A SIMPLIFIED APPROACH TO THE SETTLEMENT ESTIMATION OF PILED RAFTS

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Abstract

In this study, a simplified approach to the settlement estimation of piled rafts resting on over-consolidated clay deposits is presented. For this purpose, a series of plane-strain and three-dimensional analyses were performed and their results are compared with the available data in the literature. It was found that the percentage decrease in the total settlements with the addition of piles with respect to the unpiled case is very closely estimated by both the plane-strain and the three-dimensional, simplified, numerical analyses. Using this phenomenon, a simple method of analysis is suggested for the total settlement estimation of the piled raft foundations and design charts are provided for the cases studied (for the specific soil conditions only) throughout this study.

Keywords

piled rafts, settlement, over-consolidated clay, foundation design

1 INTRODUCTION

In the traditional design of a piled foundation the contribution of the raft to the overall bearing capacity is disregarded. However, for deep foundations on stiff soils where the piles are used as settlement reducers rather than to provide additional bearing capacity, the traditional design concepts may lead to highly over-conservative solutions (Reul and Randolph 2003 [1], Reul and Randolph 2004 [2]; Randolph 2003 [3]). For such cases, it is very convenient to use the concepts of a piled-raft foundation in the design process. Utilizing the piled-raft concept, the number of piles in a project can be significantly reduced, generally at the expense of a slight increase in the settlements with respect to the traditional design of a pile foundation.

There are various detailed or approximate methods and design concepts available in the literature developed for piled-raft design (some of these methods and concepts are described in Clancy and Randolph 1993 [4]; Katzenbach et al. 1998 [5]; Katzenbach and Moormann 2001 [6]; Katzenbach et al. 2004 [7]; Katzenbach et al. 2005 [8]; Poulos 1994 [9]; Poulos et al. 1997 [10]; Poulos 2002 [11]; Prakoso and Kulhawy 2001 [12]; Randolph 1994 [13]). However, in this study the aim to provide a simple approach that can be used as a first approximation.
For this purpose, plane-strain and three-dimensional finite-element analyses were performed using the Plaxis 2D and Plaxis 3D Foundation software packages respectively. The results of the present study are compared with those of [2] obtained by ABAQUS analyses, which were calibrated according to the in-situ measurements recorded on the foundations resting on over-consolidated Frankfurt clay. In order to provide compatibility, the analyzed cases and the parameters used for modelling the elements included in these analyses are similar to the ones given in [2].

2 ANALYSES

2.1 ANALYZED CASES

In this study, eight different piled-raft foundations were analyzed for three different pile lengths (L_p) and two different load levels in plane-strain and three-dimen-

Table 1. List of the analyzed cases[1].

Pile Configuration	*B* (m.)	*s/D*	*n*	L_p (m)	$n*L_p$ (m)	*tr* (m)	*q* (kPa)
Unpiled Raft	38	-	-	-	-	3	12.5
Unpiled Raft	38	-	-	-	-	3	50
Configuration I	38	3	169	10	1690	3	12.5
Configuration I	38	3	169	10	1690	3	50
Configuration I	38	3	169	30	5070	3	12.5
Configuration I	38	3	169	30	5070	3	50
Configuration I	38	3	169	50	8450	3	12.5
Configuration I	38	3	169	50	8450	3	50
Configuration I	38	6	49	10	490	3	12.5
Configuration I	38	6	49	10	490	3	50
Configuration I	38	6	49	30	1470	3	12.5
Configuration I	38	6	49	30	1470	3	50
Configuration I	38	6	49	50	2450	3	12.5
Configuration I	38	6	49	50	2450	3	50
Configuration II	38	3	49	10	490	3	12.5
Configuration II	38	3	49	10	490	3	50
Configuration II	38	3	49	30	1470	3	12.5
Configuration II	38	3	49	30	1470	3	50
Configuration II	38	3	49	50	2450	3	12.5
Configuration II	38	3	49	50	2450	3	50
Configuration II	38	6	16	10	160	3	12.5
Configuration II	38	6	16	10	160	3	50
Configuration II	38	6	16	30	480	3	12.5
Configuration II	38	6	16	30	480	3	50
Configuration II	38	6	16	50	800	3	12.5
Configuration II	38	6	16	50	800	3	50
Configuration II	38	6	9	10	90	3	12.5
Configuration II	38	6	9	10	90	3	50
Configuration II	38	6	9	30	270	3	12.5
Configuration II	38	6	9	30	270	3	50
Configuration II	38	6	9	50	450	3	12.5
Configuration II	38	6	9	50	450	3	50
Configuration III	38	3	73	10	730	3	12.5
Configuration III	38	3	73	10	730	3	50
Configuration III	38	3	73	30	2190	3	12.5
Configuration III	38	3	73	30	2190	3	50
Configuration III	38	3	73	50	3650	3	12.5
Configuration III	38	3	73	50	3650	3	50
Configuration III	38	6	40	10	400	3	12.5
Configuration III	38	6	40	10	400	3	50
Configuration III	38	6	40	30	1200	3	12.5
Configuration III	38	6	40	30	1200	3	50
Configuration III	38	6	40	50	2000	3	12.5
Configuration III	38	6	40	50	2000	3	50
Configuration III	38	6	33	10	330	3	12.5
Configuration III	38	6	33	10	330	3	50
Configuration III	38	6	33	30	990	3	12.5
Configuration III	38	6	33	30	990	3	50
Configuration III	38	6	33	50	1650	3	12.5
Configuration III	38	6	33	50	1650	3	50

[1] Each case is analyzed both in plane-strain and three-dimensions.

sions, which makes a total of 100 cases, when considered together with the unpiled raft analyses. The thickness (*t*) and the width (*B*) of the square raft are taken as 3 m and 38 m, respectively, for all the considered cases, while the number of piles (*n*) varies between 9 and 169, where the pile spacings (s) are equal to either 3×*D* (*D*: pile diameter) or 6×*D* (from centre to centre) and the pile lengths are either 10 m, 30 m or 50 m. The analyzed cases are listed in Table 1.

Three different configurations are considered in the study, as shown in Fig. 1. Configuration I corresponds to uniformly distributed piles, Configuration II represents the cases where the piles are concentrated near the centre, and Configuration III indicates the piles placed at the edges as well as near the centre. A uniform load of 12.5 kPa and 50 kPa, which corresponds to 5% and 20% of the net ultimate bearing capacity of an equivalent unpiled raft resting on Frankfurt clay, are applied for all the cases and named as "Load I" and "Load II", respectively.

2.2 GENERAL CONDITIONS CONSIDERED IN THE MODELS

As indicated, the piled rafts are assumed to be resting on stiff Frankfurt clay. So, the finite-element model is created in such a way that it is representative of the average soil and groundwater conditions together with the average foundation depth for tall buildings in that region.

The clay layer is assumed to be 69 m thick and the Frankfurt limestone, which underlies the clay layer, is not included in the model, since it is relatively incompressible with respect to the overlying clay. The groundwater table is assumed to be at a depth of 7 m from the ground surface and the foundation depth is taken to be 14 m in the calculations.

The systems are modeled in 2-fold and 4-fold symmetry in plane-strain and 3D analyses, respectively. The model width is taken to be equal to ten times the half raft width (190 m) in order to minimize the boundary effects (see Fig. 2 and Fig. 3).

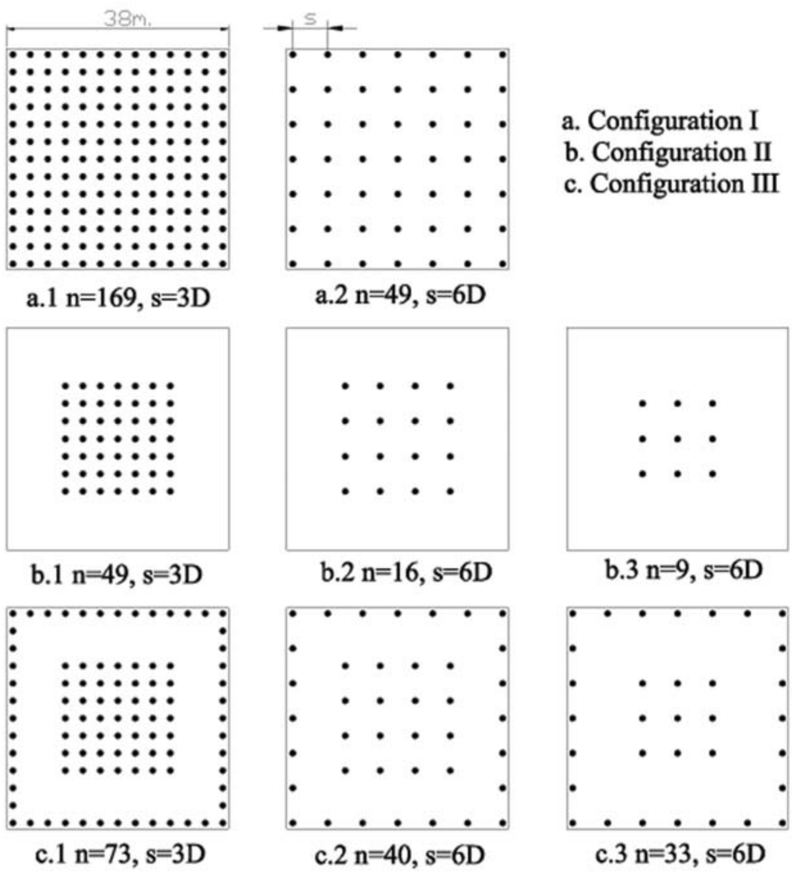

Figure 1. Analyzed cases.

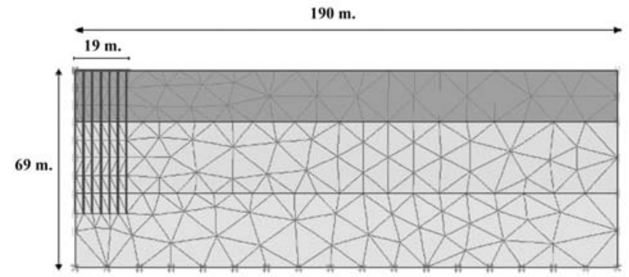

Figure 2. Sample 2D model used in the analyses.

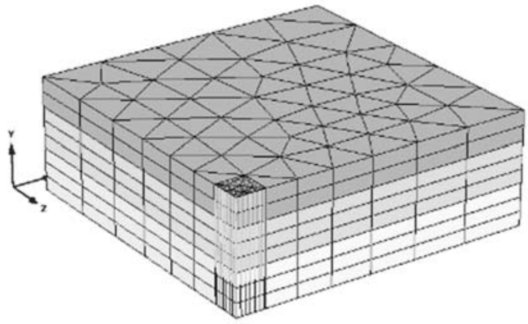

Figure 3. Sample 3D model used in the analyses.

2.3 MODELING OF THE SOIL

In the finite-element models the soil below the foundation level (assuming a groundwater level at the ground surface) is included and the soil above the foundation level (including the groundwater and its uplift pressure) is regarded as a dead load. Fifteen-node triangular elements are used in the plane-strain analyses whereas 15-node wedge (triangular prism) elements are utilized in the three-dimensional analyses.

The Mohr-Coulomb failure criterion is used in modeling the soil strength. The c^1, Φ^1 and K_0 values are selected as given in [2], which are based upon the results of the laboratory and field tests.

The change of the Young's modulus (E) with depth (z) for the soil is considered based on the empirical formulation (1) suggested in Reul (2000) [14]. The assigned parameters for the soil profile are given in Table 2. (E in MPa; z in m.).

$$E = 45 + (\tanh(\frac{z-30}{15}) + 1) \times 0.7z \qquad (1)$$

2.4 MODELING OF THE STRUCTURAL ELEMENTS

In the plane-strain analyses, the rafts and the piles are modeled as plates with linear elastic material properties and represented in the model by 5-node line elements.

Table 2. The properties of the soil profile used in the analyses.

	Layer1	Layer 2	Layer3
Thickness (m.)	18	25	26
Initial E (MPa)	45	57	110
ΔE (MPa/m)	0.66	2.138	1.584
K_0	0.72	0.57	0.57
v	0.15	0.15	0.15
C (kPa)	20	20	20
Φ^0	20	20	20
γ (kN/m^3)	19	19	19

Since the analyses are performed in two-dimensional space, the elastic parameters are converted in such a way that a row of pile provides the rigidity per meter of the system equal to that of the structure.

For the three-dimensional analyses the raft is modeled as a linear elastic plate by utilizing 6-node triangular plate elements. The piles, which are also assumed to behave linearly elastic, are modeled by 3-node line elements. The shaft and base resistances of the piles are obtained from [2].

3 RESULTS

Based on the approximation given in Davis and Taylor (1962) [15] the average total settlements of the analyzed piled raft foundations under given loads are calculated using equation (2) in which the s_{centre} and s_{corner} are the centre and the corner settlements of the raft respectively.

$$s_{avg} = \frac{1}{3}(2s_{centre} + s_{corner}) \qquad (2)$$

In order to visualize the amount of percentage decrease in the average total settlement of the foundations with the addition of the piles with respect to the unpiled case (in other words, the efficiency of the piles), a parameter named as the coefficient for average settlement "ξ_s" [2] is used, which is defined as the ratio of the average total settlement of the investigated case "s_{avg}" to that of the unpiled case "$s_{avg,r}$" under the same load (3).

$$\xi_s = \frac{s_{avg}}{s_{avg,r}} \qquad (3)$$

The calculated ξ_s parameters based on the results of the parametric study revealed that the amount of percentage decrease in the average total settlement of the foundations with the addition of the piles can be closely approximated by the simplified numerical analyses performed in this study. Interestingly, it was found that although the settlements estimated by three-dimensional analyses are closer to the reference values than those of plane-strain analyses, on average the ξ_s values are calculated with a smaller deviation by plane-strain analyses as compared to the three-dimensional analyses. This result does not mean that plane-strain solutions are closer to the reference values, but that the plane-strain analysis tools used in this study yield the efficiency of the piled rafts slightly better than the three-dimensional analysis.

For "Configuration I" in which the piles are uniformly distributed, the plane-strain analyses estimated the ξ_s values given in [2] with an average deviation of 3.15% for "Load I", while it was 7.50% for "Load II". On the other hand, for the same pile configuration, the average deviation in ξ_s values obtained from the results of the three-dimensional analyses was 3.32% for "Load I", where it was 6.56% for "Load II". The change of ξ_s with a total pile length ($n*L_p$) is given in Fig. 4 for "Configuration I".

In the case of "Configuration II" where piles are concentrated near the centre, the deviation in the estimated ξ_s values was 3.31% and 6.63% for "Load I" and "Load II", respectively, for the plane-strain analyses, whereas it was equal to 6.41% and 8.62% for "Load I" and "Load II", respectively, in the case of the three-dimensional analyses. The ξ_s vs. ($n*L_p$) plot for "Configuration II" is given in Fig. 5. In addition, as can be observed in Fig.5, for the three-dimensional analysis and "Load II", the deviation in ξ_s is found to be more noticeable than the other cases (ξ_s>1 for some cases). This is attributed to hogging of the mat, since for the cases where hogging occurs the corner settlements are more remarkably overestimated by the utilized three-dimensional analysis method. As a result, the ξ_s values deviate from the reference values more than the average trend, due to the definition (2) of the average settlement "s_{avg}" value.

For "Configuration III", where the piles are placed both at the edges and near the centre, in the case of plane-strain

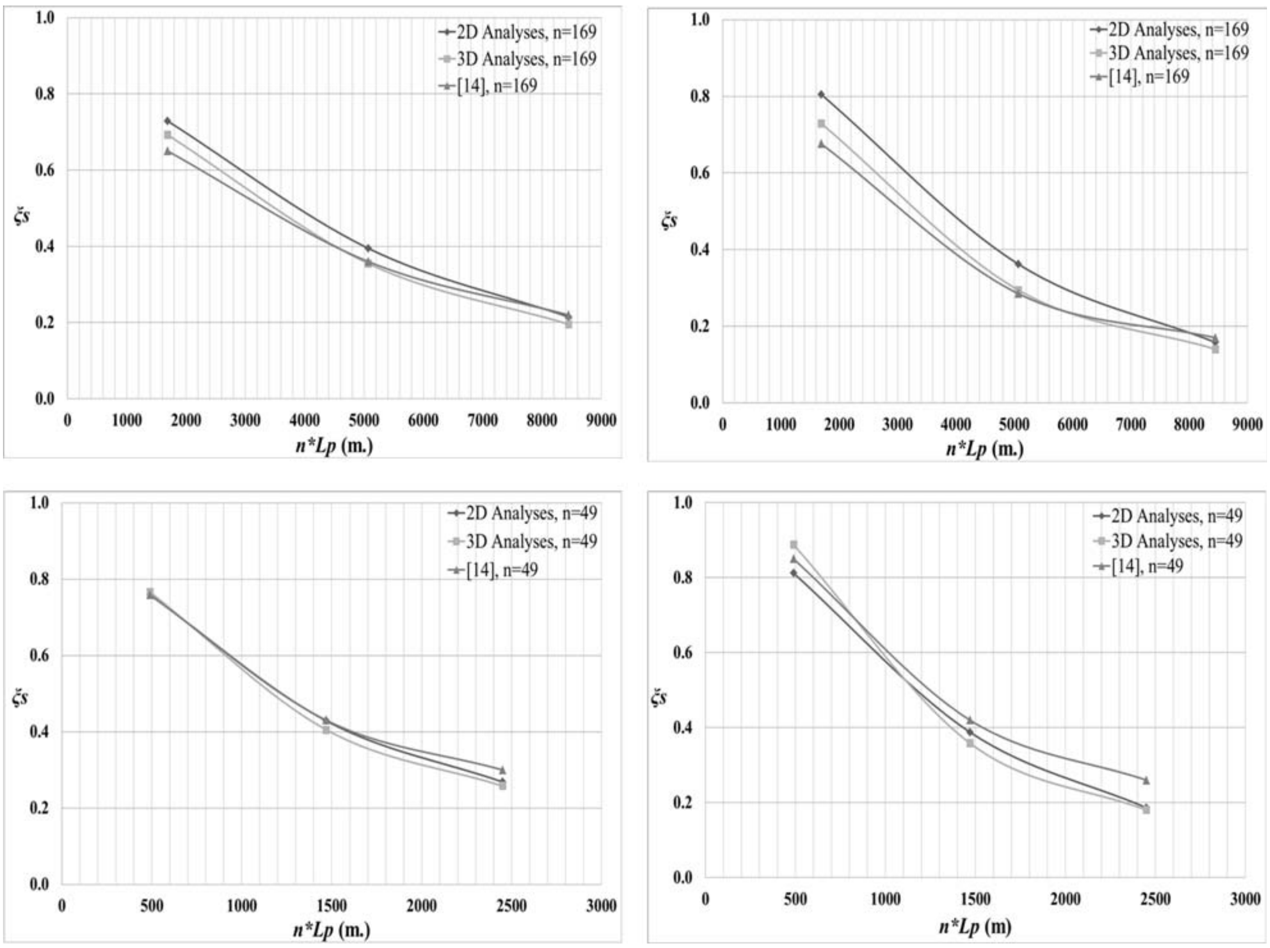

Figure 4. ξ_s vs. ($n*L_p$) for Configuration I.

analyses, the ξ_s values were estimated with a deviation of 2.56% and 5.75% for "Load I" and "Load II", respectively. On the other hand, the deviation was 2.60% for "Load I", while it was 6.43% for "Load II" in the case of the three-dimensional analyses. The deviations in the estimated values for all the analyses are given in Table 3. The ξ_s vs. $(n{*}L_p)$ plot for "Configuration III" is given in Fig. 6.

Table 3. The average percentage deviation in ξ_s values.

Pile Configuration		I	II	III
2D	Load I	3.15%	3.31%	2.56%
	Load II	7.50%	6.63%	5.75%
3D	Load I	3.32%	6.41%	2.60%
	Load II	6.56%	8.62%	6.43%

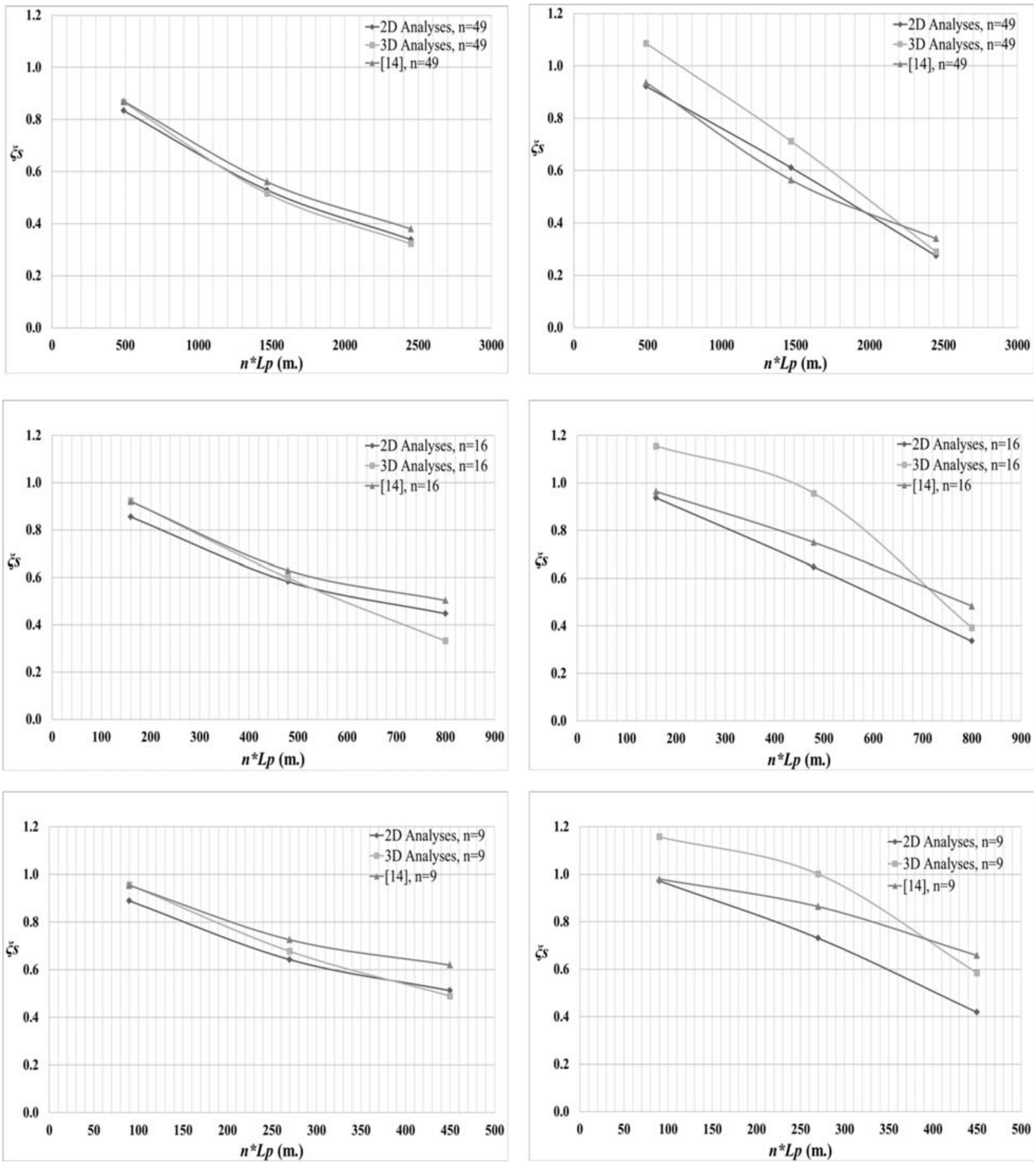

Figure 5. ξ_s vs. $(n{*}L_p)$ for Configuration II.

4 DISCUSSION

The results of the parametric study revealed that the simplified numerical analyses closely approximate the variation of the decrease in the total average settlements of the piled rafts with the addition of piles for the cases studied. The ultimate deviation in the estimated ξ_s values is 7.50% for plane-strain analyses in the case of "Configuration I" and "Load II", while it is 8.62% for "Configuration II" and "Load II" in the three-dimensional analyses. The deviation in the ξ_s values tends to increase with the increasing load level, where it almost varies in a narrow band for different pile configurations, provided that the load level is the same.

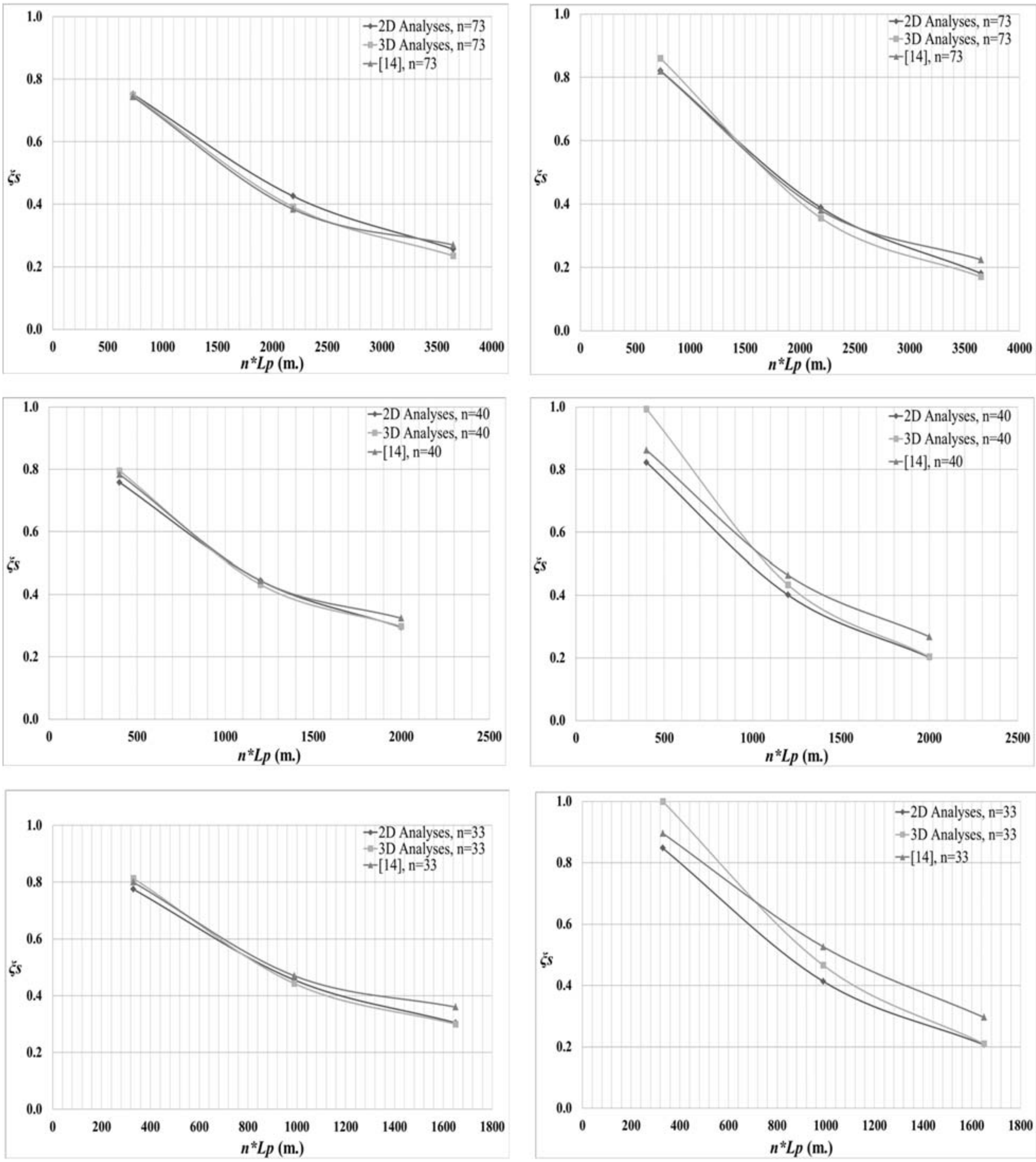

Figure 6. ξ_s vs. (n*L_p) for Configuration III.

The slight deviations in the results encourage the use of this type of approach in total settlement estimation of the piled raft foundations, in order to make an initial approximation about the performance of the piled raft prior to the more detailed analyses. Provided that the investigated case is compatible with the cases presented here, using the charts given in Fig.4, Fig.5 and Fig.6, the average total settlement of a piled raft foundation can be estimated by calculating the settlement of the raft without piles under a given load and multiplying this result with the corresponding ξ_s value. Alternatively, utilizing the described simple analysis tools, case-specific charts may be produced for cases with similar material, loading and geometrical conditions for a pile configuration with different pile lengths and load levels by analyzing these cases together with that of an unpiled raft analysis and obtaining the ξ_s values for the considered case. In this way, one can easily observe the efficiency of increasing the pile length (L_p) in reducing the total settlements for the case studied. Care should be taken where hogging is expected, since the ξ_s values may be noticeably overestimated (even ξ_s>1) in such cases, especially by the described three-dimensional analysis method.

5 CONCLUSIONS

In order to facilitate the estimation of total settlements for piled raft foundations, a total of 100 numerical analyses were performed throughout the study. The results show that the average total settlement of a piled raft may be estimated by utilizing the simplified approach presented above.

The design charts presented in this study may be utilized as a first approximation to assess the performance of a piled raft for the cases compatible with those shown in the paper. Also, an approach is recommended to produce case-specific charts for other cases with similar material, loading and geometrical conditions.

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REFERENCES

[1] Reul, O. and Randolph, M.F. (2003). Piled Rafts in Overconsolidated Clay: Comparison of In-situ Measurements and Numerical Analyses. *Géotechnique* 53, No.3, 301 – 315.

[2] Reul, O. and Randolph, M.F. (2004). Design Strategies for Piled Rafts Subjected to Nonuniform Vertical Loading. *Journal of Geotechnical and Geoenvironmental Engineering* 130, No.1, 1 – 13.

[3] Randolph, M.F. (2003). Science and empiricism in pile foundation design. *Géotechnique* 53, No.10, 847 – 875.

[4] Clancy, P. and Randolph, M.F. (1993). An Approximate Analysis Procedure for Piled Raft Foundations. *International Journal for Numerical and Analytical Methods in Geomechanics* 17, No.12, 849 – 869.

[5] Katzenbach, R., Arslan, U., Moormann, C. (1998). Design and Safety Concepts for Piled Raft Foundations. *Proc. of the Conf. on Deep Foundations on Bored Auger Piles*, Rotterdam, Germany, 439 – 449.

[6] Katzenbach, R., Moormann, C. (2001). Recommendations for the Design and Construction of Piled Rafts. *Proc. of the fifteenth Int. Conf. on Soil Mechanics and Geotechnical Engineering*, Istanbul, Turkey, Vol. 2.

[7] Katzenbach, R., Arslan, U., Moormann, C. (2004). Piled Raft Foundation Projects in Germany. *Design Applications of Raft Foundations*, Thomas Telford, 323 – 392.

[8] Katzenbach, R., Schmitt, A., Turek, J., (2005). Assessing Settlement of High-Rise Structures by 3D Simulations. *Computer-Aided Civil and Infrastructure Engineering* 20, No.3, 221 - 229.

[9] Poulos, H.G. (1994). An approximate numerical analysis of pile-raft interaction. *International Journal for Numerical and Analytical Methods in Geomechanics* 18, 73 – 92.

[10] Poulos, H.G., Small. J.C., Ta, L.D., Sinha, J. and Chen, L. (1997). Comparison of some methods for analysis of piled rafts. *In Proceedings of the fourteenth International Conference on Soil Mechanics and Foundation Engineering*, Hamburg, 1119 – 1124.

[11] Poulos, H.G. (2002). Simplified Design Procedure for Piled Raft Foundations. *In Deep Foundations. ASCE Geotechnical Special Publication* No. 116. ASCE, New York, 441 – 458.

[12] Prakoso, A. W., and Kulhawy, H. F. (2001). Contribution to Piled Raft Foundation Design. *J. Geotech. Geoenviron. Eng.*,127, No. 1, 17 – 24.

[13] Randolph, M.F. (1994). Design Methods for Pile Groups and Piled Rafts. State-of-the–art Report. *In Proceedings of the thirteenth International Conference on Soil Mechanics and Foundation Engineering*, New Delhi, 61 – 82.

[14] Reul, O. (2000). In-situ measurements and numerical studies on the bearing behaviour of piled rafts. *Ph.D. thesis*, Department of Civil Engineering, Darmstadt University of Technology, Darmstadt, Germany.

[15] Davis, E.H. and Taylor, H. (1962). The movement of bridge approaches and abutments on soft foundation soils. *In Proceedings of the First Biennial Conference of Australian Road Research Board*, Australia, 740.