Effect of Allowable Vertical Load and Length/Diameter Ratio (L/D) on Behavior of Pile Group Subjected to Torsion

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ABSTRACT

Some structures such as tall buildings, offshore platforms, and bridge bents are subjected to lateral loads of considerable magnitude due to wind and wave actions, ship impacts, or high-speed vehicles. Significant torsional forces can be transferred to the foundation piles by virtue of eccentric lateral loading. The testing program of this study includes one group consists of 3 piles, four percentages of allowable vertical load were used (0%, 25%, 50%, and 100%) with two L/D ratios 20 and 30, vertical allowable load 110 N for L/D = 20 and 156 N for L/D = 30. The results obtained indicate that the torsional capacity for pile group increases with increasing the percentage of allowable vertical load, when the percentage of allowable vertical load was 100% and L/D ratio (20) the torsional capacity for pile group increases about 42% if compared with the torsional capacity when the percentage of allowable vertical load was 0% for the same L/D ratio. Also increasing L/D ratio leads to increasing the torsional capacity of pile group, when the percentage of allowable vertical load is 100% and L/D ratio (30), the torsional capacity for pile group increased about 51% if compared with torsional capacity when L/D ratio was (20) for the same groups and the same percentage of allowable vertical load. At failure the twist angle for pile group remain constant 3° when the percentage of allowable load change from 0% to 100 and L/D ratio 20, while it decreases from 2.9° to 2.7° when the percentage of allowable load change from 0% to 100% respectively and L/D ratio 30.

Key words: torsional load, twist angle, percentage of allowable vertical load, pile group

تأثير الحمل العمودي المسموح به ونسبه طول الركيزه الى قطرها على سلوك مجموعة الركائز المتعرضه الى الالتواء

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الخلاصه

تتعرض بعض الهياكل مثل المباني العالية ، المنصات البحرية ، و الجسور، إلى أحمال جانبية بسبب الرياح ، الأمواج ، و ألآثار الناتجه عن اصطدام السفن بجسور ، أو المركبات عالية السرعة. ينتج عن ذالك انتقال أحمال كبيرة إلى مجموعة الركائز بحكم التحميل الجانبي. .يتضمن برنامج الفحص لهذه الدراسه مجموعة واحدة تتكون من 3 ركائز ، استخدمت أربعة نسب من الحمل العمودي المسموح به (0 ٪، 25 ٪ ، 50 ٪ ، و 100 ٪) مع نسبتان من طول الركيزه الى قطرها 20 و 30 ، (الحمل العمودي المسموح به 110 N عندما تكون نسبة طول الركيزه الى قطرها 20 و N 156 عندما تكون نسبة طول الركيزه الى قطرها 30)

النتائج التي تم الحصول عليها تشير إلى أن قابلية مقامة الالتواء لمجموعة الركائز تزيد مع زيادة نسبة الحمل العمودي المسموح به، فعندما كانت نسبة الحمل العمودي المسموح به 100 ٪ و نسبة طول الركيزه الى قطرها (20) زادت قابلية مقاومة الالتواء لمجموعة الركائز 42% إذا ما قورنت مع قابلية مقاومة الالتواء لنفس مجموعة الركائز عندما كانت نسبة الحمل العمودي المسموح به 0 ٪ لنفس نسبة طول الركيزه الى قطرها. أيضا زيادة نسبة طول الركيزه الى قطرها يؤدي إلى زيادة قابلية مقاومة الالتواء لمجموعة الركائز ، فعندما بلغت نسبة الحمل العمودي المسموح به 100 ٪ و نسبة طول الركيزه الى قطرها 30، زادت قابلية مقاومة الالتواء لمجموعة الركائز حوالي 51 ٪ إذا ما قورنت مع قابلية مقاومة الالتواء لنفس مجموعة الركائز عندما كانت نسبة طول الركيزه الى قطرها 20 لنفس نسبة الحمل العمودي المسموح به. وجد ان زاوية الالتواء لمجموعة الركائزعند الفشل هي 3° عندما كانت نسب التحميل العمودي المسموح به من 0٪ و 100٪ و نسبة طول الركيزه الى قطرها 20 ، بينما قلت من 2.9° الى 2.7° عند تغير نسبة الحمل العمودي المسموح به من 0٪ الى 100٪ و نسبة طول الركيزه الى قطرها 30 .

الكلمات الرئسية : قوة الالتواء، زاوية الالتواء، نسبة الحمل العمودي المسموح به، مجموعة الركائز

1. INTRODUCTION

Pile foundations of some structures, such as tall buildings, bridge piers, offshore platforms and electric transmission towers, can be subjected to significant torsional forces due to eccentric lateral loading from ship impacts, high-speed vehicles, wind and wave actions, and other sources of loading. Inadequate design of the piles against torsional loads may seriously affect the serviceability and safety of these structures with catastrophic consequences. The literature reported two cases of tall buildings in Miami and in Lubbock (Texas) which had suffered serious damage due to wind action and exhibited marked permanent deformations from torsion **Vickery, 1979**. Another case, described by **Barker and Puckett 1997**, reported the collapse of a support pier of the 6.82km long Sunshine Skyway Bridge in Florida caused by the eccentric impact of a bulk carrier. About 395m of the bridge fell into the sea, resulting in thirty-five deaths. Therefore, it is important that the strength and deformation characteristics of the foundation piles are properly addressed in design in order to ensure safety and cost-effectiveness.

2. MATERIALS

2.1 Model of Pile Groups

The models of pile groups used in this research study includes one group consists of 3 circular piles connected with Aluminum pile cap of (11.5×11.5×3) cm. The pile is modeled as Aluminum closed end tube and fixed head with (15 mm) outer diameter and (2mm) thickness. Two pile lengths were used (30, and 45 mm), the spacing between piles is 3d, see **Fig.1**. The determination of the mechanical behavior of the pile material used is very important. The sample was tested in accordance with the ASTM (2003) specifications. The results of the mechanical properties of aluminum tube used under tensile test are listed in **Table 1**.

2.2 Soil

A series of tests was performed on Karbala sand according to ASTM D 422-2001 procedures. In this study, the sand soil can be classified (SP-SM) according to the Unified Soil Classification System. The grain size distribution curves of sand are shown in Figures (2). The minimum and maximum unit weight of sand soil tested was determined according to ASTM D 4253-2000, The results of the maximum and minimum unit weights of sand soils are (17.64) kN/m^3 and (14.53) kN/m^3 respectively. The physical properties of the Karbala sand in the **Table 2**. The density of the sand soil used through the experiments was controlled by means of the raining technique. This technique includes raining the soil by different heights of drop that give different placing densities. Many investigators such as **Lee, et al., 1973** and **Sanjeev, 2007** used this technique. It was decided to employ unit weight (16.5) kN/m3 of sand soils, which corresponds to the height of drop of (50) cm. The relations between heights of drop, density, void ratio and relative density of sand soil shown in **Fig. 3.**

3. SETUP FORMULATION

Tests were carried out in a steel box with inside dimensions of (800) mm width (800) mm length and (800) mm height. The sides and bottom were made of (6) mm thickness plate. Front face of the box was includes get with dimensions (400) mm width and (400) mm length. The test box was placed over (1000) mm width and (2000) mm length of strong steel base, which was connected to a stiff frame of vertical hydraulic jack. Steel loading frame was manufactured to support the piston that is used for subjecting vertical load and insert the pile group in the soil. Steel loading frame consists of two beams in horizontal direction have (U-section) to allow the piston to move horizontally along the beam and two column in vertical direction have (square-section), at the sides of columns found holes that are used to help in controlling vertically the distance between the piston and the container surface. The soil is prepared in steel box by raining frame. This frame includes Two columns with changeable height were designed and manufactured to achieve any desired elevation. The change of the frame height is done by holes, from top and bottom. The column was connected with two valves to join 4 beams together. These beams are bolted at their ends. Two beams in the longitudinal direction have (U-section) and the other beams are used to support the U-section beams. Another beam was designed as a roller; it rests on the longitudinal beams to move along these beams. This (rolled-beam) is connected from the bottom with another beam, it is provided with screw and it can be horizontally moved along the beam; this beam was made to carry the cone that is used to pour the sand. This configuration of raining frame helps get a uniform density by controlling the height of fall. The rolled beam and the screw that connected with the cone ensure that each particle drops in equal height and uniform intensity.The torsional load applied by horizontal hydraulic jack, the horizontal hydraulic jack connected with steel plate contain many holes for applied load in any point, this plated support on the side edge of box, the load measured by load cell of 5 KN capacity. The corner and center displacement measured by two dial gauges (0.01) mm fixed on the middle and corner of the pile cap by two magnetic holders. **Fig. 4** and **Fig.5** show the general view of testing equipment.

4. TEST PROCEDURE

The steps followed for performing torsion test on model pile group are summarized as follows:

1. Soil Preparation:
    a) Prepare the soil by raining technique at the chosen density and the corresponding relative density (RD=70% for dense state),
    b) Level the sand surface at final depth when the raining is completed, the level of sand layers is checked by leveling tool,

2. Pile Group Installation:
    a) Fix the pile group in the head of vertical hydraulic jack,
    b) The group are instilled in sand by pre jacking method,

3. Testing preparation:
   a) Support the allowable vertical load (if any) on the pile group,
   b) Fit the dial gages in the horizontal direction at the corner, at the middle of the pile cap while at the vertical direction in the right and left side of the pile cap
   c) Fit the load cell with the horizontal jack and connect it with the digital indicator,
   d) Fix the horizontal jack in the upper edge of the right side of the container to be ready to subject the torsion load on the pile cap.

4. Testing:
   a) Now apply the torsion and record the readings of all the dial gages used,
   b) At the end of the test, remove all the dial gages, load cell, horizontal jack, allowable vertical load, pile group, and open the gate for removing the sand to prepare the model for another test; and

5. Repeat all the above steps in the next test.

6. Criteria of Failure

Many references indicate some of the recognized criteria for defining failure loads of piles under compressive loads or lateral loads, but no criteria were found in literature to define the failure load of torsionally loaded pile or pile group. Therefore we depend on the criteria of failure for lateral loads to determine the failure of pile group subjected to torsional load. Some of the failure criteria of laterally load pile are stated as follows:
Mc Nulty, 1956 stated that the pile head deflection under the effect of lateral load depends on the soil characteristics and the size of the pile, the suggested allowable design load was taken as the load required to produce ¼ inch (6.35 mm) deflection divided by a factor of safety of 3.

Hopkins, 1956, considerd the allowable deflection for laterally loaded pile can be assumed as only 1/16 inch (1.6 mm).

Bowles, 1988, stated that the most lateral piles were usually designed for lateral displacement on the order of 6 to 10 mm at the ground line.

Rahman and Chowdhury, 2003, stated that the load displacement curves were non- linear. Lateral failure occurred at a pile head displacement from 4 to 8 mm (0.2D to 0.4D) for L/D ratio 20. However, for L/D ratio 30, the lateral failure occurred at a pile head displacement of 6 to 10 mm (0.3D to 0.5D).

In practice, of course, the pile will fail at some stage, normally by the formation of a plastic hinge at some point down the pile. Lateral movement of the pile to cause such failure to be generally in excess of 10% of the pile diameter, **Fleming and Randolph, 2009**.

Therefore to analyze the results of the present work, a load required to produce a horizontal displacement in the corner of the pile cap of pile group 0.3D (D=15mm) is considered as failure load.

5. RESULTS AND ANALYSIS

5.1 Effect of Applied Allowable Vertical Load on the Behavior of Pile Group Subjected to Torsion.

Fig. 6 and **7** show the effect of increase in the percentages of allowable vertical load on the variation of the torsion load with displacement (that has measured at corner of the pile cap) and twist angle for pile group PG3, when L/D ratio was 20, four percentages for the allowable vertical load (0%, 25%, 50%, and 100%) were used. The torsional capacity for the pile group increases when the percentage of allowable vertical load increases due to increase in vertical stress (σ_v) that leads to increase the frictional resistance of pile group and subsequently increase the lateral and torsional resistance of pile group correspondingly. At failure (0.3D) when the percentage of allowable vertical load is 100%, the torsional capacity increases about 42% if compared with 0% percentage for the allowable vertical load, and the twist angle at failure is unchanged (3º) if the percentage of allowable vertical load changes from 0% to 100%.

Fig. 8 and **9** illustrate the torque developed (Torsion Load ×0.0575m where 0.0575m is the distance from corner to center of pile cap) in pile group with displacement at corner and twist angle at different percentages of allowable vertical load.

Fig. 10 shows the effect of percentages of allowable vertical load on the torque capacity at failure for pile group when L/D ratio is 20.

Also **Fig. 11**and **12** show the variation of the torsion load and torque (Torsion Load×0.0575m) with displacement in corner and twist angle of pile group due to the increase in the percentage of allowable vertical load. Four percentages of allowable vertical load were used (0%, 25%, 50%, and 100%) and L/D ratio is 30. The torsional capacity for pile group increases with the increase in the percentage of allowable vertical load due to the increase in frictional resistance of pile group. In this case, at failure (0.3D) the torsional capacity when the percentage of allowable vertical load is 100% increases about (70%) if compared with percentage of allowable vertical load of 0%, also the twist angle when the percentage of allowable vertical load is 100% is (2.7°) while it is (2.9°) when the percentage of allowable vertical load is 0%.

Fig. 13 shows the effect of the percentages of allowable vertical load on the failur torsion load and failure torque of pile group when L/D ratio is (30).

5.2 Effect of L/D Ratio on the Behavior of Pile Group Subjected to Torsion

Increasing L/D ratio for piles in the pile group PG3 leads to increasing the vertical stress (σ_v) and frictional resistance for pile group, therefore the torsional capacity increases. **Figs. 14** and **15** show the effect of L/D ratio on the variation of torsion load with displacement at corner and twist angle of pile group when the percentages of allowable vertical load (0% and 100%). At failure (0.3D), when the percentage for allowable vertical load 0% the torsional resistance for L/D ratio (30) is 1.51 times that of the L/D ratio (20), also when the percentage for allowable vertical load 100% the torsional resistance for L/D ratio (30) is 1.78 times that of the L/D ratio (20). The twist angle when the percentage of allowable vertical load 0% is (3°) for L/D ratio is (20) and (2.9°) for L/D ratio (30), and when percentage of allowable vertical load 100% is (3°) for L/D 20 and (2.7°) for L/D ratio

(30), this means the increase in L/D ratio leads to increase the torsional capacity and rigidity of the pile group.

6. CONCLUSIONS

1. The torsional capacity of pile group increases when increasing the percentage of allowable vertical load.
2. The increase in number of piles and L/D ratio leads to increase the torsional capacity of pile group.
3. For all tests the maximum twist angle at failure is 3º for pile group PG3 when L/D ratio is (20) and the percentages of allowable vertical load are 0% and 100%,
4. The torque decreases when the torsion load approaches from center of pile cap and increases when the torsion load goes away from center of the pile cap

7. REFERENCES

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8. NOMENCLATURE

C_c : coefficient of curvature

C_u : coefficient of uniformity

D_{10} : diameter of particle when percentage of passing is10%

D_{30}: diameter of particle when percentage of passing is 30%

D_{50}: mean grain size

D_{60}: diameter of particle when percentage of passing is 60%

Gs : specific gravity

L/D: length of pile / diameter of pile

PG3: pile group which consists of 3 piles

RD: relative density, %

σ_v : vertical stress

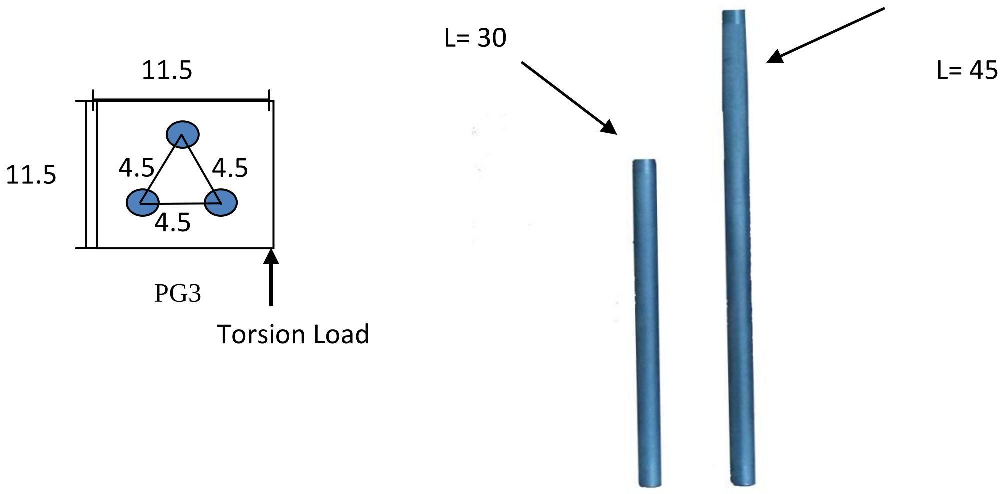


Figure 1. Pile groups pattern and piles of different lengths (all dimensions in cm).

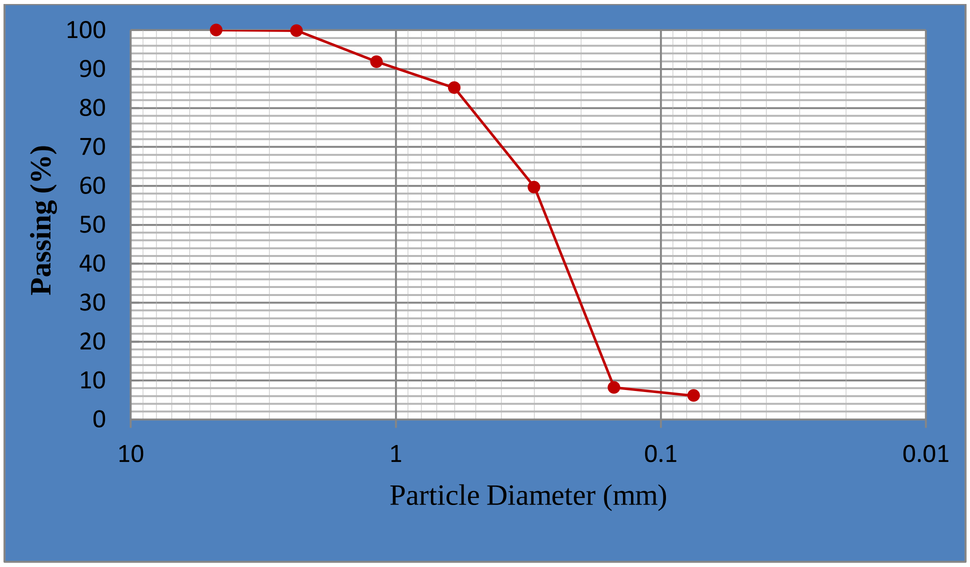


Figure 2. Grain size distribution curves of sand soil.

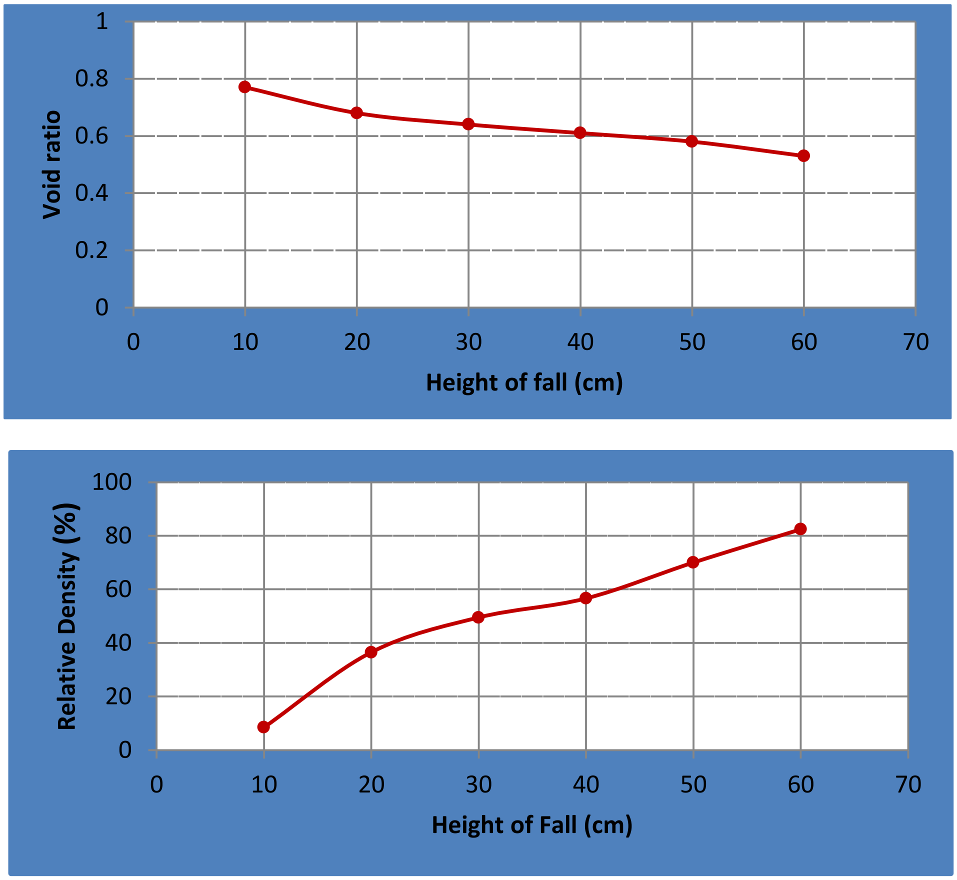


Figure 3. Relative density, and void ratio vs. height of fall relationship.

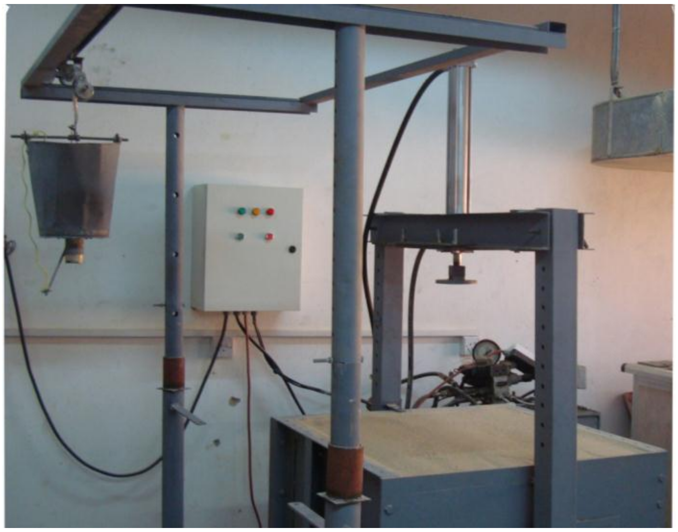


Figure 4. General view of testing equipment.

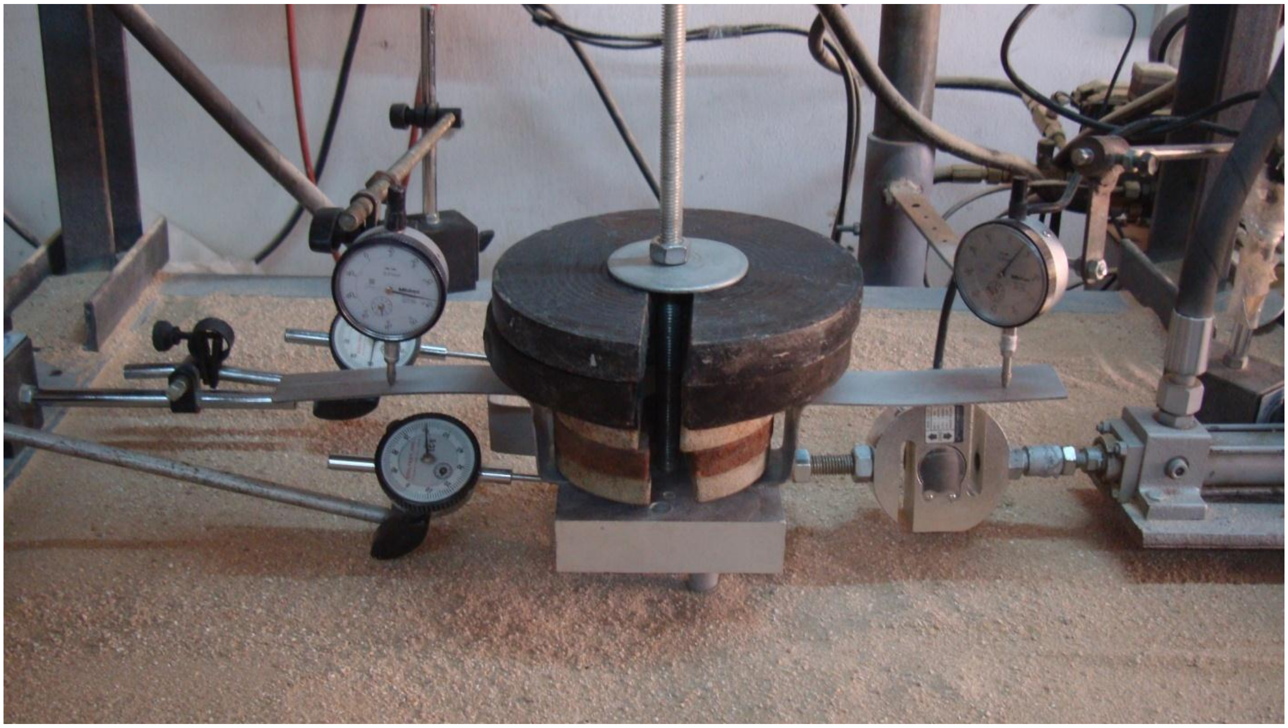


Figure 5. Pile group subjected to torsion load with allowable vertical load.

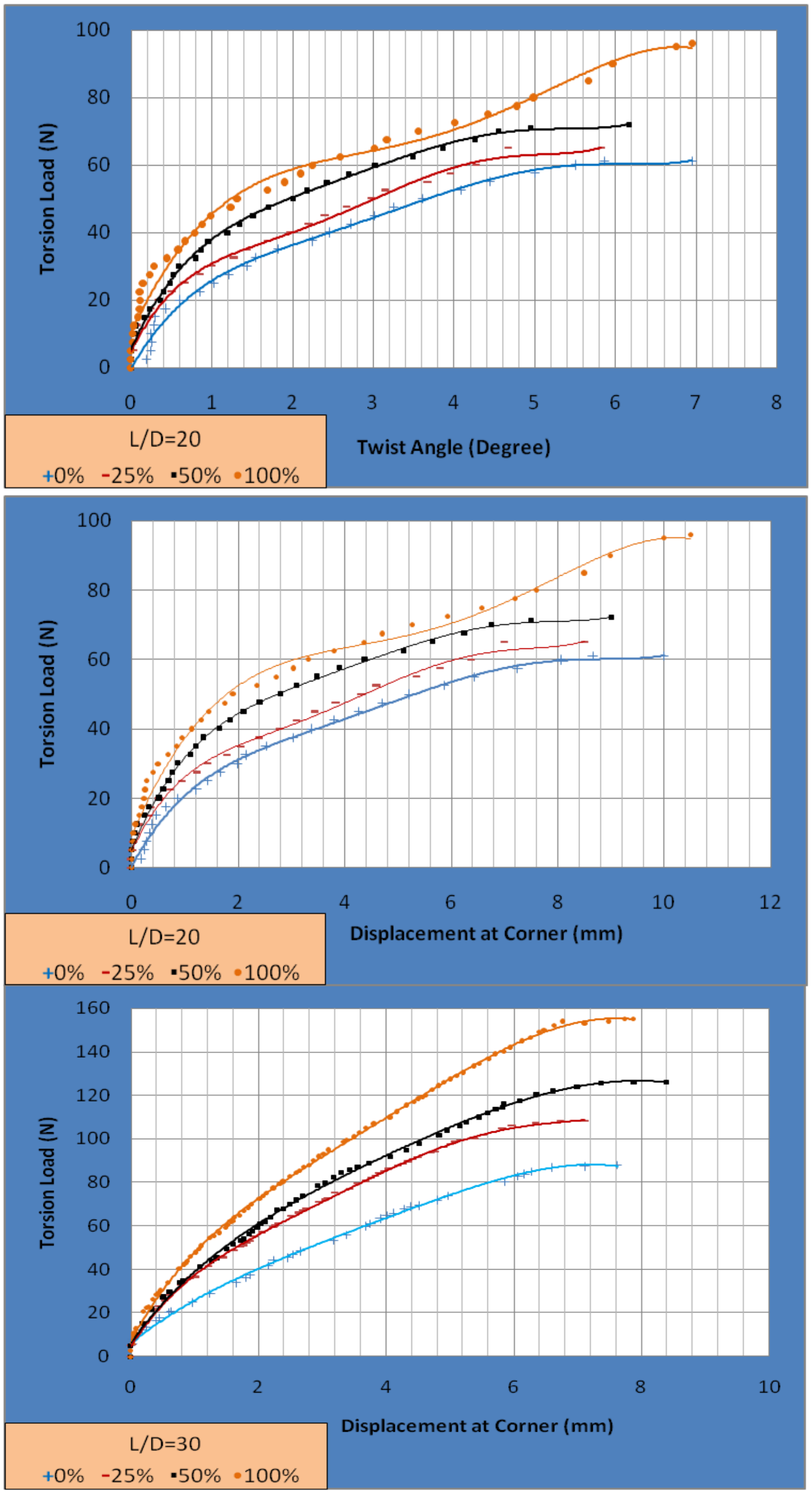


Figure 6. Effect of percentages of allowable vertical load on variation of torsion load with displacement at corner of pile group when L/D ratio is (20).

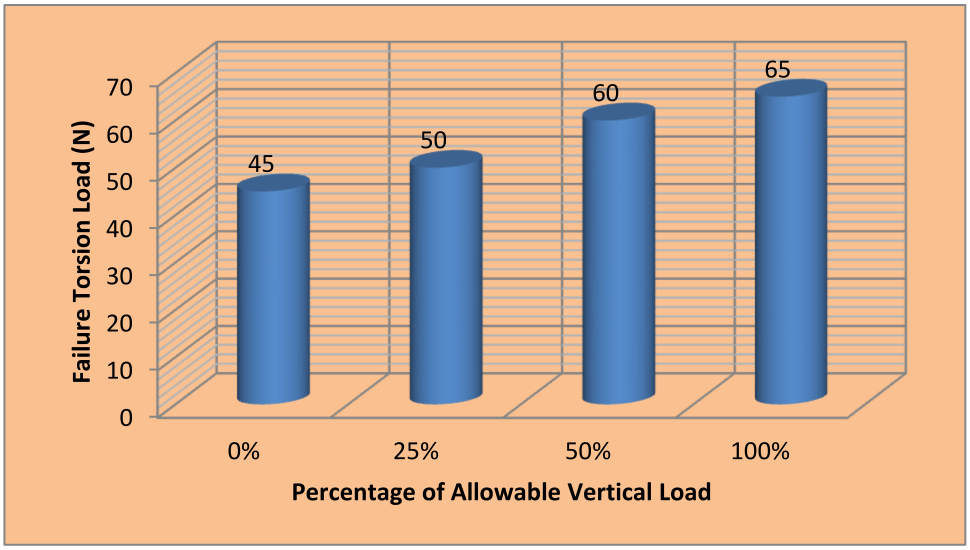


Figure 7. Effect of percentage of allowable vertical load on torsion capacity at failure of pile group when L/D ratio is (20).

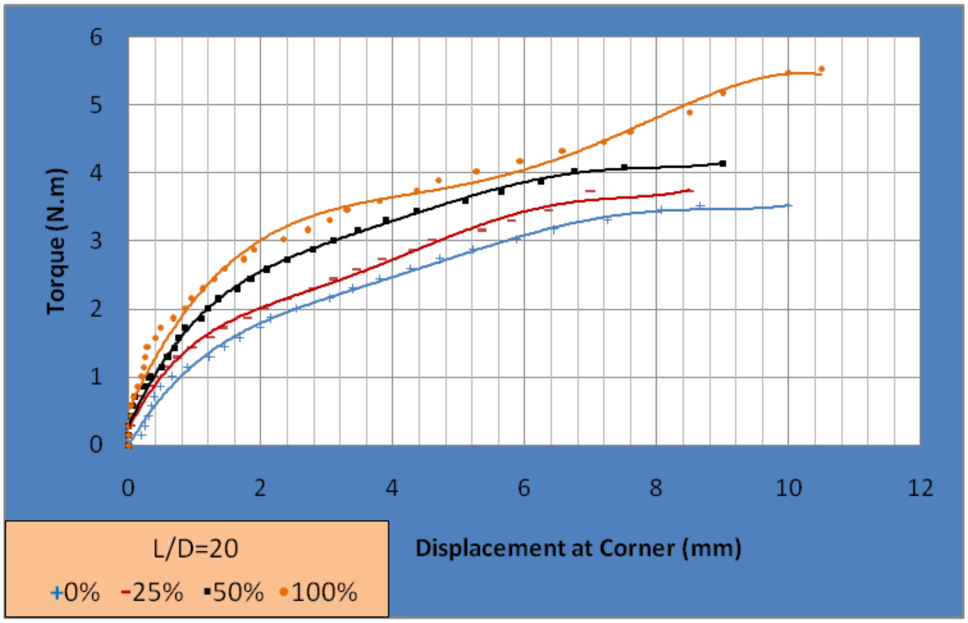


Figure 8. Effect of percentages of allowable vertical load on variation of torque with displacement at corner of pile group when L/D ratio is (20).

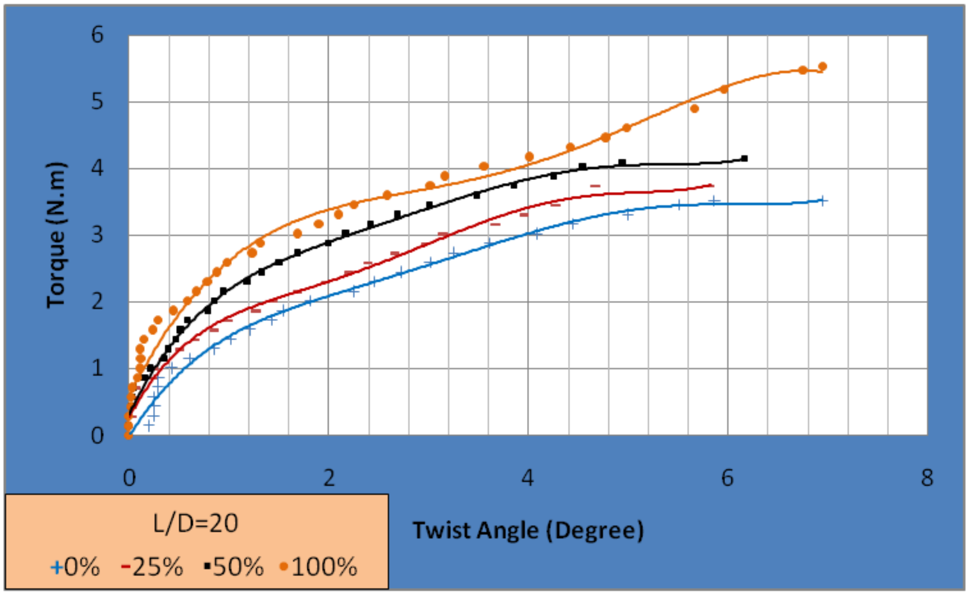


Figure 9. Effect of percentages of allowable vertical load on variation of torque with twist angle of pile group when L/D ratio is (20).

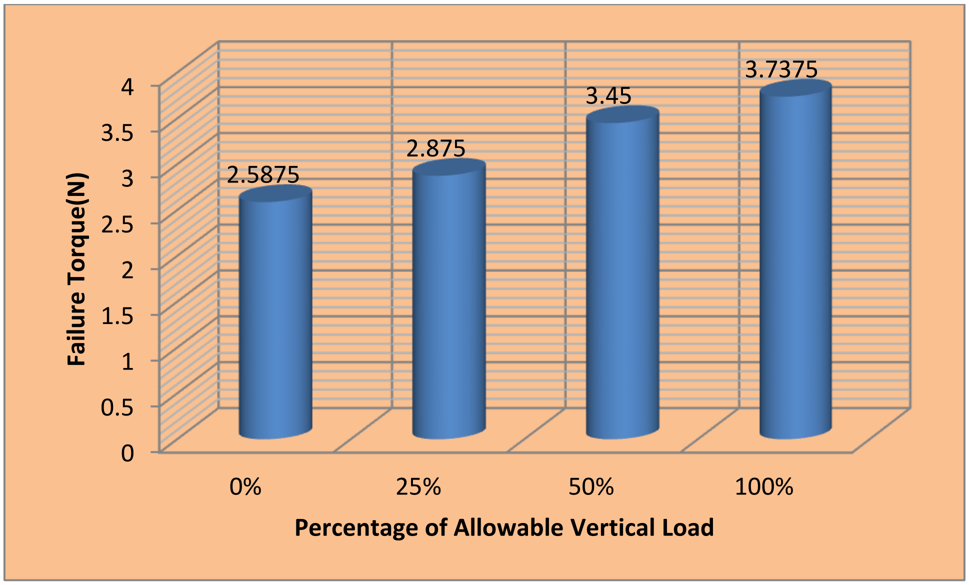


Figure 10. Effect of percentages of allowable vertical load on torque capacity at failure of pile group when L/D ratio is (20).

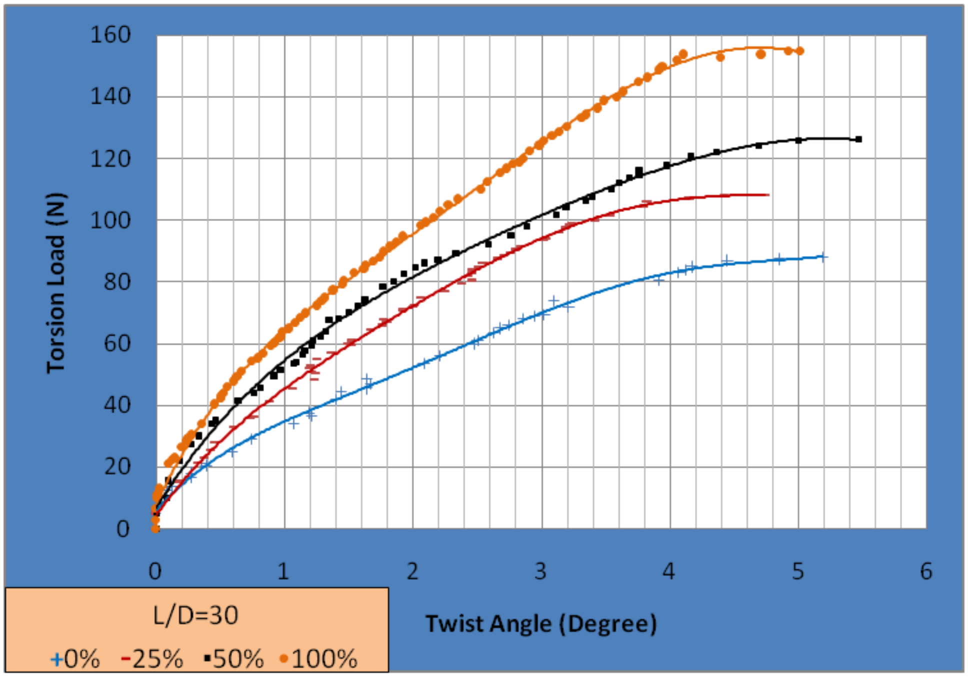


Figure 11. Effect of percentages of allowable vertical load on variation of torsion load with displacement at corner and twist angle of pile group when L/D ratio is (30).

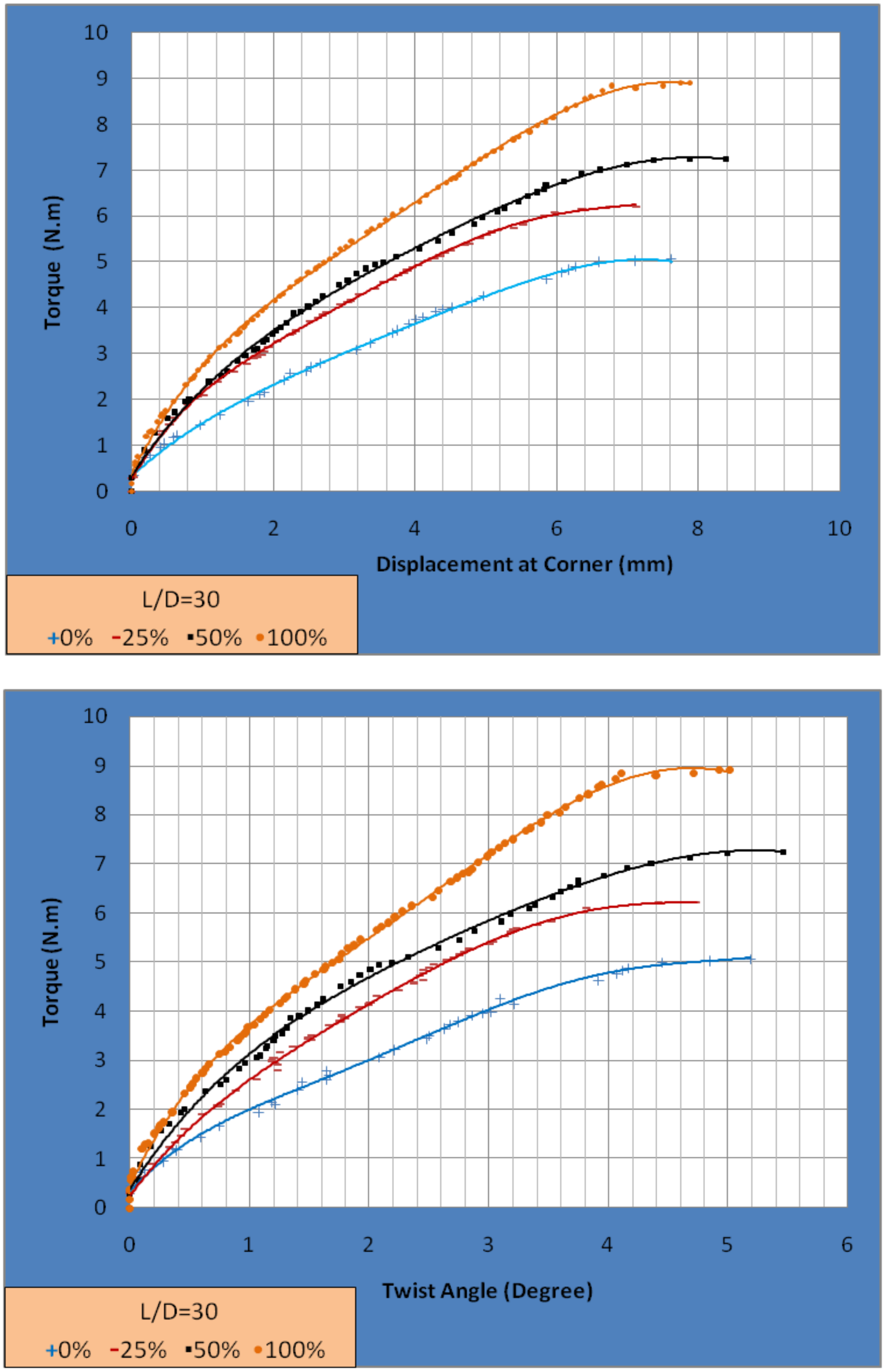
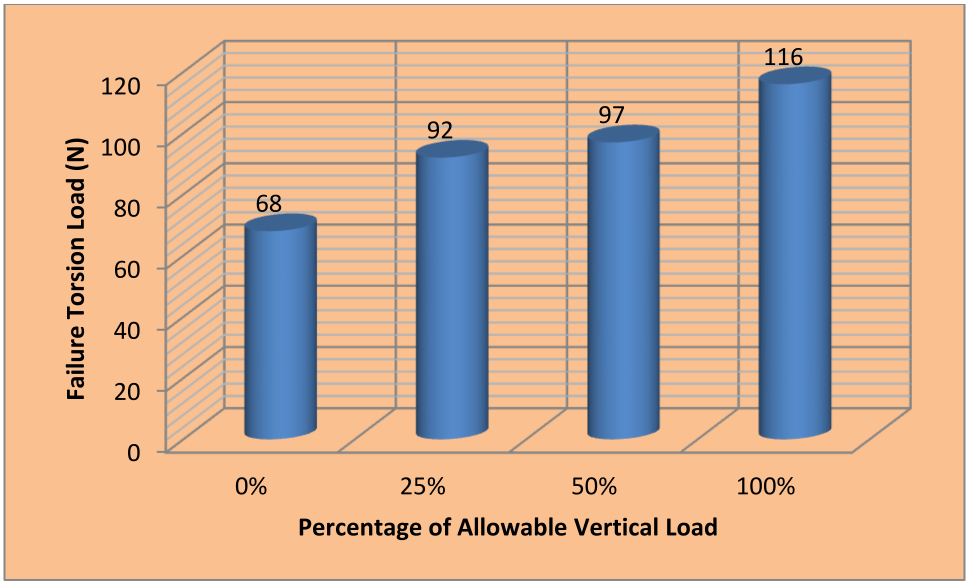


Figure 12. Effect of percentages of allowable vertical load on variation of torqe with displacement at corner and twist angle of pile group when L/D ratio is (30).



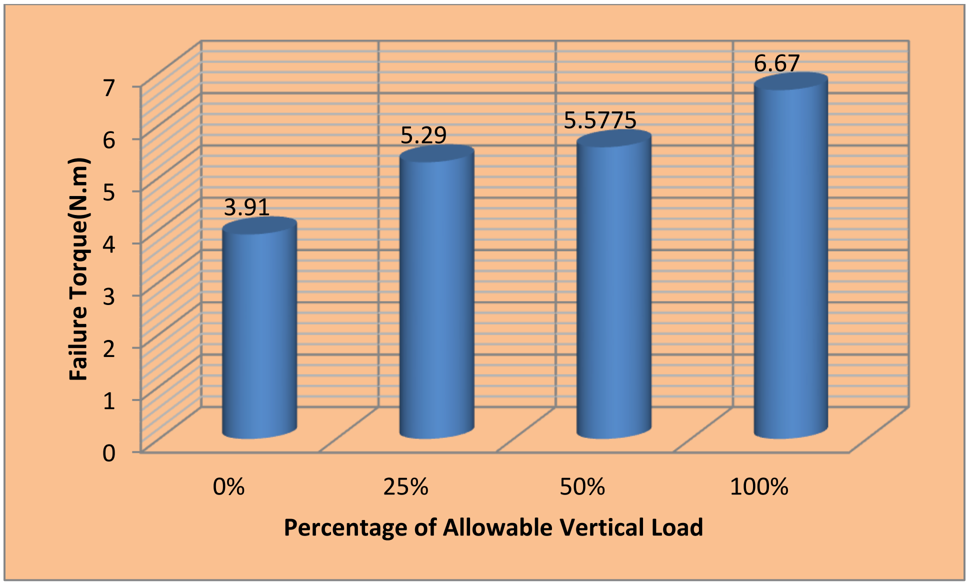


Figure 13. Effect of percentages of allowable vertical load on failure torsion load and failure torque of pile group when L/D ratio is (30).

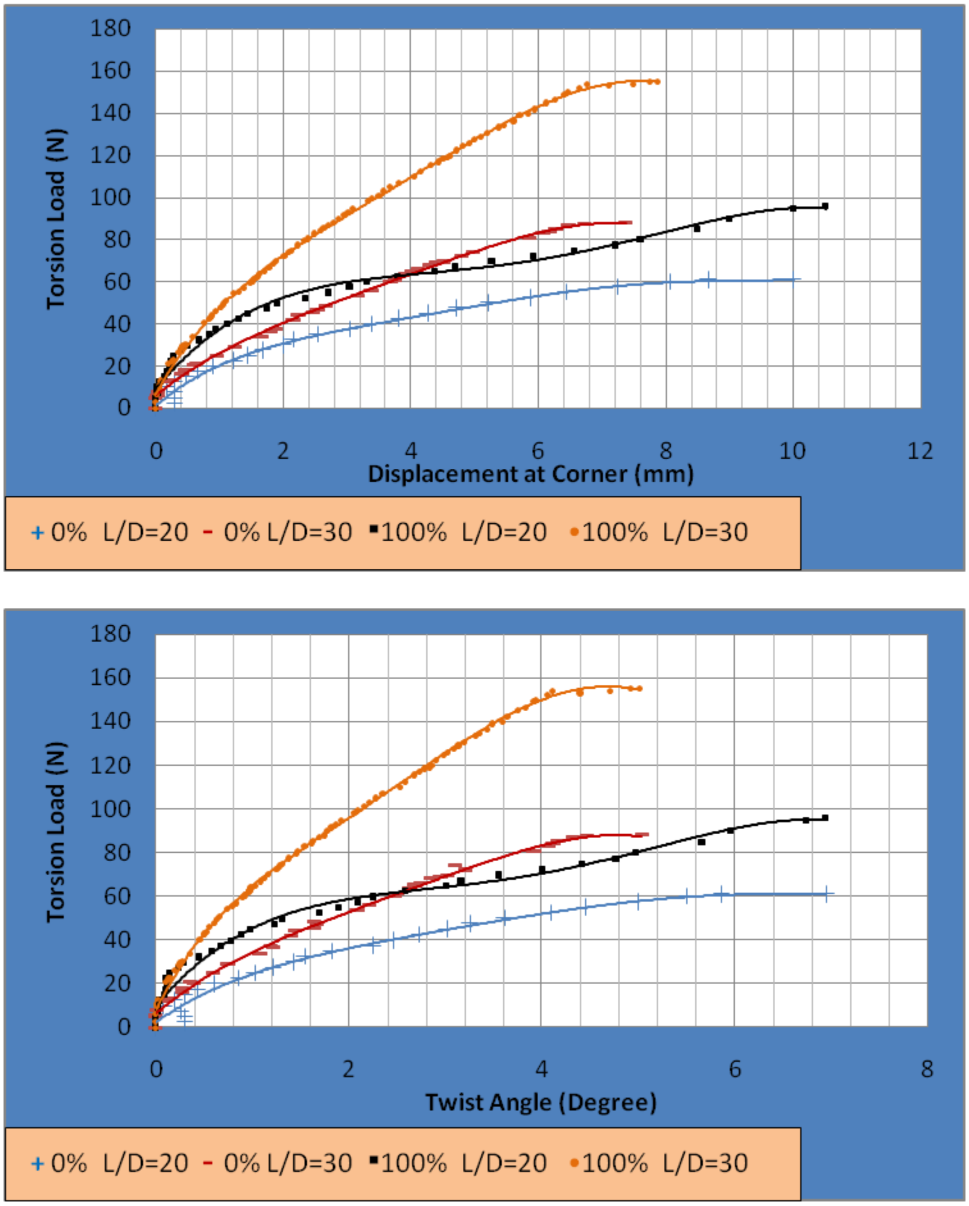


Figure 14. Effect of L/D ratio on the variation of torsion load with displacement at corner and angle of pile group when the percentages of allowable vertical load are (0% and 100%).

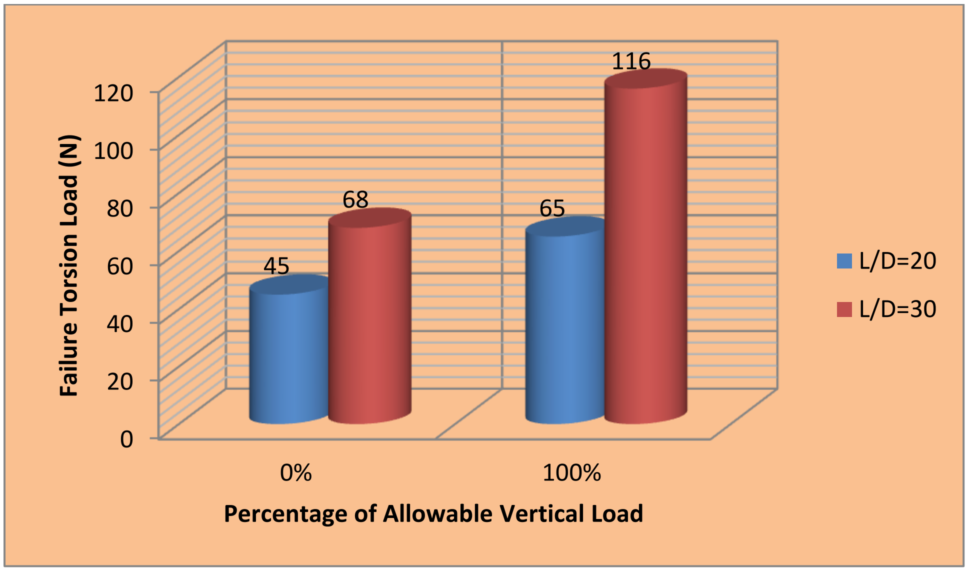


Figure 15. Effect of L/D ratio on the failure torsion load of pile group when the percentages for vertical allowable load are (0% and 100%).

Table 1. Mechanical properties of aluminum tube.

Properties	**Yield Strength Fy (N/mm^2)**	**Tensile Strength Fu (N/mm^2)**	**Poisson's Ratio ν**
Value	150	212	0.3

Table 2. Soil properties.

Index Properties	**Values**
Specific Gravity (Gs)	2.61
D_{10} (mm)	0.17
D_{30} (mm)	0.2
D_{50} (mm)	0.27
D_{60} (mm)	0.3
Coefficient of uniformity (Cu)	1.76
Coefficient of curvature (Cc)	0.784
Maximum dry unit weight (kN/m^3)	17.64
Minimum dry unit weight (kN/m^3)	14.53
Maximum void ratio	0.79
Minimum void ratio	0.47
Dry unit weight at testing (KN/m^3)	16.5
Angle of internal fraction	43^o
Soil classification (USCS)	SP-SM