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BEHAVIOR OF PILE GROUP SUBJECTED TO CYCLIC LATERAL LOADING IN CONTAMINATED SOILS

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ABSTRACT: The impact of soil contamination on the behavior of a pile group driven into clayey soils is the subject of this study. A mechanical model had been manufactured to study the behavior of pile group (2×2) subjected to one-way cyclic lateral loading, and embedded in contaminated soils. The tests were performed on a free headed pile group with two ratios of eccentricity to embedded length (e/L) equal to 0.25 and 0.5. The intact soil samples were obtained from Al-Musayib city in the center of Iraq, while the industrial wastewater is a byproduct discharged from Al-Musayib thermal electric power plant, which is located in the same region where the soil samples have been obtained. The intact clayey soil samples were contaminated synthetically with four percentages of (10, 20, 40 and 100) % by weight of distilled water used in the soaking process of soil samples, which continued for 30 days. On the basis of the results of tests, the different percentages of contaminants have nonlinear effects on the lateral load-displacement relation of the pile group. The lateral resistance of pile group decreased with increasing the concentration of contamination in the soil. The lateral bearing capacity of pile group decreased by (4–31)% for e/L equals 0.25 and 0.5, and the ratio of permanent displacement to the total displacement increased by (18–33)% with increasing the percentage of contamination in the soil. The efficiency of the pile group was (81–87)% from one single pile group.

Keywords: Industrial Wastewater; Soil Contamination; Clayey Soil; Cyclic Lateral Loading; Pile Foundation

1. INTRODUCTION

Geoenvironmental engineering is the application of environmental concepts into geotechnical engineering in what related to soil and groundwater. Contamination of soil can be defined as that caused by the buildup of persistent toxic compounds, chemicals, salts, or radioactive materials. Soil contaminants have diverse effects on the geotechnical properties of soil, such as quality, texture and mineral content [1]. Industrial waste is defined as the waste generated by manufacturing or industrial processes, where the major source of generation such wastes are the thermal electrical power plants; the integrated iron and steel mills; and production industries generating press mud, pulp and paper. This also includes industries of lime, fertilizers, and other allied industries producing gypsum [2-3].

Pile foundations are used extensively in onshore and offshore wind turbines, and other marine structures. The piles that are supporting these structures are inevitably subjected to lateral static and cyclic loading generated by wave, current, wind and other forces. Poulos and Davis [4] suggested two phenomena that could contribute to an increase in the displacement of laterally loaded piles with a growing number of cycles: the structural phenomenon is known as "shakedown" of the pile in soil, which leads to an incremental collapse, and the phenomenon of cyclic soil degradation, a decrease in hardness and strength of the soil.

Dewaikar et al. [5] studied the ultimate lateral load capacity of single pile in soft clay under cyclic loading in the field taken into consideration different pile diameters, load eccentricity and different loading cycles. The initial degradation was very high about 8% after the first five cycles, while the degradation was only 3% for cycles from 100 to 200.

Basak [6] studied the response of pile group (2×2) subjected to cyclic lateral load in soft clay. The experimental model was designed in such a manner that the cyclic loading test could be performed under both conditions, load-controlled and displacement-controlled modes. The cyclic lateral loading on the pile group in soft clay causes a decrease in capacity of the pile group. This alteration is represented by the degradation factor, which represents the ratio of ultimate lateral pile group capacities before and after the application of cyclic loading. Haigh and Bolton [7] studied the response of a large diameter single pile under one-way force of cyclic lateral loads. Also, they discussed the accumulated pile shaft horizontal displacement caused by the permanent cyclic lateral displacement, and the effects of lateral loads on the pile cyclic lateral secant stiffness. Under cyclic lateral loads with amplitudes smaller than 810 N, the minimum and maximum pile lateral displacements in each cycle increased approximately linearly with the increasing the number of loading cycles on a logarithmic scale.

Dehghanpoor and Ghazavi [8] proposed a new method for analysis of tapered piles under lateral harmonic vibration. The behavior of tapered piles is assumed to be as elastic and linear and the soil consists of some elastic horizontal layers that they are homogeneous, isotropic, and linearly visco–elastic. It has been found that under lateral harmonic vibrations, with increasing the pile taper angle, the resonant amplitude decreases. Also, a tapered pile experiences lower amplitude than a cylindrical pile of the same length and material volume. Qin and Guo [9] conducted laboratory model tests to investigate the responses of piles subjected to lateral soil movement. The major findings were the pile head conditions (free or capped) are insignificant on piles subjected to lateral soil movement when arranged in a row and the group factor decreases as the pile spacing reduces.

Lastly, the percentage of contaminated soils increased significantly due to the rapid development and expansion of industries, such as oil fields, refineries, factories and electrical power plants [10]. Iraq has several thousands of contaminated sites resulting from a combination of general industrial activities, military activities, and post conflict damages and looting [11]. This study investigates the impacts of industrial wastewater as soil contaminant on the lateral-load capacity of pile group subjected to cyclic lateral loading.

2. EXPERIMENTAL WORK

The intact soil samples obtained from Musayib city, which is located at the middle of Iraq (UTM: 33N515276, 44E28102). The soil samples were obtained from a depth of 4m below the natural ground surface to avoid wastes and roots of trees, also to be below the level of the groundwater table. The soil samples were contaminated synthetically with industrial wastewater disposed from Al-Musayib thermal electrical power plant as byproduct. The contaminant can be classified as aqueous liquid (miscible liquids) containing inorganic chemicals that are miscible in water. The soil samples were soaked with four percentages of contaminants 10, 20, 40 and 100% by weight of the distilled water used in the soaking process for 30 days in plastic covered containers. The soil samples tested in the present work are designated as C_0, C_1, C_2, C_3 and C_4 for intact and contaminated soil samples, with 10, 20, 40 and 100%, respectively. The effects of different percentages of contaminants on physical, chemical and mechanical properties of soil samples used in the present study were investigated by Karkush and Abdul Kareem [12].

The pile used in the experimental work was made from aluminum (6061) of solid circular cross-sectional area. The properties and dimensions of pile model are listed in Table 1. According to the criteria proposed by Tomlinson [13], the pile used was of L/D ≥ 20, long, flexible and a free-head pile.

Table 1 Properties and dimensions of pile model

Property	Symbol	Value
Length	e+L	500 mm
Diameter	D	19 mm
Tensile strength	fy	95 MPa
Ultimate tensile strength	fu	110 MPa
Young modulus	E	69 GPa
Moment of inertia	I	6.397×10^{-9} m^4

3. PILE GROUP TESTING MODEL

The pile testing model consists of a steel container, pile-fixing tool, dial gauge-fixing tool, and load application system, as shown in Figure 1. The instruments used in tests and fixing method are shown in Figure 2.

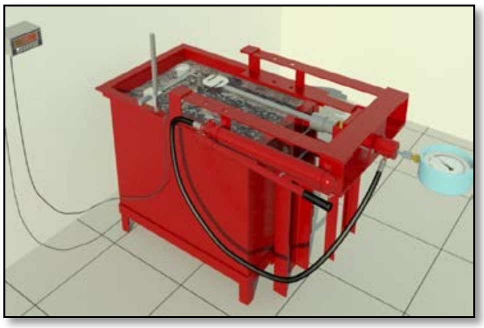

Fig.1 Lateral pile loading model

Fig.2 Instruments used in pile group testing

The steel container was made of steel plates of 2.5 mm thickness with internal dimensions of 700 mm in length, 500 mm in width, and 500 mm in height. At the top of the box, there were six holes, four of them, 8 mm in diameter, were used in the fixing of the pile during the driving process into the soil to ensure verticality of the inserted pile, and the other two holes, 10 mm in diameter, were used to fix the dial gauge. On the right side of the box, two steel angle sections of 50×50×300 mm were welded to the container to fix the loading system “hydraulic pressure” by two screws, each of 6 mm diameter. The loading system consisted of a hydraulic pressure jack with a capacity of 10,000 kg, pressure gauge of capacity 250 kg, load cell (type S) of capacity 500 kg and output rate of 2.001 mv/V, and a digital weighing indicator (SI 4010). The operating temperature is ranged –10˚C to 40˚C.

The procedure of testing can be summarized as follows:

1) Preparing the pile model, soil sample, instruments and equipment such as dial gauges, load cell, digital weighing indicator and hydraulic loading system.
2) Adding the soil in six layers, each of 80 mm thickness with tamping, to reach the field unit weight (19.3 kN/m³) and natural moisture content (32 %).
3) Inserting the piles (2×2) individually into the soil up to the required embedded depth, then connect them together with a pile cap. The spacing between piles is 3D, where D is the pile diameter.
4) Installation of the loading system (hydraulic pressure jack, pressure gauge, load cell, and digital weighing indicator), and the dial gauges at the free head of the piles.
5) Soaking the soil sample with distilled water to cover the soil sample in the box. In case of intact soil, just distilled water will be used, while chemical solution (distilled water mixed with industrial wastewater in four percentages, 10, 20, 40 and 100% by weight of water) is to be used in soaking of contaminated soil samples. Then, the soil sample was left for 6 hrs. before starting the loading process.
6) Starting the lateral loading process by adding incremental loads 20, 40, 80, 160, 200, 400, 600, 800, 1000, 1200, 1400 and 1600 N. The rate of loading cycle is 1 cycle/min for each load increment in both loading and unloading stages.
7) Recording the readings of the dial gauge during loading (lateral displacement) and when unloading (permanent displacement).

4. RESULTS AND DISCUSSIONS

The lateral total and permanent displacements and lateral load capacity of pile group have been investigated under cyclic lateral loading in contaminated soil samples. The different percentages of contamination have significant effects on the lateral total and permanent displacements of the pile group head under cyclic lateral loads as shown in Figures 3-7 for e/L = 0.25 and in Figures 8-12 for e/L = 0.5.

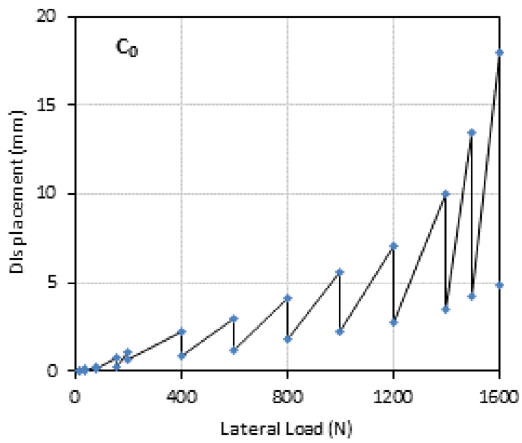

Fig.3 Displacement versus lateral load for soil sample C_0 and e/L = 0.25

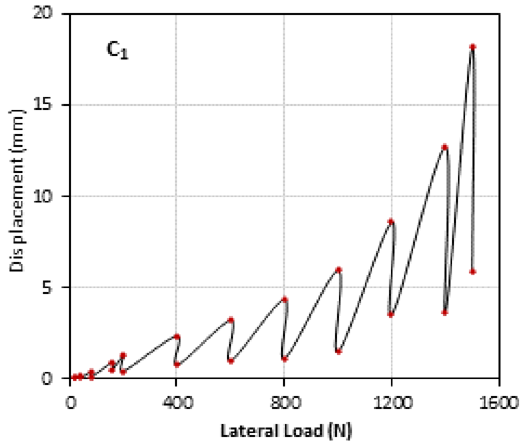

Fig.4 Displacement versus lateral load for soil sample C_1 and e/L = 0.25

The lateral load capacity of the pile group decreased with increasing the percentage of contamination in soil, where the contamination causes decreasing the soil strength and cohesion. The increase in e/L ratio causes a decrease in the lateral load capacity of the pile group. This decrease resulted from increasing the ultimate moment on the pile group cap, which causes an increase in the lateral displacement and a decrease in the soil strength around the pile shaft.

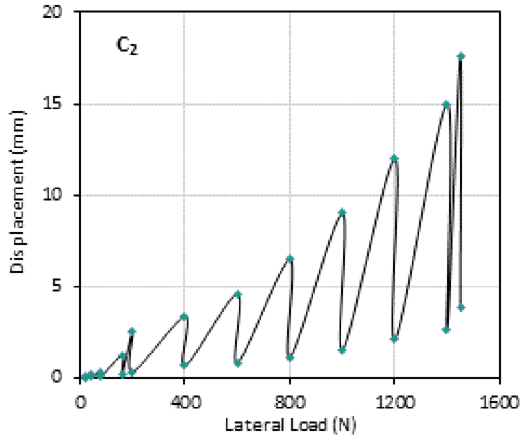

Fig.5 Displacement versus lateral load for soil sample C_2 and e/L = 0.25

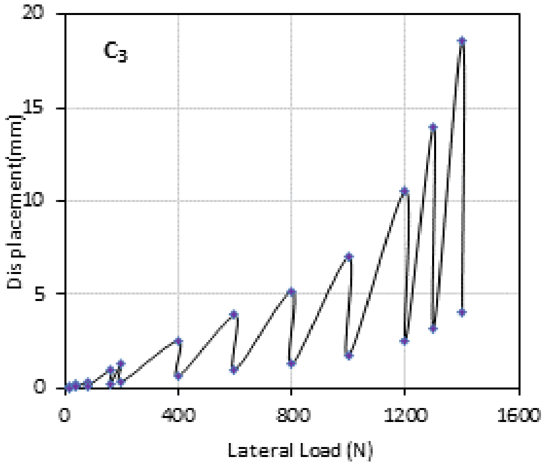

Fig.6 Displacement versus lateral load for soil sample C_3 and e/L = 0.25

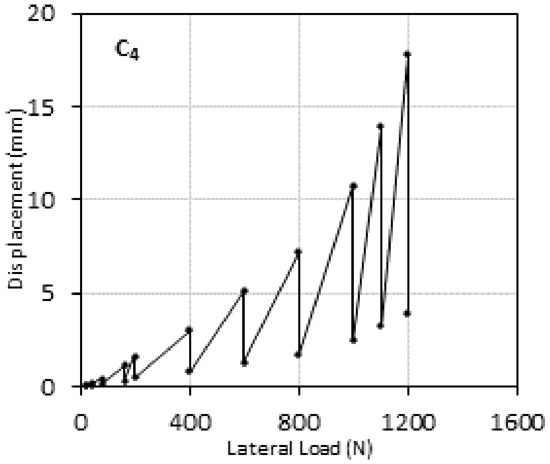

Fig.7 Displacement versus lateral load for soil sample C_4 and e/L = 0.25

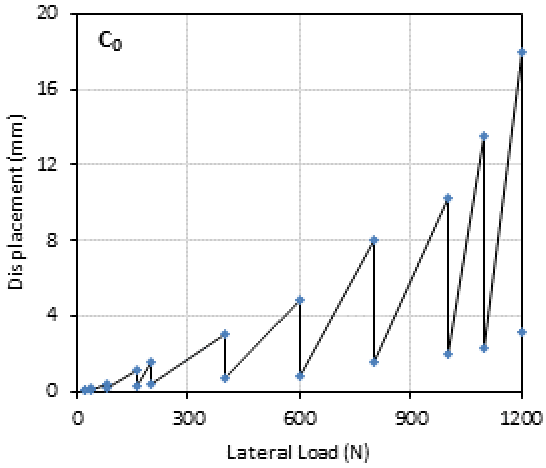

Fig.8 Displacement versus lateral load for soil sample C_0 and e/L = 0.5

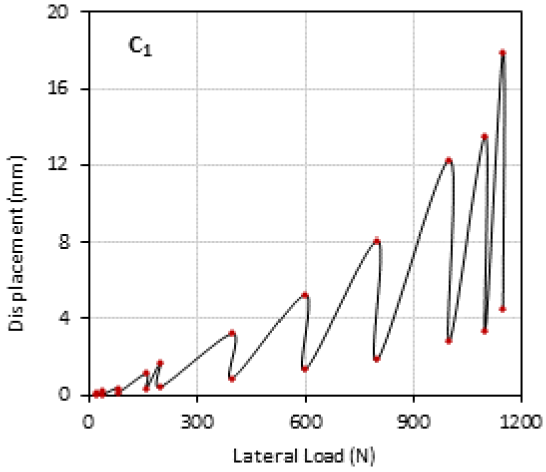

Fig.9 Displacement versus lateral load for soil sample C_1 and e/L = 0.5

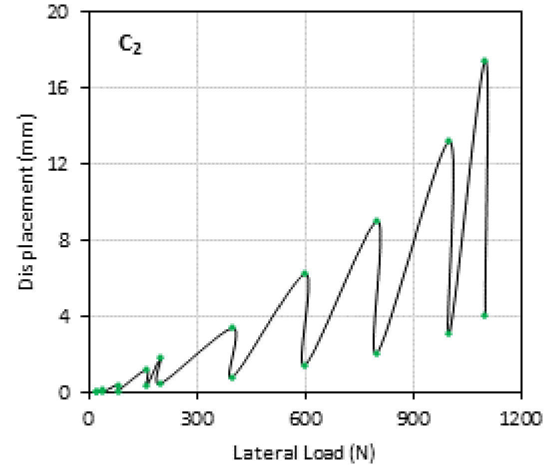

Fig.10 Displacement versus lateral load for soil sample C_2 and e/L = 0.5

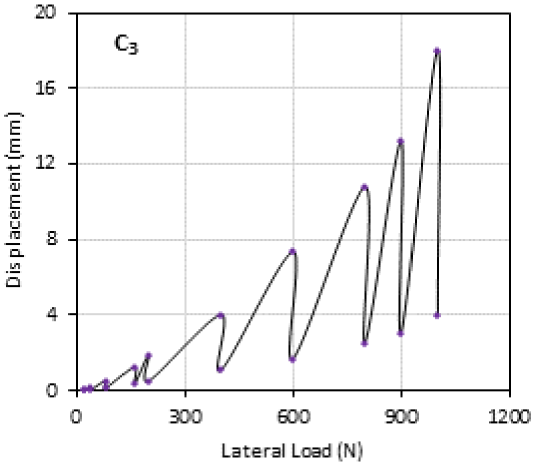

Fig.11 Displacement versus lateral load for soil sample C_3 and e/L = 0.5

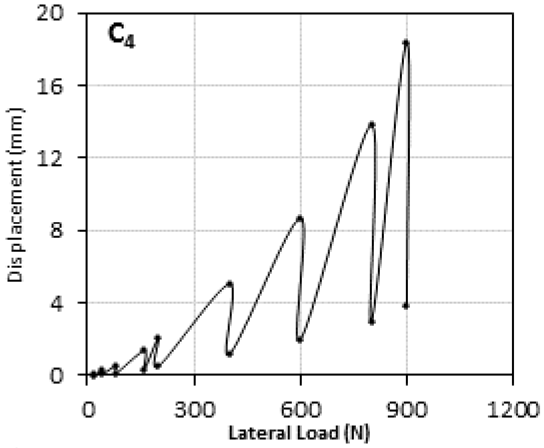

Fig.12 Displacement versus lateral load for soil sample C_4 and e/L = 0.5

A comparison of lateral load capacity with e/L is given in Table 2, which shows a reduction of (31.25–29)% with increasing e/L from 0.25 to 0.5.

Table 2 Variation of lateral load capacity with e/L

Soil Sample	Ultimate lateral load (kN)		
	e/L = 0.25	e/L = 0.5	$\frac{e/L = 0.5}{e/L = 0.25}$
C_0	1.60	1.20	0.75
C_1	1.50	1.15	0.77
C_2	1.45	1.10	0.76
C_3	1.35	0.95	0.70
C_4	1.10	0.85	0.77

Additionally, the variation of total displacement with lateral load at 1st and 100th cycles of loading are given in Figures 13-14 for e/L = 0.25 and in Figures 15-16 for e/L =0.5.

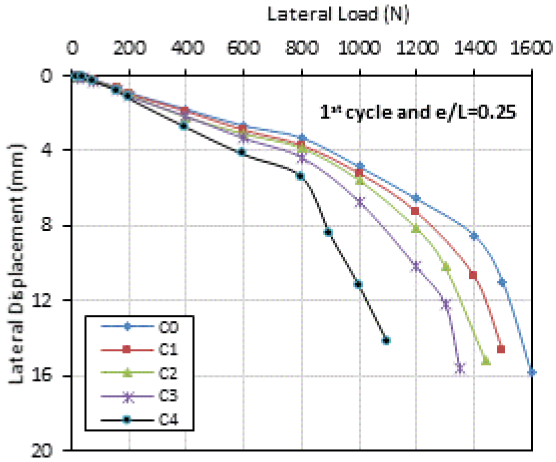

Fig.13 Total lateral displacement versus lateral load for e/L = 0.25 at N = 1 cycle

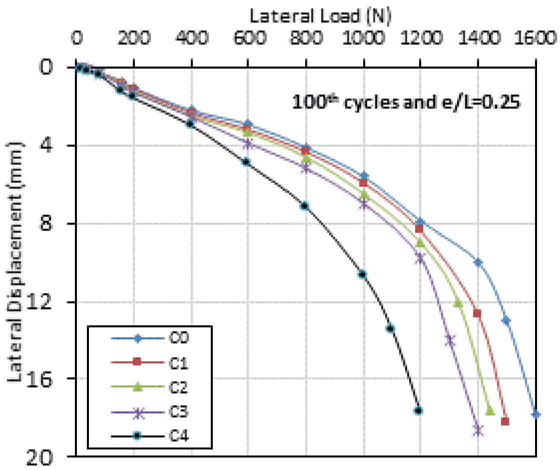

Fig.14 Total lateral displacement versus lateral load for e/L = 0.25 at N = 100 cycles

The ultimate lateral load capacity of a 2×2 pile group embedded in contaminated soil samples has decreased with increasing the percentage of concentration of the contaminant in soil. The total lateral displacement increases with increasing the concentration of the contaminant as shown in Figures 13-16 under the same magnitude and conditions of loading. On the basis of the results of tests shown in Figures 13-16, under the same magnitude of lateral displacement (18 mm), the lateral-bearing capacity of the pile group reduced by 6, 9, 16 and 31% for e/L equals to 0.25, and reduced by 4, 8, 21 and 29% for e/L equals to 0.5 for soil samples C_1, C_2, C_3 and C4, respectively.

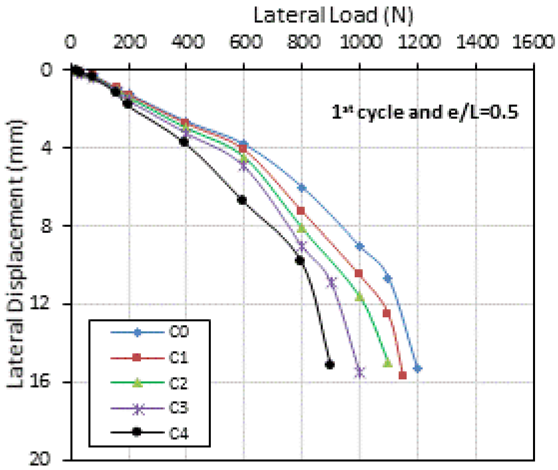

Fig.15 Total lateral displacement versus lateral load for e/L = 0.5 at N = 1 cycle

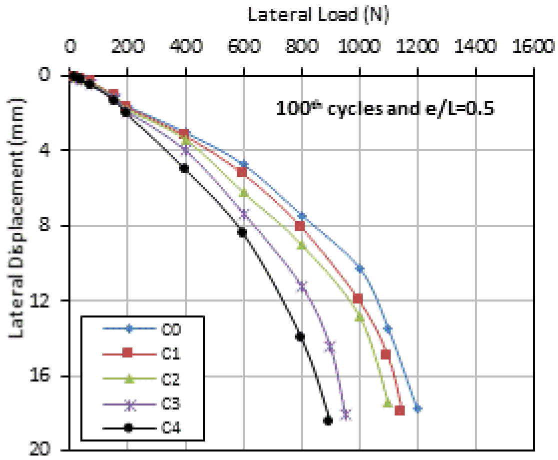

Fig.16 Total lateral displacement versus lateral load for e/L = 0.5 at N = 100 cycles

The contamination causes soil degradation and, thus, weakens the soil strength. Generally, the ratio of permanent to total displacement at the 50th cycles of loading ranged between 18% and 33%, as shown in Table 3. There is a slight difference in the ratio of displacement for different percentages of concentration of contaminant compared with that for intact soil.

The capacity of the pile group is the sum of the individual pile capacities, or something different, either more or less, which depends on the type of soil. If the capacity is the sum of the several individual pile contributions, the group efficiency, Eg, is calculated according to the following equation:

$$Q_{u,Group} = E_g * Q_{u,Single} \times No. of\ Piles \qquad (1)$$

Table 3 The ratio of permanent to total displacement at the 50th cycles

Soil sample	Ratio of permanent to total displacement (%)	
	e/L = 0.25	e/L = 0. 5
C_0	18	25
C_1	24	27
C_2	23	30
C_3	25	33
C_4	27	33

Where $Q_{u,Group}$ is the ultimate bearing capacity of the pile group, $Q_{u,Single}$ is the ultimate bearing capacity of a single pile, and E_g is the efficiency of the pile group. In the present work, the efficiency of pile group given in Table 4 is calculated from the results of tests conducted by Karkush and Abdul Kareem [14] on single pile in both intact and contaminated soils, which based on comparing the lateral load capacity of pile(s) at lateral displacement of 18 mm and at 100th cycles of loading. These results well agreed with those obtained by Al-Mhaidib [15].

Table 4 Efficiency of the pile group

Soil sample	Efficiency of pile group (%)	
	e/L = 0.25	e/L = 0.5
C_0	85	85
C_1	83	83
C_2	81	87
C_3	85	83
C_4	86	85

During cyclic lateral loading, the cap of the pile group exerts vertical displacement in addition to lateral displacement. The percentage of vertical to total lateral displacement ranges about (9–11)% for the tested soil samples. The front side of the piles cap rises, while the rear side is lowered down at the same magnitude during the application of lateral loading.

5. CONCLUSIONS

The industrial wastewater discharged from Al-Musayib thermal electric power plant has negative effects on the ultimate lateral load capacity and total lateral displacement of the pile group subjected to cyclic lateral loading. The conclusions can be summarized as follows:

1. Cracks will occur in the soil at the front side of the pile, while the clay at the rear side suffers from heave, which continues to produce a gap around the pile. This behavior well agreed with the results presented by Basack [6].
2. The lateral load capacity of the pile group decreased by 6, 9, 16 and 31% for e/L = 0.25, and decreased by 4, 8, 21 and 29% for e/L = 0.5 with increasing the percentage of contamination in the soil.
3. The ratio of permanent lateral displacement to the total lateral displacement increased by 18% to 33% with increasing the percentage of contamination in the soil.
4. Increasing the number of lateral load cycles leads to an increase in the lateral displacement by 22% for 5 cycles, 16% for 10 cycles, 14% for 25 cycles, 15% for 50 cycles, and by 3% for 100 cycles.
5. The efficiency of the pile group is ranged 81-87% for e/L = 0.25 and e/L = 0.5, which reflect approximately constant values of Eg not affected by e/L or percentage of contamination in the soil.

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