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Effect of Spacing and Cross-Sectional Shape on Piled Raft System Subjected to Lateral Cyclic Loading

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ABSTRACT

Piled raft foundations usually supporting bridge piers, offshore platforms, marine structures and others are required to resist not only static loading, but also lateral cyclic loading that developed from different sources of loadings. An experimental study was carried out to investigate the effects of spacing and cross-sectional shape of pile on the behavior of laterally loaded piled raft models (1×2), (2×1), and (2×2) having a length to diameter ratio (L/D=40) with the spacing to diameter ratio(S/D) of 3, 5, and 7 embedded in layered soil with partially saturated clay soil. The results indicated that the increase in the lateral resistance in the group of square piles compared to a circular pile under pure loading conditions within the group 1 × 2, 2 × 1 and 2 × 2 are about 16%, 20% and 23% respectively. In addition, the results show that the increase in pile spacing lead to decrease lateral displacement under the same periodic load applied. The performance of all models improved using S/D=7 due to reduce the interaction of pile-soil-pile in the group.

1. Introduction

Piled raft system is a composite structure that is different from traditional foundations in which either the piles or the raft alone transfer the load of structure. In a piled raft design, consideration is given to the contribution of the raft besides the piles. A share of the structure load transfer into more rigid layers and deeper soil by the piles to enable very economical reduction in settlement and/or differential settlement[1]. Continuously piles were exposed to vertical loads that come from weight of the structure as well as lateral loads generated by wind, earthquake and wave particularly when using the piles in the offshore structures. In fact, piles are exposed to vertical and lateral loads at the same time, so it is important to distinguish the piles behavior in these situations[2]. Many researchers conducted analytical and experimental studies of piled raft foundations and studied the effect of several parameters on their behavior [3]and[4], whereas there are limited experimental studies are available that show the distribution of load within a pile group and studying the effect of spacing[5],[6]and[7] and cross-sectional shape [8] subjected to two-way cyclic lateral loading. However, the results of these studies show that the average load on a pile in a closely spaced group (three pile diameters or 3-D center-to-center distance) is much less than that of a single insulated pile with the same deflection, and the front (leading) row piles in the group carry significantly higher loads than the following row piles at the same deflection. Hence this study presented experimental work carried out on models of

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piled raft (1×2, 2×1, and 2×2) with slenderness ratio L/D=40 with different cross-sectional shape of pile (i.e. circular and square) and various spacing between piles to diameter (S/D=3, 5, and 7) to explain the interaction effects between pile and soil.

2. Experimental work

2.1 Soil preparing

This study adopted two soil types (clay and sand) from various Iraqi cities. A series of laboratory tests are performed to define and classify their properties which listed in Table (1). The layered soil consisted of an upper layer of dry, medium dense sand covering a partially saturated clay soil and a saturated sand bed. The upper and lower layers were constructed by pouring the dry sand using a rainfall technique from a certain height of (1.15) m with a dry density of 16.7KN / m3 corresponding to a relative density of 70%. The partially saturated clay soil is prepared carefully by mixing it with ample water (moisture content= 12.73%) to achieve the desired quality and degree of saturation (Sr= 50%). After thorough mixing, the moist soil was kept for at least three days in polyethylene bags to maintain an even distribution of the water content. The overall tank height is divided in three intervals from the inside for adding a certain weight to a given volume and achieve the necessary density for the soil. Height of the bottom layer (35 cm) filled with fully saturated sand, height of the middle layer (30 cm) filled with partially saturated clay soil that simulation of environmental conditions represented by high and low groundwater levels, after preparation of the bottom bed (the lower two layers), piles are installed in the soil layout, using a hand auger designed for this purpose then the top layer with height (35cm) filled with dry sandy soil as illustrated in Figure (1).

Table (1) the properties of sandy and clay soil

Sandy soil properties	
Property	**Value**
Effective size, D10 (mm)	0.18
D30 (mm)	0.31
D60 (mm)	0.46
Coefficient of uniformity, Cu	2.56
Coefficient of curvature, Cc	1.16
Specific gravity, Gs	2.68
Angle of Internal Friction (Ø)	35
Maximum, γd (max.)(kN /m^3)	17.23
Minimum, γd (min.) (kN /m^3)	14.82
Clay soil properties	
Specific gravity	2.7
Liquid limit %	39
Plastic limit %	22
Plasticity Index %	17
Percent of clay	52%
Percent of silt	42.7%
Maximum dry density (MDD)KN/m^3	16.8

Fig. 1. Piles installation

2.2 Piled raft model

Piles layout used in the present study consist of two shape (circular and square) aluminium piles. Three models of pile groups are used (1×2), (2×1), and (2×2) with different spacing between piles (S/D=3,5and7) and slenderness ratio L/D=40.Each model includes piles and cap of piles applied contact with ground surface to simulate piled raft system as seen in Figure (2). The pile cap made of a rigid plate with a smooth surface having a thickness of (6mm) and consist of two parts, the upper part of the cap used for applying dead load and the lower part used for applying cyclic lateral loads. Piles are fixed to the cap using screws. Table (2) listed the properties of the used piles.

Fig. 2. Piles caps shapes and patterns used for laboratory model tests

Table 2 Aluminium piles properties

Pile No.	Cross section	Embedded length(L) mm	Outside diameter mm	Wall thickness mm	Bending stiffness $E_P I_P$ (10^6) N.mm^2
1	Circular	640	16	1.5	124.78
2	Square	640	14	1.5	136.210

3. Testing procedure

The current study comprised two stage:

1- The first stage comprised of the static loading testing, which piled raft system is loaded vertically to obtain the maximum bearing capacity of the group depending on [9]which assumed that ultimate axial capacity of pile group is taken as the load corresponding to overall axial movement equal to 15 % of the pile diameter, then this value divided by the safety factor (2.5) to determine the allowable loads for the group.

2- In static loading stage and separately, the group is loaded laterally depending on the Brom's failure criteria, which assumed that ultimate lateral capacity taken as the load corresponding to a deflection equal to 20% of the pile diameter [10].

3- The second stage included cyclic loading testing. In this stage two-way cyclic loads were applied on model of piled raft system at different cyclic load ratio using two load cells to generate different cyclic loading as shown in Figure (3). The cyclic load ratio (CLR) is expressed as the ratio of magnitude of cyclic lateral load to static ultimate lateral capacity of the pile [11]. The tests occur under frequency (0.2 Hz) and different (CLR) of 0.2, 0.4, 0.6 and 0.8[5]. The results are represented as Load-Deflection curves.

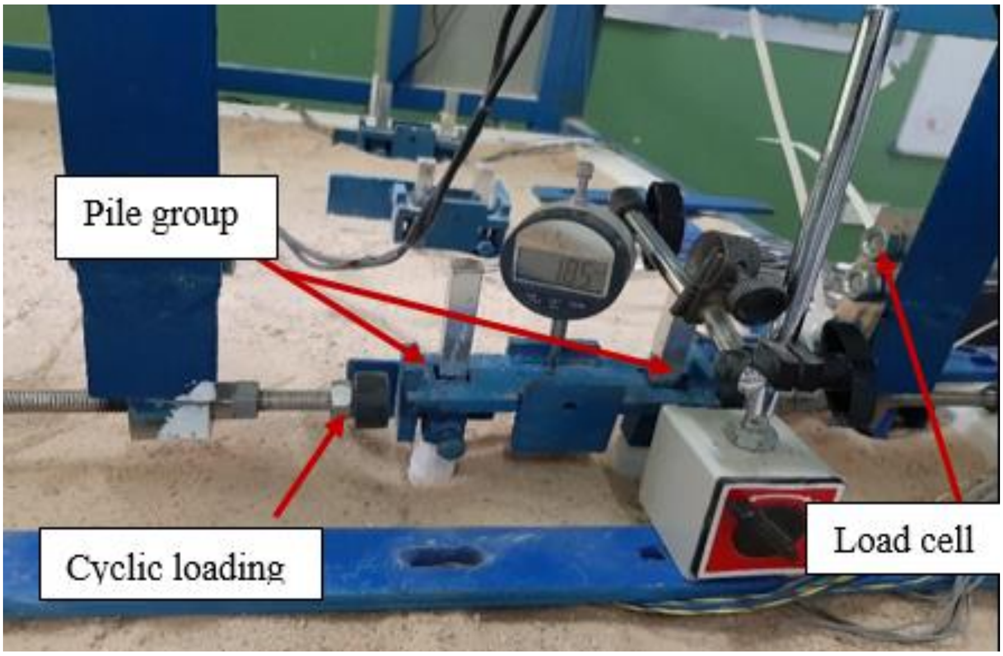
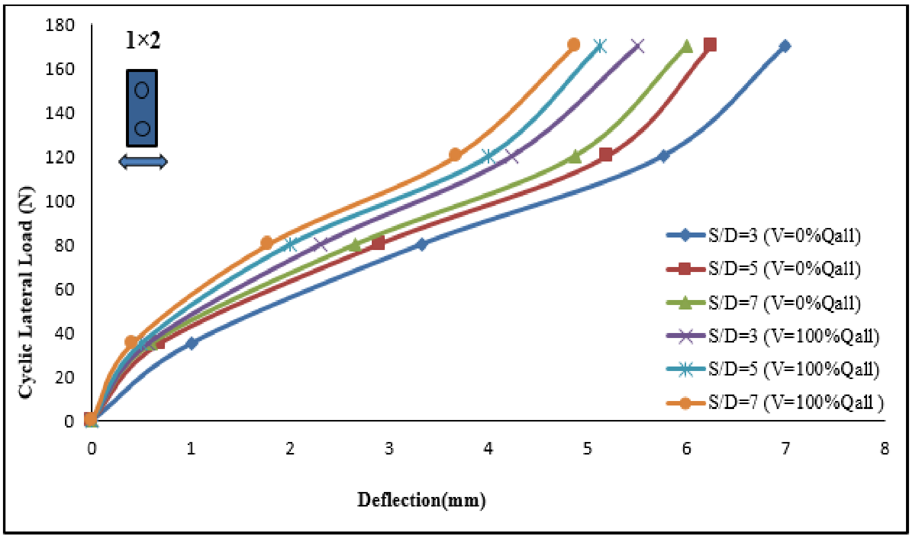


Fig. 3. Cyclic loading for laboratory model tests

4. Results and analysis

4.1 Effect of spacing on piled raft

The Figures (4) to (6) for piled raft models (1×2), (2×1), and (2×2) respectively under pure loading (V=0%Qall) that means that piled raft foundation subjected to cyclic lateral loads only, and combined loading (V=100%Qall) that means this foundation subjected to lateral and vertical loads which equal to 100% allowable static loads. These figures illustrate that lateral deflection increased considerably as the pile spacing decreased from 7D to 3D. The pile spacing has a significant influence on the load distribution in the pile groups. As pile spacing increases, pile load decreases [12]. The maximum lateral displacement occurs at S/D equal to 3 and 5 and this is attributed to group interaction (i.e. shadow effect). The tendency of a pile in a trailing row to show less lateral resistance due to the location behind another pile is commonly referred to as "pile-soil-pile interaction" or "group interaction effect", commonly referred to as "shadowing", which in turn caused by overlapping of stress zones when the spacing between piles is smaller. In this study, the increase in lateral resistance of piled raft (1×2), (2×1) and (2×2) at S/D=5 and 7 compared with (S/D=3) with both shapes circular and square, presented in Table (3).As seen from the results that the lateral resistance for all piled raft models with S/D=7 is greater than the other spacing due to the reduction in the interaction of pile-soil-pile. [13] showed that the failure zones for trailing row piles overlap with the leading row piles and reduce the lateral resistance when closely spaced pile groups move laterally.



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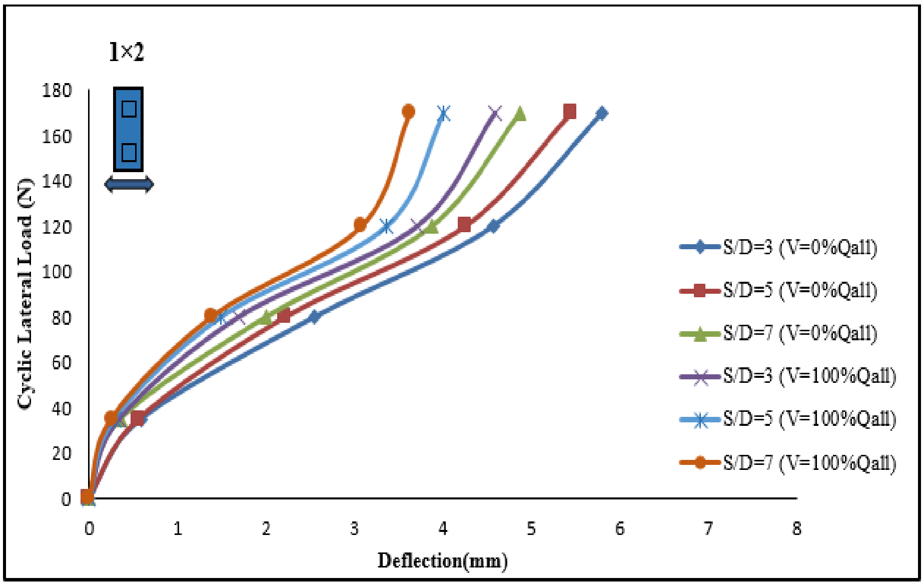
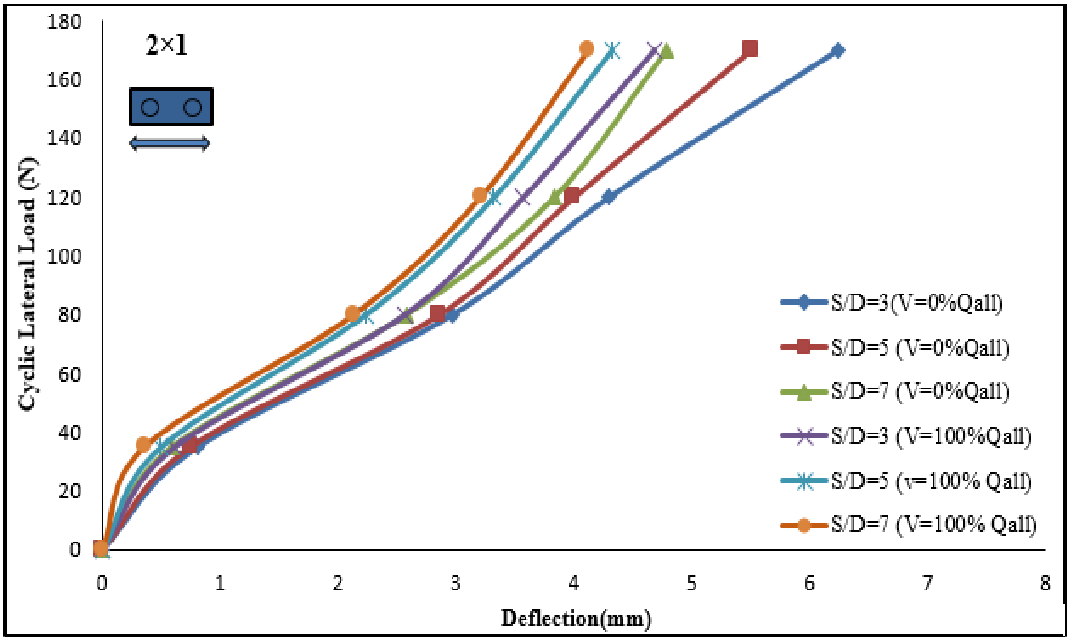


(b)

Fig. 4. Effect of spacing between piles on piled raft model (1×2) at 100 cycles under pure and combined loads, (a) Circular pile, (b) Square pile



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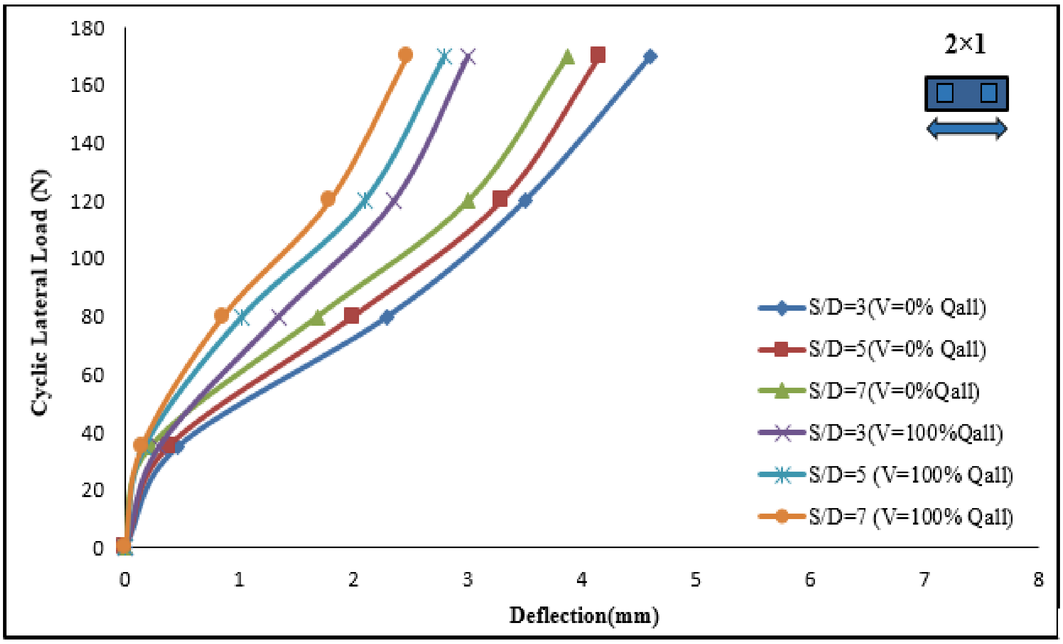
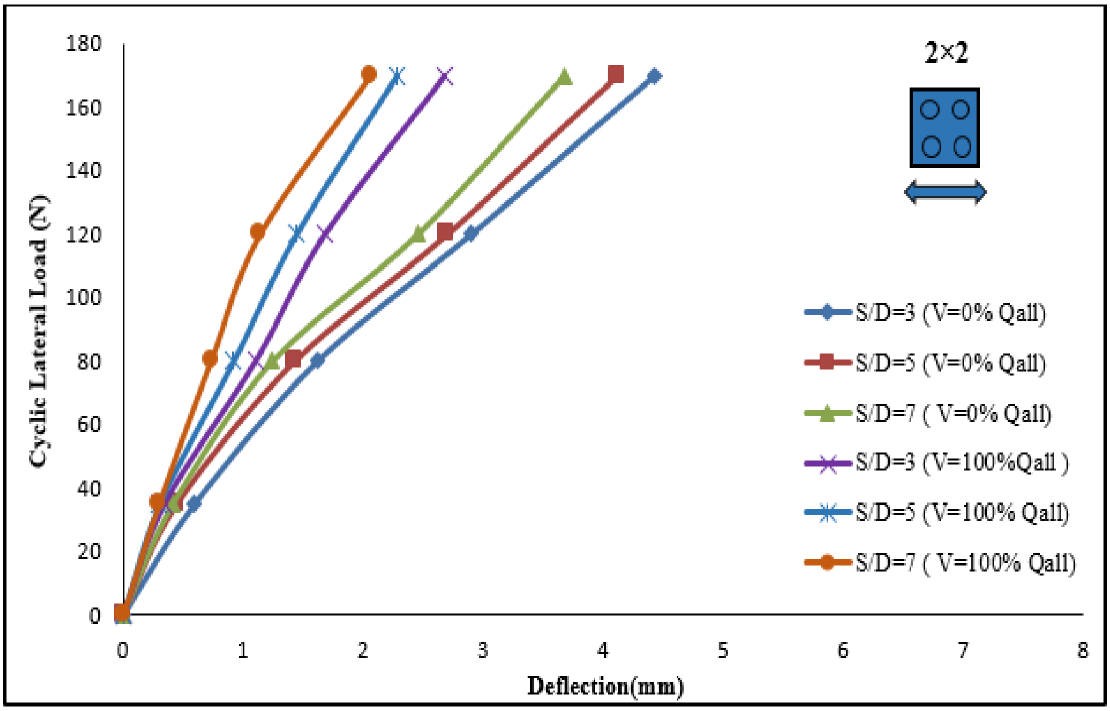
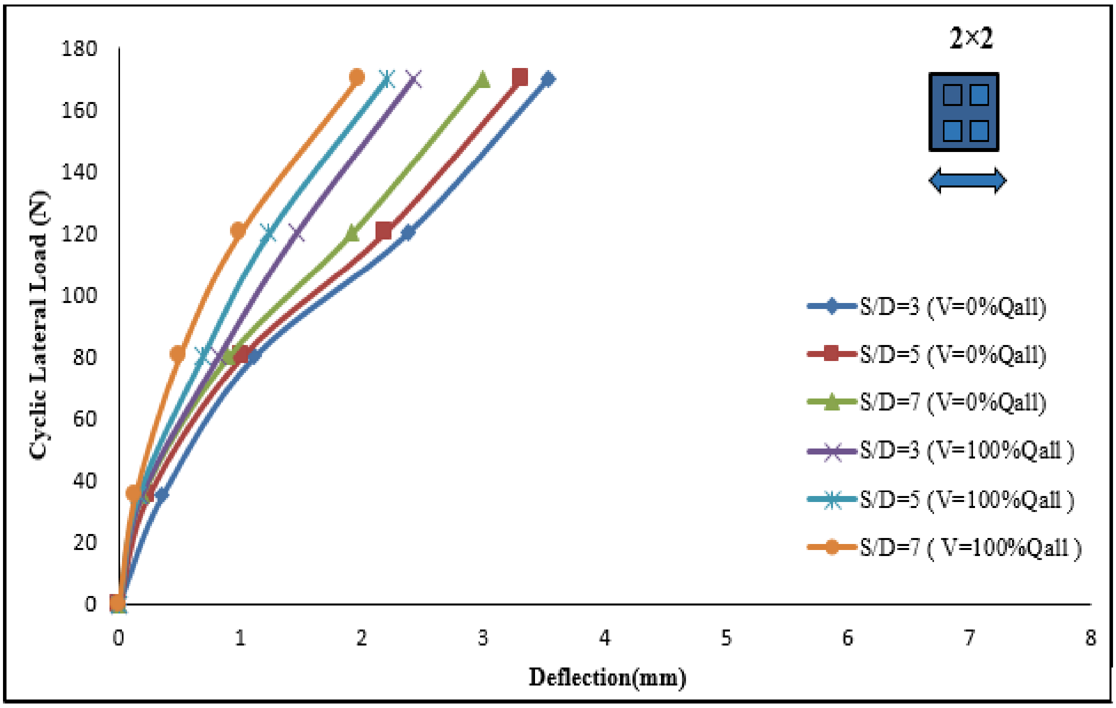


(b)

Fig. 5. Effect of spacing between piles on piled raft model (2×1) at 100 cycles under pure and combined loads, (a) Circular pile, (b) Square pile



(a)



(b)

Fig. 6. Effect of spacing between piles on piled raft model (2×2) at 100 cycles under pure and combined loads, (a) Circular pile, (b) Square pile

Table 3 Effect of pile spacing on lateral resistance of the piled raft system

Piled Raft Model	S/D	% Increasing in lateral resistance(pure loading) Vertical loads=0%Qall		% Increasing in lateral resistance (combined loading) Vertical loads=100%Qall	
		Circular	Square	Circular	Square
1×2	5	11%	6%	7%	13%
	7	14%	16%	11%	21%
2×1	5	12%	10%	8%	7%
	7	23%	16%	12%	18%
2×2	5	7%	6%	15%	10%
	7	17%	15%	23%	20%

4.2 Effect of cross-sectional shape of pile on piled raft

The results obtained from mentioned Figures (4) to (6) indicated that the group consisting of the square piles showed more resistance than the circular piles with the same periodic load, and this is attributed to the shape factor of the square greater than circular shape (0.8 for circular; 1.0 for square) from equation proposed by [17], which means that effective area to resist both of the normal earth soil pressure and shear drag of a square pile is larger than that of a circular pile that subjected to the same load intensity therefore the surface area that resists the cyclic loads is greater, which in turn cause a reduction in lateral deflection of the group consisting of the square piles. The results showed that an increase in the lateral resistance in the group of square piles compared to a circular pile under pure loading conditions within the group (1 × 2), (2 × 1) and (2 × 2) about (16%, 20% and 23%) respectively. Whereas this proportion increases by (30%) under combined loads for groups (1×2) and (2×1) and about (10%) for a group (2×2) These results agree with the study presented by [14], [15],[16] and [8].

5. Conclusion

1. As pile spacing increases, lateral displacement decreases under the same load applied. However, in the case of deflection, the variation due to pile spacing can be clearly observed in all piles and rows, which is due to the effect of overlap between the soil and the piles in the group.
2. The shape of the pile cross-section influences on the reactions of laterally loaded piles. The square cross-section leads to less displacement of the pile head. The internal forces also decrease due to the reduction in the proportion of deformation in the overall displacement, which in turn reduces the bending moment profiles. Therefore, square piles are recommended due to their better performance.

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