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The Effect of Vertical Loads and the Pile Shape on Pile Group Response under Lateral Two-Way Cyclic Loading

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Abstract

This paper is presented the lateral dynamic response of pile groups embedded in dry sand under influence of vertical loads and the pile shape in-group, which are subjected to the lateral two-way cyclic loads. The laboratory typical tests with pile groups (2×1) have an aluminum-pipe (i.e. circular, square) pile, embedded length to diameter of pile ratio (L/D=40) and spacing to diameter ratio (S/D) of 3, 5, 7 and 9 are used with different cyclic-load ratio (CLR) 0.4, 0.6 and 0.8. The experimental results are revealed that both the vertical and lateral pile capacity and displacement is significantly affected by the cyclic-loading factors i.e. (number of cycles, cyclic load ratio, and shape of pile) .In this study, important design references are presented. Which are explained that the response of the pile groups under cyclic lateral loading are clear affected by the attendance of vertical load and pile shape. Where, it is reduction the lateral displacement of group piles head and increase lateral capacity about (50) % compared without vertical loads. On the other side, the pile shape is a well affected to the pile response where the level of decline in lateral displacement at the pile groups head in the square pile is more than circular pile about 20 % at the same load intensity.

Keywords: Pile Groups; Cyclic Load; Combined Load; Shape Influence; Spacing; Configuration.

1. Introduction

Large structures, for example offshore platforms, high-rise buildings, bridges, wind turbine foundations and railway embankments is resting on compressible soil and supporting by piles foundation. Apart from the usual loads applied by these structures, the piles are subjected to vertical, lateral, and torsional types of cyclic loading arising from the actions of waves, ship impacts, and moving vehicles [1]. Such cyclic loads on piles led to the reversal of stresses in the adjacent soils, initiating progressive degradation in strength and stiffness that, in turn, caused decline in pile capacity with large irreversible deformation that leads to unsuccessful consequences in significant situations [2]. The main reasons that identify the soil dilapidation are gradual rearrangement particles in the immediate adjacent of the pile surface. In the past, significant donations were prepared to the analysis of the single pile and pile groups in different kinds of soil, under lateral cyclic load, including experimental studies [3-7]. Also theoretical approaches [8-12]. In addition, below some of the latest studies of the lateral loads.

The behavior of pile under lateral combined load embedded in sand and clay soil was studied by using finite element.it was explained that the axial load was effected on the lateral response behavior [13].

Single aluminum pile models with different slenderness ratio and two-shape (i.e. circular and square) embedded in

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sandy soil were used to study the effect of pile shape on the lateral response under combined loads. The results observed that the square pile shape had more resistance to lateral loading than circular pile and the axial load presented appositive influence on the lateral response of pile [14].

Small-scale models of pile with different slenderness ratio, which embedded in sandy soil under combined load, were used to study the effect of axial load to the lateral response of pile.it was illustrated that the effect of axial load reduced with increase slenderness ratio [15].

Laboratory typical tests with steel pile group embedded in soft cohesive soil were exposed and compared with a numerical model that was based on a two-dimensional (2D) dynamic finite-element approach were used to study the response of Pile Group in Soft Clay under Cyclic Lateral Loading. The study indicated that both the axial and lateral pile capacities and displacements were significantly influenced by the cyclic-loading parameters (number of cycles, frequency, and amplitude) [16].

Theoretical study was posited by using three-dimensional finite element to assess the lateral pile and pile group response subjected to lateral load. The results were explained, in terms of response of load with lateral displacement, load with soil resistance and corresponding p–y curves. It was found that the group interaction effect led to reduced lateral resistance for the pile in the group relative to that for the single pile [17].

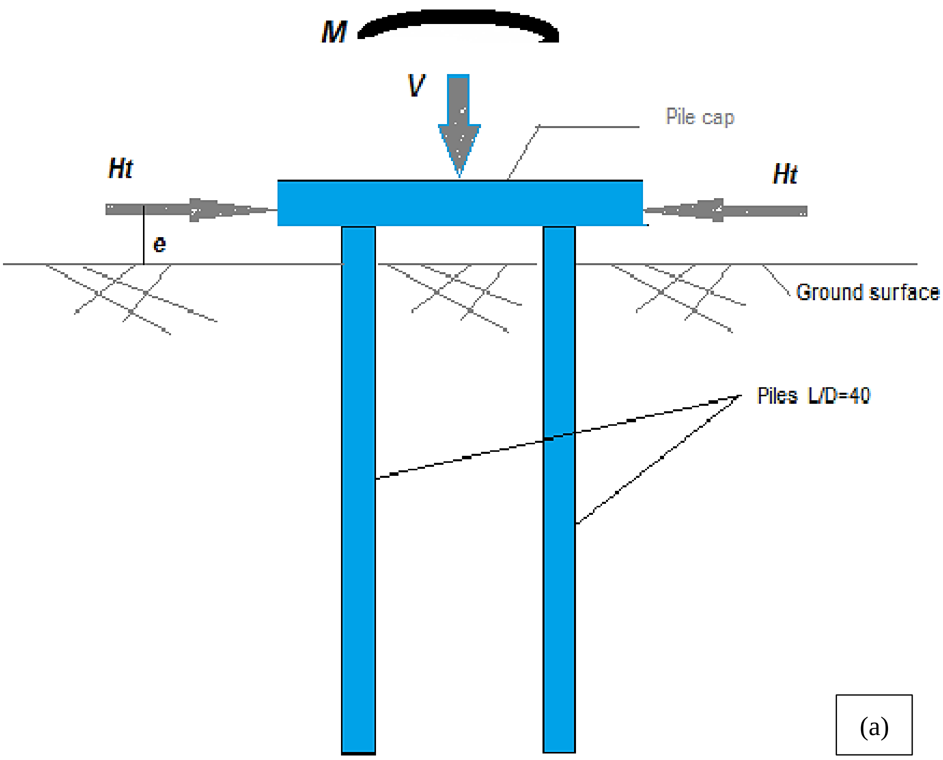
From all previous studies, it is observed that very little experimental work tests especially for group pile with two shape of pile under combined loads. Therefore, this study is very important to increase the base data information for group behavior having different two shape (i.e. circular and square) under combined loads.

According to the location of the lateral loads applied on the pile groups, the nature of the cyclic lateral loading can be classified mainly as one-way or two-way**,** depended on the maximum and the minimum load were in the same or opposite directions. The two-technique lateral cyclic loading was symmetric or asymmetric according to the degree of the maximum and minimum value of the applied cyclic loading [16].

Mathematically, it is expressing in terms of a non-dimensional cyclic load ratio CL R. In addition, Pile group under combined axial and lateral cyclic loading with wave loading represents two-way cyclic lateral loading is illustrated in Figure 1.

$$CL\ R = H_{min}/H_{max} \quad (1)$$

Where: H_{min} and H_{max} are values of maximum and minimum cyclic lateral loads, respectively.



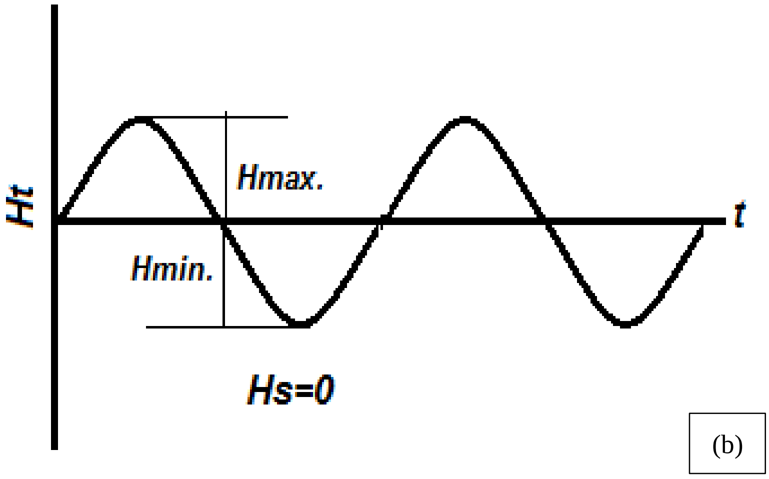


Figure 1. Pile group under combined vertical and lateral cyclic loading: (a) schematic view; (b) symmetric two-way loading

In Figure 1(a), the pile cap is subjected to a lateral load of Ht, which equal Hs + H cycle where Hs and H cycle were the cyclic and static component, respectively. In an environment where the pile group is subjected only to cyclic lateral load without any static component (i.e., Hs = 0), a symmetric two-way cyclic lateral loading is imparted (e.g., pile groups supporting an offshore construction sufficiently away from the shoreline). In such a case, the sinusoidal wave start from zero, as shown in Figure 1(b). The response of piles under combined vertical and lateral cyclic loading strongly depends on cyclic-loading parameters: the number of cycles, frequency, cyclic load ratio, spacing piles and percentage of vertical loading. Although the prevalent pattern of wave loading to offshore structures, of traffic loading to transport infrastructures, and of wind loading to high-rise buildings are random in nature, in ideal states, such random periodic load is deduced into normalized harmonic (sinusoidal) patterns for suitable engineering design [7].

2. Materials Used and Experimental Setup

2.1. Soil

The sandy soil used is brought from Karbala Governorate south of Baghdad city, in Iraq. The sand properties represented as shown in Table 1.

Table 1. properties of the sand

Property	Specific gravity, *Gs*	*(Ø)* degrees	*(C)* KPa	γ_d(max) KN/m^3	γ_d (min) KN /m^3	γ_d (test) KN /m^3
Value	2.66	35	0	17.9	14.5	**16.7**

2.2. Pile and Pile Cap

Two shape aluminum hollow pile group of (2×1) models (square and circular) shape are used in this study as shown details in Table 2 with (L/D=40) in group whereas the space in the path of loading is various (i.e. S/D=3, 5, 7 and 9).Two rigid plates of 6 mm thick are used as piles caps. The upper part of cap to apply axial load and the lower part to apply lateral cyclic load. The pile cap is involved at the top of piles leaving 50 mm above the ground surface as a freestanding length for the group. Screwing of piles in the threads providing in the pile cap leads to partial fixity state as shown in Figures 2, 3, and 4.

Table 2. Mechanical properties of aluminum piles

Pile no.	Cross section	Embedded length (*L*) mm	Outside diameter/width (mm)	Wall thickness (mm)	Bending stiffness , $E_P\,I_P$ (10^6N.mm^2)
1	circular	640	16	1.5	124.78
2	square	640	14	1.5	136.210

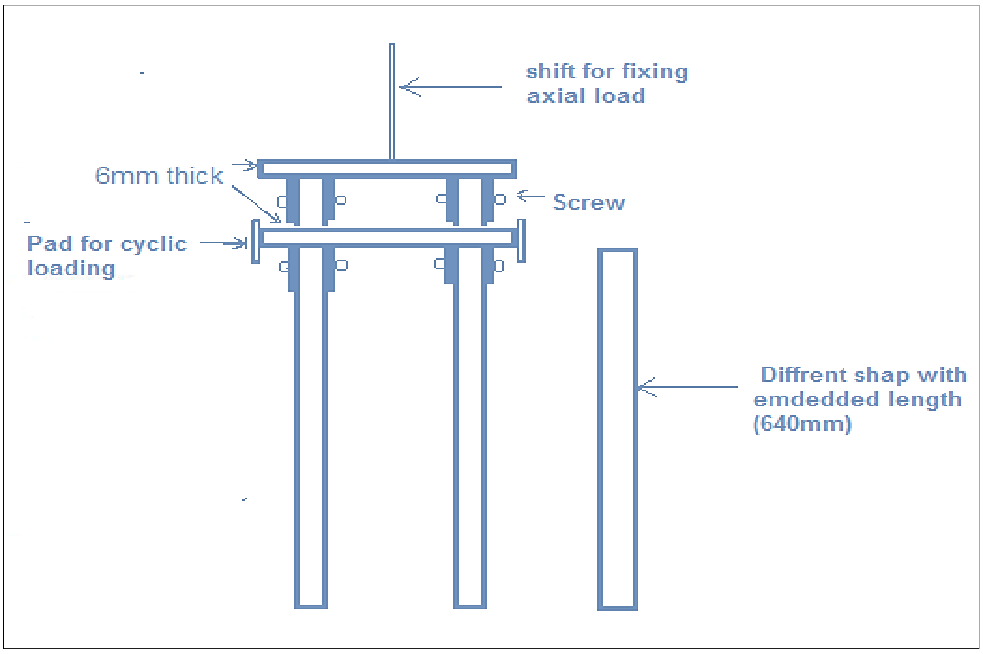


Figure 2. Schematic diagram illustrates piled cap details

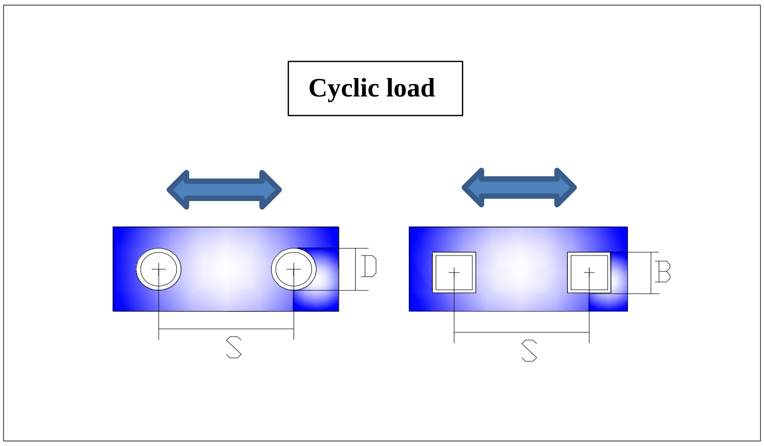


Figure 3. Configuration of pile groups (2×1)

Figure 4. Models piles cap

2.3. Test Setup

Investigational system is used for cyclic lateral loading test on pile groups as shown in Figure 5. Lateral cyclic loading tests are conducting on model piles of group embedded in dry sand in steel testing container of dimensions (1×1×1) m, the height is necessarily large enough to avoid edge effect. Lateral Cyclic loading is applied to the cap of pile groups in two stage as shown in Figure 6 that represents flowchart for study methodology .The first stage is performed on group piles without vertical loads (pure cyclic loading) , the second is performed on group piles under combined load(axial and lateral cyclic load). The axial load is comprised from allowable vertical loads for group (2×1) in one stage (100%) by using safety factor of 2.5. The different cyclic loading is applied by using two load cells. Piles head deflection in-group is controlled by using type of inductively Linear Variable Displacement Transducers (LVDTs). This will connect with data logger read which Including 8 Chanel. Lateral displacement is reading and storing the information mechanically. Symmetric two-way cyclic horizontal loading is applied on typical piles use two load cells tangled on the load frame on individually sides of the piles cap and attached to piles cap. Automatic timer is using to control the period of loading. Dial gage apply on the pile group head to record vertical displacement through the test. A raining technic device is designed to achieve a uniform soil layer with the required relative density Dr= 70%.

Capacity of the static lateral load is taking as the load equivalent to the deflection of 3.2 mm (20% diameter of pile) as recommended by [18]. Which in turn is necessary to determine the amount of two-way symmetric cyclic lateral loading which is applied on pile groups under different cyclic load ratio, CLR of 0.4, 0.6 and 0.8 [19].The tests occurs under frequency (0.2 Hz) in dry sandy soil. The Cyclic Load Ratio (CLR) is taking by means of the percentage of level of cyclic load to static ultimate lateral capacity of the pile [8]. The period of cyclic load is reticent as 5 second. The cyclic load is continued until 100 cycle in all the tests.

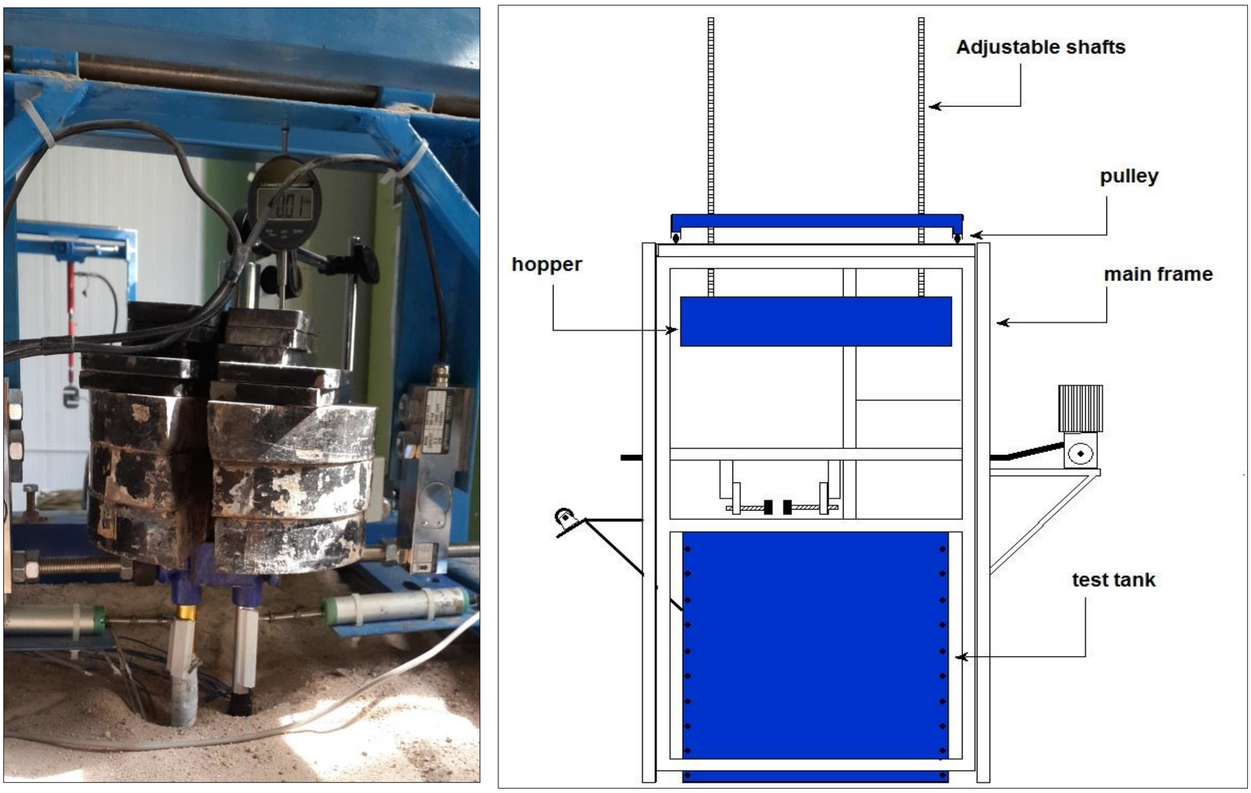


Figure 5. Sketch showing the cyclic lateral loading device

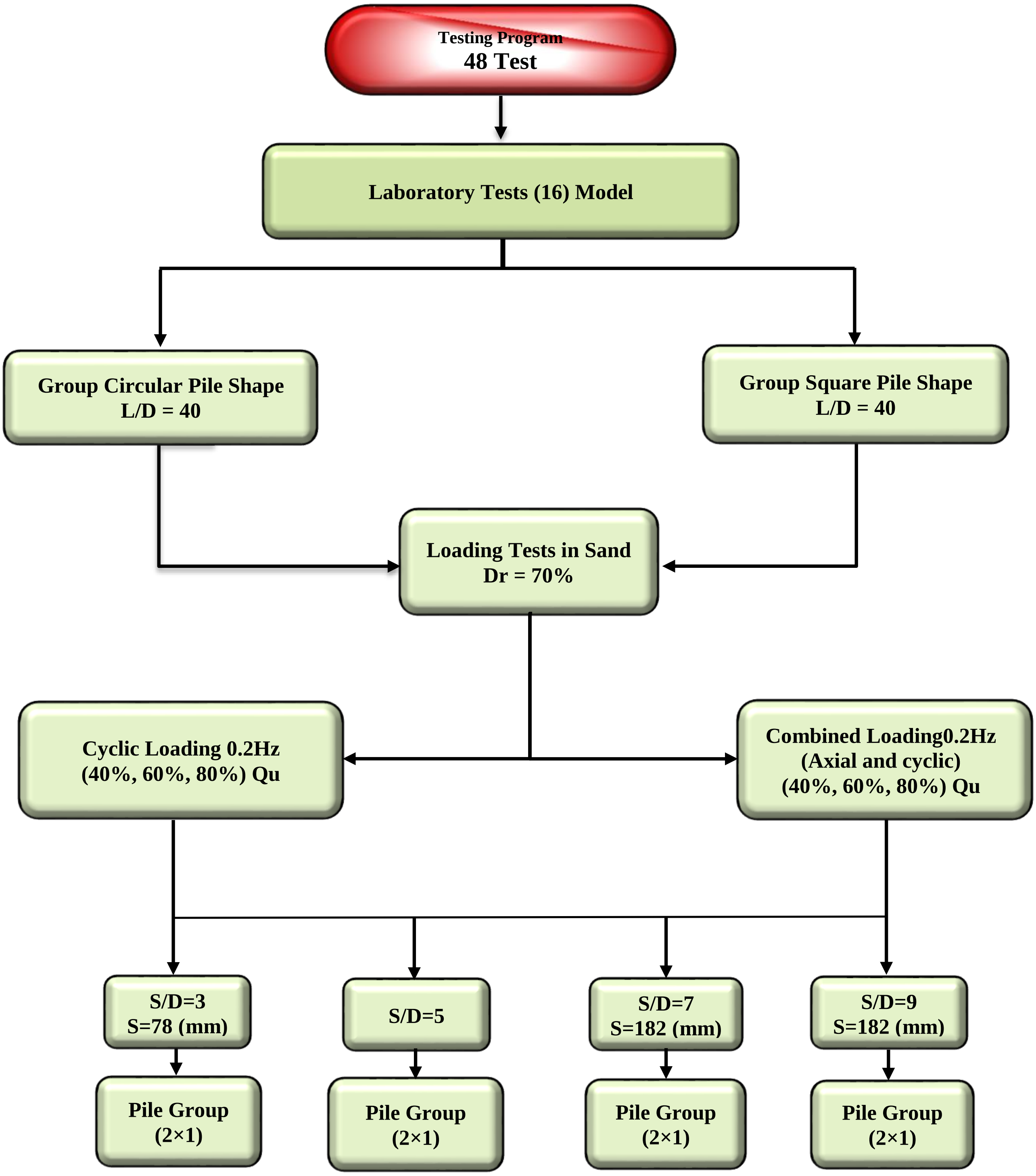


Figure 6. Flow chart for testing program

3. Results and Discussion

3.1. Effect of Cycles Number of Loading

The results are submitted as the typical load per piles in groups versus displacement cap of group piles (2×1) with (L/D = 40) and spacing i.e. (3D) under different cyclic load ratio (0.4, 0.6 and 0.8) and (0.2 Hz) environmental frequency embedded in dry sandy soil as shown in Figure7. In addition, the load for group piles versus displacement of group piles under static loading also shown in this figure. As observed from the figure, load-deflection behavior under cyclic loading is greatly nonlinear and the amount of nonlinearity growths with the number of cyclic load in individually case (pure cyclic load and combined loads). This is attributing to the growth of gap at the soil–pile line wherever the stress focus happens. Because of rise in number of cyclic load, depth and width of the gap developed more and more. Cyclic load ratio and number of cycles influence on the dimensions of gap and caused large cumulative lateral displacement of group pile [20].

Also, this figure shows that the displacement of piles in group at 100 cycles of cyclic loading with an average cyclic load for each group piles of 150 N is about 2 times more than that the same average load in static case. This mean that the first cycles of loading are significant, where the lateral displacement at the first 25 cycles of cyclic load is about nearly (75% of total displacement at 100 cycles). Accordingly, the ultimate lateral capacity of group piles at 100 cycle that equivalents of 20% pile diameter under cyclic loads reducible about 50% of static loads under the same lateral load level. The explanation for these phenomena is the soil under repetitive loading of high level and following development of related strain level lead to expansion in volume and decrease in shear strength of soil around the piles specially for the dense sandy soil at small restricting stresses, where grains of soil overriding instead of particle crushing [21].

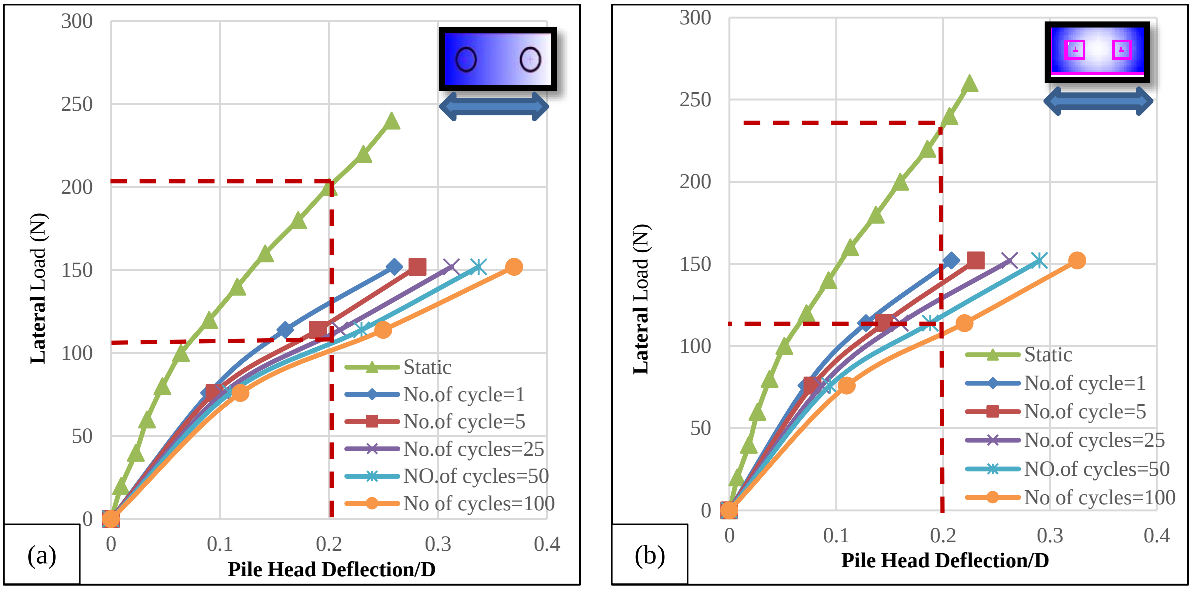


Figure 7. Effect of number of cycles of loading on load— deflection behavior of piles group (2×1, L/D =40, S/D = 3) at V=0 %Q all. (a) Circular pile (b) Square pile

Also, It can be foundied as the pile is subjected to shared symmetrical cyclic load, the same piles head displacement have noticed to both leading and rear row piles in-group for different load distribution for each row as shown in Figure 8. This figure presents the lateral displacement at 100 cycles for S/D=3, 5, 7 and 9, (2×1) group pile model for both leading and rear row (i.e. circular pile in group). In addition, it is important to explain that the locations of row in-group being transform in the current two-way cyclic lateral load, each leading row converts rear row for the interval of other half of the loading.

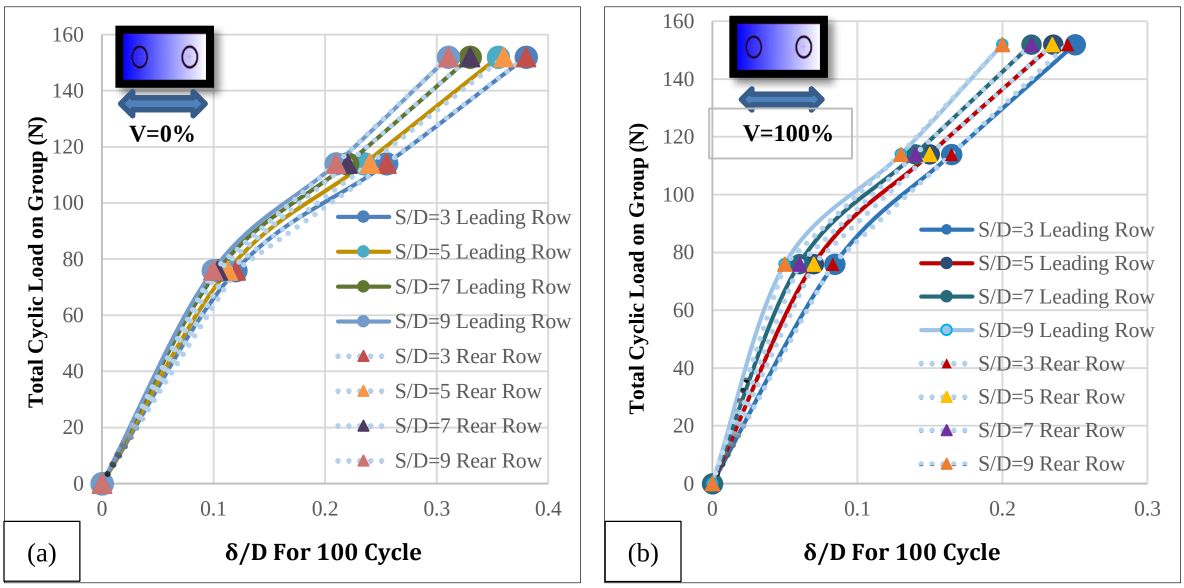
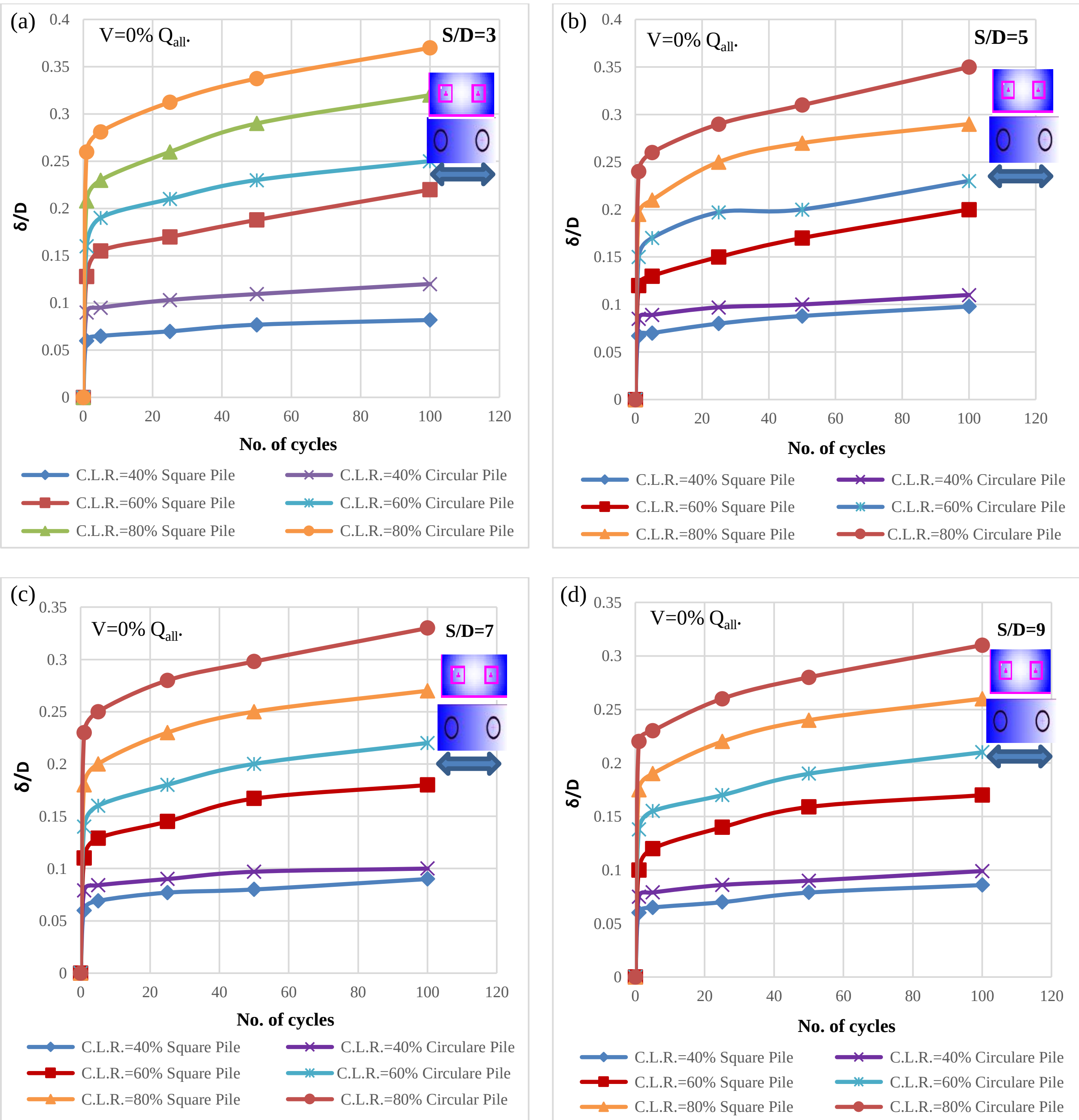


Figure 8. Effect of different cyclic loading on lateral deflection behavior at 100 cycle for (leading and rear) row piles in-group (2×1, L/D =40) circular pile: (a) V=0 %Qall - (b) V=100% Qall

3.2. Effect of Cyclic Load Ratio (CLR)

The difference of pile head displacement per number of cyclic load for various levels of cyclic load ratio (0.4, 0.6 and 0.8) for S/D 3, 5, 7 and 9, with (L/D = 40) are described in Figure 9. It can notice from the figure that at reasonably lower magnitude of loading (CLR = 0.4), the deflection of piles group head rises progressively but nonlinearly up to a definite number of cycles and then becomes approximately constant with the rising in number of cycles. However, at relatively higher magnitude of cyclic loading (CLR =0.4), there is a sudden increase in displacement at the initial few cycles and rises progressively with the growth in cycles number at CLR near about 60%. The results explain that the lateral displacement at CLR=0.6 is more than CLR=0.4 about 60% for pile group at closely space as shown in Figure 10. A similar behavior for piles in-group with S/D ratio (5, 7 and 9). The quick rise on lateral displacement is essentially due to the creation of gap about the piles, which leads to decrease resistance of passive pressure of the soil. Accordingly, the critical cyclic load level is corresponding to CLR of 0.60 [22].



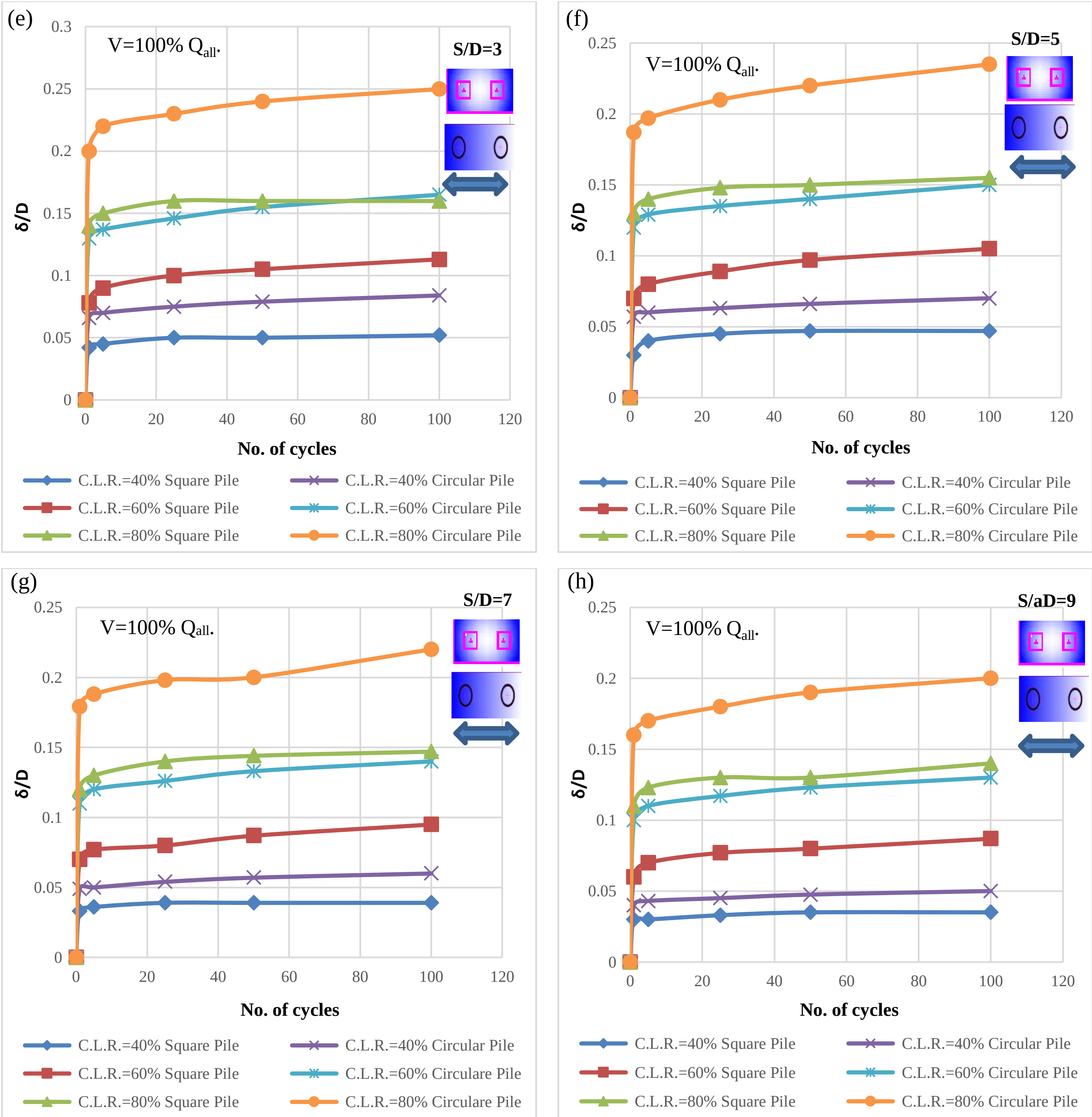


Figure 9. Effect of cyclic load ratio (CLR) on pile head deflection of 2×1 group (a-b-c-d) under combined load (V=0%Q all) and (e-f-g-h) under combined load (V=100%Q all)

Figure 10. Deformation around pile group model under combined cyclic load ratio CLR=60%

3.3. Effect of Pile Spacing

Curves of the load-deflection are obtained for 2×1-pile group with various pile spacing at 100 cycle of loading as shown in Figure 11. For a definite load, the displacement of the group pile with S/D ratio of 7and 9 is fewer comparably with S/D ratios of 3 and 5. Where, the lateral displacement at close spacing more than S/D=9 about 18%. The results are explained that the deflection for different spacing between piles has a less effect. This is ascribed to group interface effect (i.e. shadowing effect) due to overlap of stresses areas for narrowly space in pile groups. When the group piles are subjected to two-way cyclic loading and due to stress overlap, the perfect soil column enclosed by the pile group moves as a single block in one path through first half of the cyclic loading and in other path through second half of the loading cycle. Which in turn case wedge failure mode and offering less resistance for consequent cycles of loading [10]. As the spacing of piles in the group increases, the intersection of stress zones decreases, leading to improve lateral capacity of the pile group. That is the same behavior in both circular and square shape of piles in-group model. Generally, with all cases that increased, the spacing between the piles contributes to the reduction lateral displacement and attributed to reduction in pile- soil interaction (shadow effect). This is referred to by many researches (e.g. [19, 23, and 24]).

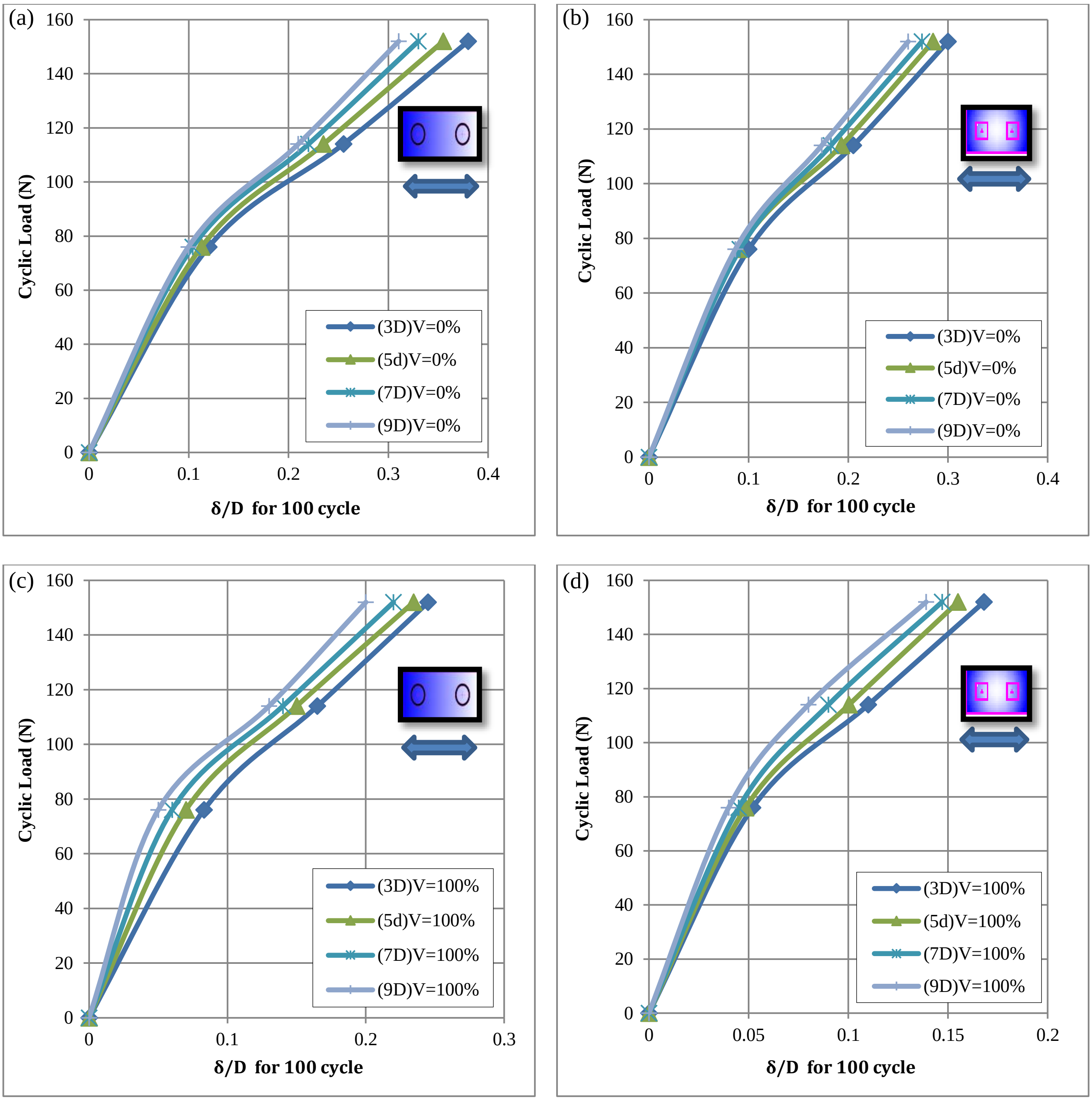


Figure 11. Effect of spacing piles group (2×1) on ultimate lateral capacities (a, b) under combined load (V=0%Qall) , (c, d) under combined load (V=100%Qall)

4. Behavior of Axially Loaded Pile Group to Lateral Cyclic Response

Piles group behavior toughly depends on the material and geometry characteristic of soil and configuration of piles in-group. In this part, the groups (2×1) are loaded by applying lateral cyclic loads without axial load, groups are pulling upward as illustrate in Figure 12(a) (i.e. circular pile, 3Dspacing). The vertical movements (upward) increase with number of cyclic loading and cyclic load ratio about 90%.This phenomena is due to rounded movement of soil surrounding the piles, inducing a change of friction between soil and pile to negative skin friction leading to upward pile movement.

On the other hand, when the groups pile is loaded of 100% from allowable axial load of group, and then lateral cyclic load is applied. The load deflection curves are schemed as shown in Figure (12- b). This figure shows that the axial behavior has a little nonlinear response at allowable vertical load with lateral cyclic loading applied. After consequent application of cyclic load to the groups, the group settle down more and more in every lateral cyclic load in both circular and square piles in-group. Quantity of extra settlement is considerable for the level of horizontal loading considered and it is gradually increase with each cycle of load about (80%)**.** The causes of extra settlement are: (1) the vertical stiffness of different piles reductions thus causing downhill movement due to the opening of the hole nearby the ground shallow; (2) the practical lateral load is resisting by the push pull action between the piles in the group. The lateral load induces uneven levels of nonlinearity at the interface due to the nonlinear stress at the piles soil interface. Under the vertical load, all piles behave identically due to the symmetric geometry. Generally, both of upward and settlement of group pile head are increased with magnitude of load cycle and the number of cycles

Furthermore, the downward movement when axial load is applied, the lateral displacement reduce about (50) % compared without axial load as shown in Figure 13. This means that is improved predictions can be obtained by relaxing the cap fixity restraint to some degree (to reduce the negative moment magnitude) and the strength with stiffening modelled soil response (to decrease displacement and improve moment with shear distribution).That is the same behavior in all spacing and both shape for piles in group. Where the axial load induces interaction effect due to simultaneous mobilization of passive stress as a result of cyclic lateral loads and pile skin resistance as a result of axial load [25]. On the other hand, the increase in the lateral capability of group piles because of the presence of axial load is credited to the growth in the restraining stresses in the sand deposit nearby the higher section of the piles in-group [11].

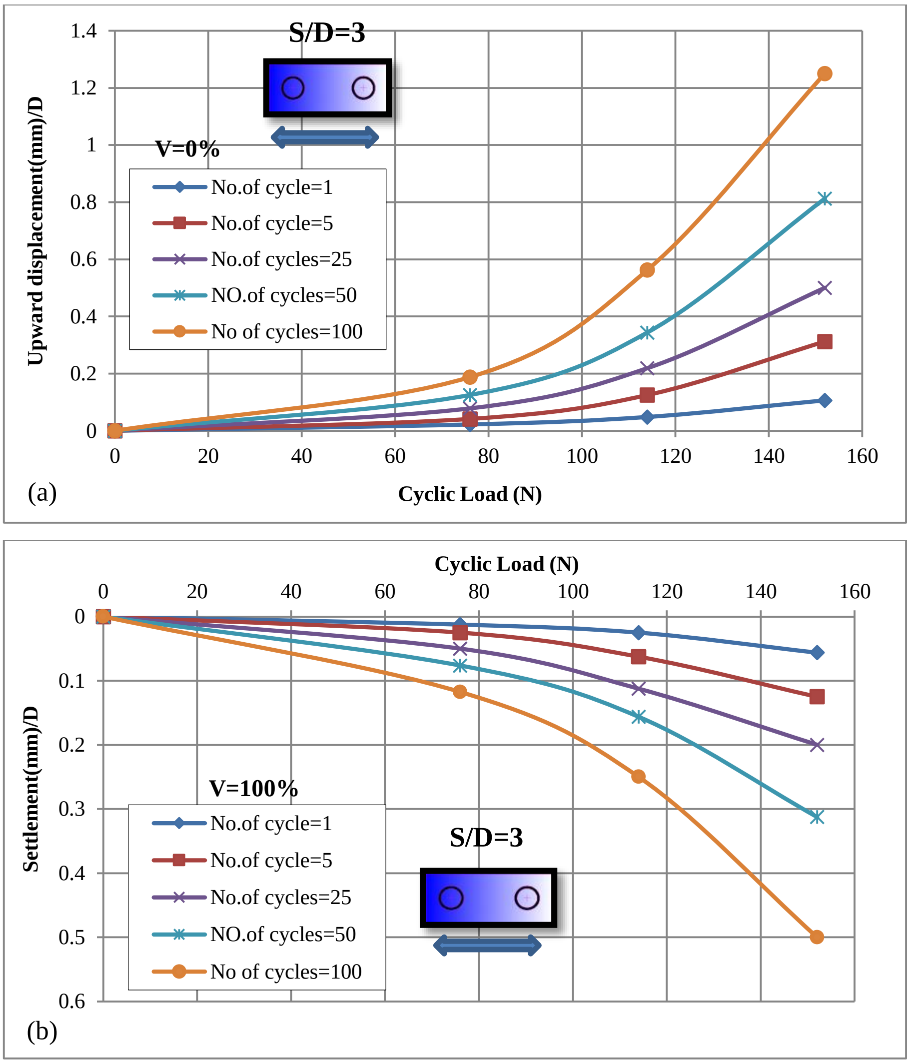


Figure 12. Effect axial load under deferent cyclic load (0.2HZ) on (2×1 pile group) (a) V=100 % Qall. (b) V=0% Qall

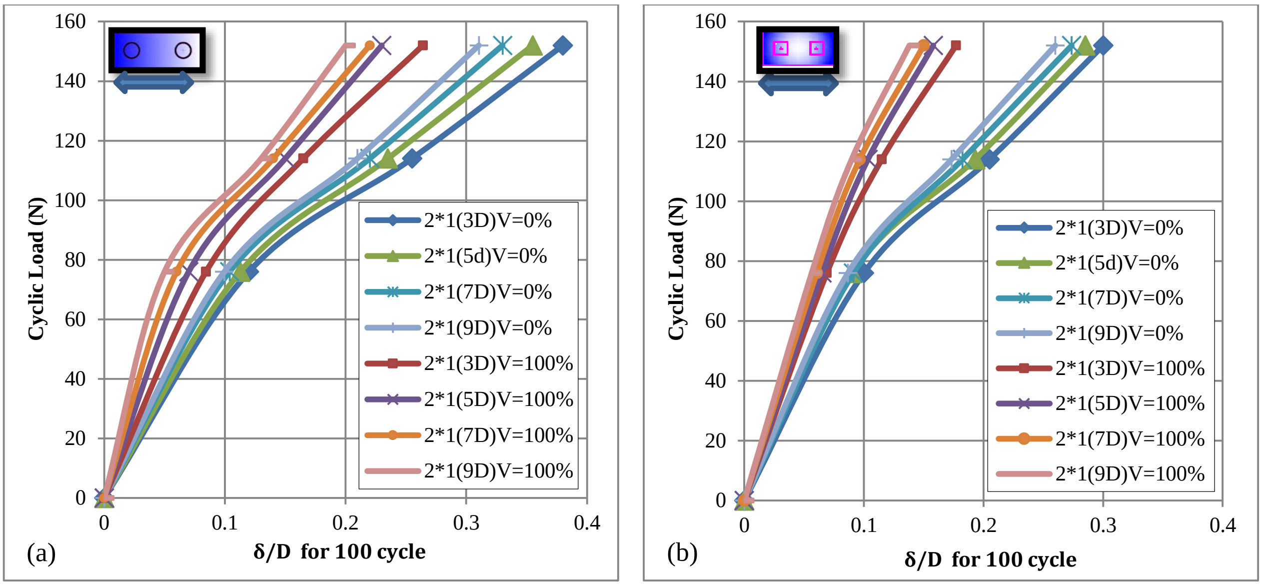


Figure 13. Effect axial load on lateral deflection (2×1 pile group) S/D=3 for 100 cycle (a) Circular piles (b) Square piles

5. Shape Factor

To make available basic comparative performance data for the different shape, applying lateral loading on piles group with circular and square sections. To facilitate comparison, all the test piles group are approximately 16mm in width or diameter using equivalent diameter for square sections. The square and circular pipe sections has similar moments of inertia. Lateral cyclic loading applied with a height of 50mm above the ground surface. The square pile is provided lateral resistance about 20% higher than circular resistance as shown in Figure 14 under different cyclic load due to an effective surface area of square pile that resists both of an earth soil pressure and shear effort more than circular pile that subjected to the same pure cyclic load concentration. It is clear from the above that the shape of pile affects clearly on behavior of pile during the lateral loading period without present vertical loads. That is very important state must be consider in analysis and design piles that exposed to such loads. In addition, regarding presence vertical loads note group piles with square pile shape respond to the effect of this loads and reduce lateral deflection more than respond circular piles about 40% as explained previously. This behavior due to the shape section where the pile with circular shape loosen contact with the adjacent soil and cannot provide the resistance. Therefor the active part, which resist shear strain and standard soil pressure of a square pile, is more than circular pile [26].

An axial resistance of the square pile in groups is smaller than the circular pile- shape. In comparison, of square pile with circular pile. The vertical displacement (e.g. Settlement or upward) values for all models is higher in a square pile comparison with the circular pile model, the difference in (settlement and upward) of the square pile shape nears 12-15% respectively more than a circular pile shape as shown in Figure 15. This is attributed to the difference of in bearing capacity (total skin resistance) of the pile foundation, which resists the pile movement in the vertical direction as result to disturb and loss of sand surrounding the pile-soil interface during cyclic loading.

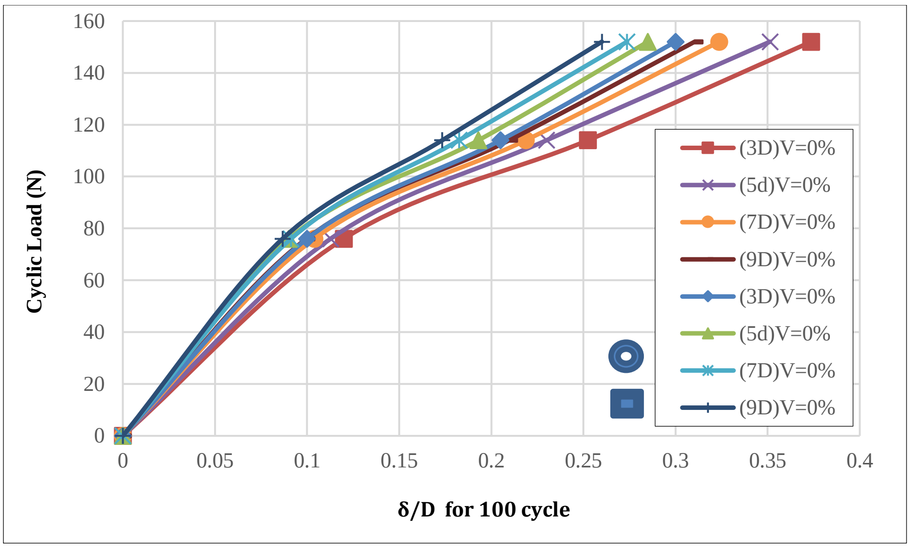


Figure 14. Effect cross sectional area of piles in-group (2×1) on lateral deflection under cyclic load

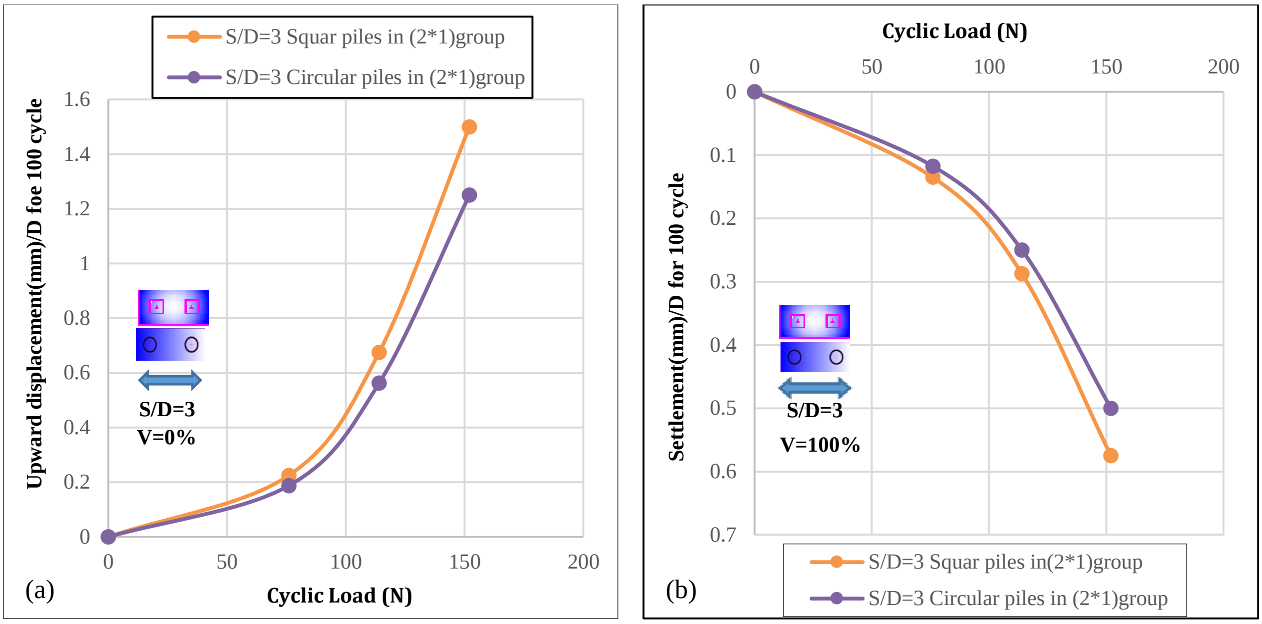


Figure 15. Effect cross sectional area of piles in-group (2×1) S/D=3 on vertical displacement under different lateral cyclic load at (a) V=0% Qall (b) V=100% Qall

6. Conclusions

- Under lateral cyclic load, ensued horizontal and vertical displacements of the pile groups that developed with an increase CLR and number of cycles.
- The cyclic lateral load produced a greater damage of soil resistance when the CLR is more than 0.6 that lead to critical cyclic loading level (critical cyclic load ratio.
- The variety of spacing between piles in group (2×1) model is not more effect on lateral deflection under different lateral cyclic loading. Where the difference between S/D=3 and 9 is about 18-20%.
- The response of the pile group in sandy soil under cyclic lateral loading is clear influence by the attendance of vertical load. Where, the attendance of vertical load reductions group piles head lateral displacement about 50% compare without vertical loads this dependent on the vertical loads amount, the amount of the cyclic load and frequency. This case is close reality, so this study recommended that the vertical load must be considered on analysis and design the piles foundations.
- The pile shape as well effect of the pile response. The level of decline in lateral displacement at the pile groups head in the square pile is less than of a circular pile reaches to 20% to the same load intensity after accounting for difference in widths and moments of inertia where lateral loading of the square pile produced the least heave compare with the circular pile. On the other side, the vertical displacements (settlement or upward) value at piles cap are more relatively in the square piles group than a circular piles group about 12-15%.
- This study explained that the reduction in lateral displacement of the square piles with presence vertical loads response more than circular piles about 40%.

7. Notation

c	Cohesion	*L/D*	Slenderness ratio of pile
D	Pile diameter	*Q all.*	allowable vertical load
Dr	Relative density of soil	*V*	Vertical load
S	Space between piles in the path of loading	*CLR*	Cyclic load ratio
S/D	Space to pile diameter ratio	δ	Lateral pile deflection
Gs	Specific gravity	γ	Unit weight of soil
HZ	Hertz	γd	Initial dry unit weight of soil
I	Moment of inertia	*Ø*	Angle of internal friction
L	Embedded pile length		

8. Conflicts of Interest

The authors declare no conflict of interest.

9. References

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