AN INSIGHT INTO THE GROUP SHAFT INTERACTION THROUGH: SOIL STRUCTURE INTERACTION ANALYSIS OF DEEP FOUNDATIONS

Dr. Eng. Özgür BEZGİN

İSTANBUL
January 2010

TABLE OF CONTENTS

1.1 Introduction 1

1.2 Two-Shaft Group (Group I) 2

1.3 Three-Shaft Group (Group II) 9

REFERENCES 13

APPLICATION OF FINITE ELEMENT ANALYSIS TO GROUP SHAFT INTERACTION

1.1 Introduction

The FE model developed in book titled "An Insight into the Finite Element Modeling Methodology of SSI" is modified for application of FEA to group shafts.

Within a group shaft, there is an interaction between the soil and the shaft and also interaction between the shafts through the soil. The analysis of multiple shafts in a group under a lateral loading takes into account the interaction among the shafts that influence the lateral capacity of the individual shafts. Group shaft behavior is mostly dependent on the spacing of the shafts. The displacement of a shaft under lateral loading creates stresses within the surrounding soil. The stresses generated within the soil are transmitted along influence zone around the shaft and have an effect on the neighboring shafts that depends on their center-to-center spacing. The further the shafts are spaced from each other the less is the mutual interaction among them and their individual capacities are similar to that of a single shaft. However, as the spacing between the shafts decreases so does their individual capacity because the soil around a shaft is also influenced by a neighboring shaft. The finite element approach has the capability of performing SSI analysis of shaft-groups in a fully coupled manner, without resorting to independent calculations of superstructure response, or application of shaft group reduction factors.

To this end, in order to observe the effect of shaft spacing on the lateral load capacity of the individual shafts, two types of shaft groups were analyzed. The first group (I) includes two shafts with a center-to-center spacing varying between 2D and 10D. The second group (II) includes three shafts, which are positioned in a triangular shape with a center-to-center spacing that varying between 2D and 10D.

The shafts are constrained at the column tips i.e. the displacement at the top of the columns are the same. In order to analyze the effect of soil strength and shaft slenderness on group shaft behavior and response, group-I shafts was analyzed for two different soil strengths and two different shaft depths. To observe the effect of soil strength on the group behavior, two shafts with 100ft depth and 6ft diameter and a column height of 20ft were analyzed for n_{h1}=50pci and n_{h2}=25pci. To observe slenderness effects on the group behavior, a 50ft deep shaft with a diameter of 6ft and a column height 20ft was analyzed in a dense dry sand with n_{h1}=50pci. For the group-II, the shafts were 6 ft in diameter and 100ft deep dry dense sand with n_h=50pci. Each shaft is loaded with a lateral load of 50kip and the columns are tied to each other as explained earlier.

1.2 Two-Shaft Group (Group I)

The two shafts in the group were aligned with varying center-to-center spacing in order to establish a relationship between the shaft response and the shaft spacing. A lateral load of 50kip is applied at the top of each column in the direction parallel to the shaft alignment. Figure 1.1 shows three-dimensional views of 100ft and 50ft deep shafts and figure 5.2 shows the typical cross-section of the two-shaft group. The shafts are fixed at the bottom. Three element types are used to model the group shafts. The outermost layer of soil shown in figure 1.2 consists of the infinite elements CIN3D8 that represent soil continuity. The remaining soil elements are full-integration C3D8 elements and the shaft elements are reduced integration C3D8R elements. The total number of elements used for the two-shaft group was 8480 and the total number of nodes was 10705 (1200 CIN3D8 elements, 4880 C3D8 elements and 2400 C3D8R elements with a total of 32115 dof). The

ABAQUS/Explicit analysis time of the two-shaft group on a 2.4GHZ processor is approximately 18 minutes.

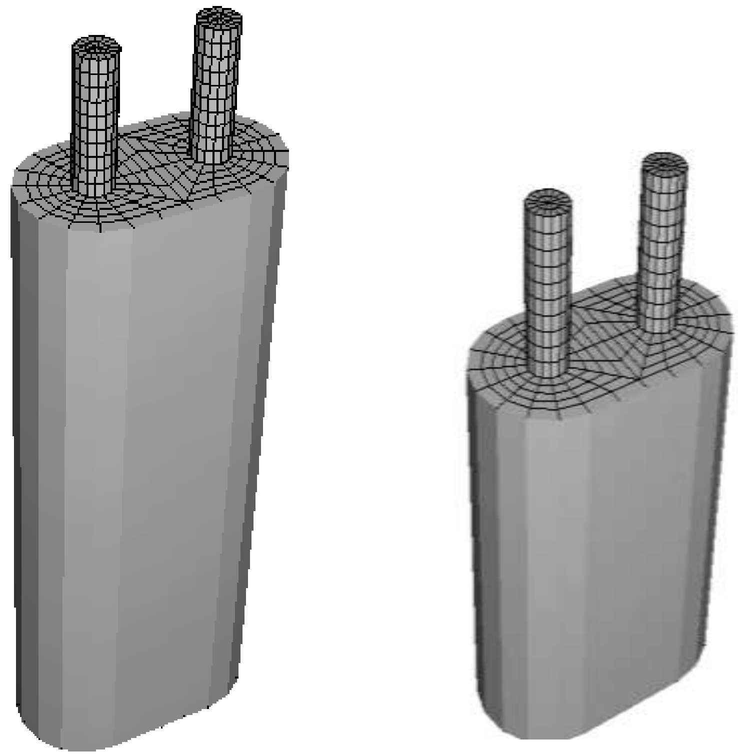


Figure 1.1 – Three-dimensional views of 100ft and 50ft deep of Group I.

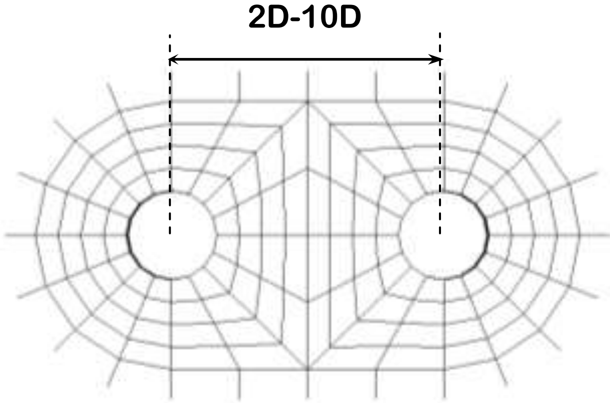


Figure 1.2 – Typical cross section of a group I.

Figure 1.3 shows a very simple and out-of-scale depiction of the resistances developed within a group shaft system with two shafts subjected to lateral loading. Under the influence of lateral loads, surface separations will form at the locations represented by *1* and *2*. The soil resistance developed due to the applied loads is represented by *a* and *b*. Under such a loading scheme, resistance *a* is a variable depending on the center-to-center spacing of the two shafts. However, there is a surface separation at location *2* due to lateral displacement of the second shaft, thus the necessary bearing cannot form which lowers the available resistance *a*. Under a lower soil support, the portion of the lateral load F that has to be resisted by the shafts increases which results in larger displacements.

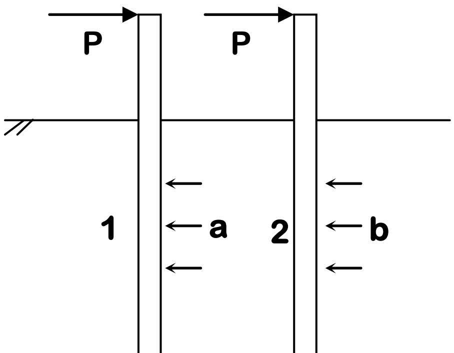
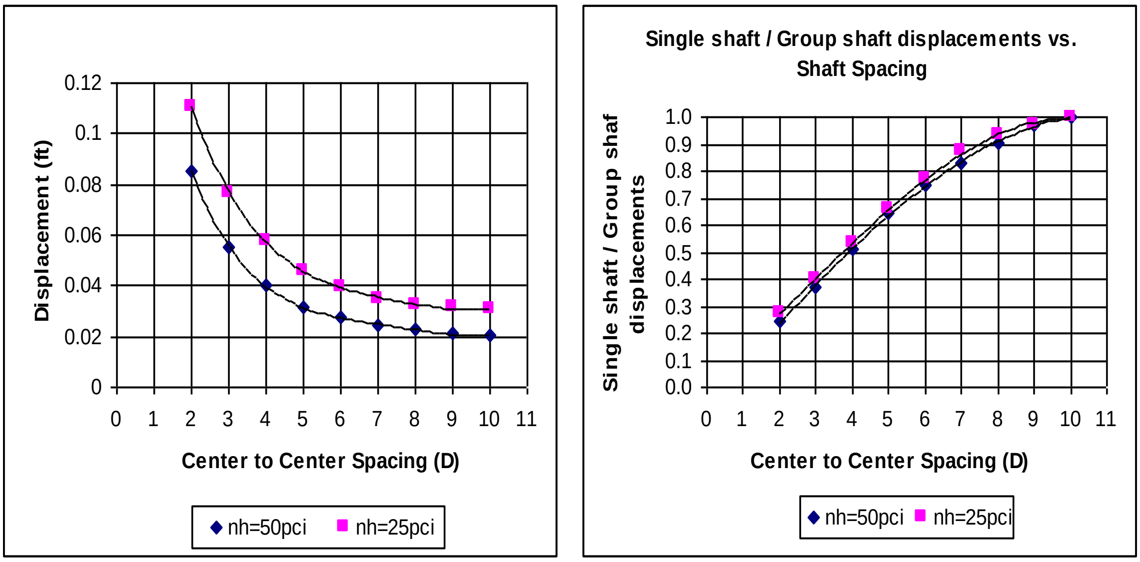


Figure 1.3 – Laterally loaded group shaft.

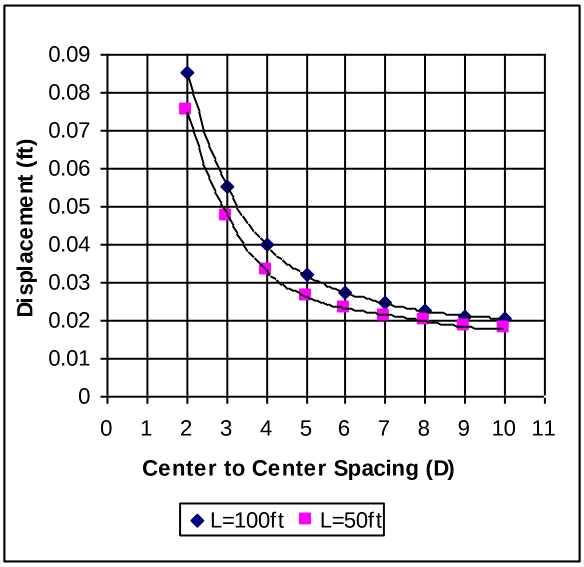
In order to identify the effect of the shaft spacing on the shaft response, the shafts were loaded parallel to their alignment and displacements were obtained. Figure 1.4(a) shows the variation in shaft displacements with increasing center-to-center spacing of the shafts for dense sand with n_{h1}=50pci and medium sand with n_{h2}=25pci. As the c-to-c spacing of the shafts decrease, the shaft displacements increase, indicating lower soil stiffness. Figure 1.4(a) shows the variation of maximum shaft displacement with c-to-c spacing. The displacement values become lower and the mutual influence of the shafts diminish as the results converge to a value at 10D. In order to relate the influence of shaft spacing to shaft response, the displacements of a single shaft has been divided by the displacements of a shaft within the group. The ratio of these displacements has been plotted in figure 1.4(b).



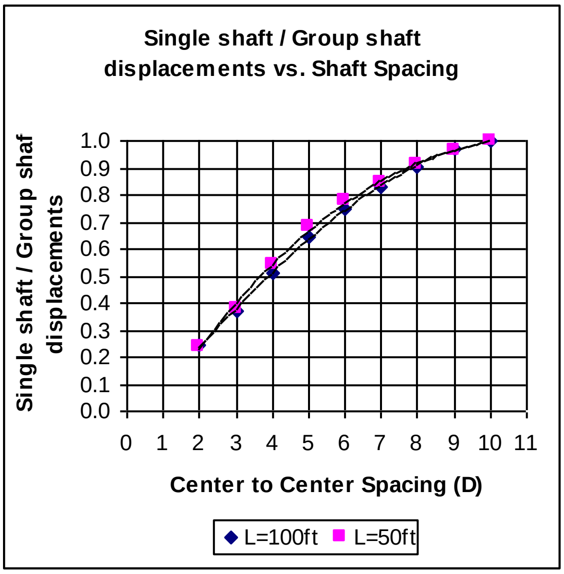
(a) (b)

Figure 1.4 – (a) Variation in shaft displacements and (b) Displacement ratios with respect to single shaft, versus center-to-center shaft spacing. (Group I)

Figure 1.5(a) shows the variation in maximum displacements for 100ft deep and 50ft deep shafts with 6ft diameter in dense sand (n_h=50pci). Figure 1.5(b) shows the variation of the displacement ratios with respect to the displacement of a single shaft, with variable shaft spacing.



(a)

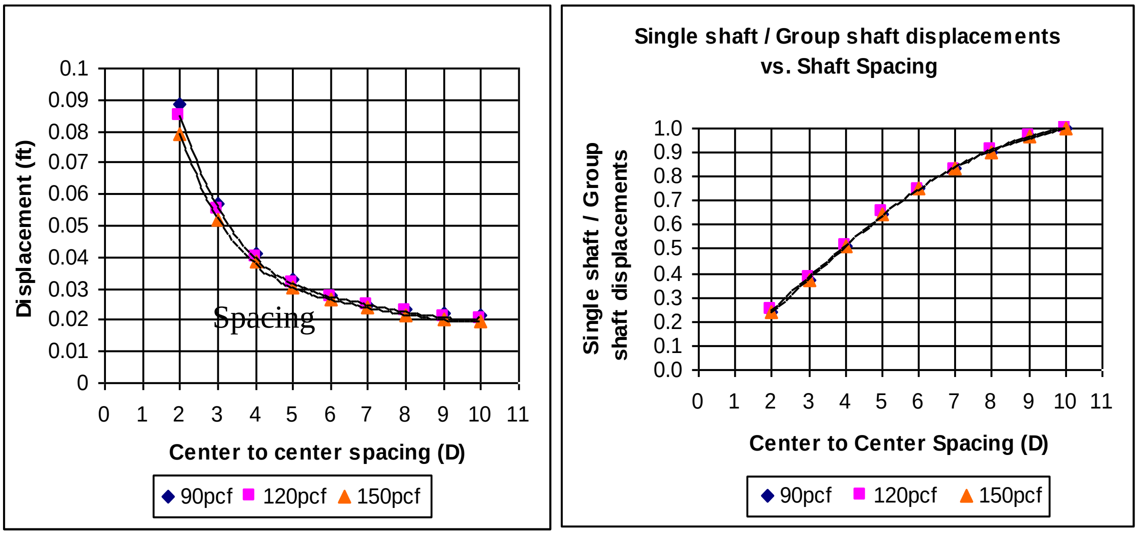


(b)

Figure 1.5 – (a) Variation in shaft displacements and (b) Displacement ratios with respect to single shaft, versus center-to-center shaft spacing. (Group I)

The higher flexural stiffness of the 50ft shaft results in slightly lower displacements; however, the variation of the displacements with increasing c-to-c spacing of the shafts is the same.

Since the ABAQUS/Explicit procedure was used to analyze the soil-structure interaction of the group shafts, the soil mass and the concrete mass were included within the analysis. To this end, in order to observe the effect the soil mass has on the displacement results as well as the variation of the displacement with shaft spacing, the group-shaft model was analyzed for three different soils with the following densities (ρ):2.795 lb.s^2/ft^4, 3.7267 lb.s^2/ ft^4, and 4.6583 lb.s^2/ ft^4 which has the unit weights (w) of: 90pcf, 120pcf, and 150pcf. Figure 1.6(a) shows the variation of maximum shaft displacement with varying center-to-center spacing. Figure 1.6(b) shows the variation of the displacement ratios with respect to single shaft, with shaft spacing.



(a) (b)

Figure 1.6 – (a) Variation in shaft displacements and (b) Displacement ratios with respect to single shaft, versus center-to-center shaft spacing. (Group I)

Typical variation of displacement with changing center-to-center spacing is shown in figure 1.7. Note that as the c-to-c spacing decreases, the soil stiffness decreases resulting in larger displacements.

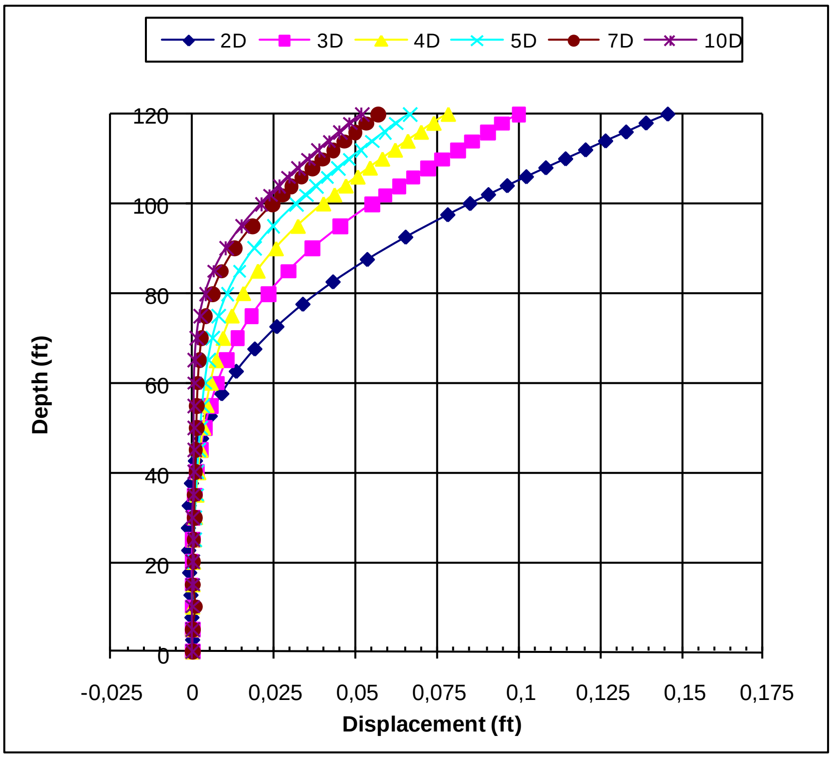


Figure 1.7 – Variation of shaft displacement with varying c-to-c spacing. (Group I)

Typical variation of moment along the shaft with varying center-to-center spacing is shown in figure 1.8. Figure 1.8 shows that as the c-to-c spacing decrease, the bending moments along the shaft increase. This increase becomes evident below 10-15 ft below the ground surface and becomes significant as the spacing becomes 4D or less. Larger moments were also observed at the shaft support, as the lateral soil support to the shaft decreased with decreasing spacing.

Overall, the reduced soil support decreases the stiffness of the SSI system resulting in a higher shaft displacements and moments.

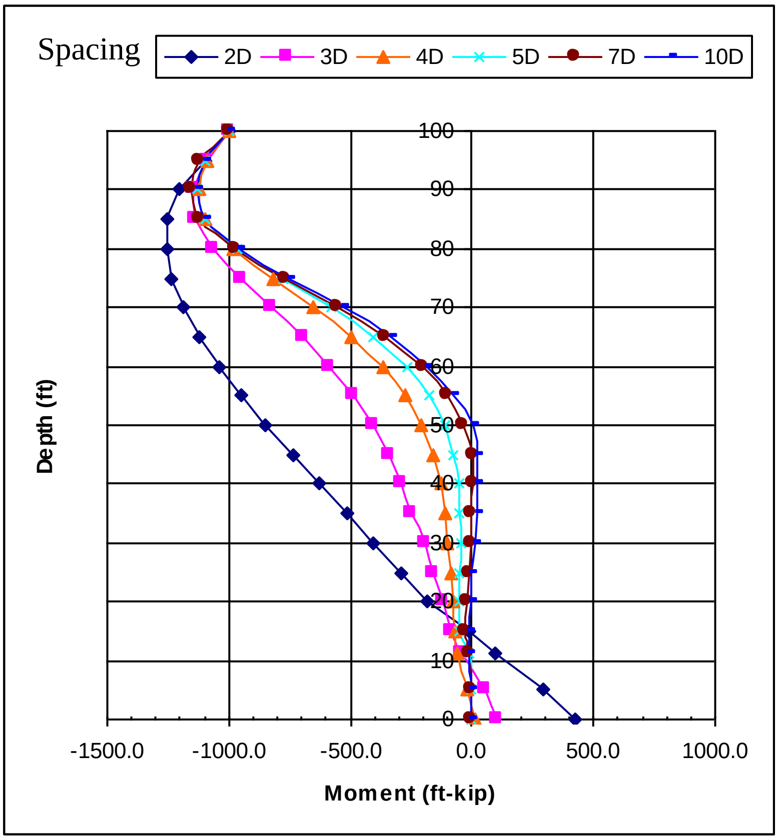


Figure 1.8 –Variation of moment along the shaft depth with varying c-to-c spacing. (Group I)

1.3 Three-Shaft Group (Group II)

In the previous section, the lateral loads were applied in the longitudinal direction to Group I. In order to examine the effect of a different type of shaft configuration as well as the effect of c-to-c spacing on lateral load capacities of shafts, a three-shaft group (Group II) was analyzed as shown in figure 1.9. Figure 1.9 shows the three-dimensional view and the cross-section views of the three-shaft group.

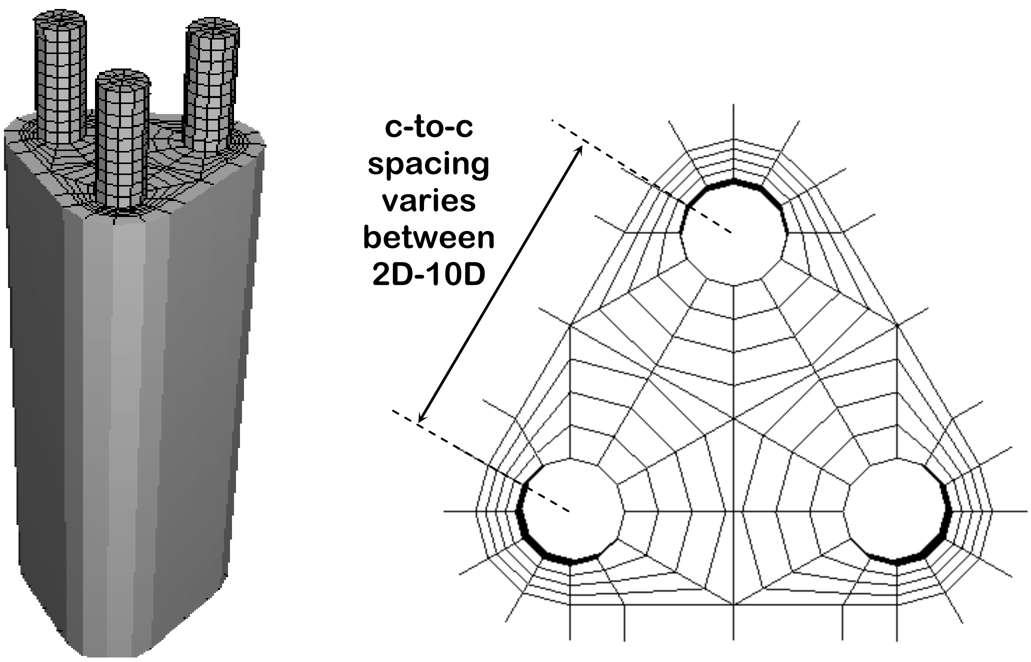
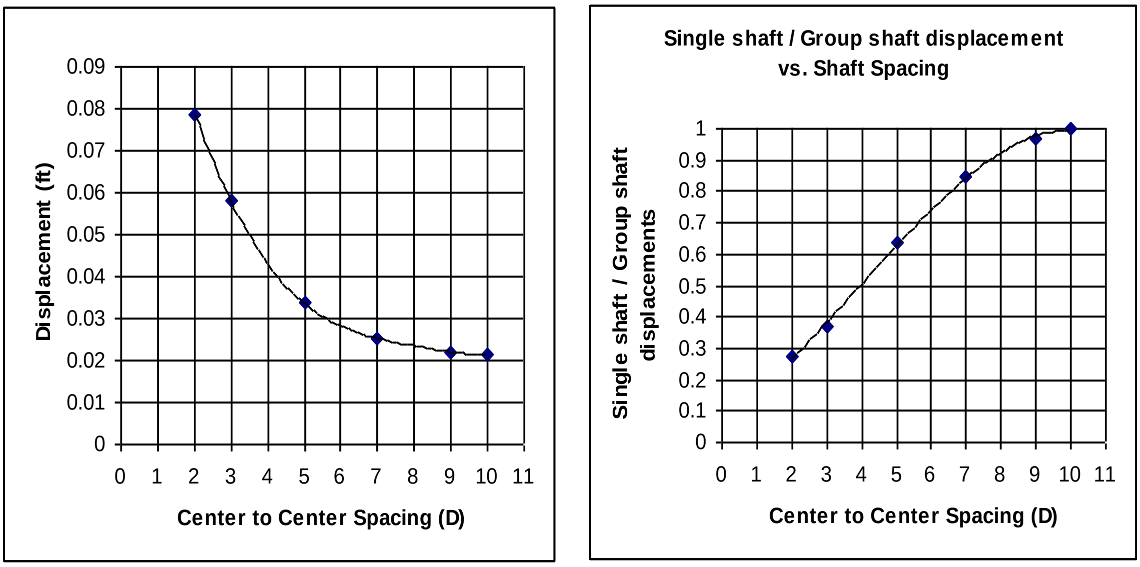


Figure 1.9 – Perspective and plan views of 3-shaft group. (Group II)

The outermost layer of soil shown in figure 1.9 consists of the infinite elements CIN3D8 that represent soil continuity. The remaining soil elements are full-integration C3D8 elements and the shaft consists of reduced integration C3D8R elements. The total number of elements used on the three-shaft group is 9420 and the total number of nodes is 11864 (960 CIN3D8 elements, 5760 C3D8R elements and 2700 C3D8R elements) with a total of 35601dof. The ABAQUS/Explicit analysis time of the two-shaft group on a 2.4Ghz processor is approximately 20 minutes.

Each shaft is 6ft in diameter and 100ft deep with 20ft column height in dry dense sand (n_{h1}=50pci). Each shaft is laterally loaded with 50kips at an angle 45° with respect to the horizontal axis in order to observe whether the application of lateral loads at an angle to alignment of the shafts has an effect in the variation of shaft capacity. The c-to-c spacing was varied between 2D and 10D, similar to group I. Figure 1.10(a) shows the change in maximum displacement with spacing while figure 1.10(b) shows the variation of the displacement ratio of the group shaft with respect to the single shaft, versus shaft spacing. Note that the behaviors are almost identical to those observed for the two-shaft group (Group I).



(a) (b)

Figure 1.10 – (a) Variation in shaft displacements and (b) Displacement ratios with respect to single shaft, versus center-to-center shaft spacing. (Group II)

Figure 1.11 shows the lateral capacity reduction of the shaft with changing c-to-c spacing for the all the cases analyzed so far. The variation of the group shaft displacement results obtained by the FEM have been compared to capacity reduction in group-piles embedded in cohesionless soils presented by Davisson (1970) which is also used in Canadian Geotechnical Society Foundation Engineering Manual and reduction coefficients presented by Oteo(1972). Also

Prakash (1990) states according to theoretical studies that group action will not develop when the shafts are spaced more than six to eight diameters parallel to the direction of the loading. Table 5.1 is a tabulation of the reduction factors for group shaft proposed by Davisson and Oteo.

Table 1.1 – Shaft capacity reduction factors for a shaft within a group with respect to a single shaft. (Davisson and Oteo)

c-to-c spacing	Davisson (1970)	c-to-c spacing	Oteo (1972)
3	0.25	3	0.5
4	0.4	4	0.6
6	0.7	5	0.68
8	1	6	0.7

Figure 1.11 is a combined plot of the previously presented figures and it shows that beyond a spacing of 8D the difference in displacements of the group shafts steadily diminishes. Using regression analysis for the data extracted from FE analysis, similar coefficients to that of Davisson and Oteo (table 1.1) that relate the ratio of the response of a shaft within a group to the response of a single shaft with varying c-to-c spacing can be proposed. Table 5.2 shows a similar tabulation of capacity reduction coefficients for shafts within a group with varying c-to-c spacing.

Table 1.2 – Shaft capacity reduction factors for a shaft within a group with respect to a single shaft. (Based on FEA results)

c-to-c spacing	BEZGİN (2005)
2	0.25
3	0.38
4	0.53
5	0.66
6	0.76
7	0.85
8	0.91
9	0.97
10	1.00

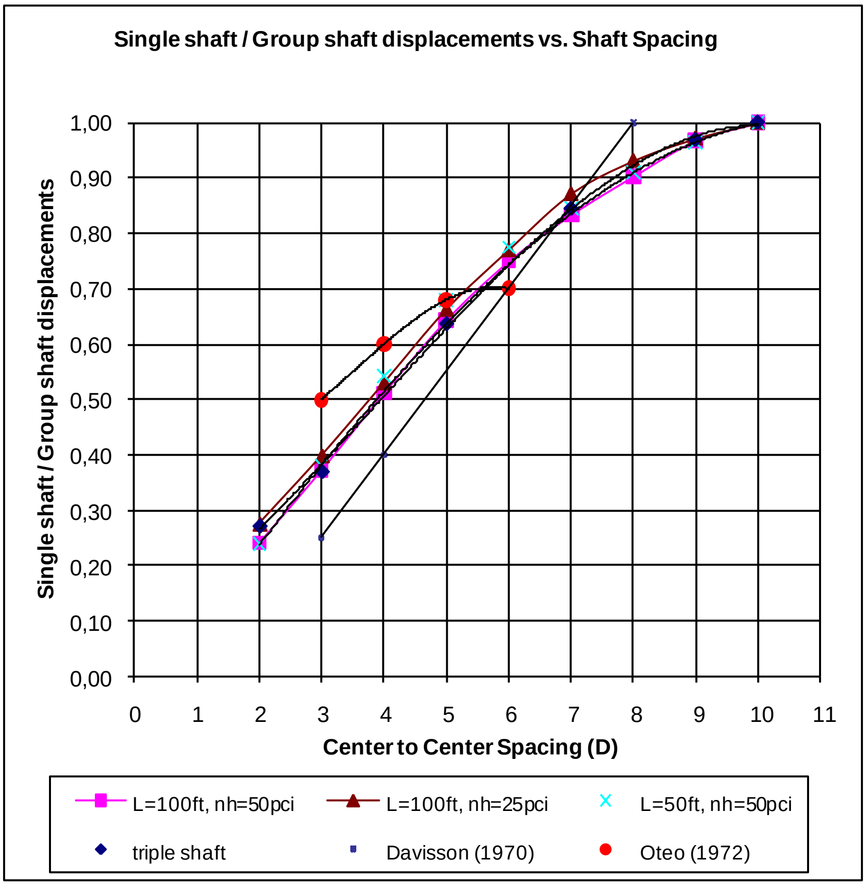


Figure 1.11 – Comparison of displacement ratios with shaft spacing from FE models and existing relations.

REFERENCES

1. ABAQUS Standard/Explicit Manuals versions 6.3&6.4

2. Anderson, Townsend. (2002) “A Laterally Loaded Pile Database”. Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance pp. 262-273

3. Baker (1993). “Use of Pressuremeter in Mixed Highrise Foundation Design”. Design and Performance of Deep Foundations: Piles and Piers in Soil and Soft Rock pp. 1-13

4. Boulanger, Hutchinson, Chai, Idriss (2004). "Estimating Inelastic Displacements for Design: Extended Pile-Shaft-Supported Bridge Structures” Earthquake Spectra, Vol. 20, No. 4, pp. 1081-1094.

5. Bowles (1997). “Foundation Analysis and Design 5th Edition” MacGraw-Hill Companies

6. Briaud, Buchanan (2000) “Introduction to Soil Moduli”.

7. Briaud, L.L., Smith, T.D. Tucker, L. (1985). "Pressuremeter Design Method for Laterally Loaded Piles," Proceedings of the XI International Conference on Soil Mechanics and Foundation Engineering, San Francisco, CA, U.S.A.,

8. Briaud, Johnson, Stroman (1984). “Lateral Load Test of an Aged Drilled Shaft” Laterally loaded deep foundations: Analysis and performance, STP 835 pp. 172-181

9. Britto, Gunn, (1987) Critical State Soil Mechanics Via Finite Elements Ellis Horwood Limited

10. Chen, Liu (1990). “Development in Geotechnical Engineering 52 -Limit Analysis and soil plasticity” -Elsevier Publishing

11. Chen, Mizuno (1990) “Developments in geotechnical engineering53 -Nonlinear Analysis in Soil Mechanics Theory and Implementation”- Elsevier Publishing

12. Chen (1975) “Development in Geotechnical Engineering 7 -Limit Analysis and soil plasticity”- Elsevier Publishing

13. Choi, Oh, Kwon, Kim. (2002) “A Numerical Analysis for Axial and Lateral Behavior of Instrumented Steel Pipe Piles”. Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance pp. 289-304

14. Cook, Malkus, Plesha, Witt (2002). “Concepts and Applications of Finite Element Analysis 4th Edition” John Wiley and Sons Inc.

15. Dameron, Arzoumanidis, Bennett, Malik (1999). “Seismic Analysis and Displacement Based Evaluation of the Brooklyn-Queens Expressway”.

16. Das (1999) “Principles of Foundation Engineering 4th edition” PWS Publishing

17. Dessai, Abel (2002). “Introduction to Finite Element Modeling”. CBS Publishers & Distributers

18. Duggal, Bohinsky, Chu. (1989) “Comparative Performance of Two Pile Types” Foundation Engineering, pp. 943-956

19. Habigaghi, K. and Langer, J.A. (1984). “Horizontal Subgrade Modulus of Granular Soils”. Laterally loaded deep foundations: Analysis and performance, STP 835 pp. 21-34

20. Horvath, (1984). “Simplified Elastic Continuum Applied to the Laterally Loaded Pile Problem”. Laterally loaded deep foundations: Analysis and performance, Laterally loaded deep foundations: Analysis and performance, STP 835 pp. 229-238

21. Horvath J.S. (2002) “Soil-Structure Interaction Research Project:Basic SSI Concepts and Applications Overview” Report No. CGT-2002-2

22. Huang, Ye, Tang. (2002) “Dynamic Coupled Analysis for Earthquake Response of Pile Foundations”. Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance pp. 396-404

23. Kappos, Sextos (1999) “Effect of Foundation Type and Compliance on Seismic Response on RC Bridges”. Journal of bridge engineering, Vol.6, No.2, March 2001.

24. Kulhawy. (2002) “Observations on Some Shortcomings in Foundation Analysis and Design”. Deep Foundations 2002 (GSP 116), pp.1-5.

25. Kulhawy, Cushing.(2002) “Drained Elastic Behavior of Drilled Shafts in Cohesionless Soils”. Deep Foundations 2002: An International Perspective on Theory, Design, Construction pp. 22-36

26. Kulhawy, Agaiby, Trautmann (1996) "On large scale model testing of laterally loaded drilled shafts in sand " Geotechnical Testing Journal , vol.v19., no.n1., pp.pp32-40.

27. Kulhawy, F. H. (1991). “Drilled shaft foundations , Foundation engineering handbook”.

28. Kumar, Kort, Hosin, and Chong (2004) “Lateral Load Tests on Small Diameter Drilled Piers”

29. Kumar, Alizadeh (2002). “Lateral Load-Deflection Response of Single Piles in Sand”.

30. Kort, Kumar, Hosin, Ng (2002) "Lateral Load Tests on Small Diameter Drilled Piers".

31. Lin,Yang, Juang, Lee (2000). "Analysis of Laterally Loaded Piles in a Two-Layered Elastic Medium".

32. Lee, Kane, Bennett, Drumm (1989) "Investigation and Modeling of Soil-Structure Interface Properties"

33. Lee (1991) "Discrete Layer Analysis of Laterally Loaded Piles".

34. Long, Reese (1984). "Testing and Analysis of Two Offshore Drilled Shafts Subjected to Lateral Loads". Laterally loaded deep foundations: Analysis and performance, STP 835 pp. 215-228

35. Luna, Jadi (1998) "Determination of Dynamic Soil Properties Using Geophysical Methods".

36. Macklin, Nelson, Chou (1993) "A Lateral Load Test on Seven Foot Diameter Caissons".

37. Maharaj (1997)"Load-Deflection Response of Laterally LoadedSingle Pile by Nonlinear Finite Element Analysis".

38. Matlock, Reese, (1960). Generalized Solutions for laterally Loaded Piles, Journal of the Soil Mechanics and Foundations Division, ASCE, Vol.86, No SM5, Proc.Paper 2626, pp.63-91

39. Motan, Gabr. (1989) "A Flat-Dilatometer Study of Lateral Soil Response."

40. Neate (1983) "Augered Cast in Place Piles".

41. Neely (1979) "Bearing pressure-SPT Correlations for Expanded Base Piles in Sand".

42. Olson, Clifford, Wright (1983) "Nondestructive Testing of Deep Foundation with Sonic Methods".

43. Petek, Felice, Holtz. "Capacity Analysis of Drilled Shafts with Defects".

44. Pise, P. J. (1983), Lateral Response of Free-Head Pile, Journal of Geotechnical Engineering, ASCE, Vol. 109, No.8 pp. 1126-1131.

45. Popov (1998) "Engineering Mechanics of Solids 2nd Edition" Prentice Hall Publishing.

46. Prakash, Sharma (1990) "Pile Foundations in Engineering Practice". John Wiley and Sons Inc.

47. Puppala, Moalim (1986) "Evaluation of Driven Pile Load Capacity Using CPT Based LCPC and European Interpretation Methods".

48. Pyle, R. and Beikae, M. (1984). “A New Solution for the Resistance of Single Piles to Lateral Loading” Laterally Loaded Deep Foundations: Analysis and Performance, STP 835 835 pp. 3-20

49. Reese, Wright, Aurora (1984). “Analysis of a Pile Group Under Lateral Loading”. Laterally loaded deep foundations: Analysis and performance, STP 835 pp. 56-71

50. Reese, L.C., and Matlock, H., (1956). “Non-Dimensional Solutions for Laterally Loaded Piles with Soil Modulus Assumed Proportional to Depth”, Proceedings, Eighth Texas Conference on Soil Mechanics and Foundation Engineering,

51. Roberston, Hughes (1984). “Design of Laterally Loaded Displacement Piles Using a Driven Pressuremeter”. Laterally loaded deep foundations: Analysis and performance, STP 835 pp. 229-238

52. Sogge (1984). “Microcomputer Analysis of Laterally Loaded Piles”. Laterally Loaded Deep Foundations: Analysis and Performance, STP 835 pp. 35-48.

53. Smith, T.D., (1989) "Fact or Friction: A Review of Soil Response to a Laterally Moving Pile", Proceedings of the Foundation Engineering Congress, Northwestern University, Evanston, Illinois, pp. 588-598

54. Smith, T.D., Slyh, R. (1986) "Side Friction Mobilization Rates for Laterally Loaded Piles from the Pressuremeter, “ Proceedings of the Second International Symposium, The Pressuremeter and its Marine Application”, Texas A&M, May ASTM STP 950, pp. 478-491

55. Taciroglu, Rha, Stewart, Wallace, (1999). “Robust Numerical Models for Cyclic Response of Columns Embedded in Soil”.

56. Vennalaganti, Endley, Rao (1992) “Lateral Loads on Long piles and piers in granular soils”.

57. Wang, Rinne (1999) “Pile Foundation Construction Practice in Stiff Clays with Dense Granular Layers”.

58. Woodward, Gardner, Greer. (1972) “Drilled Pier Foundations” McGraw Hill Publishing

59. Zhang, Tulla, Grismala (1977) “Ultimate Resistance of Laterally Loaded Piles in Cohesionless Soils”.

60. Zafir (1986) “Seismic Foundation Stiffness for Bridges”.