Prediction of Piled Raft Foundation Settlement – A Case Study

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ABSTRACT: Piled raft foundation is an effective foundation method. For the last few decades, the rapid growth of cities all over the world led to a tremendous increase in the number as well as the height of high-rise and super high-rise buildings, even in unfavourable subsoil conditions. Piled raft foundation concept, in which piles are only used for reducing the settlement, not for carrying the whole load from the structure, has been successfully applied for many projects. In this paper the result from the Author's experimental study, which strongly supports the concept of settlement-reducing piles is reviewed. Basing on the experiment, which is surprisingly in good agreement with the monitoring results of case histories many years later, a simplified design method is proposed. In this paper, the method is used for conceptual design of a large high-rise complex. In combination with FEM analyses using Plaxis 3D, the simplified method is a reliable tool for conceptual design of piled-raft.

KEYWORDS: Piled-raft, Pile foundation, Field model test, Simplified method, FEM, Plaxis 3D

1. INTRODUCTION

Piled raft foundations become recently more and more accepted in many countries. Conventional pile foundations are designed with an assumption that the entire load from the superstructure is taken by piles, and the raft does not take any load. According to most standards, the piles must be designed with a safety factor of 2 to 3. This design requirement results in more and longer piles, and therefore the pile foundation is considerably conservative and expensive. As a result, settlement of the pile foundations is unnecessarily small. The conventional pile is commonly used for high-rises worldwide, especially in the US and Southeast Asia. Foundations are predominantly founded on large-diameter bored piles, barrettes or diaphragm walls, which are in most cases installed deeply into the ground to reach bearing layers. The concept of piled raft foundations, in which piles are designed only to reduce the settlement, not to take the full load from superstructure, leads to a considerable savings. However in Southeast Asia, particularly in Vietnam, piled raft foundations have not been commonly applied. In this paper, some successful cases with piled raft foundation worldwide are summarized. Some well-known conventional pile foundations are also reviewed. It is noted that even in foundations designed with conventional piles, a certain part of the total load is still taken by the raft. This can also be seen in many monitored cases.

Settlement prediction for piled raft foundations is a difficult task. Various methods of analysis of piled raft foundations have also been developed, but there appears to be only limited information on the comparative performance of these methods in predicting the foundation settlement behavior. In the design practice, simplified methods are needed, especially for the conceptual design. Many simplified analytical methods have also been suggested. However, they are still complicated, and computer programs need to be developed for these methods. Unfortunately, such programs are not commercially available (Poulos, 2011). Besides, as indicated by the Author, most of these methods are based on theory of elasticity, which is not suitable for the piled footings with complicated pile-soil-raft interaction (Phung, 1993).

A systematic experimental field model study was carried out by the Author for piled groups in non-cohesive soil. The study clarified the complicated interaction between the piles, the pile cap and the surrounding soil. The experimental results can be used as a base for a simplified method, which can be easily used for the design practice. This method can be used in combination with FEM for design of piled raft foundations, at any desired settlement. In this paper the experimental results are summarized, and a case study, in which concept design of a pile raft foundation for a high-rise building, is presented. The design is carried out using the proposed simplified method in combination of FEM analysis, with a required settlement of 20mm. This approach is quite useful and effective for design practice.

2. CASE HISTORIES OF CONVENTIONAL PILE AND PILED-RAFT FOUNDATIONS

During the last few decades, the rapid growth of cities all over the world led to a tremendous increase in the number and height of high-arise and super high-rise buildings, even in unfavorable subsoil conditions. Piled raft foundation concept has been successfully applied for many projects, which are shown in Table 1. Some of the well-known conventional pile foundations are also presented in the table for comparison purpose.

From Table 1, a clear connection can be seen between the settlement and the load carried by piles: the larger the load taken by piles, the smaller the settlement occurs.

It can be also noted that some foundations were designed as a pile foundation, but they acted as a combined piled-raft-foundation, i.e. the raft can take some part of building load. In fact the line separating between a piled raft and a conventional pile foundation is not very clear in some cases. Foundations with frictional piles would act like a piled raft if the number of piles small enough.

Petronas twin Towers in Kuala Lumpur, Malaysia is a good example. The foundation was designed as a conventional pile foundation. However, a certain part of the total load was still taken by the raft. According to the measurement, 15% of the dead load was taken by the raft when the structure reached the height of 34 stories.

ICC Tower in Hong Kong is another example. The foundation was also designed as a conventional pile foundation. However, in his independent peer-review, the Author indicated that a considerable part, up to 30% of the total load, could be carried by the raft, Phung (2002).

In Vietnam, piled raft foundation is not accepted by the Regulations yet. Monitoring of load shared on piles and raft was carried out for a small building in Hanoi, Trinh *et al* (2013). The building with RC frame structure has 10 floors and a basement floor, with a plan area of about 550 m^2. Concrete jacked-down piles with a 30cm x30cm square cross-section were installed to a fine to medium dense sand at a depth of about 20m. Piles are arranged in group under the columns. The pile spacing in the groups is 90-120 cm, i.e. 3-4 times pile width. The foundation is designed as conventional piles, i.e. the piles take the full superstructure load, with a safety factor of 2.5 to 3.0. The monitoring was performed only during the construction period. The axial loads at the pile top, the contact pressure under the basement slab, and the settlement of the building were measured. The measurement showed a very small settlement of 7 to 8mm, which is typical for conventional piles. At final stage, up to 77% of the total load was transferred to the piles and 23% to the raft. With this low settlement, the percentage of load taken by the raft in this case seems too high in comparison with the case histories quoted in Table 1. This can be explained by the fact that the building is quite low-rise, or due to the heave of the excavation bottom.

Table 1 Piled raft and conventional piled foundations for high-rise buildings - Case Histories (Phung, 2011)

No	Tower	Structure		Load share (%)		Measurement	Settlement
		Height, m	Stories	Piles	Raft		s_{max} (mm)
1	Messe-Torhaus, Frankfurt	130	30	75	25	Yes	120
2	Messeturn, Frankfurt	256	60	57	43	Yes	144
3	Westend 1, Frankfurt	208	53	49	51	Yes	120
4	Petronas, Kuala Lampur CPF)	450	88	85	15	Yes	40
5	QV1, Perth, West Australia	163	42	70	30	N.A.	40
6	Treptower, Berlin	121		55	45	Yes	73
7	Sony Center, Berlin	103		N.A.	N.A.	Yes	30
8	ICC, Hong Kong CPF)	490	118	70 cal)	30 cal)	N.A.	40 cal)
9	Commerzbank, Frankfurt CPF)	300	56	96	4	Yes	19
10	Skyper, Frankfurt	153	38	63	27	Yes	55
11	Dubai Tower in Qatar	400	84	67	23	N.A.	200 cal)
12	Incheon Tower CPF)	601	151	98	2	N.A.	43 cal)
13	Emirates Twin Towers CPF)	355	56	93 cal)	7 cal)	N.A.	12

Note: CPF) conventional pile foundations; cal) predicted load share by calculation; N.A. = not available info

3. SIMPLIFIED DESIGN METHOD

In order to create a better understanding of the load-transfer mechanism and of the load-settlement behaviour of a piled footing in non-cohesive soil, especially the settlement-reducing effect of the piles, three extensive series of field large-scale model tests were performed by the Author (Phung, 1993). In each series, four separate tests on a shallow footing/cap alone, a single pile, a free-standing pile group, and a piled footing with cap in contact with soil were performed under equal soil conditions and with equal geometry. All pile groups were square and consisted of 5 piles, one central and 4 corner piles, with a center-to-center pile spacing of 4b, 6b and 8b for test series No.1, 2 and 3 respectively. The soil relative density in the three test series was different. Comparison of the results from the tests on free-standing pile groups with those on single pile shows the *pile-soil-pile interaction*, while comparison of the results on piled footings with those on free-standing pile group on unpiled footings (cap alone) shows the *pile-soil-cap interaction*.

The results from all the three test series show the same tendency. Comparison of the results from the separate tests in Test series T2 is shown in Figure 1. In this figure, we can see that the load taken by cap in the piled footing test, the curve *T2F-Cap*, is very close to the load taken by cap in the test on footing alone, *T2C-Cap*. This means that the load-settlement curve of the cap in a piled footing is very similar to, and can therefore be estimated as, that of the unpiled footing under the same load. The load taken by piles in the piled footing, *T2F-Piles*, is however much larger than the load taken by piles in the free-standing pile groups, *T2G-Piles*. The increase is due to the cap-soil contact pressure. From these conclusions, a simplified design procedure for piled footings in sand can be carried out with the following steps:

1) Step 1: Require a settlement for the foundation.
2) Step 2: At the required settlement $s_{required}$, the load taken by cap/unpiled raft, P_{cap} ,is determined using any available shallow footing approach, such as empirical, analytical, or numerical analysis.
3) Step 3: Estimate the load taken by the piles:

$$P_{piles} = P_{total} - P_{cap} \tag{1}$$

where, P_{total} is the total applied load.

4) Step 4: Determine the number of piles:

$$n = P_{piles} / P_s \tag{2}$$

where, P_s is the single pile capacity.

It is known that with a very small relative soil-pile displacement, the pile shaft resistance can fully be mobilized. In Equation (2), P_s can therefore be taken as the failure load of a single pile, i.e. with a safety factor of unity. This is very different from the conventional piles with a high safety factor of between 2 and 3.

The required settlement is a topic to be discussed. Foundations for the high-rise buildings are often designed to be satisfied conventional design values of 80 mm. It should be discussed between structural engineers, geotechnical engineers and investor, considering safety and serviceability. Some of the buildings supported by piled rafts in stiff Frankfurt clay have settled more than 100mm, see Table 1. Despite this apparently excessive settlement, the performance of the structures appears to be quite satisfactory. It may therefore be suggested that the tolerable settlement for tall structures can be well in excess of the conventional design values. A more critical issue for such structures may be overall tilt, and differential settlement between the high-rise and low-rise portions of a project, Poulos (2012). Zhang and Ng (2006) suggested serviceability criteria for structures: 106mm for tolerable settlement, and 1/500 for tolerable angular distortion.

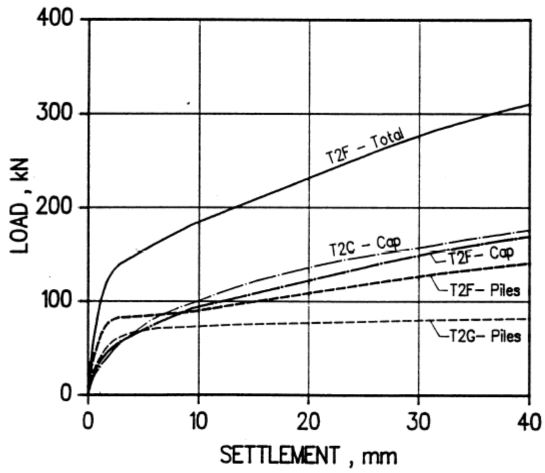

Figure 1 Test series T2 – Summary of test results

According to the above design procedure, the load-settlement curve for a shallow footing can be first predicted by any method, including FEM. The load carried by the cap P_{cap} can be taken at the required settlement. The remaining load will be taken by the piles. In piled raft foundations, the shaft resistance of these piles will be fully mobilized and therefore no factor of safety is applied. From the experiment results, even with the full pile capacity being used, the design is still on the safe side because under the raft contact pressure the pile shaft capacity is considerably increased. This can be seen by comparing the curves T2G-Piles and T2F-piles in Figure 1. Burland (1995) suggested that a "mobilization factor" of about 0.9 be applied to the 'conservative best estimate' of ultimate shaft capacity, P_{su}. Experience in Sweden with piled raft foundation in clay showed that the piles can take a load corresponding to a state of creep failure, Hansbo (1984). The creep load is the load, at which significant creep starts to occur, typically 80-90% of the ultimate load capacity. The number of piles can then be estimated by dividing the load taken by piles P_{piles} to the mobilized capacity of a single pile as discussed above. This simplified design method is good for the concept design phase. Poulos & Makarchian (1996) also used this method to estimate the settlement of the model footing in their study and found a fair agreement with the test results.

4. CASE STUDY

In the last few decades, there has been considerable development of methods for calculating settlement of free-standing pile groups and piled footings. However, most of the methods are based on the theory of elasticity. From the above-mentioned experimental study, the Author had drawn conclusions different from those obtained from the studies basing on theory of elasticity. For example, the comparisons of settlement of a piled footing with that of a free-standing pile group show that due to the contribution of the cap, the increase in stiffness of the piled footing, as compared with the corresponding free-standing pile groups, is considerable. This conclusion is contrary to that drawn in most of the theoretical studies basing on the theory of elasticity (Butterfield & Banerjee, 1971; Poulos & Davis, 1980; and Randolph, 1983).

In practice, a simplified and less time-consuming method should first be used for the conceptual design, especially for a feasible foundation option study. The detailed design of piled raft foundation for high-rises should later be done by numerical analyses using FEM or explicit finite difference codes. Foundation design using FEM is now becoming a must for high-rise buildings especially when they become higher and heavier, with more complex configurations. This can recently be realized due to faster computers and more advanced commercial programs, 2D or 3D, available. The most common codes are: PLAXIS 2D and 3D, FLAC 2D and 3D, ABAQUS 3D, DIANA 3D, Midas 3D, etc.

4.1 Studied project

In this section a pile foundation for a large high-rise complex is studied as a case study. The foundation was designed by the project engineers as conventional pile foundation, i.e. the piles would take the full load from superstructure. Piled raft is studied by the Author as an alternative option with a much smaller number of piles used as settlement reducers. The piled raft is designed using the simplified method proposed in Section 3. The FE analysis is carried out using Plaxis 3D in this study and mainly concerns to the settlement behaviour. A settlement of 20 mm is required.

The studied project is Datum Jelatek, located about 4 km from central Kuala Lumpur, Malaysia. The development has a 12-floor podium consisting of retail, office and car park bay floors, and four multi-storey residential towers with a number of stories varying between 41 and 47, Figure 2. The development has three levels of underground basement for parking vehicles and retail. A circular-shaped bridge connects the four towers together at level 24. The podium distributed load is about 167 kPa, while the distributed loads in Tower A, Tower B, Tower C, and Tower D respectively on top of the podium, q_A = 470.4 kPa, q_B = 475.9 KPa, q_C = 505.4 kPa, q_D = 458.4 kPa.

The layout of the conventional pile foundation designed by the project engineers is shown in Figure 3, in which 387 piles are used, including 67 piles with a diameter of 0.9 m, 110 piles 1.2 m, and 210 piles 1.5 m. With a large number of piles, conventional pile foundations are often too safe and have too small settlements (Phung, 2011).

4.2 Soil conditions and 3D model

The soil condition at the site is complicated. In order to avoid the unnecessary complication for a conceptual design, it is assumed that the soil profile is even with data from the borehole B12-2, 70m deep. The soil consists two layers: 1) Silty sand, 22m thick, and 2) Gravelly sand, 38 m thick. The Hardening Soil model (HS) is used to model the soil behavior. The material parameters are summarized in Table 2. Calculations are carried out as drained analysis; as a result the final settlements are obtained.

Figure 2 Project Datum Jelatek in KL, Malaysia

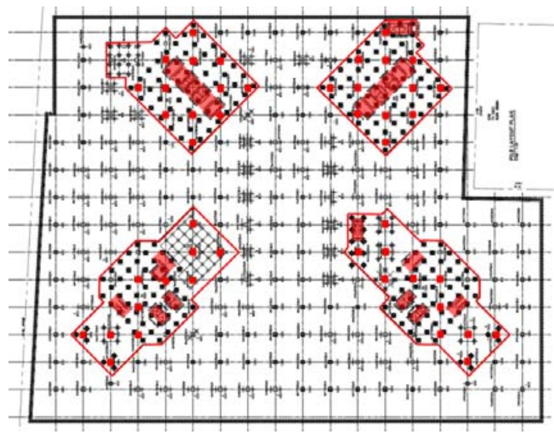

Figure 3 Conventional pile foundation layout

Table 2 Material Parameters for Soil Layers

Parameter		Silty sand	Gravelly Sand
γ_{unsat}	[kN/m³]	17	20
γ_{sat}	[kN/m³]	20	20
φ	[°]	35	42
C	[kPa]	1	1
ψ	[°]	5	12
ν_{ur}	[-]	0.2	0.2
E_{50}^{ref}	[kPa]	60,000	100,000
E_{oed}^{ref}	[kPa]	60,000	100,000
E_{ur}^{ref}	[kPa]	180,000	300,000
m	[-]	0.5	0.5
p_{ref}	[kPa]	100	100
K_0^{nc}	[-]	Automatic	Automatic
R_f	[-]	0.67	0.67
$\sigma_{Tens.}$	[kPa]	0.0	0.0

4.3 FE analysis of unpiled raft

In the simplified method, proposed in Section 3, the allowable settlement is first required. In this case study, a settlement of 20 mm is taken by request of the project owner. The load taken by the raft can then be estimated using any available method for predicting the load-settlement behavior of shallow footings. The methods can be empirical, analytical or numerical analysis. In this study, FEM analysis with PLAXIS 3D is used.

The main purpose for this case study is a conceptual design, the FEM analysis is therefore performed in the simplest way. In order to avoid complication in modeling of the excavation and basement construction process, the whole basement is simulated as a volume with a unit weight equal to the total weight of the basement dividing to the depth of the basement, i.e. about 6 kN/m^3. Non-porous linear elastic volume elements were used for modeling the raft, whose bottom is located at -12.0 m below the ground surface. The analysis was done with increasing podium load, to establish the load settlement curve for the unpiled raft. At the load level of 200 kPa, the settlement exceeded 20mm. Because the full excavation phases are not modeled in this study, it is not easy to define exactly the load at 20 mm settlement. It is therefore reasonable to assume the full podium load, i.e. 167 kPa, being taken by the raft. The construction process was simulated with the phases as follows:

1) Generation of initial stresses;
2) Activation of raft by changing raft material;
3) Loading on raft (100, 200, 300, 400, 500 kPa)

Figure 4 shows the settlement of the unpiled raft with a loading of 300kPa.

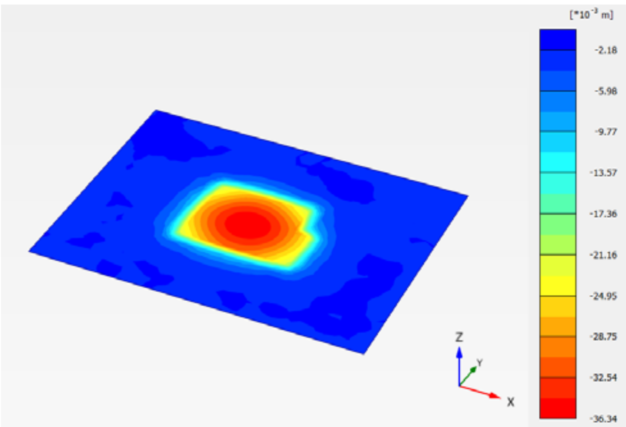

Figure 4 Settlement of the unpiled raft at q_0 = 300 kPa

4.4 FE analysis of piled raft

The simplified approach shown in Section 3 is used to estimate the number of piles. The load taken by the piles is calculated according to equation (1).

In the analysis of the unpiled raft, it is concluded that the full podium load can be taken by the raft. This means that the total load for each tower above the podium can be directly used for defining the number of piles under each tower.

The piles will be then arranged directly under the towers. Pile with 1.5 m diameter is chosen. In the piled-raft concept, piles have to work as friction piles, and therefore they have not to socket to the limestone layer. The pile base is therefore decided to be located at a level of 2 m above the limestone, or -58 m, and the pile length is 46 m. According to the study carried out by a local consultant, an ultimate load of 20,000 kN can be accepted for such a pile.

As a result, 16 piles are needed for each tower A and D, and 21 piles are needed for each tower B and C; or a total of 74 piles are used for the four towers, see the pile layout in Figure 5. Diaphragm wall, DW, with a thickness of 0.8 m being constructed on the foundation perimeter, can act as a bearing component. In the Plaxis 3D model, piles are modeled as embedded pile elements, and DW as plate elements. Loads from the superstructure are simulated as distributed load in the four tower areas. The 3D FE piled-raft model is shown in Figures 6 and 7. The construction was simulated with the following phases:

1) Generation of initial stresses,
2) Basement construction in one stage,
3) Podium loading q_0 over the raft/podium;
4) Tower loading, q_A, q_B, q_C, and q_D.

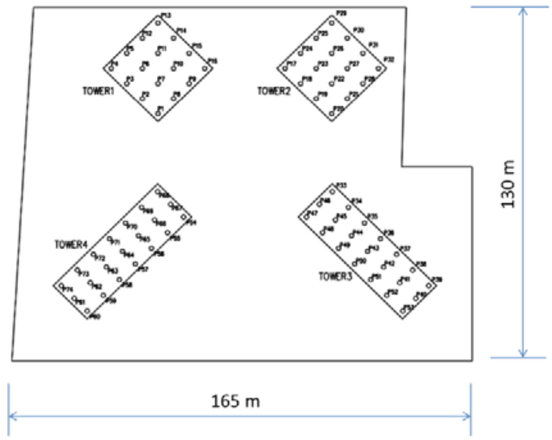

Figure 5 Piled raft foundation - Pile layout

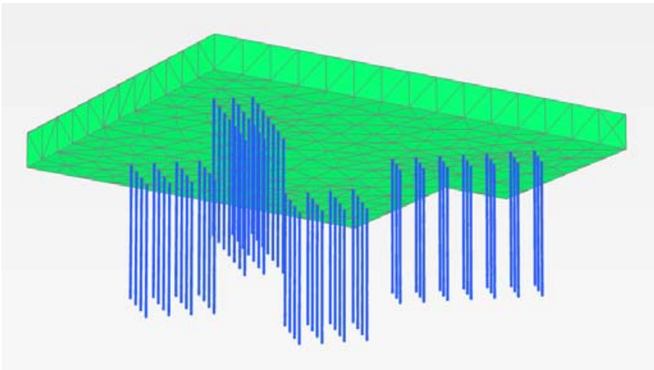

Figure 6 Plaxis 3D piled raft foundation model

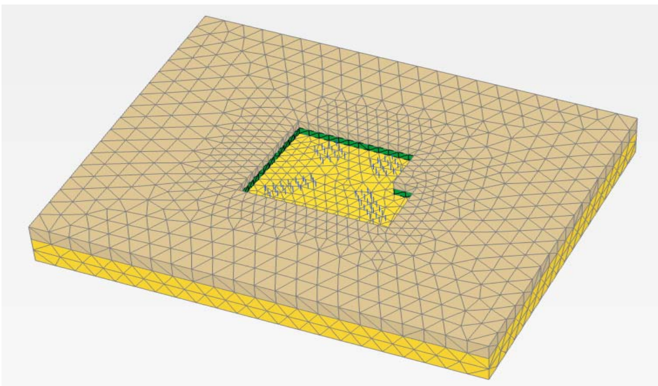

Figure 7 Top view of Plaxis 3D model

4.5 Analysis results

3D FEM is a powerful computational tool and can give very comprehensive output useful for detailed design. However, the main purpose of this case study is the foundation settlement behavior that is useful for a conceptual design; the FEM analysis is therefore performed in a simple way.

From the output results, the maximum settlement of the piled-raft system is almost 20 mm, and the required settlement of 20mm mentioned in Section 4.3 is satisfied. The maximum differential settlement is about 8mm. The settlement of the ground surface is shown in Figure 8.

Two cross-sections A-A* and B-B* are created to see the settlement contours along x-x axis and y-y axis. , through the raft center, are showed in Figure 9. The vertical contact pressure distributed under the raft bottom is shown in Figure 10. The main purpose of this study is the settlement of the piled raft foundation, and therefore other obtained results are not discussed here.

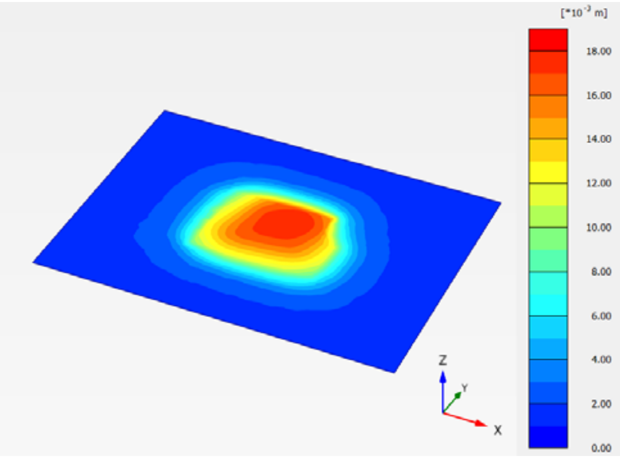

Figure 8 Piled raft-settlement at soil surface level

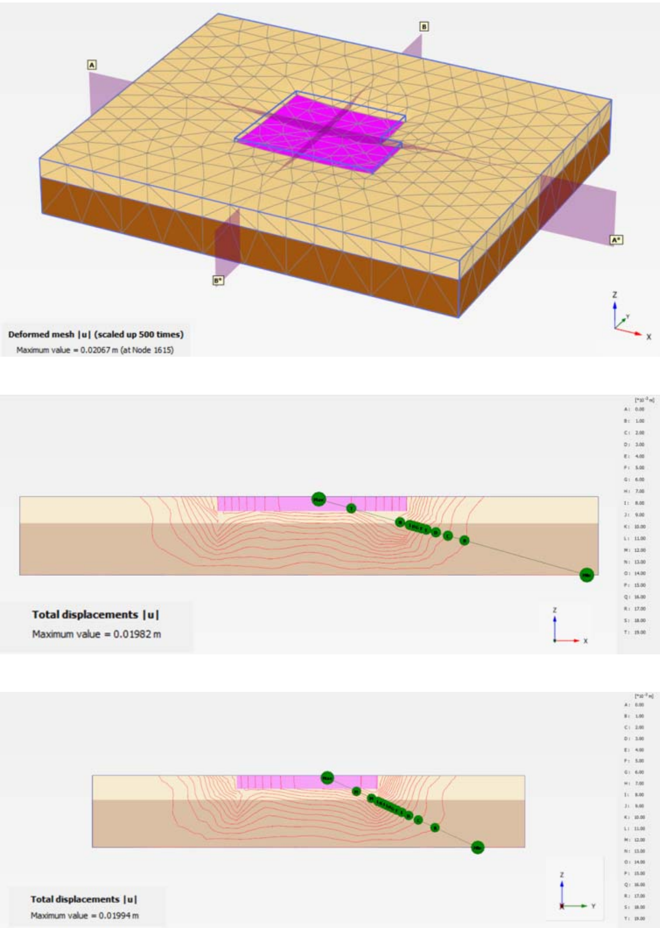

Figure 9 Settlement at cross section along x-x axis (top) and along y-y axis (bottom)

Lines A to M: equal settlement contours with an acceptably small settlement less than 20 mm, the number of piles is reduced considerably. It is known that the settlement (maximum value, differential settlement and its pattern) can be controlled by changing the number of piles, and their layout. The number of piles used for the piled raft option in this study, even plus the additional piles for reducing large bending moments and shear forces in the raft, is much smaller than that used in the conventional pile option. If the required settlement is higher, the number of used piles can be further reduced.

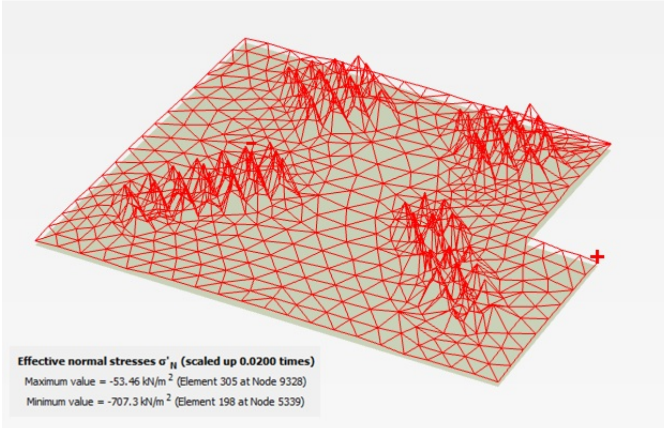

Figure 10 Effective normal stress distributions under the raft bottom

5. CONCLUSIONS

Piled-raft foundation, in which piles are designed to reduce the settlement, not to take full loads from superstructure, is an effective foundation method for high-rise buildings. However, predicting the settlement for piled-rafts is a difficult task for geotechnical engineers due to the complex pile-cap-soil interaction. Most of the available prediction methods are not suitable for piled-raft foundations because they are based on the theory of elasticity. The simplified method, proposed in this paper, is based on the experimental study performed by the Author, and can be easily used for the conceptual design of a piled raft foundation.

In this simplified method, the load from structure is shared between the raft and the piles. The load taken by the raft can be first estimated using any available method for predicting the load-settlement behavior of shallow footings. Such methods can be empirical, analytical or numerical analysis. In this study, FEM analysis with PLAXIS 3D is used. This load is estimated at a required settlement.

The required settlement is a topic to be discussed. Foundations for the high-rise buildings are often designed to be satisfied conventional design values of 80 mm. This value however should be discussed between structural engineers, geotechnical engineers and investor, considering safety and serviceability. Despite excessive settlement of more than 100 mm, the performance of a number of structures appears to be quite satisfactory. This may suggest a higher tolerable settlement for tall structures can be suggested. A more critical issue for such structures may be overall tilt, and differential settlement.

The remaining load is carried by piles. In piled raft foundations, the shaft resistance of these piles will be fully mobilized and therefore no factor of safety is applied. The number of piles can then be estimated by dividing the load taken by piles P_{piles} to the mobilized capacity of a single pile as discussed in Section 3.

In the case study, after the number of piles is determined according to the above simplified method, the settlement of the piled raft foundation is also analyzed using PLAXIS 3D. The results are therefore quite reliable.

The main purpose for this case study is a conceptual design. The FE analysis is therefore performed in a simple way, i.e. ignoring the modeling of the excavation and basement construction process. The whole basement is simulated as a volume with an equivalent unit weight, and non-porous linear elastic elements are used. With this simplified model, the calculation time can considerably be reduced. However, the results are only limited for conceptual design purpose and many things cannot be studied, e.g. the bending moment or internal forces in the raft.

The case study for the large high-rise project showed in this paper is a clear illustration how to use the proposed simplified analysis method for design piled-raft foundations, and how to define the number of piles used for reducing the settlement of the piled-raft foundation to the required level. Applying the piled raft foundation method, a large number of piles can be saved in comparison to the traditional conventional pile foundation.

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