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Optimal distribution of piles under a concrete bridge abutment subject to vertical and torsion loads

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Abstract. The transmission of torsional load from the bridge abutment to the pile foundation has a great influence on the behavior of piles The situation is worsened by the combined loading on the outriggers, such as torsion, vertical, and lateral loads. This study focuses on the importance of distributing the piles under bridge abutment subjected to torsion loads in addition to vertical loads, where a suitable distribution is found to provide better behavior of the piles. Four groups of piles were taken under the bridge abutment, each containing six piles with different distributions. Torsional and vertical loads were applied to the bridge abutment to ensure the transfer of loads with a realistic effect. ABAQUS software was used for the simulation after the experimental work. The results of different pile distributions were very from the design point of view, as it was found that the distribution of the piles under the bridge abutment must be in a multi-line shape (rectangular distribution of the piles), because it forms a rigid mass with the surrounding soil, which is able to withstand torsional loads. In addition, it is preferable to avoid using single-distributed piles, since their response is very high and the failure occurs faster than in other groups.

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1. Introduction

Numerous studies have investigated group piles under lateral, vertical, torsion, and combined loading conditions in recent years [1–6].

In [7], a model consisting of pile groups was used represented by a flexible beam-column elements with soil represented by an elastic linear spring to study the torsion behavior that occurred in the pile heads as a result of applying simultaneously horizontal and torsion loads on the group of piles. The study proved that uneven shear force distribution is important in pile design.

In [8], an analytical method to study the behavior of the pile group was developed, by coupling torsional resistances with lateral force. The approach involved analyzing piles under multidirectional lateral loads to compute induced torsion, followed by evaluation of horizontal load effects, ultimately combining these interactions for both single piles and pile groups consisting of 2×2 and 3×3 piles. This research provided key insights into torsion angles under random horizontal loading and the influence of pile spacing on torsional stiffness.

In [9], a finite element model was used to study the nonlinear behavior of groups of piles subjected to torsion loads. Groups of 1×2, 2×2, and 3×3 piles embedded in sandy soil were subjected to buckling and bending. The study assumed linear pile behavior and non-linear soil response. The results showed that the torsional strength increased with the increase in the pile size, spacing, length, and the soil stiffness, while the pile cap contributed 7 % of the total head resistance.

The present study analyzes the behavior of concrete bridge abutment subjected to vertical and torsion loads transmitted to the concrete piles. The change in the distribution of the piles under the bridge abutment will be studied to identify optimal configuration for the best structural behavior.

2. Methods

2.1. Problem

Bridge abutments are important structural elements that bear the loads from the bridge deck. They are subjected to vertical, lateral, and torsion loads that are transmitted directly to the piles through the pile cap. A bridge abutment (Fig. 1) located on the Khawr az-Zubayr Waterway in Basra governorate was analyzed, and the static and dynamic loads from the bridge deck were calculated and transferred directly to the abutment. A hypothetical dynamic torsion load was applied to the bridge abutment to simulate torsional loads on the abutment.

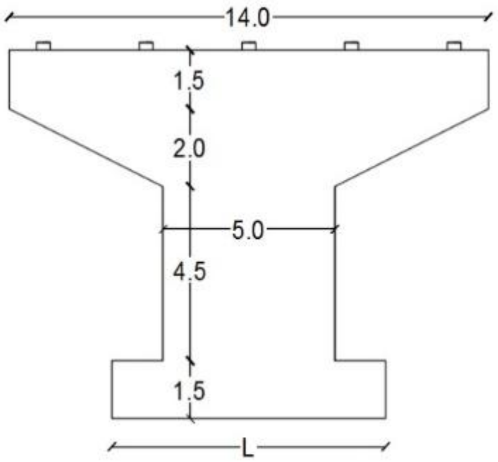

Figure 1. Bridge abutment dimensions.

For the pile distribution (Fig. 2), four groups were considered, each containing six piles with the same diameter of 80 cm and length of 20 m, but with different configurations:

- the first group was arranged with one line;
- the second was arranged with two lines;
- the third had a random distribution;
- the fourth had a circular distribution.

All the piles were connected with a pile cap, whose dimensions depended on the distribution of piles.

Soil is another critical factor influencing the behavior of the piles. The site soil was characterized as sandy clay soil, and the piles were submerged in it.

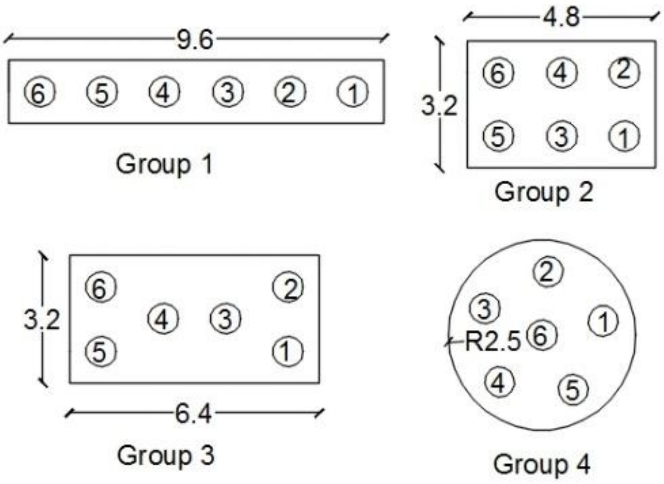

Figure 2. Pile distribution in groups under bridge abutment.

2.2. Modeling of the Problem

ABAQUS software was used for the simulation after the experimental work.

Element selection

Reinforced concrete abutments and piles were represented by a 20-node quadratic brick element C3D20, which is a three-dimensional non-linear element consisting of 20 nodes. While the soil was represented by a 20-node quadratic brick porous element C3D20P to accurately model soil plasticity and consolidation under loading. Reinforced bars were represented by a three-dimensional elastic beam element B32 consisting of three nodes, assumed to be embedded in the concrete. Fig. 3 shows the modeling in the ABACUS software of the problem for four case studies, including bridge abutments and soil [10–13].

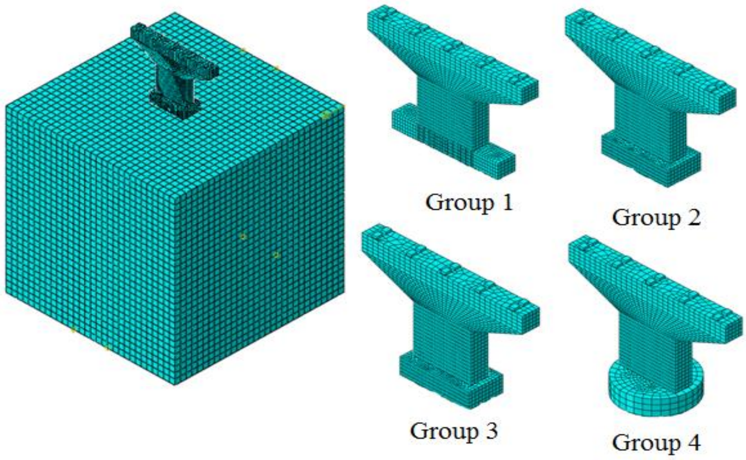

Figure 3. Finite element modeling of abutments and soil for all the four case studies.

Material properties

The material behavior reflects the actual distortions that occur in the material. For example, the Concrete Damage Plasticity (CDP) model was used to represent the concrete behavior (bridge abutment and piles), while the Mohr–Coulomb model was used to represent soil plasticity and deformations (Table 1). The plastic material was used for the steel with a yield strength of 420 MPa, zero plastic strain, an elastic modulus of 210 GPa and Poisson's ratio of 0.3 [14–16].

Table 1. Material Properties [15].

Concrete				
Dilation angle	**Eccentricity**	**fb0/fc0 ratio**	**Stress invariant ratio *k***	**Viscosity parameter μ**
35	0.1	1.16	0.667	0
Elastic modulus, GPa		23.5	Poisson's ratio	0.2
Density, kg/m^3		2400		
Soil				
Elastic modulus, GPa		14	Poisson's ratio	0.4
Density, kg/m^3		1600		
Cohesion		30	Friction angle, degrees	40

Boundary conditions

A surface-to-surface interaction was defined between piles and soil, a penalty friction coefficient was adopted equal to 0.36, and all reinforced steel was represented by an embedded element in the concrete. As for the soil boundaries, it was fully fixed at the bottom, and pinned at the sides according to the movement direction. The distance from the pile cap to the soil edge was approximately 8 times the pile width [17, 20].

Loading and analysis

Vertical loads were calculated from the dead loads (bridge self-weight and additional permanent loads) and live loads (vehicle traffic). Torsion load was simulated using two equal and opposite forces. A dynamic analysis was performed to obtain realistic structural responses [21-24].

Verification in the ABAQUS software

The validation, based on [25], involved a 2×2 pile group embedded in loose sandy soil (Fig. 4). The piles consisted of aluminum tubes (diameter = 15.74 mm, thickness = 0.9 mm, length = 300 mm), with a 30 mm-thick aluminum alloy pile cap. ABAQUS simulation results for horizontal displacement vs. shear force (Fig. 5) and torque vs. twist angle (Fig. 6) at the pile head showed good agreement with experimental data [25]

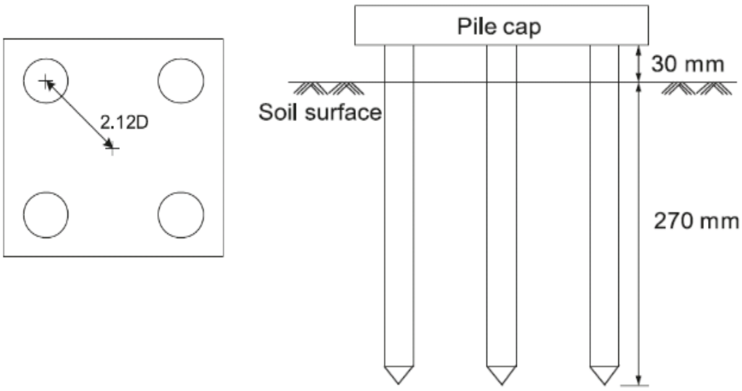

Figure 4. Pile group details for experimental work [20].

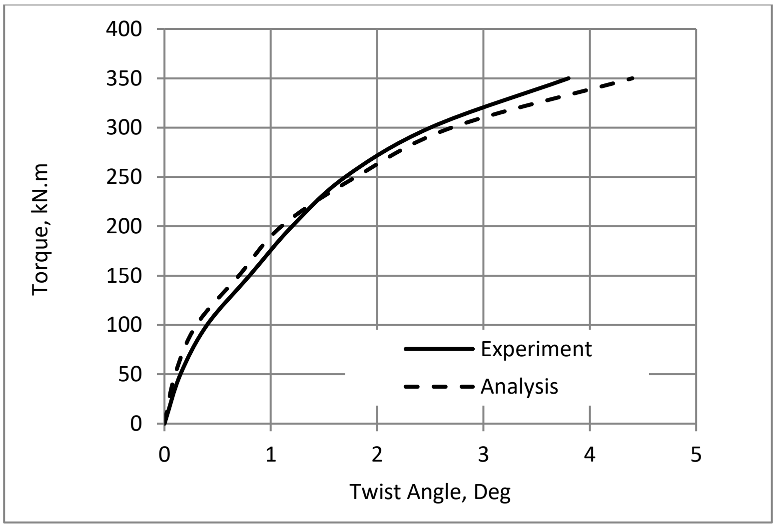

Figure 5. Shear force vs. displacement for experiment and analysis verification.

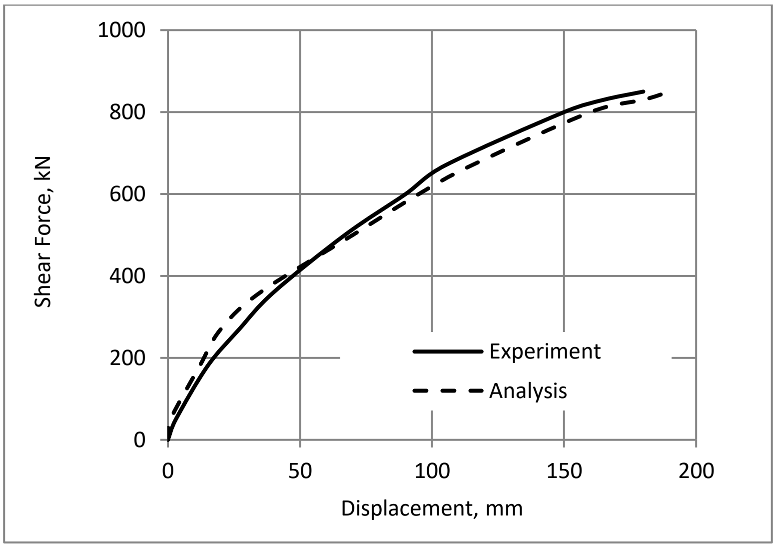

Figure 6. Torque vs. twist angle for experiment and analysis verification.

3. Results and Discussion

3.1. Load – vertical displacement

Fig. 7 shows the relationship between the load and the vertical displacement in the pile cap for the four groups. It can be observed that Group 1 exhibited the highest response, while Group 2 showed the lowest response. This is due to the distribution pattern of the piles. Despite having equal surface areas, Group 1 showed higher stiffness along the long side of the cap compared to the other groups, which makes the greater response. Groups 3 and 4 were characterized by a large surface area but demonstrated lower stiffness compared to Group 1. When changing the distribution of the piles from Group 1 to the other groups, the load capacity was reduced by 60, 27, and 22 %, respectively.

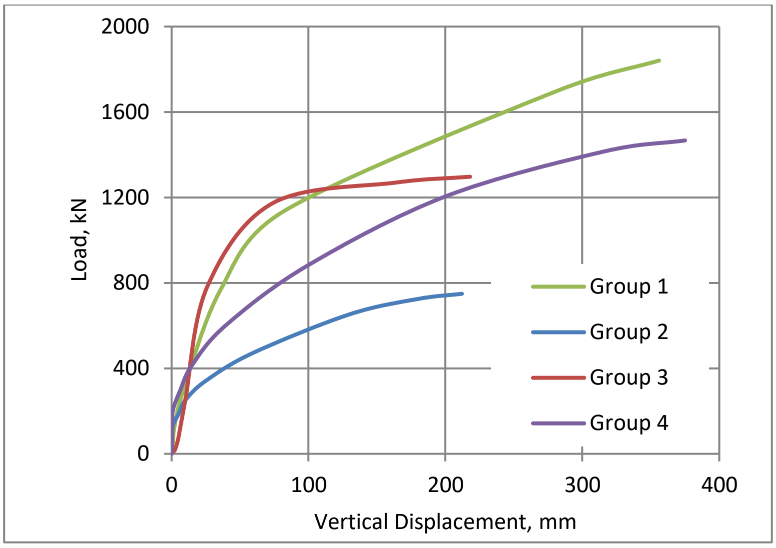

Figure 7. Load–vertical displacement for all the four pile groups.

3.2. Torsion vs. twist angle

Although Group 1 exhibits strong stiffness in the longitudinal direction, which gave the highest endurance of the forces, it showed the lowest results for torsion vs. twist angle due to the weakness in the transverse direction. The other groups, especially Group 3, demonstrated excellent endurance because of the high stiffness in the longitudinal and transverse directions, with the amount of torsion increased by 66 %. And Group 4 demonstrated a 15 % increase in torsional capacity. Group 2 exhibited excellent torsional behavior with high stiffness but with an increase in the moments, the twist angle became minimal, due to the near equal stiffness in both directions. Fig. 8 show the torsion and Twist angle relation for the groups.

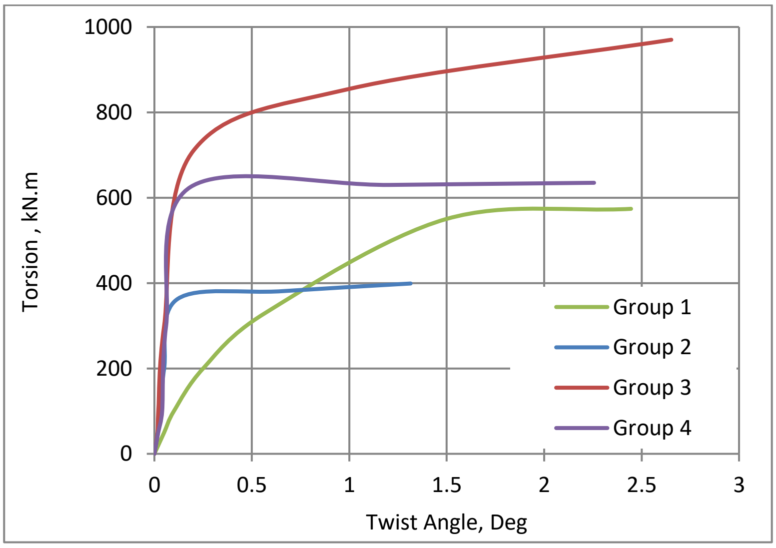

Figure 8. Torsion vs. twist angle for all the four pile groups.

3.3. Displacement along pile length

Fig. 9 shows the lateral displacement along the piles. The displacement distribution depends on the location of the pile and the amount of lateral load applied to it. In Group 1, displacements at the pile head ranged from 25 mm in the outriggers far from the load (P1) to 150 mm in the piles close to the load (P2), representing the highest lateral displacements. Group 2 had the lowest lateral displacement of 30 mm for almost all the piles due to the proximity of the piles to each other, making it work as a single block. The load was applied almost equally on all the piles. In Group 3, the displacement distribution varied in the pile head: some of the nearby piles (in the middle, P3) had high displacement of 75 mm, while the other (P4) – 70 mm, and the side piles ranged between 45 and 60 mm due to the position of the load. In Group 4, the results of the displacements in the pile head varied from 40 to 50 mm due to the distribution of the piles symmetrically and closely under the load. The ratio of the pile fixed depth varied from 15 to 17 m due to the torsion occurring in the groups.

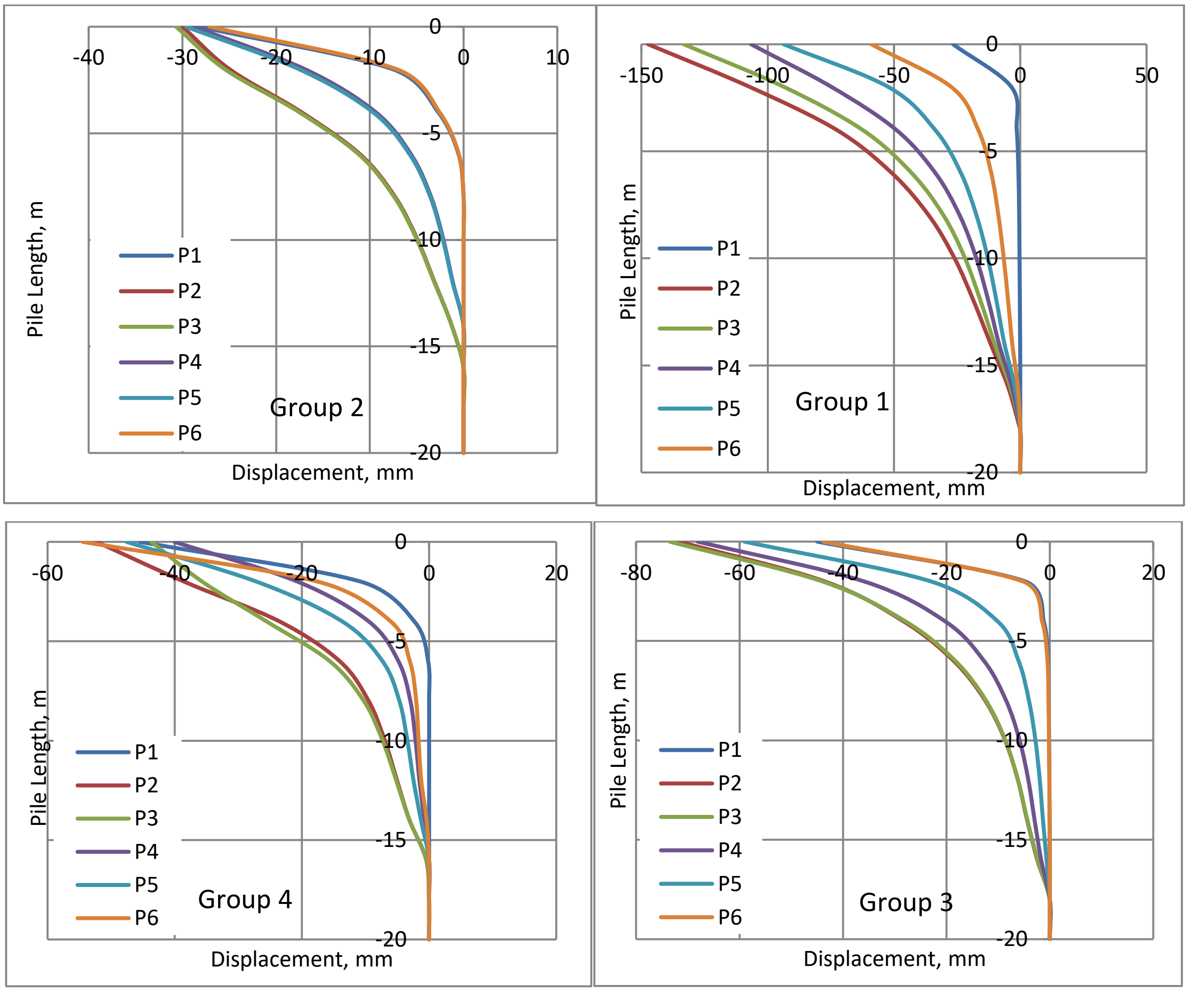

Figure 9. Lateral displacement along pile length for all the four pile groups.

3.4. Twist angle along pile length

Group 2 also had the lowest response in case of the deflection angle (Fig. 10) due to the proximity location of the piles to each other, where the maximum twist angle was 1.3°, significantly smaller than the other groups. Group 4 had similarly small twist angle of 2.1° due to the distribution of the piles close to each other. Groups 1 and 3 had almost the same maximum twist angle of 2.5°, because the bridge abutment is directly supported by these piles. All the twist angles disappear (become zero) at a depth of 14 m, and this is a good indicator that corresponds to the fixed pile depth.

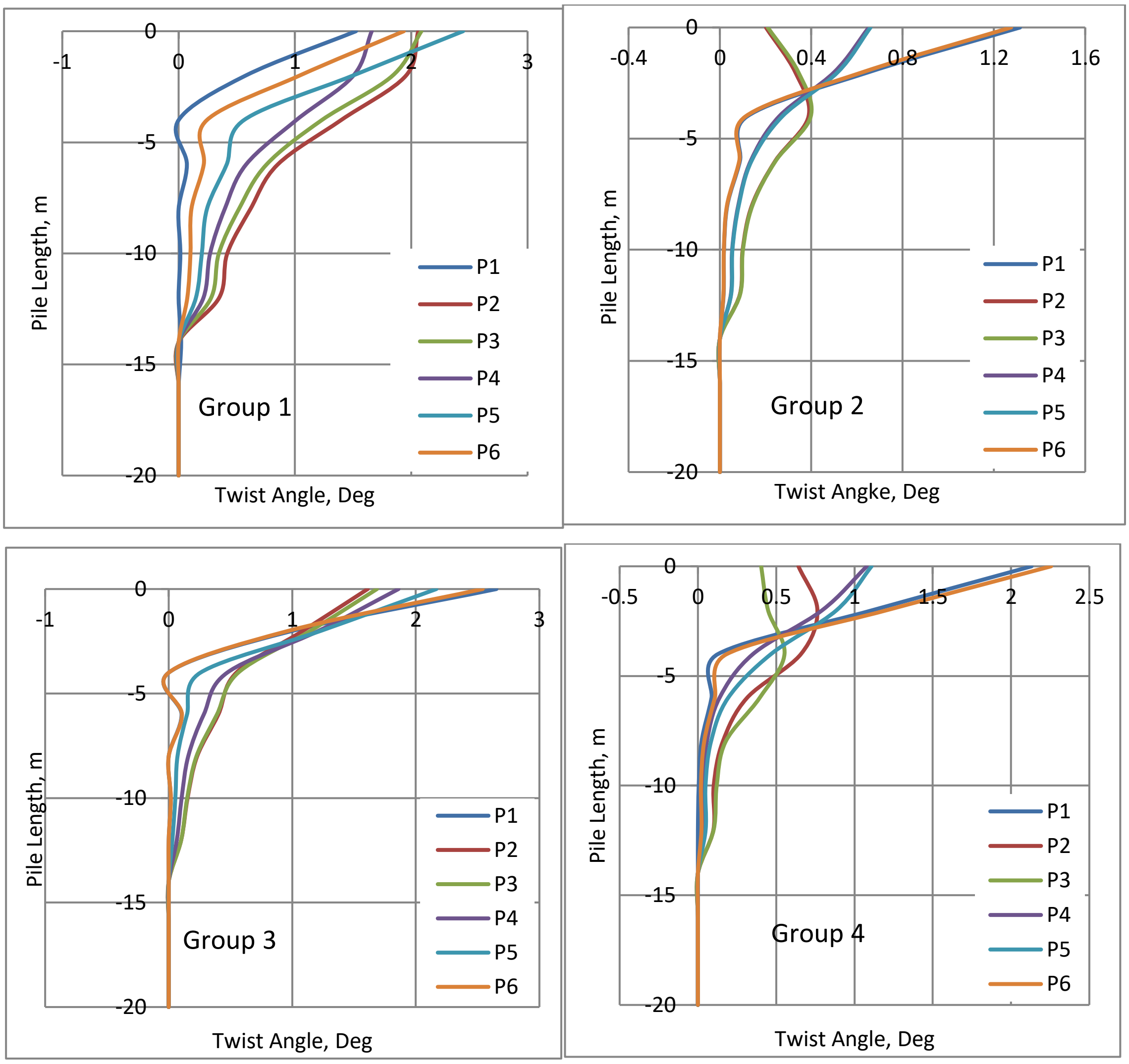

Figure 10. Twist angle along pile length for all the four pile groups.

3.5. Shear force along pile length

Shear forces distributed on the pile head are very important, with lower shear forces indicating greater stability. Fig. 11 shows the distribution of piles for the four pile groups. Group 2 had the lowest shear forces (600 kN) on the pile head among the other groups, while Group 1 had the highest shear forces (1900 kN). Groups 1 and 3 differed in the distribution of shear forces on the pile head, but Groups 2 and 4 had almost equal shear forces at the pile head, because the distribution of the piles was close to each other and the distribution of loads was equal. The inflection point of the shear forces (Fig. 11) at a depth of 1 m was the result of the strong resistance of the soil to the applied loads. The forces reduced to zero at a depth of 7.5 m, indicating that all force was transferred from piles to the soil.

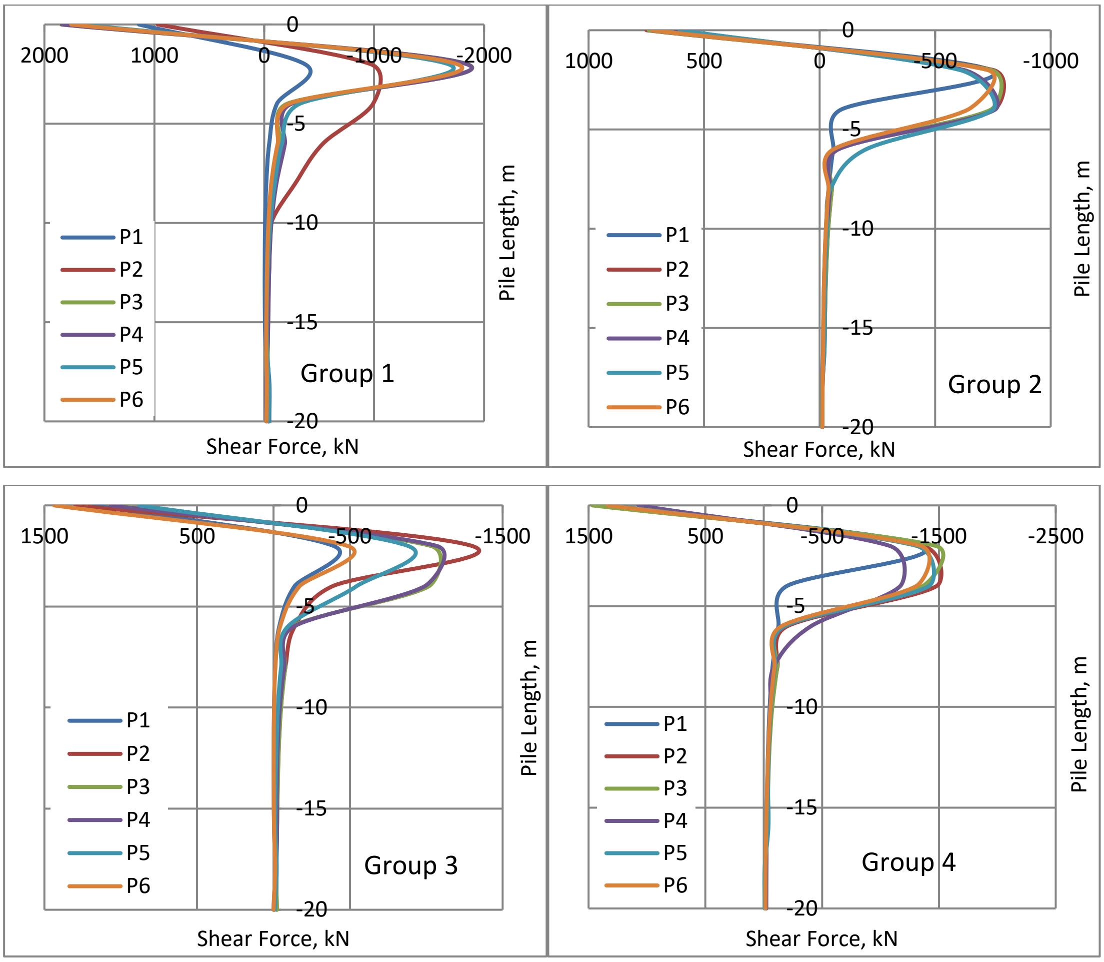

Figure 11. Shear force along pile length for all the four pile groups.

3.6. Bending moment along pile length

Fig. 12 shows the distribution of bending moment along the pile length for the four pile groups. Group 2 was less responsive than the other groups. Groups 2 and 4 had the same distribution of bending moment along the pile length with minor differences in value, while in Group 3, the corner piles (P1, P6) had the highest bending moment values due to its distance from the center of the applied torsion. In Group 1, the distribution of bending moment was successive between the piles, with piles P1, P3, and P5 showing smaller values compared to the piles P2, P4, and P6. The fixed moment depth occurred at 12 m from the soil level, the zero value indicating the transfer of all moments from the pile to the soil.

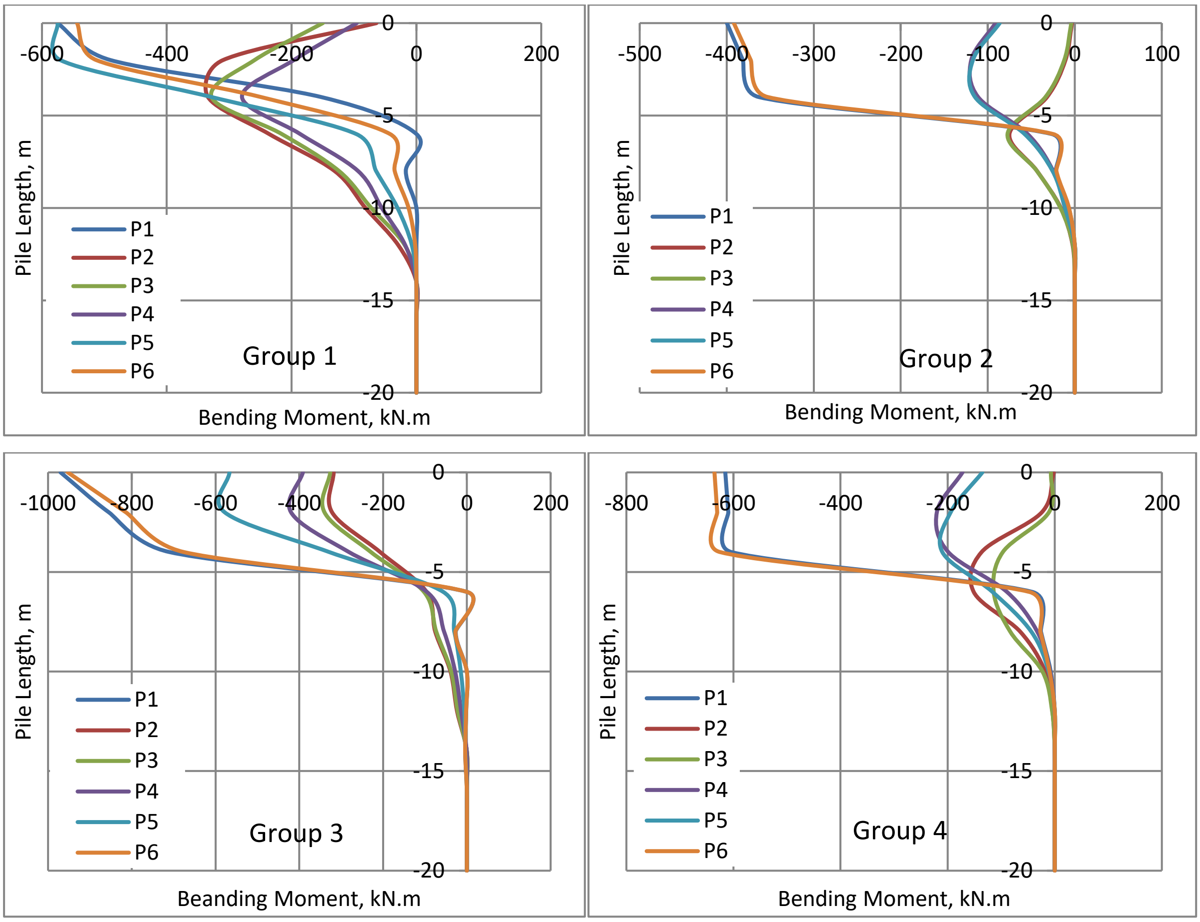

Figure 12. Bending moment along pile length for all the four pile groups.

4. Conclusion

From the results and discussion above, some important factors that are useful when designing deep foundations (piles) can be deduced, which are as follows:

1. The distribution of piles under bridge abutments is very important and needs to be considered in foundation design.
2. Distributing piles in multiple closely spaced lines (rectangular or square arrangement) is much more effective than a random pile distribution.
3. The ABAQUS analysis produced results very close to experimental data, confirming its reliability for solving torsion-related problems.
4. Group 1 (single-line piles) exhibited high displacement due to weak stiffness in the short direction, where the load concentrated on only two middle piles.
5. The higher load in Group 1 resulted from its 9.6 m pile cap length, followed by Group 3 (6.4 m), Group 4 (5 m), while Group 2 showed minimal load and displacement.
6. Group 1 had the poorest torsion-twist angle response due to low stiffness, whereas Group 2 showed marginally better performance.
7. Displacement along the pile length was lowest in Group 2, followed by Group 4, Group 3, and finally Group 1 with the highest response.
8. Group 2's minimal twist angle resulted from closely spaced piles acting as a rigid mass; Group 4 performed similarly, while other groups suffered from suboptimal pile arrangements.
9. The fixed pile depth occurred at 14–17 m for both lateral displacement and twist angle, with variations attributable to pile distribution and soil conditions.
10. Shear forces peaked in Group 1 due to load concentration on central piles, while Group 2's uniform force distribution yielded the lowest values. Group 4's results were comparable to Group 2.

11. Bending moments were highest in distant piles and lowest in proximate ones. Group 2 showed minimal moment response, contrasting with Group 3's higher values for the aforementioned reason.
12. Complete shear force transfer occurred at 7.5 m depth, and bending moments fully transferred at 12 m for all groups, owing to surrounding soil stiffness.
13. The shear force inflection point at 1 m depth for all piles reflected the soil's high load resistance.
14. Fixity moment depth and fixed pile length remained constant regardless of pile group distribution.
15. For this study, Group 2 (rectangular distribution) is recommended due to its low response, as closely spaced piles and soil formed a rigid mass resisting torsional loads. Group 4 (circular distribution) is a viable alternative given its similar performance.

References

1. Hasan, A.Q., Qasim, R.M. A Study of The Effect of Loaded Pile Groups on Neighboring Fuel Storage Tanks. IOP Conference Series: Materials Science and Engineering. 2020. 671. Art. no. 012077. DOI: 10.1088/1757-899X/671/1/012077
2. Zhang, L., Tsang, C.Y.M. Three-dimensional analysis of torsionally loaded large-diameter bored pile groups. Tall Buildings. 2005. Pp. 311–317. DOI: 10.1142/9789812701480_0048
3. Zidan, A.F., Ramadan, O.M. A hybrid MC-HS model for 3D analysis of tunnelling under piled structures. Geomechanics and Engineering. 2018. 14(5). Pp. 479–489. DOI: 10.12989/gae.2018.14.5.479
4. Stuedlein, A.W., Barbosa, A.R., Li, Q. Evaluation of torsional load transfer for drilled shaft foundations. Final report. SPR 304-701. Oregon Department of Transportation. Salem, OR. Federal Highway Administration. Washington, DC, 2016. 159 p. URL: https://rosap.ntl.bts.gov/view/dot/30955/dot_30955_DS1.pdf (date of application: 25.07.2025).
5. Hasan, A.Q. Analytical and Experimental Response of Single Pile to Pure Torsion. International Journal of Civil Engineering and Technology. 2019. 10(3). Pp. 841–851.
6. Kong, L.G, Chen, R.P., Wang, S.H., Chen, Y.M. Response of 3×3 Pile Groups in Silt Subjected to Eccentric Lateral Loading. Journal of Geotechnical and Geoenvironmental Engineering. 2015. 141(7). Art. no. 04015029. DOI: 10.1061/(ASCE)GT.1943-5606.0001313
7. Hasan, A.Q., Qasim, R.M. Study The Behavior of Pile Group Under Torsional and Horizontal Load. Journal of Physics: Conference Series. 2021. 1773. Art. no. 012032. DOI: 10.1088/1742-6596/1773/1/012032
8. Chen, S.L., Kong, L.G., Zhang, L.M. Analysis of pile groups subjected to torsional loading. Computers and Geotechnics. 2016. 71. Pp. 115–123. DOI: 10.1016/j.compgeo.2015.09.004
9. Zidan, A.F., Ramadan, O.M.O. Three-dimensional analysis of pile groups subject to torsion. Geotechnical Research. 2019. 7(2). Pp. 103–116. DOI: 10.1680/jgere.19.00037
10. Qasim, R.M., Hasan, A.Q. Investigating the Behavior of Offshore Platform to Ship Impact. Civil Engineering Journal. 2020. 6(3). Pp. 495–511. DOI: 10.28991/cej-2020-03091486
11. Naylor, D.J., Pande, G.N., Simpson, B., Tabb, R. Finite elements in geotechnical engineering. Pineridge Press. Swansea, UK, 1981. 245 p. DOI: 10.1002/nag.1610060409
12. ABAQUS/CAE User's Manual. Hibbitt, Karlsson & Sorensen, Inc. 2000. URL: https://www.researchgate.net/profile/Slimani-Faouzi/post/Can_anybody_provide_me_the_tutorial_for_warm_deep_drawing_in_Abaqus/attachment/59d63615c49f478072ea3d1c/AS%3A273635439251467%401442251180785/download/ABAQUS%5B1%5D.CAE+Users+Manual.pdf (date of application: 25.07.2025).
13. Reese, L.C., Van Impe, W. Single Piles and Pile Groups Under Lateral Loading. 2nd edn. CRC Press. Boca Raton, 2011. 53 p.
14. Wood, D.M. Soil Behaviour and Critical State Soil Mechanics. Cambridge University Press. NY, 1990. 462 p.
15. Poulos, H.G. Torsional Response of Piles. Journal of the Geotechnical Engineering Division. 1975. 101(10). Pp. 1019–1035. DOI: 10.1061/AJGEB6.0000203
16. Fioravante, V. On the Shaft Friction Modelling of Non-Displacement Piles in Sand. Soils and Foundations. 2002. 42(2). Pp. 23–33. DOI: 10.3208/sandf.42.2_23
17. Hasan, A.Q. Dynamic analysis of steel offshore structures considering the effect of soil-structure interaction. PhD thesis. Basrah, 2016.
18. Anoyatis, G., François, S., Orakci, O., Tsikas, A. Soil–pile interaction in vertical vibration in inhomogeneous soils. Earthquake Engineering & Structural Dynamics. 2023. 52(14). 4582–4601. DOI: 10.1002/eqe.3968
19. Boyko, I., Krivenko, O., Gavryliuk, O. Numerical simulation of interaction bored pile and soil mass with taking into account the dilatancy of the soil. Bases and Foundations. 2023. DOI: 10.32347/0475-1132.46.2023.9-16
20. Alver, O., Eseller-Bayat, E. Effect of Soil Damping on the Soil–Pile–Structure Interaction Analyses in Cohesionless Soils. Applied Sciences. 2022. 12(18). 9002. DOI: 10.3390/app12189002
21. Qiao, S., Dong, Ch., Li, G., Wang, G. Modified Interaction Method for Response of Group Piles Considering Pile–Soil Slip. Mathematics. 2022. 10(15). 2616. DOI: 10.3390/math10152616
22. Yu, Y., Bao, X., Liu, Z., Chen, X. Dynamic Response of a Four-Pile Group Foundation in Liquefiable Soil Considering Nonlinear Soil-Pile Interaction. Journal of Marine Science and Engineering (JMSE). 2022. 10(8).:1026. DOI: 10.3390/jmse10081026
23. Tretiakova, O. Model of pile-frozen soil interaction in a closed form. Magazine of Civil Engineering. 2022. 115(7). Article No.1501. DOI: 10.34910/MCE.115.1
24. Ali, A.M., Essa, M.J.K., Hassan, A.Q. Dynamic analysis of offshore piles embedded in elastoplastic soft clay. Proceedings of International Engineering and Construction. 2016. DOI: 10.14455/ISEC.res.2016.112
25. Kong, L.G., Zhang, L.M. Experimental study of interaction and coupling effects in pile groups subjected to torsion. Canadian Geotechnical Journal. 2008. 45(7). Pp. 1006–1017. DOI: 10.1139/T08-038

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