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# The Influence of Soil Reinforcement on the Performance of Single Pile and Pile Group Under Pullout Loads


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**Abstract**

The influence of soil reinforcement on the uplift performance of single pile and pile group embedded in reinforced and non-reinforced is investigated for cohesionless soil with 60% relative density (Dr). Single pile and pile group models were conducted utilizing steel circular pile with bulges surface conditions. The pile group model was (2x1) piles with spacing of three times the single pile diameter (D). Several configurations of soil reinforcement were compared by varying the reinforcement type, the embedded depth, the width, and the number of reinforcement layers. Specifically, two types of reinforcement (SS30) and (TX150) were utilized in the laboratory experiments. The test results exhibit that the pullout resistance of the single pile and the pile group increase with the increase of the reinforcement layer width. For the single pile, the pullout resistance increases with the increase of the reinforcement width up to width of nine times the pile diameter. While for the pile group, the pullout resistance increases with the increase of the reinforcement width up to (nine + three) times the pile diameter, three times the pile diameter is the spacing between piles. In addition, for both single pile and pile group, inclusion of a double layer of geogrid with spacing between geogrid layers equal to twice the pile diameter will improve the pile capacity ratio more than in the case of the single layer of geogrid. However, the pile group efficiency using a single layer of geogrid is better than the group efficiency using a double layer of geogrid.



**Keywords:** Soil reinforcement, Single pile, Pile group, Pullout resistance, cohesionless soil.

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# 1 Introduction

Understanding the pile behavior and predicting the capacity of piles under uplift loading are important topics in foundation design. Most of the current design methods used for the pile groups under the uplift forces are based on the experimental knowledge which is obtained from the laboratory model test. Das, Seeley and Smith (1976), O'Neill, Hawkins and Mahar (1982), Das (1983), Levacher and Sieffert (1984), Chattopadhyay and Pise (1986), Madhav (1987), Das and Shin (1992), CHATTOPADHYAY (1994), Shelke and Patra (2008), Shanker et al. (2009), and Sun et al. (2024)) performed both theoretical and experimental studies on a single pile and pile group embedded in sand so as to investigate the effect of some parameters such as pile surface, pile diameter, relative density of sand, pile embedment ratio and the spacing ratio between piles on the uplift capacity.

Although, geosynthetic materials have been increasingly used in geotechnical engineering applications for different purposes, e.g. stable embankments over soft soil, road construction layers, construction of footing (e.g. [Ling and Liu (2009), Latha and Somwanshi (2009), Choudhary, Jha and Gill (2010), Lovisa, Shukla and Sivakugan (2010), Tafreshi, Khalaj and Halvaee (2011), Sawwaf and Nazir (2012), Leshchinsky and Ling (2013), Tanyu et al. (2013), Yang et al. (2013)]), but relatively little attention has been paid to the response of anchors, anchor/belled piles in reinforced soil subjected to uplift load [Ilamparuthi and Dickin (2001b), Ilamparuthi and Dickin (2001a), El Sawwaf and Nazir (2006), Ghosh and Bera (2010)].

Ilamparuthi and Dickin (2001b) investigated the influence of geogrid reinforcement on the uplift performance of small-scale belled piles or piers embedded in sand. They reported that pull-out resistance increases with the diameter of the geogrid cell, sand density, pile bell diameter, and embedment depth.

Ghosh and Bera (2010) presented the results of experimental investigation on the effect of geotextile ties on uplift capacity of anchors/enlarged pile base embedded in sand. They indicated that the uplift capacity of the anchor increases with an increase in the ratio of embedment depth to base diameter, and with an increase in the number of geotextile layers. The optimum number of geotextile layers of ties was found to be two.

Rao and Nasr (2010) investigated the influence of sand reinforcement with geogrid on the uplift performance of the model piles. The test results show that the pullout resistance increases with the concrete surface roughness, sand density, and the inclusion of a reinforcing layer. It was also found that the effectiveness of the reinforced layer is dependent on the concrete surface roughness.

The previous studies on the pull-out load–displacement behavior of piles was concerned about the case of unreinforced foundation, and reinforced foundation with planar reinforcement (e.g. geotextile and geogrid reinforcement) under static uplift loads. Therefore, the above-mentioned literature indicates that there is a major lack of studies about the behavior of piles subjected to pull-out loads utilizing soil reinforcement.

In the research described here, and to develop a better understanding of the behavior of pull-out single piles and pile group embedded in reinforced soil, a series of different laboratory tests was performed. The overall goal was to demonstrate the benefits of reinforcement, with the detailed objective of this study, and to compare the performance of reinforced and unreinforced systems on the uplift response of the single pile and the pile group.

# 2 Experimental Work Description

This section outlines the experimental methodology employed to investigate the enhancement of single piles and the pile group performance under pullout loads through soil reinforcement. In this study, a comprehensive series of experiments were conducted to evaluate the effectiveness of soil reinforcement in improving the resistance of single piles and the pile group to pullout loads. The experimental setup and instrumentation are described in detail to provide a clear understanding of the experimental framework.

## 2.1 The Soil Container

The experimental program was carried out utilizing the test apparatus, which consists of the test box, the loading system, and the data acquisition system. According to ((Kishida, 1963)), the soil container needs to be large enough so the container's edges will not affect the test results, as the zone of influence of the pile due to loading was reported to be within 3 and 8 of the pile diameters (D). Accordingly, for the laboratory experiment, the compacted soil samples were prepared in a metal box (Mold) of 100x100x50 cm as the pile diameter was 3.5 cm (Fig. 1). Although no end-bearing stress is expected at the pile tip, a vertical clearance of about three times the pile diameter was provided beneath the pile tips. As a result, it seems that the soil container's boundaries had no effect on the test results.


**Fig. 1.** The metal box (mold) for soil sample preparation.

## 2.2 Model Pile

Pullout tests of the single pile model are performed on a circular steel pile with bulges connected with a square rigid plate of 3 mm thickness at the top, which were used as pile cap for the structure. Mazurkiewicz (1968) reported that the height/diameter ratio of 1:10 is a good ratio for model pile tests. Therefore, the dimension of the model pile was set to be 35 mm in diameter (D) and 350 mm in length (L) considering the same ratio of 1:10. Additionally, the pile group model is performed on a (2x1) piles with spacing of three times the single pile diameter. Figs. 2 and 3 show the models of the single pile and the pile group utilized in the experiments.

**Fig. 2.** The model of the circular steel pile with bulges used in the present study.

**Fig. 3.** The model of the pile group with a spacing of three times the single pile diameter used in the present study.

## 2.3 Properties of Tested Soils

In the current study, sandy soil that are widely required in compaction works for construction purposes were considered to investigate the influence of soil reinforcement on the performance of single pile and pile group under pullout loads. Sieve analysis and modified Proctor compaction tests were conducted in the laboratory for the sandy soil. Table 1 summarizes the results obtained for the investigated soil including its constituent, classification, maximum dry density, and the corresponding optimum moisture contents. In addition, the obtained minimum dry density and the angle of shearing resistance are given. Figs. 4 and 5 show the particle size distribution curves and the compaction curves for the tested soil.

**Table 1.** Results of sieve analysis and modified Proctor compaction tests for the tested soil.

| ***Parameter*** | **Maximum dry unit weight** | **Minimum dry unit weight** | **Maximum void ratio** | **Minimum void ratio** | **Specific gravity** | **Gravel** | **Coarse sand** | **Medium sand** | **Fine sand** | **Effective grain size** | **Classification** | **Water content** | **Shear strength parameter** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Symbol and unit*** | $\gamma_{dmax}$ (t/m$^3$) | $\gamma_{dmin}$ (t/m$^3$) | $e_{max}$ | $e_{min}$ | Gs | % | % | % | % | $D_{10}$ (mm) | SP | O.M.C (%) | Φ (degree) |
| ***Value*** | 1.93 | 1.72 | 0.52 | 0.36 | 2.62 | 13.6 | 52.9 | 33.3 | 0.21 | 0.34 | - | 5.8 | 38.3º |

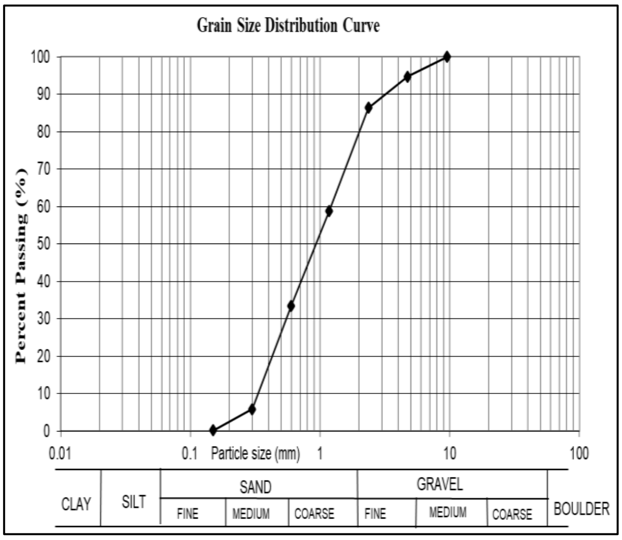



**Fig. 4.** Particle size distribution for the tested soil.

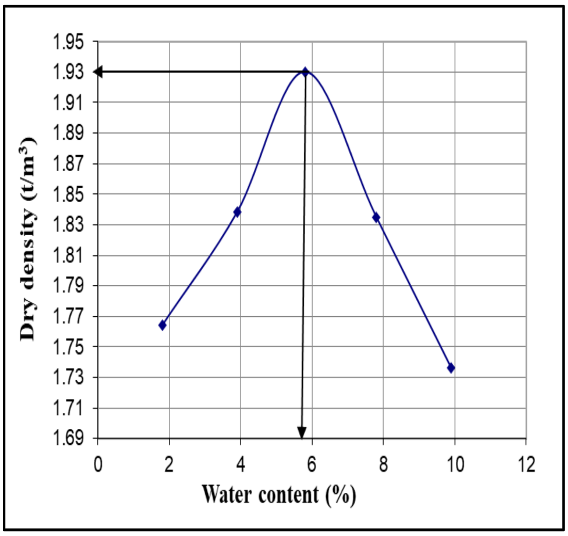



**Fig. 5.** Compaction curves using the Modified Proctor test, for the SP soil.

## 2.4 Geogrid Reinforcement Properties

The performance of reinforced layered soil system was studied in the present study using two types of soil reinforcement. The first type of the soil reinforcement was a biaxial geogrid of Tensar SS geogrids called (SS30) and the second type of the soil reinforcement was a triaxial geogrid of Tensar TriAx geogrids called (TX150) as shown in Figs. (6) and (7). Table 2 and 3 show the properties of SS30 and TX150 geogrids, respectively.

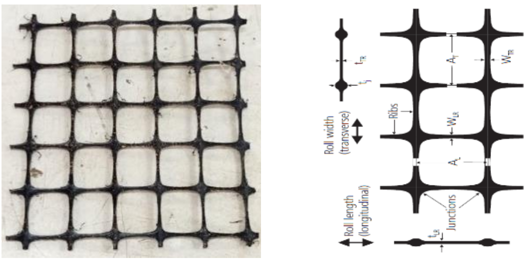



**Fig. 6.** Biaxial SS30 geogrid used for soil reinforcement.

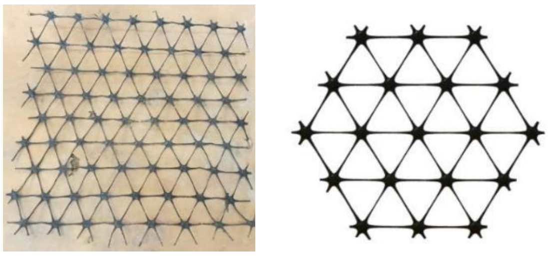


**Fig. 7.** TriAx geogrids TX150 used for soil reinforcement.

**Table 2.** Properties of biaxial SS30 geogrid used for soil reinforcement.

| Property | Units | SS geogrid Tensar **SS30** |
|---|---|---|
| Polymer | | Polypropylene |
| Minimum carbon black | % | 2 |
| Roll width | m | 4.0 & 3.8 |
| Roll length | m | 50 |
| Unit weight | $kg/m^2$ | 0.33 |
| Roll weight | kg | 67 & 64 |
| **Dimensions** | | |
| AL | mm | 39 |
| AT | mm | 39 |
| WLR | mm | 2.3 |
| WTR | mm | 2.8 |
| tJ | mm | 5.0 |
| tLR | mm | 2.2 |
| tTR | mm | 1.3 |
| **control strength longitudinal Quality** | | |
| Tult | kN/m | 30.0 |
| **Load at 2% strain** | kN/m | 10.5 |
| **Load at 5% strain** | kN/m | 21.0 |
| Approx strain at Tult | % | 11.0 |
| **Junction strength** | % | 95 |
| **control strength transverse Quality** | | |
| Tult | kN/m | 30.0 |
| **Load at 2% strain** | kN/m | 10.5 |
| **Load at 5% strain** | kN/m | 21.0 |
| Approx strain at Tult | % | 10.0 |
| **Junction strength** | % | 95 |

**Table 3.** Properties of TriAx geogrids TX150 used for soil reinforcement.

| Parameter | | Longitudinal | Diagonal | Transverse | General | Declared Value | Tolerance |
|---|---|---|---|---|---|---|---|
| **Geogrid opening size (mm)** | Rib pitch (mm) | 40 | 40 | - | - | - | - |
| | Mid-rib depth (mm) | - | 1.4 | 1.1 | - | - | |
| | Mid-rib width (mm) | - | 1 | 1.2 | - | - | |
| | Nodal thickness (mm) | - | | | 3 | - | |
| | Rib shape | - | - | - | rectangular | - | - |
| | Aperture shape | - | - | - | triangular | - | - |
| | (%) Open area aspect ratio | - | - | - | > 85 | - | - |
| **Tensile strength (KN/m)** | | - | - | - | - | MD – 20 | -4 |
| | | - | - | - | - | CMD – 16 | -3 |
| **Weight ($kg/m^2$)** | | - | - | - | - | 0.205 | -0.035 |
| **Where: MD: Machine Direction, CMD: Cross- Machin Direction.** | | | | | | | |

# 3 Experimental Work Program

An experimental work program was conducted on the previously described tested soil to evaluate the uplift capacity of the single pile and the pile group within both non-reinforced and reinforced soil. Table 4 shows the outline of the laboratory test parameter values utilized for both the single pile and the pile group models. The laboratory test program was conducted to cover the effect of different parameters as follows:

1. The number of reinforcement layers (N),
2. The reinforcement depth ratio (Z/D), the ratio between the depth of reinforcement to the pile diameter.
3. The reinforcement width ratio (B/D), the ratio between the width of reinforcement to the pile diameter.
4. Type of reinforcement.

**Table 4.** The laboratory test parameters

| Parameter | single pile | pile group |
|---|---|---|
| Type of reinforcement layer | SS30 | SS30 |
| | TX150 | TX150 |
| Reinforcement depth ratio (Z/D) | 1 | 2 |
| | 2 | |
| | 3 | |
| Reinforcement width ratio (B/D) | 6 | 6+3 |
| | 9 | 9+3 |
| | 12 | 12+3 |
| Number of reinforcement layers (N) | 1 | 1 |
| | 2 | 2 |
| Spacing between reinforcement layers ratio (h/D) | 2 | 2 |

# 4 Testing Procedure

The experimental testing procedure was divided into two phases. The first phase of preparing the unreinforced compacted soil sample, which is the phase of testing the single pile or the pile group without soil reinforcement. Furthermore, during the second phase of reinforced compacted soil sample preparation, the single pile or the pile group is evaluated utilizing two different types of soil reinforcement.

To determine the unit weight and required relative density of the sand, a predetermined quantity of sand was poured into the testing tank to completely fill each layer, Subsequently, the tank was leveled and compacted. The soil samples were compacted in layers in the tank using a manual compaction hammer. The sand bed was prepared up to the base level of the model pile in one layer of 100 mm thickness for a relative density of 60%. For all the tests the minimum depth of sand below the base of the model was maintained at 100 mm.

For the first phase of preparing the unreinforced compacted soil sample, the sand was carried out in layers up to the level of the pile cap plate that will be located. The single pile or the pile group model was then hammered down into position in the middle of the tank, on the soil's surface. Additionally, the model of the single pile or the pile group was positioned by passing a steel wire over the pulley and connecting the other end to the load hanger.

While for the second phase of reinforced compacted soil sample preparation, the sand was continued in layers up to the level of the reinforcement layer. The geogrid reinforcement was then placed on the compacted level surface. The single pile or the pile group model was then hammered down into position in the middle of the tank, on the soil's surface. Additionally, the model of the single pile or the pile group was positioned by passing a steel wire over the pulley and connecting the other end to the load hanger. The sand was continued to the desired height, leaving a fill thickness (Z) above the reinforcement layer.

Finally, the steel wire was fixed to the load hanger through pulleys fixed onto the frame and the dial gauge was placed in its position. The load was applied incrementally by adding weight increments until reaching failure. Each load increment was maintained constant till the single pile, or the pile group vertical displacement was stabilized. This soil layer and the geogrid layers represent the case of the single pile reinforced with geogrid, as shown in Fig. 8. While Fig. 9 shows the pile group reinforced with geogrid layers.

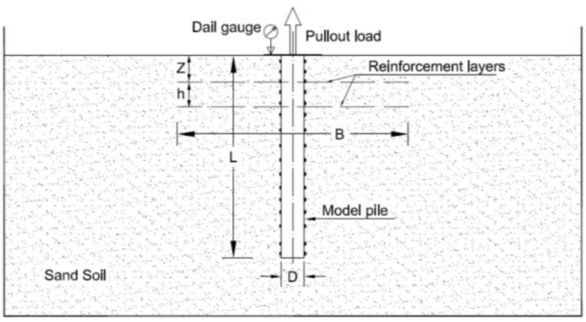
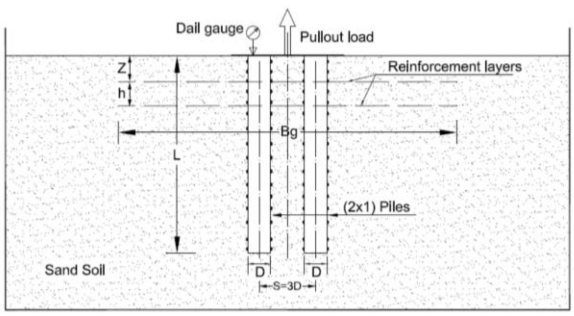



**Fig. 8.** Single pile reinforced with geogrid.




**Fi. 9.** Pile group reinforced with geogrid.

## 5 Testing Results and Analysis

The test program primarily consists of pullout tests on single pile and pile group models embedded in unreinforced and reinforced sand. The ultimate pullout capacity and the associated vertical displacement of failure were determined from the load-displacement relationship as the point at which the curve exhibits a peak or maintains a continuous displacement increase with no further increase in the pullout resistance. Figs. 10, and 11 exhibit the load-displacement relationship for the single pile reinforced by SS30 and TX150 geogrid. While Figs. 12, and 13 show the load-displacement relationship for the pile group (2x1) reinforced by SS30 and TX150 geogrid.

The results of the single pile pull-out tests performed for the tested soil sample were expressed in terms of Improvement Ratio, (IR). The improvement ratio is defined as the single pile pullout capacity of reinforced soil divided by the single pile pullout capacity of unreinforced soil. While the results of the pile group pull-out tests performed for the tested soil sample were expressed in terms of Group Improvement Ratio, (GIR). The group improvement ratio is defined as the group pullout capacity of reinforced soil divided by the group pullout capacity of unreinforced pile group soil.

For each experimental test result the value of the IR and the GIR were calculated as follows:

$$\mathrm{IR} = \frac{T_R}{T_{un}} \quad (1)$$

$$\text{GIR} = \frac{T_{Rg}}{T_{ung}} \quad (2)$$

Where:

IR: The single pile improvement ratio.

$T_R$: The ultimate pullout capacity of the single pile in reinforced soil.

$T_{un}$: The ultimate pullout capacity of the single pile in unreinforced soil.

GIR: The pile group improvement ratio.

$T_{Rg}$: The ultimate pullout capacity of the pile group in reinforced soil.

$T_{ung}$: The ultimate pullout capacity of the pile group in unreinforced soil.

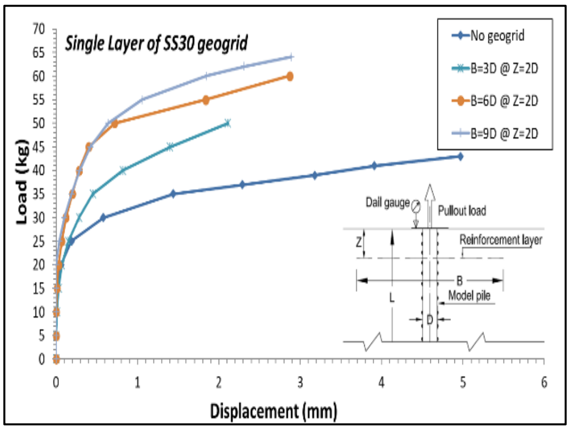
Furthermore, the vertical displacement obtained from the single pile pullout tests (Δh) and the vertical displacement obtained from the group pullout tests (Δhg) were recorded for all the examined samples. The results of the pull-out tests of the single pile and the pile group performed for the tested soil sample are provided in Table 5 and Table 6, respectively.

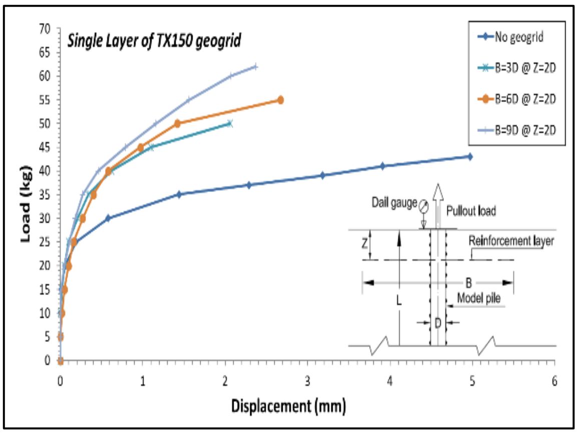
**Table 5.** The results of the pull-out tests of the single pile performed for the unreinforced and reinforced soil.

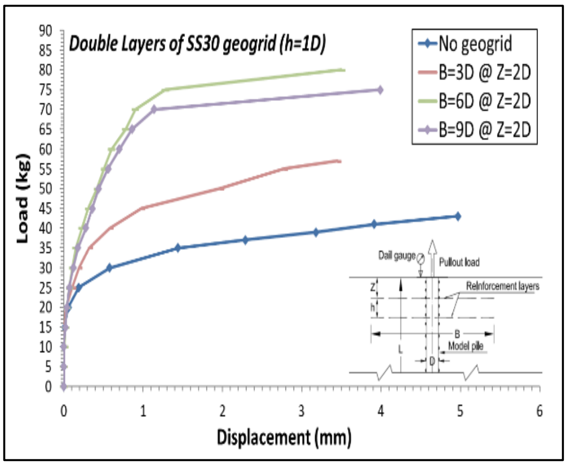
| Test No. | Group | Soil Type | Dr (%) | Geogrid Type | (N) | (Z/D) | (h/D) | (B/D) | Tu(kg) | Δh(mm) | $IR=T_R/T_{un}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | - | Sand | 60 | No geogrid | - | - | - | - | 43 | 4.97 | 1.00 |
| 1 | A | Sand | 60 | SS30 | 1 | 1 | - | 6 | 55 | 3.64 | 1.28 |
| 2 | | Sand | 60 | | | | | 9 | 62 | 4.09 | 1.44 |
| 3 | | Sand | 60 | SS30 | 1 | 2 | - | 6 | 60 | 2.87 | 1.40 |
| 4 | | Sand | 60 | | | | | 9 | 64 | 2.89 | 1.49 |
| 5 | | Sand | 60 | | | | | 12 | 64 | 3.55 | 1.49 |
| 6 | | Sand | 60 | SS30 | 1 | 3 | - | 6 | 60 | 2.2 | 1.40 |
| 7 | | Sand | 60 | | | | | 9 | 64 | 2.85 | 1.49 |
| 8 | B | Sand | 60 | SS30 | 2 | 1 | 2 | 6 | 72 | 2.85 | 1.67 |
| 9 | | Sand | 60 | | | | | 9 | 76 | 2.39 | 1.77 |
| 10 | | Sand | 60 | SS30 | 2 | 2 | 2 | 6 | 85 | 3.8 | 1.98 |
| 11 | | Sand | 60 | | | | | 9 | 88 | 4.08 | 2.05 |
| 12 | | Sand | 60 | | | | | 12 | 88 | 3.95 | 2.05 |
| 13 | | Sand | 60 | SS30 | 2 | 3 | 2 | 6 | 72 | 3.54 | 1.67 |
| 14 | | Sand | 60 | | | | | 9 | 79 | 2.76 | 1.84 |
| 15 | C | Sand | 60 | TX150 | 1 | 1 | - | 6 | 54 | 2.74 | 1.26 |
| 16 | | Sand | 60 | | | | | 9 | 60 | 1.03 | 1.40 |
| 17 | | Sand | 60 | TX150 | 1 | 2 | - | 6 | 55 | 2.67 | 1.28 |
| 18 | | Sand | 60 | | | | | 9 | 62 | 2.37 | 1.44 |
| 19 | | Sand | 60 | | | | | 12 | 62 | 2.00 | 1.44 |
| 20 | | Sand | 60 | TX150 | 1 | 3 | - | 6 | 50 | 2.02 | 1.16 |
| 21 | | Sand | 60 | | | | | 9 | 60 | 2.75 | 1.40 |
| 22 | D | Sand | 60 | TX150 | 2 | 1 | 2 | 6 | 70 | 1.69 | 1.63 |
| 23 | | Sand | 60 | | | | | 9 | 75 | 1.5 | 1.74 |
| 24 | | Sand | 60 | TX150 | 2 | 2 | 2 | 6 | 76 | 3.62 | 1.77 |
| 25 | | Sand | 60 | | | | | 9 | 78 | 2.03 | 1.81 |
| 26 | | Sand | 60 | | | | | 12 | 78 | 2.54 | 1.81 |
| 27 | | Sand | 60 | TX150 | 2 | 3 | 2 | 6 | 71 | 2.01 | 1.65 |
| 28 | | Sand | 60 | | | | | 9 | 75 | 2.74 | 1.74 |

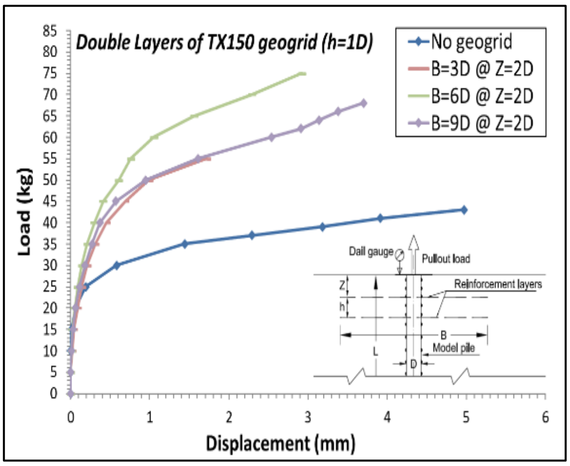
**Table 6.** The results of the pull-out tests of the pile group performed for the unreinforced and reinforced soil.

| *Test No.* | *Group* | *Soil Type* | *Dr (%)* | *Geogrid Type* | *(N)* | *(Z/D)* | *(h/D)* | *(B/D)* | *$(B_g/D)$ = $(B+S)/$* | *$T_R$ (kg)* | *$T_{Rg}$(kg)* | $\eta=T_{Rg}/(n*T_R)$ | GIR=TRg/Tung |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***0*** | - | Sand | 60 | No geogrid | - | - | - | - | - | *43* | *55* | *0.64* | *1.00* |
| 1 | A | Sand | 60 | SS30 | 1 | 2 | - | 6 | 6+3 | 60 | *100* | *0.83* | *1.82* |
| 2 | | Sand | 60 | | | | | 9 | 9+3 | 64 | *108* | *0.84* | *1.96* |
| 3 | | Sand | 60 | | | | | 9 | 12+3 | 64 | *108* | *0.84* | *1.96* |
| 4 | B | Sand | 60 | | 2 | 2 | 2 | 6 | 6+3 | 85 | *115* | *0.68* | *2.09* |
| 5 | | Sand | 60 | | | | | 9 | 9+3 | 88 | *119* | *0.68* | *2.16* |
| 6 | | Sand | 60 | | | | | 9 | 12+3 | 88 | *119* | *0.68* | *2.16* |
| 7 | C | Sand | 60 | TX150 | 1 | 2 | - | 6 | 6+3 | 55 | *90* | *0.82* | *1.64* |
| 8 | | Sand | 60 | | | | | 9 | 9+3 | 62 | *100* | *0.81* | *1.82* |
| 9 | | Sand | 60 | | | | | 9 | 12+3 | 62 | *100* | *0.81* | *1.82* |
| 10 | D | Sand | 60 | | 2 | 2 | 2 | 6 | 6+3 | 76 | *100* | *0.66* | *1.82* |
| 11 | | Sand | 60 | | | | | 9 | 9+3 | 78 | *104* | *0.67* | *1.89* |
| 12 | | Sand | 60 | | | | | 9 | 12+3 | 78 | *104* | *0.67* | *1.89* |



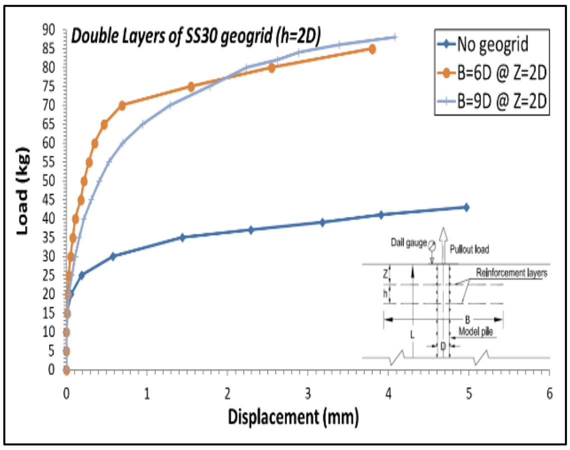



**Fig. 10.** Pullout response of single pile in unreinforced soil and reinforced soil for reinforcement type SS30.

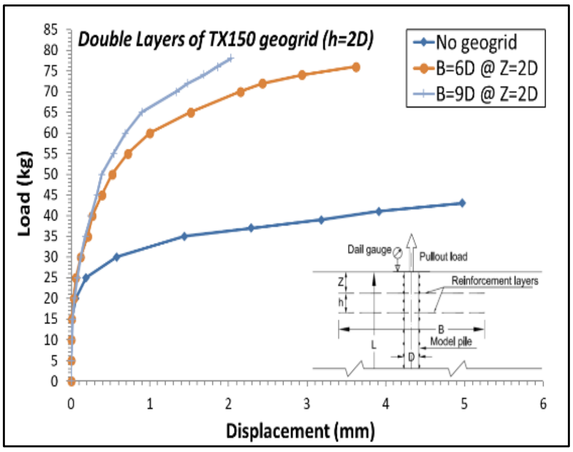



**Fig. 11.** Pullout response of single pile in unreinforced soil and reinforced soil for reinforcement type TX150.

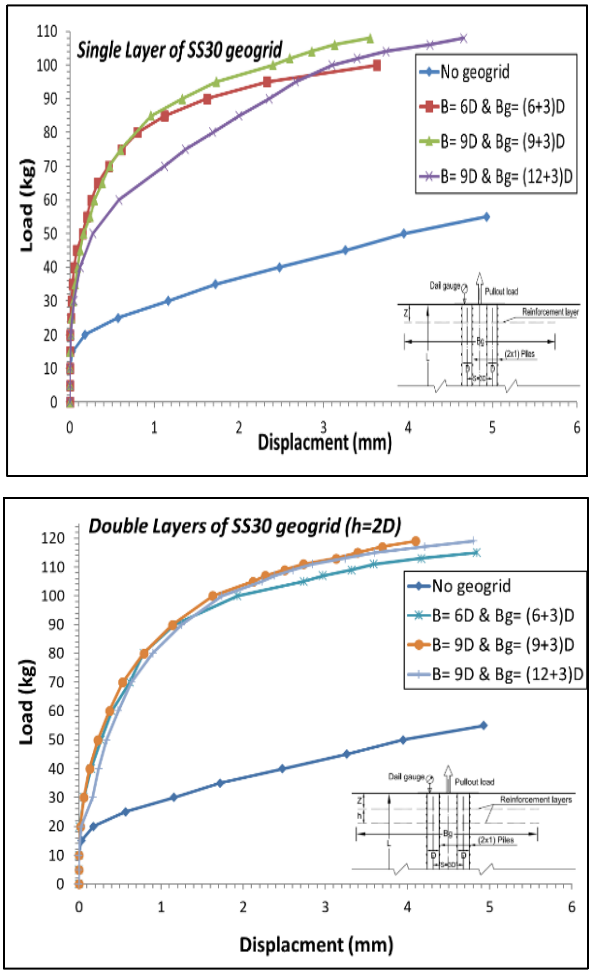



**Fig. 12.** Pullout response of pile group in unreinforced soil and reinforced soil for reinforcement type SS30.

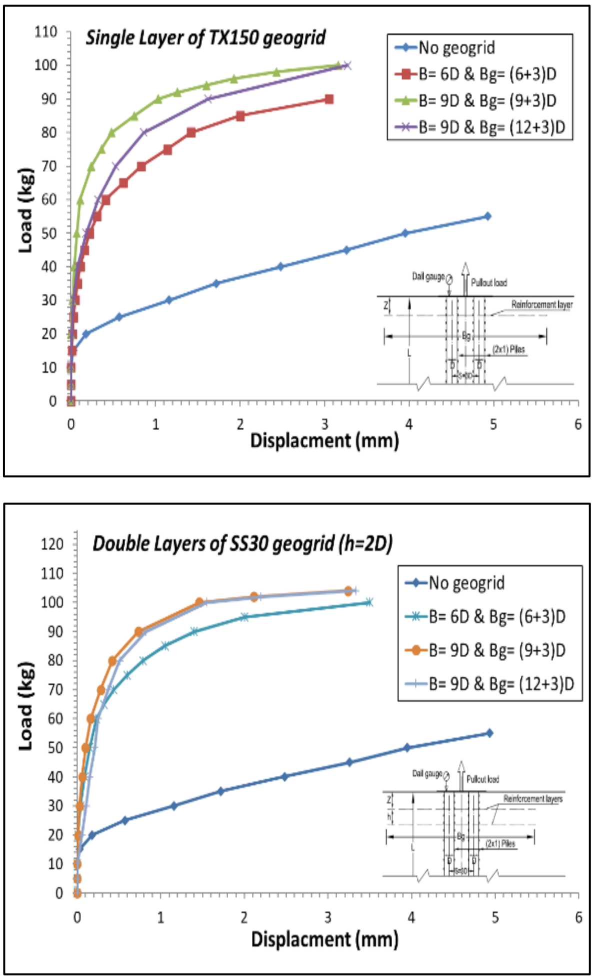



**Fig. 13.** Pullout response of pile group in unreinforced soil and reinforced soil for reinforcement type TX150.

### 5.1 The Influence of the Number of Reinforcement Layers (N)

For the tested soils, Fig. 14 and 15 present the relationships of the improvement ratio (IR) versus the number of reinforcement layers of single pile for type (SS30) and type (TX150), respectively for samples prepared at different reinforcement width ratio (B/D). In addition, Fig. 16 and 17 present the relationships of the group improvement ratio (GIR) versus the number of reinforcement layers of pile group for type (SS30) and type (TX150), respectively for samples prepared at different reinforcement width ratio (Bg/D). As shown in Figs. 14 and 15 the IR increases with increasing the number of reinforcement layers for the single pile. Furthermore Figs. 16 and 17 exhibit also that the pullout capacity of pile group (2x1) is substantially increased by incorporation of the geogrid layer around the pile. In addition, inclusion of a double layer of geogrid with spacing between geogrid layers equal twice the pile diameter will improve the single or group pile capacity ratio more than in the case of the single layer of geogrid. However, the group efficiency of the single layer of geogrid is more than the group efficiency of a double layer of geogrid. Therefore, for the single pile it is concluded that using double layers of geogrid with spacing between geogrid layers equal to two times the pile diameter is better and more economical than reinforcing the soil itself with single layer of geogrid. But for the pile group it is concluded that using a single layer of geogrid is better and more economical than reinforcing the soil itself with double layers of geogrid.

The increase in the improvement ratio (IR) and the group improvement ratio (GIR) may be due to a combination of the following reasons:

- Interlocking friction along the reinforcement, which provides additional confining pressure to the soil.
- Increase in the quantity of soil involved in resisting the pull.
- The stiffness of the reinforcement layers.

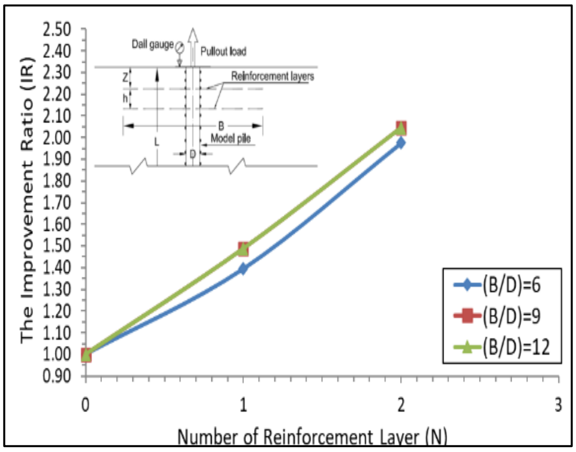



**Fig. 14.** The improvement ratio (IR) versus the number of reinforcement layers type (SS30) for the single pile.

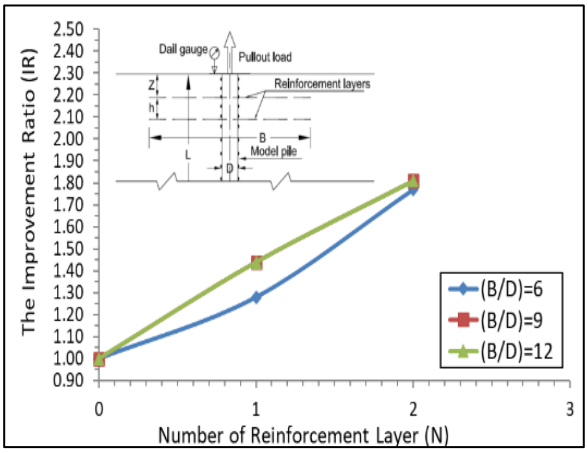



**Fig. 15.** The improvement ratio (IR) versus the number of reinforcement layers type (TX150) for the single pile.

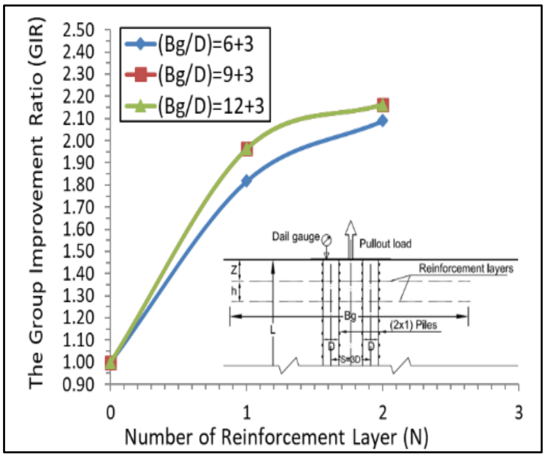



**Fig. 16.** The group improvement ratio (GIR) versus the number of reinforcement layers type (SS30) for the pile group.

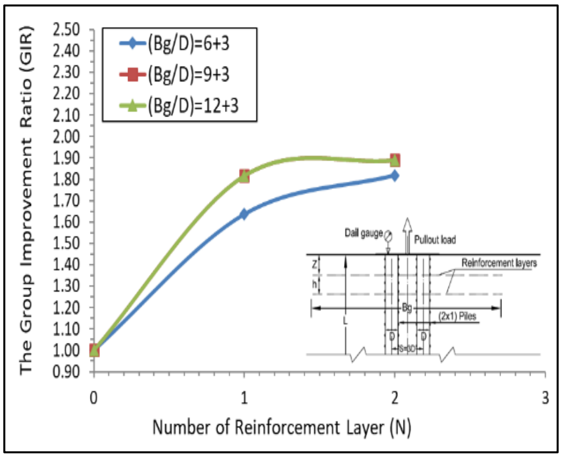



**Fig. 17.** The group improvement ratio (GIR)versus the number of reinforcement layers type (TX150) for the pile group.

## 5.2 The Influence of the Reinforcement Width Ratio

To study the effect of reinforcement width ratio on the performance of the single pile and the pile group capacity, tests were conducted with varying the number of reinforcement layers (N). For the tested soils, Fig. 18 and 19 present the relationships of the improvement ratio (IR) versus the reinforcement width ratio (B/D) for the single pile of type (SS30) and type (TX150), respectively. In addition, Fig. 20 and 21 present the relationships of the group improvement ratio (GIR) versus the reinforcement width ratio (Bg/D) for the pile group of type (SS30) and type (TX150), respectively. The (B/D) ratio was varied from 6 to 12 for the single pile of the reinforcement types (SS30) and (TX150). While the (Bg/D) ratio was varied from (9+3) to (12+3) for the pile group of the reinforcement types (SS30) and (TX150).

For all pile group experimental tests, the (Bg/D) ratio were calculated as follows:

$$(Bg/D) = (B+S)/D \qquad (3)$$

Where:

Bg: The reinforcement width of the pile group.

D: The single pile diameter.

B: The reinforcement width of the single pile.

S: the spacing between the piles in pile group equal to three times the single pile diameter = 3D.

It is seen from Figs.18 and 19 that there is an increase in the improvement ratio (IR) with the increase in the reinforcement width ratio (B/D) for all tests of number of geogrid N = 1 and N = 2 with spacing between geogrid equal to two times the pile diameter up to B/D = 9 for the single pile. Also, it is seen from Figs. 20 and 21 that there is an increase in the group improvement ratio (GIR) with the increase in the reinforcement width ratio (Bg/D) for all tests of number of geogrid N = 1 and N = 2 with spacing between geogrid equal to two times the pile diameter up to (Bg/D) = (9+3) for the pile group. Further increases in the reinforcement width ratio (B/D) or (Bg/D) for these tests result in approximately enhances the same effect of the inclusion of reinforcement width ratio B/D = 9 for the single pile or (Bg/D) = (9+3) for the pile group.

The increase in the improvement ratio (IR) or the group improvement ratio (GIR) may be due to a combination of the following reasons:

- The larger contact area between the geogrid and the soil, increasing the frictional resistance along the surface of geogrid.
- The stiffness of the reinforcement layers.

Furthermore, due to the fact that around the single pile and the pile group there exists a failure zone of soil and only that portion of reinforcement which lies within this zone will have its tensile strength effectively mobilized. Some part of the reinforcement area beyond this zone serves as anchorage to provide pullout resistance to the geogrid. Hence, the optimum single reinforcement width ratio (B/D) and the group reinforcement width ratio (Bg/D), required will be equal to the sum of length of reinforcement within the failure zone around the pile group and the length in the anchorage zones on both sides of the piles. Hence, any additional length of single reinforcement width ratio and the group reinforcement width ratio beyond optimum value of (B/D) and (Bg/D), will be ineffective.

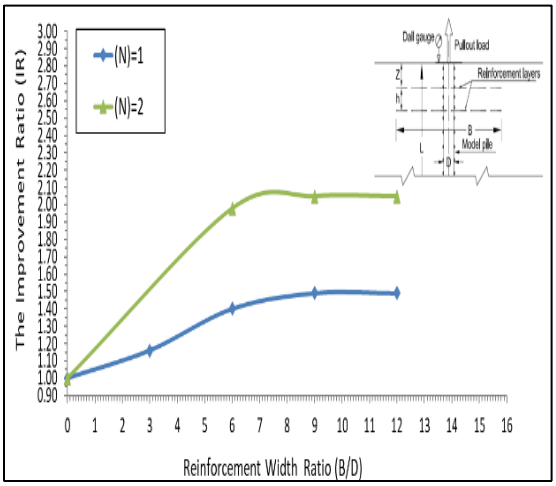



**Fig. 18.** The improvement ratio (IR) versus the reinforcement width ratio (B/D) of type (SS30) for the single pile.

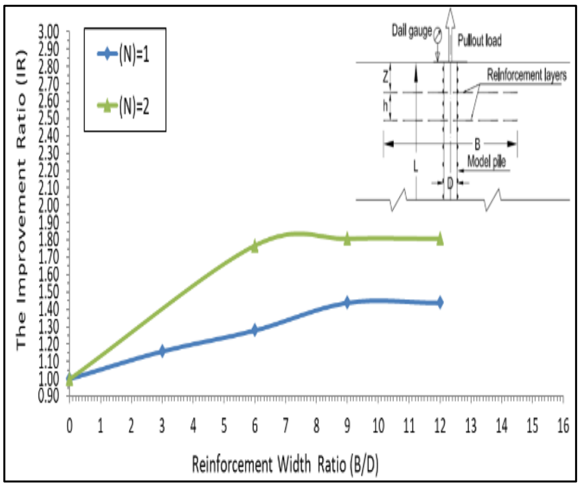



**Fig. 19.** The improvement ratio (IR) versus the reinforcement width ratio (B/D) of type (TX150) for the single pile.

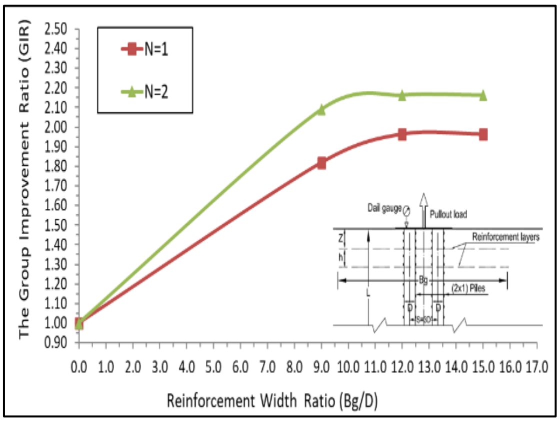



**Fig. 20.** The group improvement ratio (GIR) versus the reinforcement width ratio (Bg/D) of type (SS30) for the pile group.

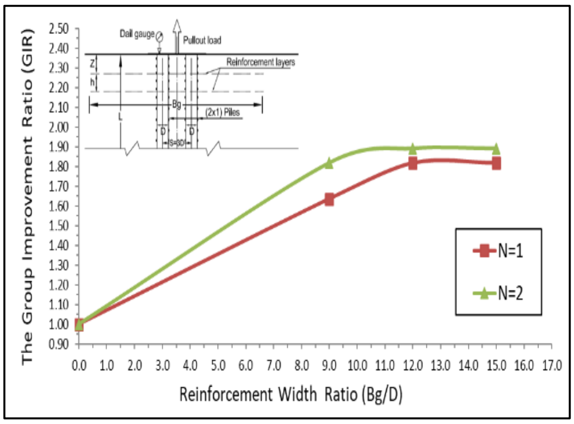



**Fig. 21.** The group improvement ratio (GIR) versus the reinforcement width ratio (Bg/D) of type (TX150) for the pile group.

### 5.3 Comparison Between the Improvement Ratio in Unreinforced Soil and Reinforced Soil for Reinforcement Types (SS30) And (TX150)

Results of tests conducted in the unreinforced and the reinforced conditions with reinforcement types (SS30) and (TX150) by varying the parameters such as the reinforcement width ratio (B/D) and the number of reinforcement layers (N) were compared for the single pile and the pile group. To do a comparison between the pullout capacity in unreinforced soil and the pullout capacity in reinforced soil the improvement ratio (IR) is determined for the single pile and the group improvement ratio (GIR) is determined for the pile group. Figs. 22 and 23 show the comparison between the improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150) for the single pile. While Figs. 24 and 25 show the comparison between the group improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150) for the pile group. As shown in the figures there is an increase in the improvement ratio (IR) for the reinforcement type SS30 than the reinforcement type TX150 for the single pile however there is a decrease in the vertical displacement (Δh) for the reinforcement type TX150 than the reinforcement type SS30 for the single pile. In addition, there is an increase in the group improvement ratio (GIR) for the reinforcement type SS30 than the reinforcement type TX150 for the pile group however there is a decrease in the vertical displacement (ΔhRg) for the reinforcement type TX150 than the reinforcement type SS30 for the pile group.

The increase in the improvement ratio (IR) or the group improvement ratio (GIR) for the reinforcement type (SS30) than reinforcement types (TX150) may be due to the Increase of the stiffness and the tensile strength for the reinforcement type (SS30) than the reinforcement types (TX150).


**Fig. 22.** The comparison between the improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150) of (N)=1 for the single pile.

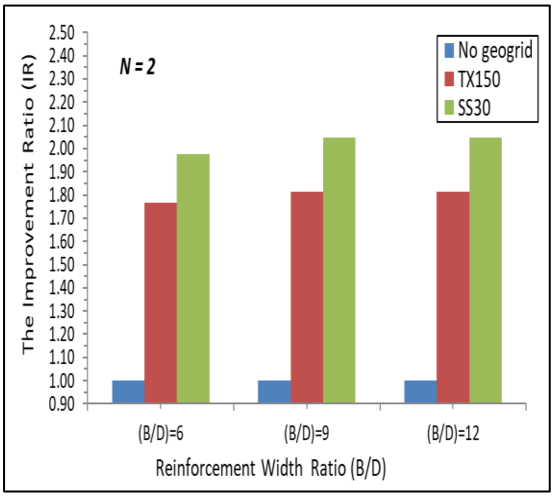



**Fig. 23.** The comparison between the improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150) of (N)=2 for the single pile.

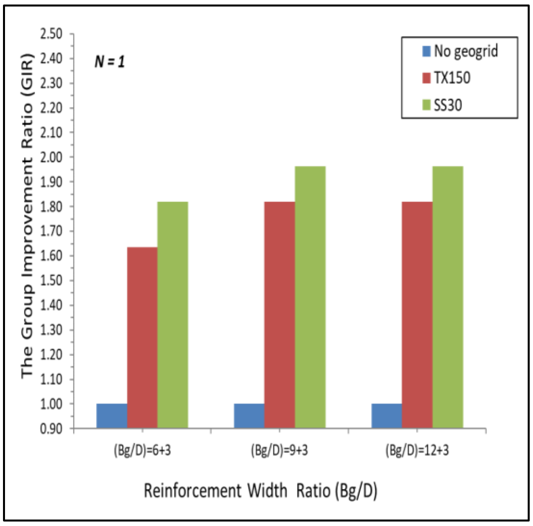



**Fig. 24.** The comparison between the group improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150) of (N)=1 for the pile group.

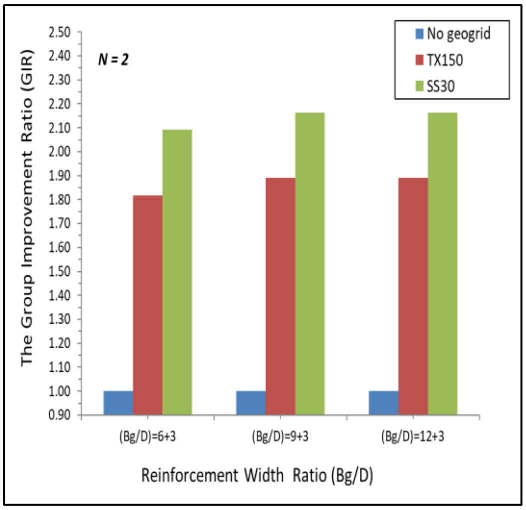



**Fig. 25.** The comparison between the group improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150) of (N)=2 for the pile group.

### 5.4 The Influence of the Number of Reinforcement Layers (N) on the Group Efficiency

For the tested soils, Fig. 26 and 27 present the relationships of the pile group efficiency (η) versus the number of reinforcement layers of the pile group for type (SS30) and type (TX150), respectively for samples prepared at different reinforcement width ratio (Bg/D). For all pile group experimental tests, the pile group efficiency (η) were calculated as follows:

$$\eta = T_{Rg}/(n*T_R) \qquad (4)$$

Where:

η: The efficiency of the pile group.

$T_{Rg}$: The ultimate pullout capacity for the pile group.

n: The number of piles in pile group.

$T_R$: The ultimate pullout capacity for the single pile.

As shown in the figures the group efficiency (η) increases with adding the soil reinforcement layers up to a single layer of reinforcement. Further increase in the number of reinforcement layers (N) does not show important contributions in increasing the group efficiency (η) of the pile group. Thus, the results clearly indicate that there is an optimum value for the number of reinforcement layers (N) at which the maximum group efficiency (η) can be derived, after which an additional number of reinforcement layers (N) consequences in decrease the group efficiency (η).

The decrease in the group efficiency of the pile group in the reinforced and unreinforced soil is due to that the zones of stress around the pile will overlap, and the ultimate pullout capacity of the pile group is less than the sum of the individual single pile capacities.

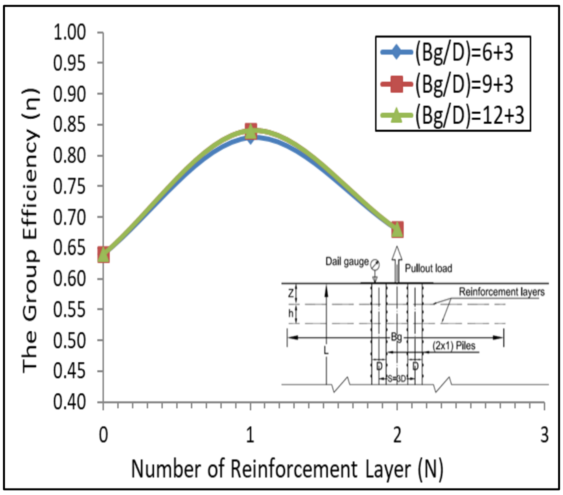



**Fig. 26.** The group efficiency (η) versus the number of reinforcement layers type (SS30) for the pile group.

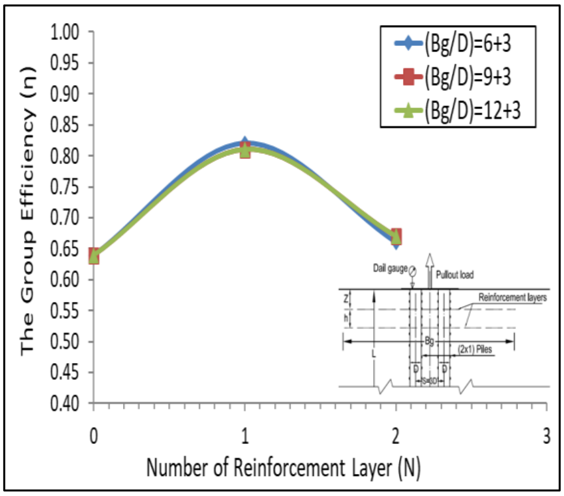



**Fig. 27.** The group efficiency (η) versus the number of reinforcement layers type (TX150) for the pile group.

## 6 Conclusions

The conclusions obtained from this study can be summarized as follows:

For the single pile:

1. The pullout capacity of piles is substantially increased by incorporation of the geogrid layer around the pile. Inclusion of a double layer of geogrid with spacing between geogrid layers equal twice the pile diameter will improve the pile capacity ratio more than in the case of the single layer of geogrid.

2. The optimum reinforcement width ratio (B/D) is considered to be approximately equal to 9.0 times the pile diameter. The results clearly indicate that there is an optimum value for the reinforcement depth ratio (B/D) at which the maximum pullout load can be derived, after which additional width of reinforcement becomes ineffective.

3. For the improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150). There is an increase in the improvement ratio (IR) for the reinforcement type SS30 than the reinforcement type TX150. In addition, there is a decrease in the vertical displacement (Δh) for the reinforcement type TX150 than the reinforcement type SS30.

For the pile group:

4. The pullout capacity of pile group is substantially increased by incorporation of the geogrid layer around the pile group. However, the group efficiency of the single layer of geogrid is more than the group efficiency of a double layer of geogrid. Therefore, for the pile group, it is concluded that using a single layer of geogrid is better and more economical than reinforcing the soil itself with double layers of geogrid.
5. The optimum reinforcement width ratio (Bg/D) is considered to be approximately equal to (9+3) times the pile diameter. The results clearly indicate that there is an optimum value for the reinforcement depth ratio (Bg/D) at which the maximum pullout load can be derived, after which additional width of reinforcement becomes ineffective.
6. For the group improvement ratio in unreinforced soil and reinforced soil for reinforcement types (SS30) and (TX150). There is an increase in the group improvement ratio (GIR) for the reinforcement type SS30 than the reinforcement type TX150. In addition, there is a decrease in the vertical displacement (ΔhRg) for the reinforcement type TX150 than the reinforcement type SS30.
7. The group efficiency (η) of the piles decreased in the group of piles that the zones of stress around the pile will overlap, and the ultimate pullout capacity of the pile group is less than the sum of the individual single pile capacities.
8. The group efficiency (η) increases with adding the soil reinforcement layers up to a single layer of reinforcement. Further increase in the number of reinforcement layers (N) does not show important contributions in increasing the group efficiency (η) of the pile group. Thus, the results clearly indicate that there is an optimum value for the number of reinforcement layers (N) at which the maximum group efficiency (η) can be derived, after which an additional number of reinforcement layers (N) consequences in decrease the group efficiency (η).

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