Impacts of Soil Contamination on the Response of Piles Foundation under a Combination of Loading

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Abstract— The behavior of single piles driven into contaminated clayey soil samples subjected to a combination of static axial and cyclic lateral loadings have been studied in this research. A laboratory model was manufactured especially for studying such behavior. A solid circular cross sectional area pile of diameter 19 mm and made from aluminum, the pile was embedded into the soil with an eccentricity to embedded length (e/L) ratio of 0.334. The intact soil samples and industrial wastewater were obtained from the center of Iraq. The industrial wastewater is a byproduct disposed from Musayib thermal electric power plant. The intact clayey soil samples were synthetically contaminated with four percentages of 10, 20, 40 and 100% from the weight of water used in the soaking process which continued for a period of 30 days. The different percentages of contaminant concentrations have significant effects on the lateral load-displacement relation of the piles subjected to a combination of axial and lateral loadings. The vertical displacement under the same vertical load increased by 5–95%, the axial strength of piles decreased by 10–34% and the lateral-bearing capacity of the piles decreased by 10–34% with increasing the percentage of contamination from 10 to 100%. The ratio of permanent lateral displacement to the total lateral displacement was increased by 23–27% when the concentration of contaminant increased by 10-100%. Generally, the application of axial loading increases the lateral-bearing capacity of piles, and reduces the total lateral displacement.

Keywords-industrial wastewater; soil contamination; clayey soil; axial loading; cyclic lateral loading; pile foundation; Al-Musayib city

I. INTRODUCTION

Soil contamination can be defined as the sum of all factors that deteriorate the quality, texture and mineral content of the soil [1]. Soil contamination becomes a contentious issue due to the large-scale development of industries, raising the standard of living, and the urbanization of small towns. The main sources of soil contamination are agricultural activities, urban activities, industrial effluents, and solid waste [2]. The major generators of industrial solid wastes are the thermal power plants producing coal ash, the integrated iron and steel mills, processing industries generating press mud, pulp and paper. Manassero and Shackleford [3] classified the industrial wastes as residue from incineration processes (fly ash), residues from metallurgical industrial processes, residues from construction, oil industries, electric power stations, subsoil treatment and investigation, and residues from waste liquid, and gas treatment plants. Piles are columnar elements in a foundation which have the function of transferring load from the superstructure through weak compressible strata or through water, onto stiffer or more compact and less compressible soils or onto rocks [4]. Pile foundations are extensively used in onshore, offshore, wind turbine, and marine structures. The piles that are supporting these structures are inevitably subjected to lateral static and cyclical loading generated by wave, current, wind and others. Combinations of vertical and horizontal loads are carried out where piles are used to support retaining walls, bridge piers and abutments, and machinery foundations.

The response of piles subjected to lateral cyclic loading had been studied by many researchers [5-10], the main observations on the response of a pile subjected to quasistatic cyclical lateral loading are summarized as follows:

- both lateral displacement and moment increase with increasing the number of cyclic loading level
- the ultimate lateral load capacity decreases when increasing the number of cyclic loading level
- the cyclical behavior of the pile is similar in homogenous and heterogeneous soils
- the lateral displacement and the bending moments developed near the piles of a group are greater than that of a single pile
- for cohesionless soils, no gap is observed at the end of the cyclic loading
- effects of cyclical degradation are more severe for stiff soils than in soft clay
- the loading rate has a significant effect on the displacement action of the pile
- one-way cyclic lateral loading produces higher permanent displacement and greater cumulative deflection of the piles than the two-way cyclic lateral loading.

Poulos and Davis [11] referred two phenomena that contribute to an increase in the displacement of laterally loaded piles with a growing number of cycles: the structural phenomenon known as "shakedown" of the pile in soil, and the phenomenon of cyclical soil degradation. Dewaikar et al. [8] studied the ultimate lateral load of flexible free-headed piles in a soft clayey soil under cyclical loading. The initial degradation is very high at about 8% for the first five cycles, while the degradation was only 3% of cycles from 100 to 200. Haigh and Bolton [10] studied the response of a large-diameter single-pile under one-way force of cyclical lateral loads. Also, they discussed the accumulated pile shaft horizontal displacement caused by the permanent cyclical lateral displacement, and the effects of lateral loads on the pile cyclical lateral secant stiffness. Basack [9] studied the response of 2×2 piles group subjected to horizontal cyclical load in soft clay. The experimental setup was designed in such a manner that the cyclical loading test could be performed under both the displacement-controlled and the load-controlled modes. Following investigation, it has been observed that under the effect of lateral cyclic loading on a pile group in soft clay, the pile capacity decreases.

Karkush and Abdul Kareem in [12] studied the effects of soil contamination on the behavior of a single pile subjected to lateral cyclic loading, and in [13] studied the effects of contamination on the behavior of a group of piles subjected to lateral cyclic loading. In both cases of a single pile and a group of piles, increasing the concentration of contamination causes a decrease in the lateral-bearing capacity of piles, and an increase in the total and permanent lateral displacements. In this research, the impacts of industrial wastewater on the performance of single pile foundation driven in contaminated clayey soil under a combination of static axial load and lateral cyclical loads has been investigated experimentally, where several ratios of contaminant mixed with soil synthetically.

II. EXPERIMENTAL WORK

The intact soil samples were obtained from Al-Musayib city which is located at the center of Iraq (UTM: 33N515276, 44E28102), from a depth of 4 m below the natural ground level. The contaminant is an industrial wastewater discharged of the thermal electrical power plant as byproduct. The soil samples were soaked by industrial wastewater for 30 days in plastic covered containers. The industrial wastewater was added in four ratios of 10, 20, 40 and 100% from the weight of the distilled water used in the soaking process, where these soil samples are designated as C_0, C_1, C_2, C_3 and C_4 for intact and contaminated soil samples, respectively. The properties and dimensions of the used pile models are listed in Table I.

TABLE I. MATERIAL 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
Bending Stiffness	EI	4.41×10^{-4} MN.m^2

The pile used in the present work with L/D≥20 is considered long, flexible and a free-head pile [4]. The pile-loading model consisted of a steel container, pile-fixing tool, dial gauge-fixing tool, and load application system, as shown in Figures 1 and 2. The details and specifications of this model, pile material and geotechnical properties of soils were well explained in [12].

Fig. 1. Pile loading model-vertical displacement.

Fig. 2. Pile loading model-lateral displacement.

III. PILE MODEL LOADING TEST

The basic scheme for the test follows the below steps:

- preparing the pile model, soil sample, and the necessary prescribed instruments and equipment.
- add the soil in six layers (each 80 mm thick) with tamping to reach the field unit weight and moisture content.
- insert the pile into the soil up to the required embedded depth with (e/L) equal to 0.334
- install the loading system (hydraulic pressure jack, pressure gauge, load cell, and digital weighing indicator) and dial gauge at the free head of the pile
- soak the soil sample in distilled water to cover the soil sample in the box. For intact soil, only distilled water was used, whereas a chemical solution (distilled water mixed with industrial wastewater in four concentrations 10, 20, 40 and 100% by weight of water) was used for soaking the contaminated soil samples. Then, the soil sample was soaked for 6 hours before starting the loading process

- start the axial loading process by adding incremental loads of 0, 10, 20, 40, 60, 80, 100, 120, 140 and 160 N
- record the readings of the dial gauge during axial loading to calculate the vertical displacement of the piles cap
- start the lateral loading process by adding incremental loads of 10, 20, 40, 80, 120, 160, 200, 250, 300, 350, 400, 450 and 500 N. The rate of loading cycle was 1 cycle/min for each load increment in both the loading and unloading stages.
- the rate of cyclical loading should be at a uniform rate, the best rate is one loading cycle in each minute. When the rate is rapid, the lateral displacement records the largest or less than a displacement of the previous cycle. When the loading rate is one cycle in five minutes, the next displacement becomes less than a displacement in a previous cycle due to the recovery of soil deformation.
- record the readings of the dial gauge during loading (total lateral displacement) and when unloading (permanent lateral displacement).
- stop the test when the total lateral displacement reach 14 mm, so the number of increments may change according to the ultimate lateral-bearing capacity of the pile and soil.

IV. RESULTS AND DISCUSSIONS

The contamination has significant effects on the behavior of piles subjected to a combination of axial loading and lateral cyclical loading. The main relations obtained from this research are: axial static load–vertical displacement and lateral cyclic load–total and permanent lateral displacements. The variation of vertical displacement with axial load and time are shown in Figures 3 and 4 respectively. At the same level of axial loading of 300 N, the vertical displacement was decreased by 5, 10, 26 and 95% for soil samples C_1, C_2, C_3 and C_4, respectively, compared to the pile inserted in intact soil. The variation of total lateral displacements with lateral cyclic loading are given in Figures 5 to 8, while the variation of permanent lateral displacement with lateral cyclic loading are given in Figures 9 to 12.

The lateral load capacity of the piles decreased with increasing the concentration of contaminat in soil due to increasing the ultimate moment on the pile head, which causes an increase in the lateral displacement and a decrease in the soil strength around the pile shaft. The lateral-bearing capacity after 100 cycles of loading decreased by 10, 10, 24 and 34% for soil samples C_1, C_2, C_3 and C_4, respectively. It is noticed that there is no difference in the ultimate bearing capacity of C_1 and C_2, but there is a noticible difference in the total lateral displacement. The soil degradation caused by contamination led to weakening of the soil strength, where the degradation rate of lateral displacement increases with increasing the number of loading cycles. Based on the results, the degradation of displacement is high for the first 10 cycles. The results obtained from this study for e/L = 0.334 were compared with those obtained by Karkush and Abdul Kareem [12] for e/L equals 0.25 and 0.5 as shown in Table II. Based on the results, the application of axial load causes an increase in the lateral-bearing capacity and a decrease in the total lateral displacement of pile. Also, the lateral-bearing capacity of pile decreased with increasing the ratio of contamination and e/L, while an adverse effects was observed in lateral displacement of pile.

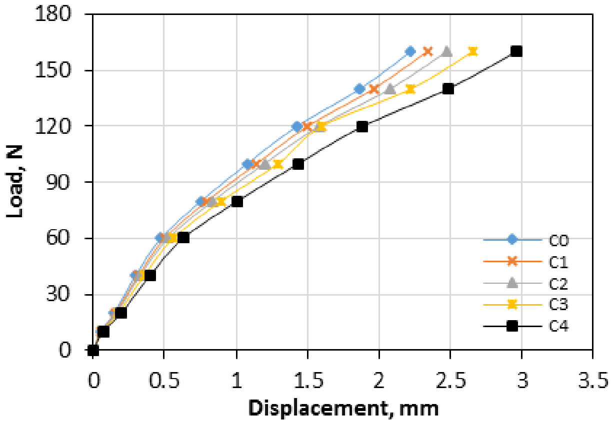

Fig. 3. Vertical displacements versus vertical load.

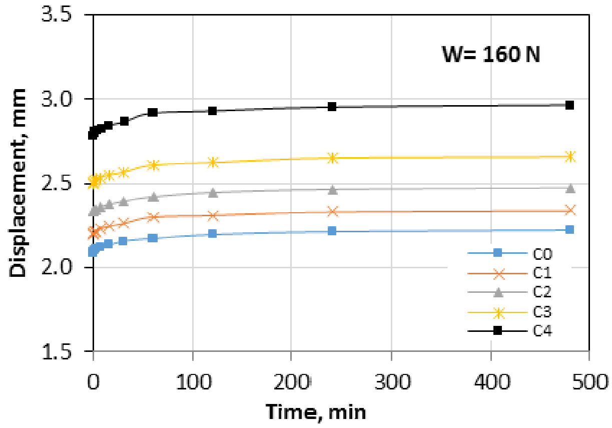

Fig. 4. Vertical displacements versus time.

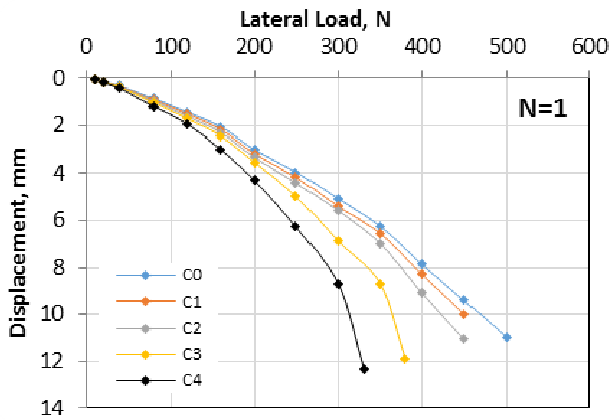

Fig. 5. Total lateral displacement versus lateral load at N = 1 cycle.

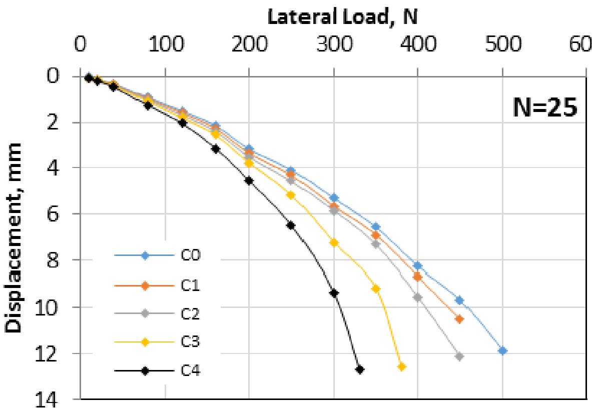

Fig. 6. Total lateral displacements versus lateral load at N = 25 cycles.

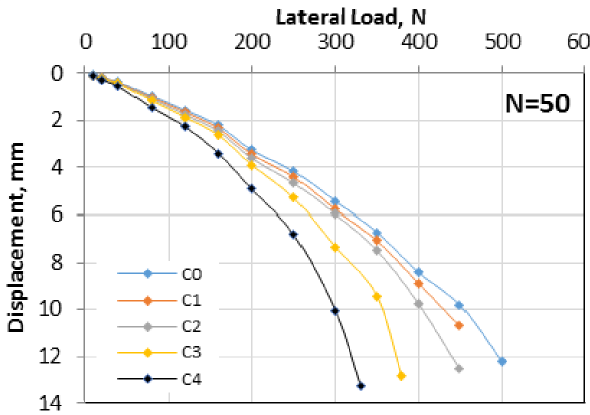

Fig. 7. Total lateral displacements versus lateral load at N = 50 cycles.

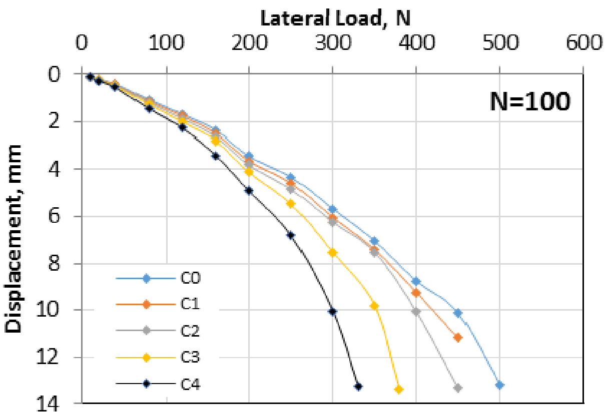

Fig. 8. Total lateral displacements versus lateral load at N = 100 cycles.

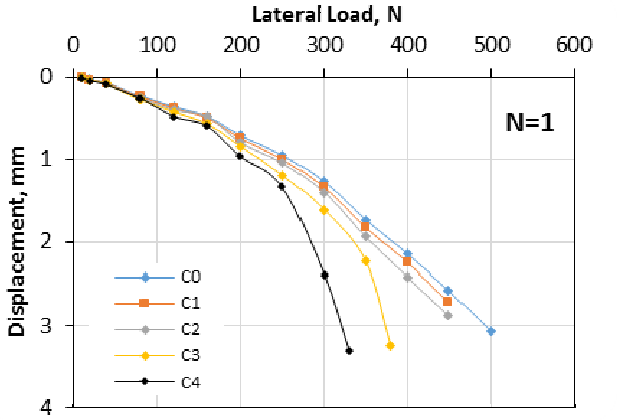

Fig. 9. Permanent lateral displacements versus lateral load at N = 1 cycle.

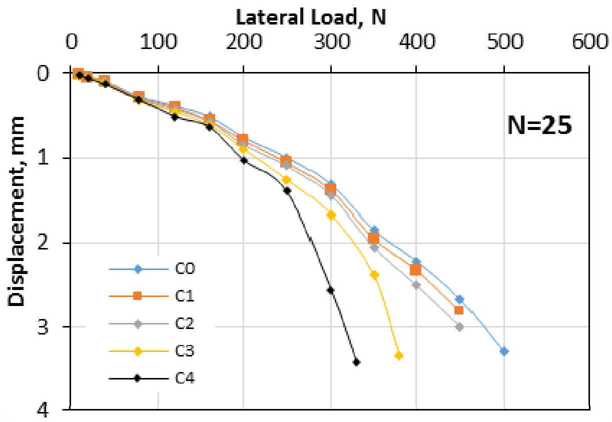

Fig. 10. Permanent lateral displacements versus lateral load at N = 25 cycles.

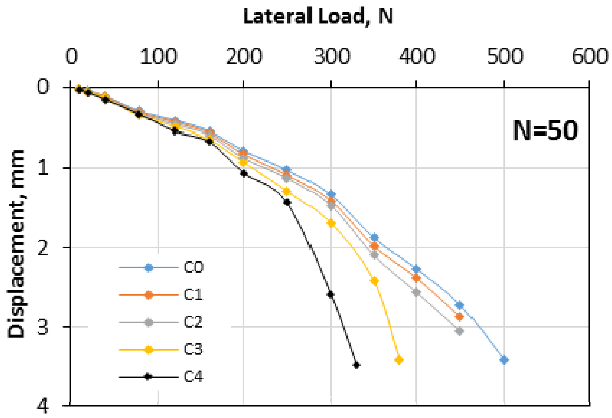

Fig. 11. Permanent lateral displacements versus lateral load at N = 50 cycles.

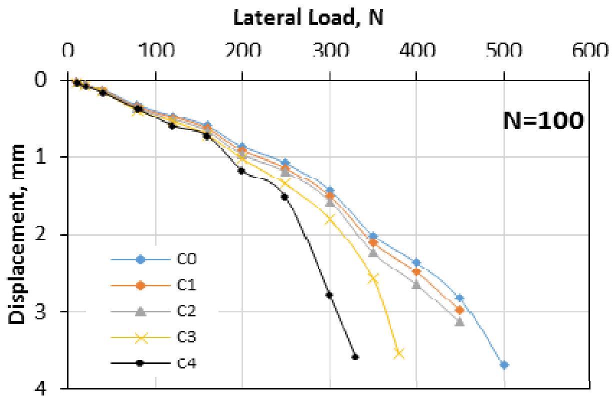

Fig. 12. Permanent lateral displacements versus lateral load at N = 100 cycles.

TABLE II. LATERAL DISPLACEMENTS AND LOAD CAPACITY

Soil sample	Total Lateral displacement (mm)			Lateral load capacity (N)		
	e/L			*e/L*		
	0.25	*0. 5*	*0.334*	*0.25*	*0. 5*	*0.334*
C_0	13.25	13.10	13.20	440	320	500
C_1	13.39	13.42	11.17	420	300	450
C_2	13.46	12.88	13.29	400	280	450
C_3	13.28	13.45	13.40	360	270	380
C_4	13.36	13.46	13.23	280	220	330

The ultimate single pile lateral capacity is calculated using the model proposed in [14]. The proposed degradation model is a function of number of load cycles, the ratio of the elasticity modulus of soil to the undrained shear strength, and the degradation factor (D_f). The degradation factor is the ratio of total lateral displacement at first cycle to the total lateral displacement of cycle 100. The proposed equation is:

$$P_{u,p} = P_f\,(1 - \log(\frac{E}{c_u}) \cdot \ln(N) \cdot D_f \cdot 0.031) \qquad (1)$$

where, $P_{u,p}$ is the proposed ultimate lateral load, P_f is the maximum lateral load lead to failure of pile, E is Young modulus of pile material, c_u is the undrained shear strength of soil and N is the number of loading cycles.

The results obtained from the proposed equation are compared with those obtained experimentally as shown in Table III.

TABLE III. VARIATION OF LATERAL CAPACITIES OF PILES WITH LOADING CYCLES

Soil Sample	D_f	E/c_u	P_f (N)	$P_{u,p}$ (N)				
				N=1	*N=10*	*N=25*	*N=50*	*N=100*
C_0	0.897	106	500	500	435	409	390	370
C_1	0.892	102	450	450	392	369	352	335
C_2	0.876	100	450	450	394	371	354	337
C_3	0.845	108	380	380	333	315	301	287
C_4	0.829	98	330	330	291	276	264	252

The ratio of proposed $P_{u,p}$ to P_f from the first loading cycles to one hundred ranges (0.74~1), (0.744~1), (0.749~1), (0.755~1) and (0.764~1) for soil samples C_0, C_1, C_2, C_3 and C_4, respectively. These ratios offers to the validity of the proposed model, as the proposed model shows well agreement between the estimated value of lateral bearing capacity and that measured experimentally when compared at the first cycle of loading, but the difference between estimated and measured lateral bearing capacity increases with increasing the number of loading cycles.

V. CONCLUSIONS

Industrial wastewater has diverse effects on the lateral carrying capacity of piles subjected to lateral cyclical loading. Also, it has diverse impacts on the vertical and total and permanent lateral displacements. The conclusions can be summarized as follows:

- at the same level of axial loading (300 N) on the piles, the vertical displacement increased by 5, 10, 26 and 95% in soil samples C_0, C_1, C_2, C_3 and C_4, respectively, in comparison with the vertical displacement of the piles driven into intact soil
- the axial loading resistance of piles decreased with an increase of the percentage of contamination, where the axial loads decreased by 10, 10, 24 and 34% in soil samples C_0, C_1, C_2, C_3 and C_4, respectively. It is important to note that samples C_2 and C_3 failed at different magnitudes of vertical displacement
- the lateral-bearing capacity of the piles decreased by 10, 10, 24 and 34% in soil samples C_0, C_1, C_2, C_3 and C_4, respectively, in comparison with the lateral-bearing capacity of the piles in intact soil
- the ratios of permanent lateral displacement to the total lateral displacement are 28, 27, 23, 26 and 27% in soil samples C_0, C_1, C_2, C_3 and C_4, respectively. These ratios are approximately constant because they depend on pile material properties, not on the soil properties
- the presence of axial loading increased the lateral-bearing capacity of piles, and reduced the lateral displacement of piles
- more studies required about the effects of drainage from the soil when pile foundation subjected to axial and lateral loading simultaneously.

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