The lateral behavior of vertical pile group embedded in reinforced sand slope

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Experimental investigations of the lateral behavior of vertical pile groups embedded in reinforced and non-reinforced sandy earth slope were carried out. The model tests include studies of group configuration, pile spacing, embedment length of pile, relative densities of sand, and location of pile group relative to the slope crest. Several configurations of geogrid reinforcement with different lengths, widths, and number of layers were used to reinforce a sandy slope of 1 (V): 1.5 (H). Pile groups of 2×2 and 3×3 along with center-to-center pile spacing of 2D, 3D, and 4.5D and piles with embedment length to diameter ratios of L/D = 12 and 22 were considered. Test results indicate that the inclusion of geogrid layers to reinforce a sandy slope has significant enhancement in the order of 200 % in the lateral load capacity of the pile group. However, the geogrid reinforcement is found most effective when the pile group is located in dense soil closer than four pile diameters away of the slope crest. Recommended geogrid length and width that give the maximum lateral capacity improvement are presented and discussed.

يتناول هذا البحث دراسة معمليه للسلوك الجانبي لمجموعة خوازيق رأسية مقامة في تربة رمليه ذات ميل تم زيادة مقاومتها بشرائح التسليح الجيوتكنيكية. و تم عمل مقارنة بين قدرة تحمل مجموعة الخوازيق الجانبية قبل و بعد استخدام تسليح التربة. أيضا تم دراسة أهم العوامل المؤثرة على السلوك الجانبي لمجموعة الخوازيق وهي كثافة التربة و طول الخازوق المدفون من سطح الأرض الطبيعي و تقسيط الخوازيق والمسافة بين مجموعة الخوازيق وقمة ميل التربة مع دراسة تأثير عناصر التسليح المختلفة و تشمل طول الشرائح وعرضها و عددها. وقد تم عمل الدراسة العملية على مجموعتين من الخوازيق وهما (٢×٢) و (٣×٣) مع استخدام تقسيط خوازيق قيمته ٢ و٣ و ٤,٥ مرة قطر الخازوق. وتمت دراسة سلوك المجموعتين في حالتي إنشائهما في تربة رملية كثيفة و تربة رملية متوسطة الكثافة و تربة رملية هائشة. و قد تم عرض و مناقشة نتائج التجارب المعملية في صورة جداول و منحنيات و تلخيص تأثير العوامل المختلفة.

Keywords: Model test, Vertical pile group, Sand slope, Lateral load, Geogrid reinforcement

1. Introduction

There are many practical situations where piles are constructed adjacent to the edge of a slope and subjected to horizontal loading such as the support of bridge abutments, overhead signs, noise barrier walls, television and transmission towers, and offshore structures. The behavior of these piles under such loading conditions depends essentially on the stiffness of the piles and the strength of the soil. Under such loads, the piles may not only induce slope failure particularly at shallow depths, but also may undergo sever reduction in its lateral capacity. Therefore, these foundations must be designed to resist both axial forces and lateral forces. Generally, vertical piles resist lateral loads or moments by deflecting laterally until the necessary reaction in the surrounding soil is mobilized. Several experimental and numerical studies on laterally loaded single pile and pile groups installed in sites with horizontal ground surface have been performed (Broms [1], Meyerhof et al. [2], Sastry and Meyerhof [3], McVay et al. [4], Wakai et al. [5] and Patra and Pise, [6], etc.). Broms [1] developed a method of calculating the ultimate lateral load capacity of piles in sand for a level ground surface. Meyerhof et al. [2] investigated the response of free head laterally loaded rigid vertical piles embedded in two-layered soils. Sastry and Meyerhof [3] studied the effect of eccentric and inclined loads on the behavior of vertical single flexible model piles in layered sand. McVay et al. [4] conducted centrifuge tests on free head single pile and 3 × 3 pile groups at 3D and 5D pile spacing. Wakai et al. [5] carried out model tests on free or fixed headed pile groups subjected to lateral loading and analyzed the behavior by 3D Finite element analysis. Patra and Pise [6] conducted experimental investigations on model pile group of different configurations, different number of piles, different pile length to pile diameter ratios, and varied piles spacing.

The effect of sloping ground on the lateral response of vertical pile in/adjacent to slope has been also studied (Poulos [7], Schmidt [8], Bouafia and Bouguerra [9], Mezazigh and Levacher [10], Ng and Zhang [11], and Chae et al. [12], etc.). Poulos [7] analyzed the influence of a slope on the behavior of laterally loaded single pile. Schmidt [8] performed a series of laboratory model tests with rigid model piles to study the behavior of piles installed at the crests of four different sandy slopes. Bouafia and Bouguerra [9] and Mezazigh and Levacher [10] performed centrifuge tests to study the responses of piles in/adjacent to a slope under lateral loads. Ng and Zhang [11] studied the influence of the sleeving (an annulus of compressible material constructed between the piles and the adjacent soil to minimize the transfer of lateral load from the piles to the shallow depths of the slopes) on the pile performance in a sloping ground.

There have been several techniques used to stabilize an earth slopes to improve the stability of sloping ground and hence the behavior of structure and foundations adjacent to earth slopes. These methods include construction of rock buttress, soil nailing, installation of piles and/or drilled piers, and reinforcing with layers of geogrids. (Selvadurai and Gnanendran [13], Huang et al. [14], Zornberg et al. [15], Yoo [16], and El Sawwaf [17], etc.). Selvadurai and Gnanendran [13] reported the results of an experimental study of strip footings located on sloping ground reinforced with a single geogrid layer. Huang et al. [14] studied the failure mechanism of the reinforced slope by conducting a series of laboratory model tests on a reinforced slope loaded with a footing. Yoo [16] studied the effects of geogrid boundary conditions such as geogrid length, number of layers, and vertical spacing on the bearing capacity behavior of a strip footing located on the reinforced earth slope. El Sawwaf [17] studied the behavior of a strip footing supported on reinforced replaced layer of sand constructed on/near earth slope crest. In summary, stabilizing earth slope has a significant effect on the overall stability of the slope and on improving the bearing capacity of a shallow foundation supported on/adjacent to a reinforced ground slope.

The effects of reinforcing a sandy slope on the response of laterally loaded single vertical pile embedded near to the slope were studied by El Sawwaf [18]. It was reported that the inclusion of reinforcement layers in sandy slope causes significant increase in single pile lateral capacity. However, the behavior of pile groups located adjacent to such reinforced slope has not yet been studied. Consequently, there exists a lack of knowledge concerning the soil-pile group-geogrid reinforcement interactions effects in case of closely spaced piles. Therefore, the aim of this paper was to study the response of pile groups located adjacent to reinforced sandy slopes. The main objective was to investigate the effects of the different geogrid parameters, location of pile group relative to slope crest, center to center pile spacing, and soil relative density on the response of pile groups of different configuration.

2. Laboratory model tests

2.1. Soil bin

Fig. 1 shows a schematic view of the experimental apparatus used in the study. It consists of two main elements; the soil bin and the loading system. The soil bin having inside dimensions of 1.00 m × 0.50 m in plan and 0.5 m in depth is made from steel with the front wall made of 20 mm thickness glass and is supported directly on two steel columns. These columns are firmly fixed in two horizontal steel beams which are firmly clamped in the lab ground using 4 pins. The glass side allows the sample to be seen during preparation and sand deformations to be observed during testing. The inside walls of the tank are polished smooth by attaching fiber glass to minimize side friction with the sand as much as possible. Detailed description of the apparatus was given in El Sawwaf and Nazir [19].

The loading system consisted of a 3.0 mm diameter steel rope which was connected to the pile cap using an eye bolt and placed horizontally in the sand passing through the box side wall and the column frame to end vertically through smooth pulley with a load hanger.

2.2. Test materials

The sand used in this research is medium to coarse sand, washed, dried, and sorted by particle size. The sand has a very low impurity level with a quartz (SiO_2) content of 97 %. The specific gravity of the soil particles was measured by ASTM standards 854. Three tests were carried out and the average value is 2.654. The maximum and the minimum dry unit weight of the sand were found to be 19.95 and 16.34 kN/m^3 according to ASTM standards 4253 and 4254 and the corresponding values of the minimum and the maximum void ratios are 0.305 and 0.593 respectively. The particle size distribution was determined using the dry sieving method according to ASTM standards 422 and the results are shown in fig. 2. The effective size (D_{10}), uniformity coefficient (C_u), and coefficient of curvature (C_c) for the sand are 0.152 mm, 4.071, and 0.771 respectively.

In order to achieve reasonably homogeneous sand beds of reproducible packing, controlled pouring and tamping techniques were used to deposit sand in 50 mm thick layers into the model box. In this method the quantity of sand for each layer, which was required to produce a specific relative density, was first weighed and placed in the tank and tamped until achieving the required layer height. The relative density achieved during the tests and uniformity of the sand samples were monitored by collecting samples in small cans of known volume placed at different locations in the test tank. Each mould was carefully excavated and the density of the sample was calculated. The pouring and tamping technique adopted in this study provided samples with average unit weights of 17.44, 18.15, and 19.10 kN/m^3 representing loose, medium-dense, and dense conditions, respectively. The relative densities of the samples were 35%, 55%, and 80.0%, respectively. Series of direct shear tests was performed to evaluate the shear strength properties of the model ground using specimens prepared by dry tamping. The estimated internal friction angle at the same relative density used in the model tests was 34°, 37.5° and 43° determined from direct shear tests under normal stresses ranging between 25 and 100 kN/m^2.

2.3. Model piles

Model piles with 15 and 12 mm outer and inner diameters respectively were fabricated from steel tube (modulus of elasticity, E_s=2.14 × 10^7 t/m^2). The piles were 180 and 330 mm in length and the corresponding length to diameter ratios of piles were 12 and 22. Model pile groups of configuration 2×2 and 3×3 having center to center spacing between the piles as 2D, 3D, and 4.5D were studied. The model piles were connected by pile caps made of steel plates, 20 mm thick, with an eye bolt at the center of its front face as shown in fig 1. The pile caps were made with threaded internally holes so that the piles could be put in vertical position at the required spacing of piles.

There are several factors that affect the lateral resistance of a pile but the dominant one is the pile stiffness, which determines whether the pile behaves rigidly, or as flexible pile. Broms [1] showed that a laterally loaded pile behaves as rigid pile based on the value of the stiffness factor T. In cohesionless soils, this factor is calculated as:

$$T = \sqrt[5]{\frac{E_p I_p}{n_h}} \; . \qquad (1)$$

Where E_p = modulus of elasticity of the pile material (21.4 × 10^7 kN/m^2), I_p = moment of inertia of the pile cross section (1.467 × 10^{-9} m^4), and n_h is the constant of subgrade reaction at pile tip. Broms suggested that the embedment depth of the pile has to be less than $2T$ to be considered as a short rigid pile and greater than $4T$ for behavior as a long elastic pile. Possible values suggested for n_h (considering that the value of n_h decreases near the crest of the slope) are 1700, 4500 and 10500 kN/m^3 for loose, medium-dense, and dense sands respectively (Terzaghi [20]). Furthermore, the value of n_h decreases near the crest of the slope. The estimated value of $2T$ for different relative densities are 0.36, 0.30 and 0.25 m. Most of the experimental tests were carried out using pile embedment length of 0.33 m which is slightly greater than 0.25 m and much less than $4T$ (0.50) indicating that the test pile satisfy the criterion for a short rigid pile or intermediate length pile.

2.4. Geogrid reinforcement

Tenax TT Samp with peak tensile strength of 45 kN/m was used as reinforcing material for the model tests. These geogrids were manufactured by extruding and mono-directional drawing of High Density Polyethylene (HDPE) grids. Typical physical and technical properties of the grids were obtained from manufacturer's data sheet and are given in table 1.

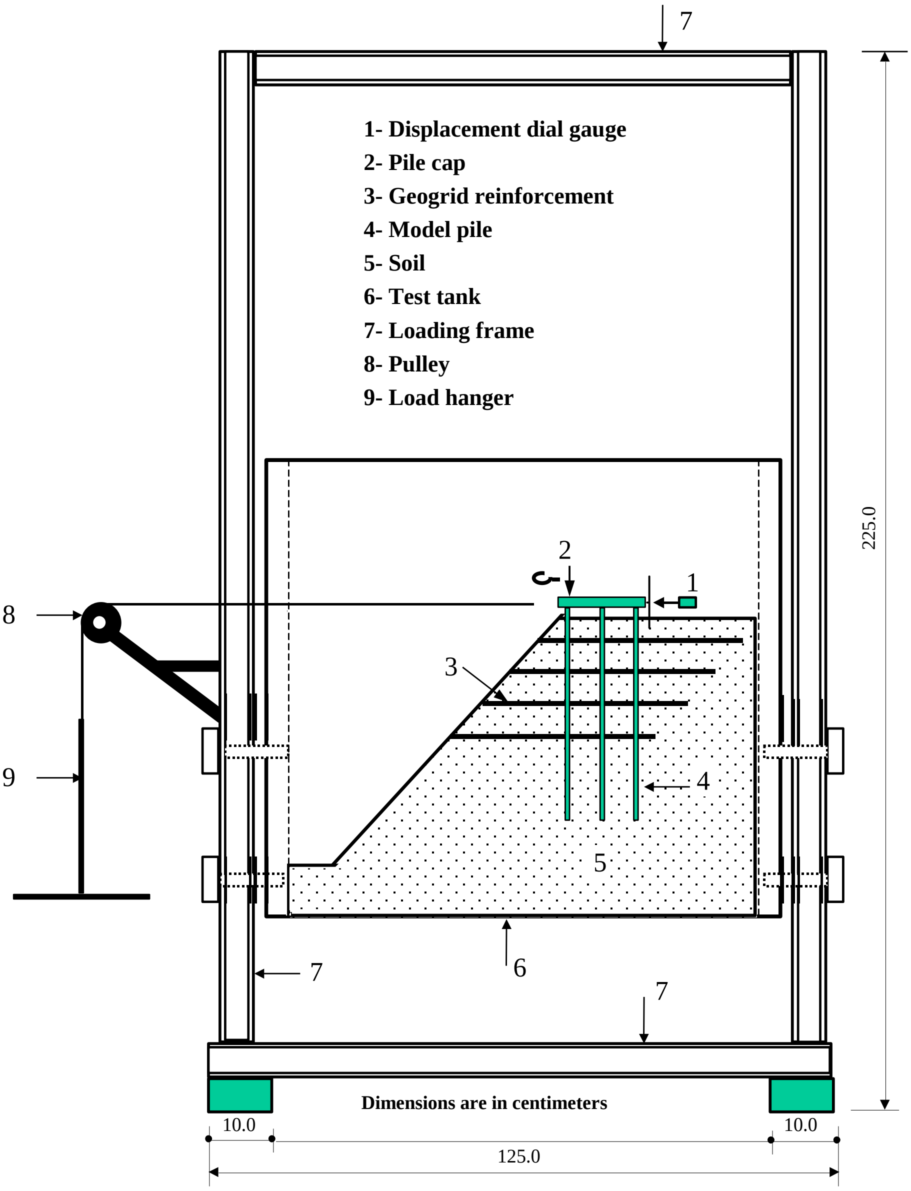


Fig. 1. Schematic view of the experimental apparatus.

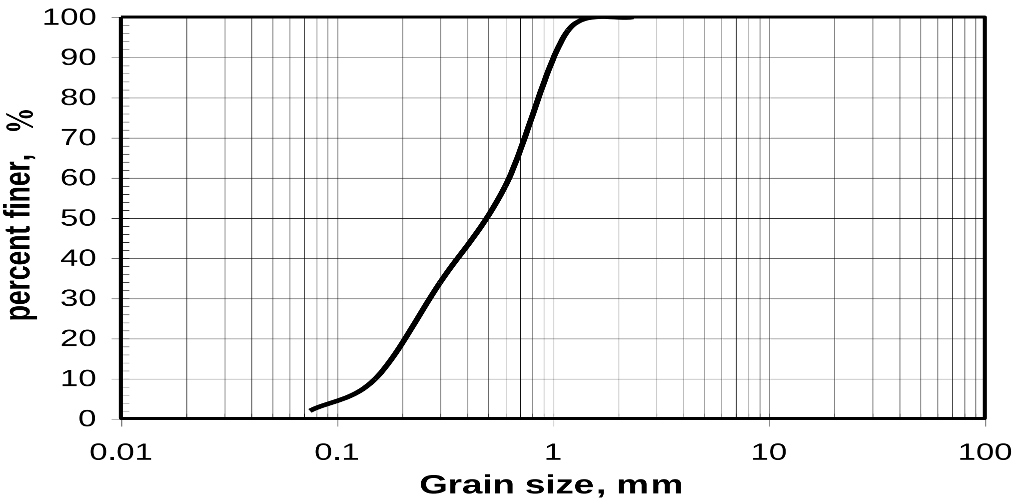


Fig. 2. Grain size distribution of the sand.

Table 1
The engineering properties of Geogrid

Structure		Mono-oriented Geogrids
Aperture shape		Oval apertures
Aperture size,	mm x mm	(13/20) x 220
Weight,	g/m^2	300.00
Polymer type		HDPE
Tensile strength at 2 % strain	kN/m	11
Tensile strength at 5 % strain	kN/m	25
Peak Tensile strength	kN/m	45
Yield point elongation	%	11.5
Long term design strength	kN/m	21.2

2.5. The experimental setup and test program

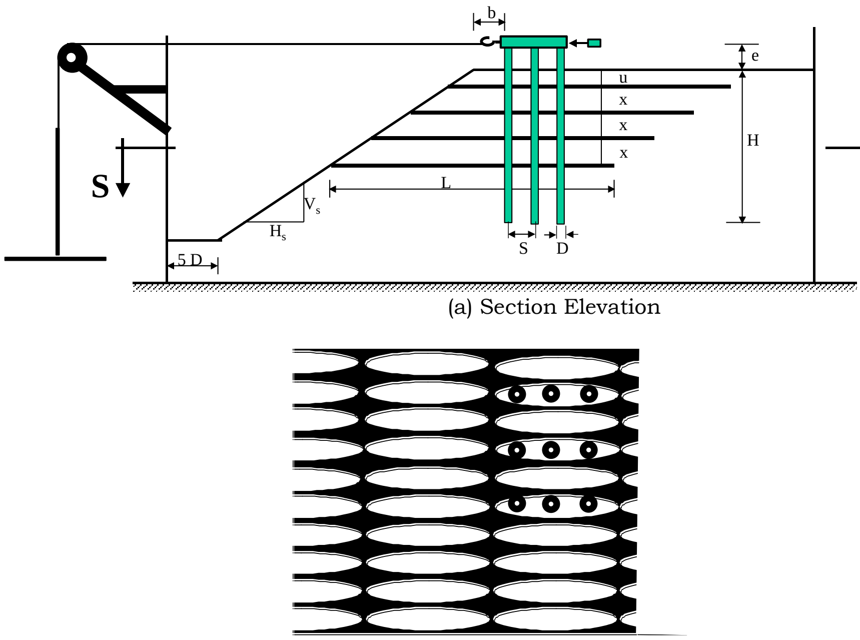
An experimental program was carried out to evaluate the lateral behavior of model pile groups located adjacent to reinforced earth slope. Model slopes, 425 mm in height, were constructed in layers by controlled pouring and tamping technique with the bed level and slope observed through the front glass wall. In the reinforced tests, layers of geogrid were placed in the sand at predetermined depths during preparing the ground slope. The depth of sand below the base of the model pile was 95 mm (>5 D). The slope line and the sand top surface was drawn in the inner faces of the tank with horizontal lines marked at 50 mm intervals to facilitate accurate preparation of the sand bed in layers. On reaching the level of pile base, the pile group was placed on position and was held vertical. Special clamp which was fixed in the tank edges at locations previously determined according to the required location was used to warranty the verticality and location of pile group. Geogrid layers were placed passing through the piles and were held attached to the pile cap until reaching its required level. On reaching the reinforcement level, a geogrid layer was placed and the next layer of sand was poured and tamped. A piece of steel 15 mm in width, 20 mm in depth and 300 mm in length was used to tamp the sand in between piles. One to four geogrid layers were placed with different lengths and spacing. The preparation of the sand bed above the geogrid reinforcement was continued in layers up to the level required for a particular depth of embedment. Great care was given to level the slope face using special rulers so that the relative density of the top surface was not affected. Finally the lateral load was applied incrementally until reaching failure. Each load increment was maintained constant until the pile lateral deflection had stabilized. All tests were conducted with an artificially made slope of 1 (V_s): 1.5 (H_s) with a new sheet of geogrid used for each test. The pile displacements were measured using a 50 mm travel dial gauge accurate to 0.001 mm placed at the level of load application as shown in fig. 1.

Sixteen series of tests on model pile groups on both stabilized and non-stabilized slopes were carried out. Initially, eight series of tests (series 1 to 8) were performed to study the effects of the different geogrid parameters and relative density of sandy slope on the lateral performance of pile groups. These parameters include the length of geogrid layer (L), the width of geogrid layer (W), and the number of geogrid layers (N) as shown in fig. 3. Then, the response of the model pile groups located at different locations relative to the slope crest (b) (the distance measured from the crest of the ground slope to the outer surface of piles in the closest row) of slope with and without geogrid reinforcement was determined (series 9 to 12). Finally four series of tests (13 to 16) were conducted to study the effects of the pile spacing (S), and pile embedment length (H). Both the depth of the first geogrid layer and the vertical spacing between layers were kept constant and equal to 3.6. Table 2 summaries all the tests programs with both the constant and varied parameters illustrated. Several tests were repeated at least twice to verify the repeatability and the consistency of the test data.

Table 2
Model tests program

Series	Constant parameters	Variable parameters
1	b/D=0, S/D=4.5, R_d=80%, (3×3), H/D=22, N=4, W/D=24,	L/D=8.5,17,1, 25.6, 34.3, 42.8
2	b/D=0, S/D=4.5, R_d=80%, (2×2), H/D=22, N=4, W/D=24,	L/D=8.5,17,1, 25.6, 34.3, 42.8
3	b/D=0, S/D=4.5, R_d=80%, (3×3), H/D=22, N=4, L/D=34.3,	W/D=10, 17, 20, 24,30
4	b/D=0, S/D=4.5, R_d=80%,(2×2), H/D=22, N=4, L/D=34.3,	W/D=10, 17, 20, 24,30
5	b/D=0, S/D=4.5, 3×3, H/D=22, non-reinforced	R_d = 35, 55 and 80%
6	R_d=35%, b/D=0, S/D=4.5, L/D=34.3, W/D=24, 3×3, H/D=22	N= 1, 2, 3 and 4
7	R_d=55%, b/D=0, S/D=4.5, L/D=34.3, W/D=24, 3×3, H/D=22	N= 1, 2, 3 and 4
8	R_d=80%, b/D=0, S/D=4.5, L/D=34.3,W/D=24, 3×3, H/D=22	N= 1, 2, 3 and 4
9	S/D=4.5, R_d=80%, 3×3, H/D=22, non-reinforced	b/D=0.0, 2.5, 5, 10
10	S/D=4.5, R_d=80%, 2×2, H/D=22, non-reinforced	b/D=0.0, 2.5, 5, 10
11	S/D=4.5, R_d=80%, 3×3, H/D=22, N=4, L/D=34.3, W/D=24	b/D=0.0, 2.5, 5, 10
12	S/D=4.5, R_d=80%, 2×2, H/D=22, N=4, L/D=34.3, W/D=24	b/D=0.0, 2.5, 5, 10
13	b/D=0, R_d=80%, 3×3, H/D=12, non-reinforced	S/D =2, 3, 4.5
14	b/D=0, R_d=80%, 3×3, H/D=12, N=4, L/D=34.3, W/D= 24	S/D =2, 3, 4.5
15	b/D=0, R_d=80%, 3×3, H/D=22, non-reinforced	S/D =2, 3, 4.5
16	b/D=0, R_d=80%, 3×3, H/D=22, N=4, L/D=34.3, W/D= 24	S/D =2, 3, 4.5

Note: See fig. 3 for definition of the variable.
Pile Diameter (D) is always constant 15 mm. In reinforced tests, u/D and x/D are always constant = 3.6.
N is number of reinforcing layers. S is spacing between piles.



(a) Section Elevation

(b) Plan view Section S-S

Fig. 3. Geometric parameters of pile group on reinforced sand slope model; (a) Section elevation, (b) Plan view section S-S.

3. Results and discussion

A total of 55 tests were carried out on model pile groups embedded in both reinforced and non reinforced sandy slope at three relative densities. The improvement in the lateral resistance of the pile group due to slope stabilization is represented using a non-dimensional factor, called Lateral Resistance Improvement factor, LRI. This factor was derived by dividing the lateral load for a given group located in stabilized slope at a specific lateral displacement by the lateral load of the same group when placed in non-stabilized slopes at the same lateral displacement. The pile lateral displacement (y) is also expressed in non-dimensional form in terms of the pile diameter (D) as the ratio (y/D %). Ultimate pile groups' lateral capacities for different cases have been estimated from the load displacement diagrams. It is taken corresponding to the point when the pile head movement is equal to 10% of the pile diameter (Tomilson [21]).

3.1. The effect of reinforcement layer length

The variations of lateral load with displacement ratio of 3x3 pile group embedded in dense sand reinforced by four layers of geogrid of various lengths are compared with the test results for same pile group in non reinforced bed in fig. 4. For the same displacement ratio, the inclusion of the geogrid layers resulted in an increased lateral resistance of pile group. The load-displacement diagrams are practically linear in the early stages of the loading up to 100 N loads but afterwards they become non-linear with gradual increase in the lateral load resistance. For the same lateral load, the lateral displacements of the pile groups decrease as the length of geogrid layer increases. At displacement ratio y/D = 20%, the figure shows significant increase in lateral resistance of pile groups located in reinforced sand with long layers. However, at larger displacements, lower LRI was for pile groups in the reinforced slopes with various layer lengths. Fig. 5 shows the LRI in pile groups for the various geogrid layer lengths. For layer length of L/D ≤ 10, the improvement is less than 10 % of the carrying load of pile group in slopes without reinforcement. For longer layers of geogrid, the increase in the lateral resistance of pile group with layer length is significant until layer length becomes to 34.3 times pile diameter beyond which further increase in the layer length does not show significant contribution in increasing the lateral load carrying capacity of pile.

These improvements in pile lateral resistance with inclusion of widespread soil reinforcement can be attributed to the fact that sufficient anchorage length beyond the pile group is essential for reinforcing layers to maximize the transferred shear stresses built up in front of pile group to unstressed area of soil behind the pile group. With short layers of geogrid, the anchorage length of geogrid in sand is insufficient and the mobilized lateral resistance by apparent adhesion, friction and interlocking in the back of the pile is less than the transferred horizontal shear stresses and the geogrid layers tend to move with the pile group movement. With longer layers, sufficient anchor length mobilized larger lateral resistance than that built up in front of pile group and transferred to geogrid layer. With several layers of geogrid, placed at different depths of sand surface, a wider and deeper failure zone develops. This in turn means that longer failure surface develops and hence a greater lateral bearing load capacity of pile group is mobilized. Ultimate pile groups' lateral loads for different studied parameters are given in tables 3 to 6. These results are discussed in the following sections.

3.2. The effect of reinforcement layer width

Ten tests were carried out on 2×2 and 3×3 pile groups located at the crest of dense sand slopes in order to study the effect of geogrid layer width on the behavior of pile groups under lateral loads. All the parameters of relative density along with geogrid, length, number, pile spacing, pile length, and the group location were kept constant with W/D ratios of 10, 17, 20, and 24. Fig. 6 shows that the increase in layer width results in improving the lateral load resistance. A gain in 3x3 pile group lateral resistance as much as 1.90 times the resistance of same group in non reinforced cases can be obtained when four layers of geogrid with w/D ratio of 30 were placed. Same trend can be seen for 2×2 pile groups with slightly lower values of LCI

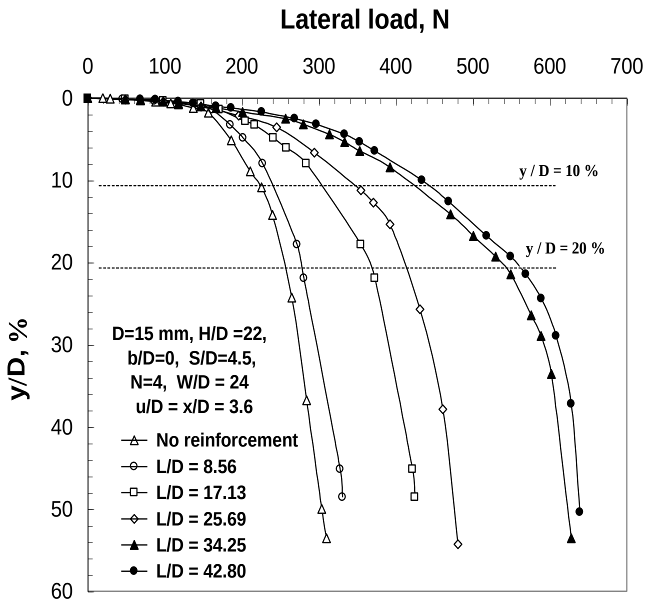


Fig. 4. Variations of lateral load with y/d for 3x3 pile group for various layer lengths (series 1).

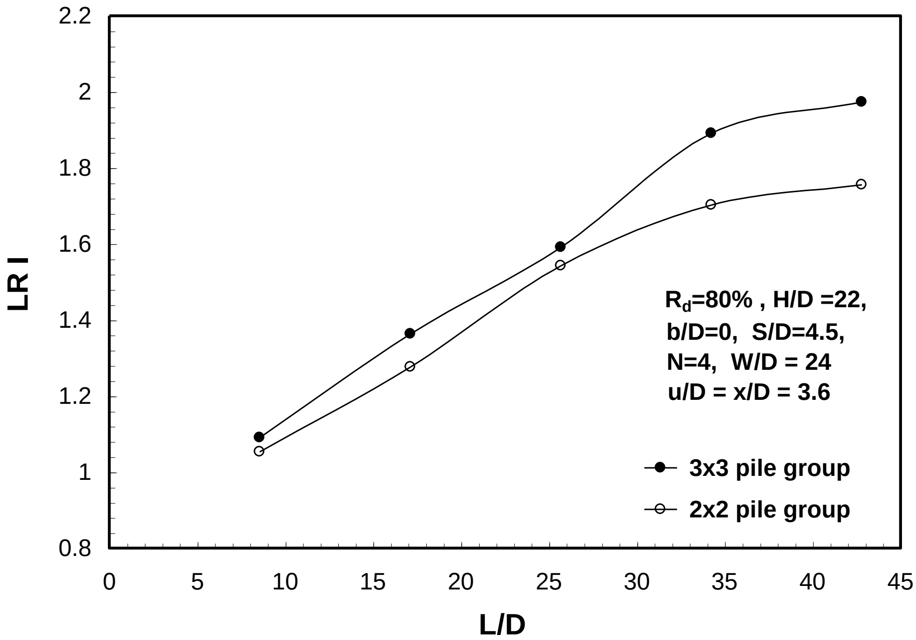


Fig. 5. Variation of LRI with the normalized length of geogrid layer.

Table 3
Ultimate lateral loads for pile groups located in reinforced slopes with geogrid layers of different lengths and widths (series 1 to 4)

Test results	L/D					W/D				
	8.5	17.1	25.6	34.3	42.8	10	17	20	24	30
2x2 pile group	99	120	145	160	165	110	137	150	160	165
3x3 pile group	240	300	343	416	434	316	385	405	416	420

Table 4
Ultimate lateral loads for pile groups located in different relative densities and different number of layers (series 5 to 8)

Test results	N				
	0	1	2	3	4
Loose	138	139	141	143	145
Medium dense	174	180	190	205	220
Dense	220	285	330	373	416

Table 5
Ultimate lateral loads for pile groups located at different locations (Series 9 to 12)

Test results	b/D							
	2×2 pile group				3×3 pile group			
	0	2.5	5	10	0	2.5	5	10
Non reinforced	94	113	127	132	220	255	300	304
Reinforced	160	171	180	185	416	430	480	482

Table 6
Ultimate lateral loads for pile groups with different pile spacing (Series 13 to 16)

Test results	S/D					
	H/D = 12			H/D = 22		
	2	3	4.5	2	3	4.5
Non reinforced	80	88	102	178	209	220
Reinforced	92	111	160	211	290	416

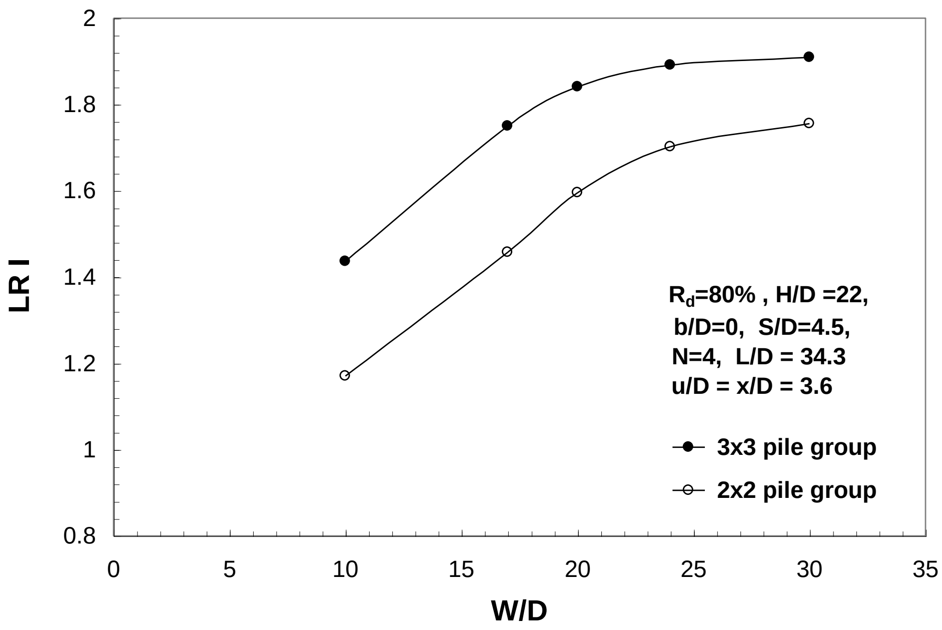


Fig. 6. Variation of LRI with the normalized width of geogrid layer.

with W/D. However, the improvement in the lateral resistance is significant with increasing geogrid width until it reaches a value of 24 times the pile diameter, beyond which the increase in lateral load is slightly minimum with the increase in reinforcement size. As geogrid width increase, the contact area and hence the adhesion, friction and interlocking between geogrid layers and soil become larger. Therefore, greater lateral displacements and horizontal shear stresses built up in the soil in front of pile group were resisted and transferred by geogrid layers to larger mass of soil in the back of the pile group. However, this increase in lateral resistance is proportional with the increase in layer size, until it reaches the width of the affected zone in front of the pile group after which there is no effect of the layer width.

3.3. The effect of number of geogrid layers

Fig. 7 shows the variations of the lateral load improvement of 3×3 pile group with the number of geogrid layers for different relative densities. The LRI significantly increases with the number of geogrid layers. However, the rate of increase of LRI of pile group in dense sand is much greater than that in the medium dense and loose sand (for N=4, the LRI in dense slope is approximately twice that of loose sand). However, the figure clearly indicates that there is no an optimum number of geogrid layers which increases the lateral resistance up to maximum extent for particular density and geogrid conditions. As the number of geogrid layers increases, the contact area between the geogrid and soil and hence the confined zone of soil in front of pile group becomes larger. With sufficient anchorage length of geogrid layers in stable zone at the back of pile group, the geogrid material tends to expand and result in increased confinement around the pile group. Consequently, the failure wedge becomes larger leading to greater frictional resistance on failure planes and hence greater lateral loads of pile group.

3.4. The effect of sand relative density

The influences of relative soil density on the response of laterally loaded pile groups were examined by carrying out three series of tests on 3×3 pile group located at the crest of sandy slopes. Variations of the LRI of pile groups against the relative density for different number of geogrid layers are shown in fig. 8. As expected, the improvements in lateral resistance of pile groups are much dependent on the sand relative density. While the LRI for pile group in loose sand is only about 5%, the LRI for the same group in dense sand is 90%. This observation that soil reinforcement is significant when placed in dense soils than loose soils is consistent with Guido and Sweeny [22] that the most dramatic increases in bearing capacity for reinforced earth slabs occurred at relative densities of medium dense to dense sand. This improvement in pile lateral resistance with relative density can be attributed to the increase in both soil density and the angle of friction of the sand. Increased soil density leads to greater soil passive resistance to lateral displacements and hence greater pile lateral bearing loads. Increased angle of friction of the sand turns in increasing the friction and interlocking between ribs and soil leading to greater pile group lateral resistance. Also the transmitted shear stresses and the mobilized lateral resistance of the soil at the back of the pile increase due to the dilation of dense sand producing better interaction between the sand and geogrid.

3.5. The effect of pile group location relative to slope crest

Four series of tests were carried out on 2×2 and 3×3 pile groups to study the effect of the proximity of the pile group to the crest of the ground slope. The pile groups were placed at b/D=0, 2.5, 5, and 10 in reinforced and non reinforced dense sandy slope. Test results in table 5 show that the lateral bearing capacities of pile groups increase significantly as the pile groups move away from the crest of ground slope. Same trend can be seen for 2×2 and 3×3 pile groups in both reinforced and non reinforced sand. Fig. 9 shows the variation of the lateral load improvement for the laterally loaded pile groups at different locations. The figure shows that the LRI of the pile group decreases as its location moves away from the crest. However, this decrease in the lateral resistance improvement is obvious until a value of about b/D = 5 after which the effect can be considered constant.

3.7. The depth of first layer of reinforcement and layer spacing

The ratios u/D and x/D represent the depth of the first geogrid layer to the ground surface and the vertical spacing between layers. The effects of these two parameters on the lateral load behavior of single model pile were investigated in a previous study (El sawwaf 2006). It was demonstrated that geogrid reinforcements are much effective in improving the pile lateral resistance when the layers are placed at a moderate depth at closer spacing. Therefore, in this research, ratios u/D and x/D = 3.6 were considered and kept constant in studying the effect of other parameters.

3.6. The effects of pile spacing

Four series of tests on 3×3 pile groups with pile embedment to diameter ratio of 12 and 22 and placed at the crest of dense sandy slope were performed to study the effect of pile spacing on the lateral response of pile groups. The variations of LRI with normalized pile spacing S/D are shown in fig. 10. Significant increase in the lateral pile response can be seen with the increase in pile spacing. Same trend can be seen for pile groups with embedment/ diameter ratio of 12 and 22

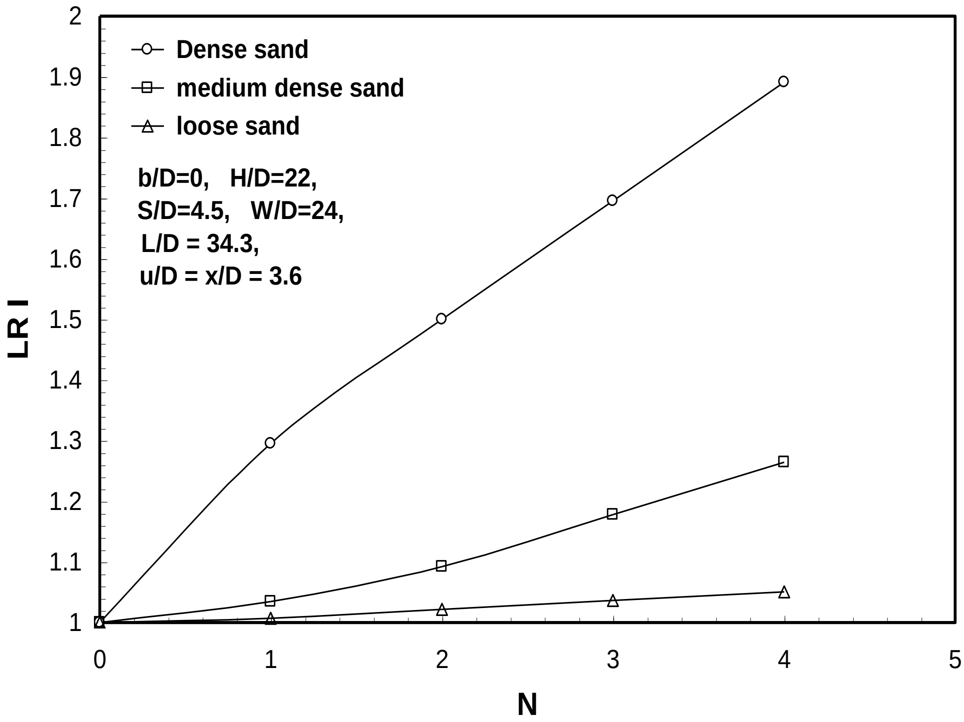


Fig. 7. Variation of LRI with the Number of geogrid layers.

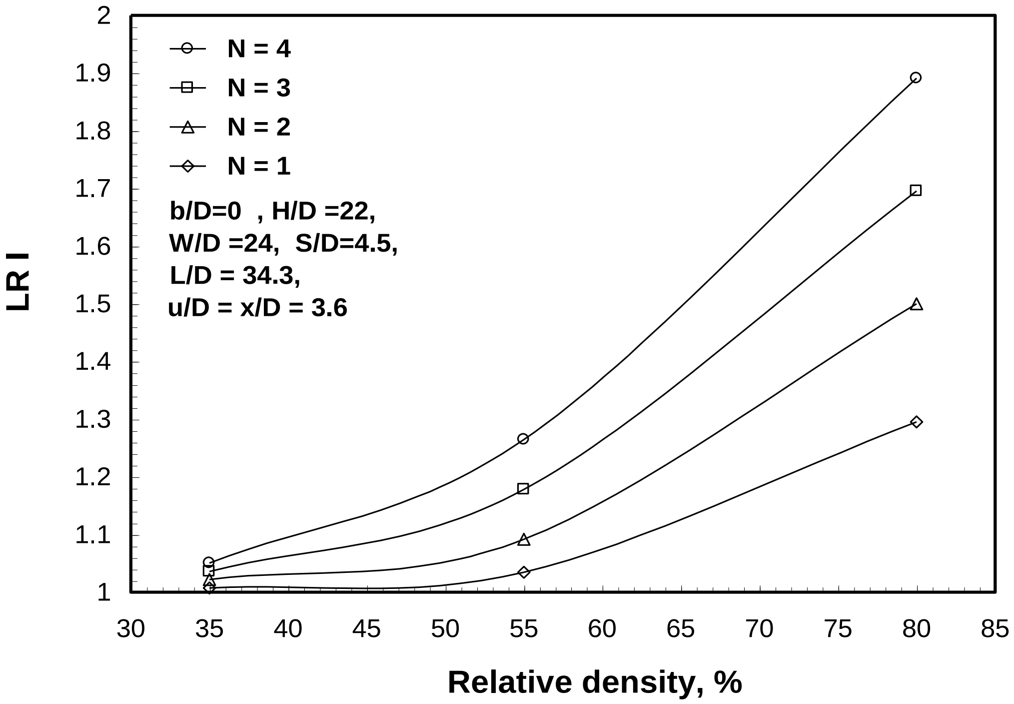


Fig. 8. Variation of LRI with the sand relative density.

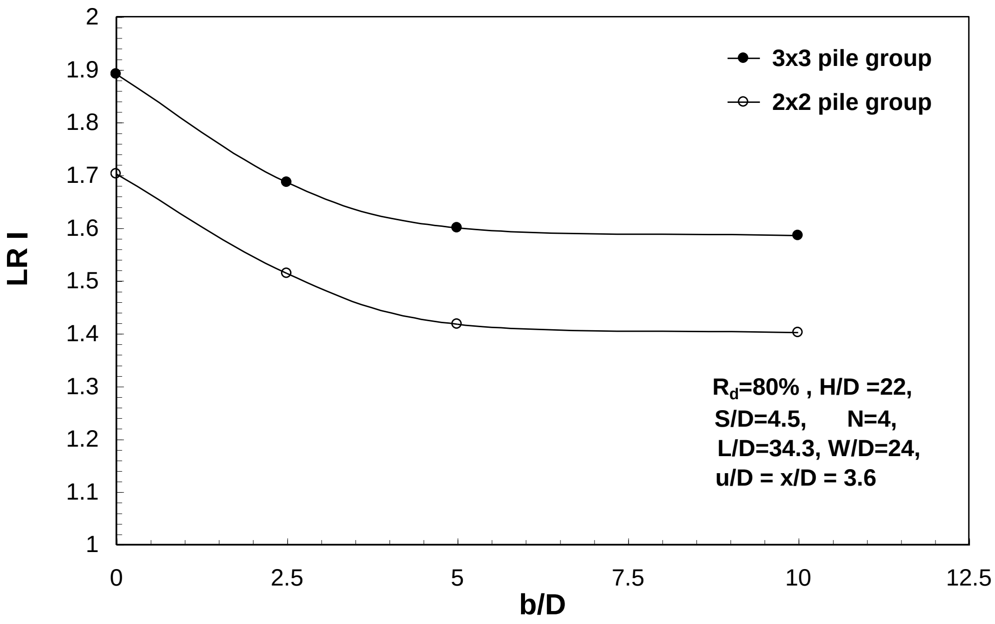


Fig. 9. Variation of LRI with the pile group location.

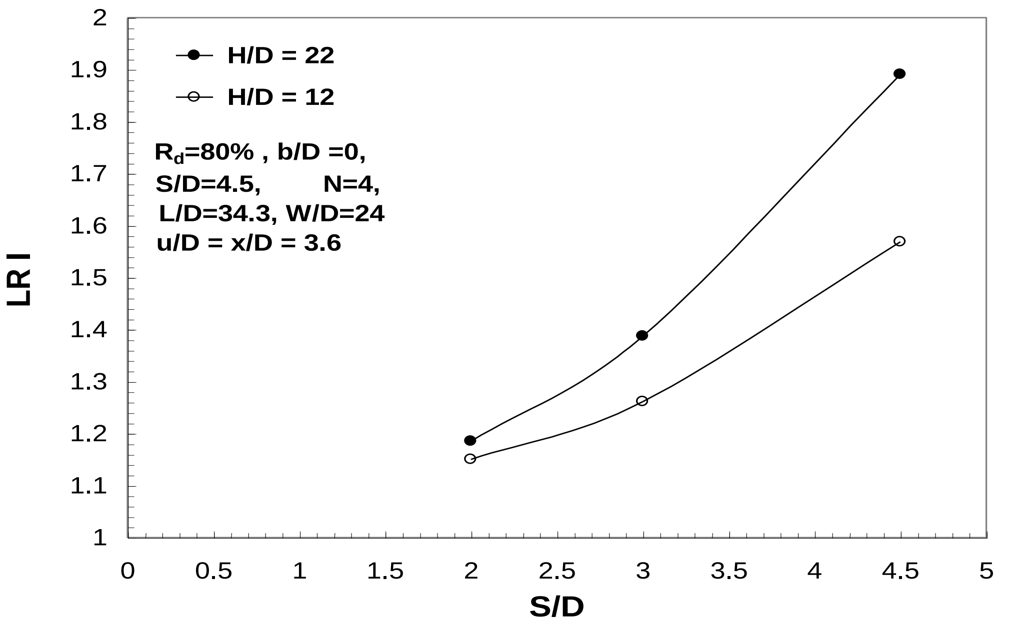


Fig. 10. Variation of LRI with normalized pile spacing.

with greater values of LRI for pile groups with H/D=22. This increase in pile group with pile spacing can be attributed to soil-pile-geogrid interaction and group size effects. As the size of confined soil in front of and around the pile group increases the failure wedge becomes larger leading to greater lateral loads of pile group. This observation for pile group in non-reinforced sand slope is consistent with the conclusion given by Chae et al. (2004) that the group efficiency increases as the pile spacing increases.

4. Scale effects

The model pile adopted in this study was reduced to a certain scale while the used sand and geogrid were the same as that in the prototype. Therefore, model pile or the soil may not play the same role as in the prototype and it might cause some influence on the experimental results, which is called scale effects (Vesic, [23]). These differences occur primarily because of the differences in stress level between the model tests and the field tests (Vesic, [23]) and the influence of the footing width/grain size ratio (Steenfelt [24]). The stress level under small model footing in the earth's gravity is much smaller than that under a prototype footing. The low stress level in model tests corresponds to a greater angle of internal friction when compared to the friction angle at higher stress level in field condition. The low stress levels in model tests would also prevent mobilization of complete interaction between soil-pile and geogrid as it may occur in field condition. Ovesen [25] and Franke and Muth [26] recommended ratio of pile circumference and grain size in excess of 15–30 in order to avoid scale effects. In the present study, the used pile diameter was 30 times the mean particle size, which is within the recommended ratio. However, scaling effects due to variations in stress level and using prototype grid will occur in 1 g (earth gravity) modeling.

Despite of the mentioned disadvantages that scaling effects due to using prototype geogrid will occur in model tests and we cannot rely on these tests to predict the exact behavior of a particular prototype, the study indicated the benefits could be obtained when using geogrid to reinforce sandy slopes on the lateral response of vertical pile. Moreover, the data provide a useful basis for further research using full-scale tests or centrifugal model tests and numerical studies leading to an increased understanding of the real behavior and accurate design in application of soil reinforcement.

5. Conclusions

The behavior of pile groups located adjacent to sand slope under lateral loads was investigated. Pile groups of different configuration, pile spacing and pile length were considered. The effect of sand relative density and the location of pile group relative to the slope crest along with geogrid parameters such as, the geogrid length, width, and the number of layers are studied. Based on the experimental results, for the studied cases and geometry the following conclusions are drawn:

1. Slope reinforcement significantly increases the lateral capacity of pile groups embedded adjacent to the slope crest. It has enhancement in the order of 200 % in the lateral load capacity of the pile group. However, this improvement is much dependent on the pile location relative to the slope crest, the relative density of sand and geogrid parameters.
2. Sufficient anchorage lengths beyond the potential failure surface must be provided to maximize the reinforcing effect. The recommended length of geogrid layers should be greater than thirty four times pile diameter (L/D=34).
3. Increasing the layer width is significant in improving the lateral response of pile group. The optimum width of reinforcement is found to be twenty four times the pile diameter (W/D=24).
4. Pile group behavior in reinforced sand slope is strongly dependent on the number of reinforcement layers and the relative density. Soil reinforcement is more significant when placed in dense slopes than loose slopes.
5. Lateral capacities of pile groups decrease as the pile group gets closed from the slope crest but the LRI increases. However, the effects of slopes in ground surface on the lateral response of pile groups can be neglected when the distance between pile groups and slope crest is ≥ 5 times the pile diameter.

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