry density, etc.) are reduced due to the hydrocarbon contamination dispersion in the continuous soil medium, the maximum load carried by buried structures (e.g. deep piles) is considerably reduced.

REFERENCES

[1] Heidarpoor M., Aliai M., "Oil Contamination Dispersion in Soil under Different Contaminator- Soil Conditions", Omran-e Modarres Scientific-Research Periodical, 13th Issue, pp 39-51, 2013.

[2] Das B. M., Tahooni S., "Principles of Geotechnique Engineering", Vol. 1, (Soil Mechanics), Pars Aeen Publications, 2012.

[3] Shooshpasha, I., Sharafkhah M., "Experimental and Analytical Investigation of the Settlement of Insitu Concrete Piles in Sandstone", Environmental and Civil Engineering Periodical, 43rd year, No. 4 (73 Consecutive), pp 35-46, Tabriz University, winter 2013.

[4] Fathollahzadeh S., "Mechanical and Dynamic Modeling of Earth Structures in PLAXIS", 1st printing, Noavar Publications, Tehran, 2014.

[5] Mohammadi Akbarabadi M., Yasrebi S., Khoshneshin-e Langaroodi M., "Effects of Crude Oil Contamination on some of the Geotechnical properties of Sandy Soil", 5th National Conference of Civil Engineering, Mashhad, Iran, 2010

[6] Pousti s., "Effects of the Type and Geotechnical Properties of Soil on the Dispersion of Contaminators", M. Sc. Thesis, Azad Islamic University, Najafabad Branch, Esfahan, Iran, pp 4-40, 2014.

[7] Aiban, "The effect of temperature on the engineering properties of oil-contaminated sand," Journal of Environmental International, Vol. 24, pp. 153–161, 1998.

[8] R. Zulfahmi, H. Umar, T. Mohd. Raihan, S. I. Norsheila, and A. Noorulakma, "Influence of oil contamination on geotechnical properties of basaltic residual soil," American journal of applied sciences, Vol 7, pp. 954-961, 2010.

[9] Pandey, and Y. K. Bind, "Effects of Oil Contamination on Geotechnical Properties of Alluvial Soil Naini, Allahabad," International Journal of Innovative Technology and Exploring Engineering, Vol. 3, pp. 39-42, 2014.

[10] E. Evgin, and B. M. Das, "Mechanical behavior of an oil contaminated sand," Envir. Geotech. Proc. Mediterranean Conf. Usmen and Acar, eds., Balkema Publishers, Rotterdam. The Netherlands, pp. 101-108, 1992.

[11] E. C. Sheen, J. B. Lee, and B. M. Das, "Bearing Capacity of a Model Scale Footing on Crude Oil-Contaminated Sand," J. Geotech. Geolog. Engineering, Vol. 17, pp. 123-132, 1999.

[12] H. A. Alsanad, and N. F. Ismael, "Aging effect on oil contaminated Kuwaiti sand," Journal of Geotechnical and Geoenvironmental Engineering, Vol. 123, pp. 290–294, 1997.

[13] H. A. Alsanad, W. K. Eid, and N. F. Ismael, "Geotechnical properties of oil contaminated Kuwaiti sand," Journal of Geotechnical Engineering, ASCE, Vol. 121, pp. 407-412, 1995.

[14] K. Terzaghi, "Disscussion of the Progress Report of the Committee on the Bearing Value of Pile Foundation," Proc. ASCE, Vol. 68, pp. 311-323, 1942

[15] M. Khamehchiyan, A. H. Charkhabi, and M. Tajik, "Effects of crude oil contamination on geotechnical properties of clayey and sandy soils," Engineering Geology, Vol. 89, pp. 220–229, 2007.

[16] M. Kermani, and T. Ebadi, "The Effect of Oil Contamination on the Geotechnical Properties of Fine-Grained Soils," Soil and Sediment Contamination: An international journal, Vol. 21, pp. 655–671, 2012.+

[17] S. Pousti, M. Vafaean, and A. Hajiannia, " Effect of Porosity and Hydraulic Conductivity Coefficient on Contamination Penetration Depth in Soils," Adv. Environ. Biol, vol. 8, pp. 173–179, November 2014.

[18] Ogata, and R. B. Banks, A Solution of the Differential Equation of Longitudinal Dispersion in Porous Media, U.S. Geological Survey Professional Paper 411-A, U.S. Government Printing Office, Washington, DC, 1961.

[19] W. Fetter, Contaminant Hydrogeology, 2nd ed., Prentice Hall, Upper Saddle River, NJ, 1999.

[20] Schanz, T. and Vermeer, P., "Angles of friction and dilatancy of sand", Geotechnique, Vol. 46, pp. 145–151,1996.

[21] H. D. Sharma, and K. R. Krishna, Geoenvironmental Engineering: Site Remediation, Waste Containment, and Emerging Waste Management Technologies, John Wiley & Sons, Inc. United States of America, 2004, pp. 167-211.

[22] P. Binning, "Discussion: on the misuse of the simplest transport model," Ground Water, Vol. 38, No. I, pp. 4-5, 2000.

[23] Onyelowe, Kennedy Chibuzor: Pure Crude Oil Contamination on Amaoba Lateritic Soil Onyelowe, Kennedy Chibuzor" *Electronic Journal of Geotechnical Engineering*, 2015(20.3): 1129-1142. Available at ejge.com.

[24] Adejumo T. Elisha: "Effect of Crude Oil Contamination on the Geotechnical Properties of Soft Clay Soils of Niger Delta Region of Nigeria" *Electronic Journal of Geotechnical Engineering*, 2012(17.H): 1157-1162. Available at ejge.com.

[25] Ijimdiya, T.S.a and Igboro, T.: "The Compressibility Behavior of Oil Contaminated Soils" *Electronic Journal of Geotechnical Engineering*, 2012(17.Y): 3653-3662. Available at ejge.com.

[26] Habib-ur-Rehman, Sahel N. Abduljauwad, Tayyeb Akram: "Geotechnical Behavior of Oil-Contaminated Fine-Grained Soils" *Electronic Journal of Geotechnical Engineering*, 2007(7): Paper 720. Available at ejge.com.