Modelling the behaviour of piled raft applying Plaxis 3D Foundation Version 2

Yasser El-Mossallamy, Associate Prof., Ain Shams University, Cairo, Egypt c/o ARCADIS GmbH, Berliner Allee 6, D - 64295 Darmstadt, Germany y.el-mossallamy@arcadis.de

Introduction

The quick growth of cities in the last two decades all over the world led to a rapid increase in the number and height of high rise buildings even in unfavourable subground conditions. Since the 80's, a new foundation technique, the so-called piled rafts, has been developed and used extensively in order to reduce the maximum as well as the differential settlements and the associated tilting of the buildings. The analysis of piled raft is a very interesting example of the soil-structure interaction that requires the co-operation between the geotechnical and structural engineers to reach the most economic foundation system. Enhanced numerical analyses play a decisive role for the analyses of such complex foundation system. The piled raft foundation has shown its validity as a very economic geotechnical foundation type, where the structural loads are carried partly by the piles and partly by the raft contact stresses. This foundation system was successfully applied in stiff as well as soft subsoil. An innovative application of the piled raft is its special adjustment to cases of foundations with large load eccentricities or very different loaded parts of buildings to avoid the need of complex settlement joints especially below ground water table.

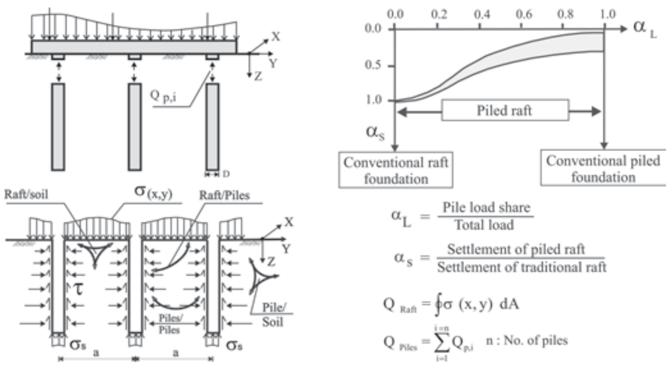


Figure 1: Principles of piled raft

The piled raft is a composite geotechnical foundation system consisting of piles, raft and soil. Figure 1 demonstrates the principles of piled raft foundation and the different interactions (e.g. pile/pile and pile/raft) that govern its behavior.

Extensive measurements of the load transfer mechanism of piled raft foundations during and after the construction were performed to verify the design concept and to prove the serviceability requirements. The piled raft foundation is extensively applied as suitable foundation technique of high-rise buildings in Frankfurt, Germany to achieve economic solutions that fulfill the stability as well as the serviceability requirements. The measured settlements of different case histories of piled rafts in comparison with traditional raft as well piled foundation are shown in Figure 2. The factor α_L is a load factor representing the load taken by the piles relative to the total structural load.

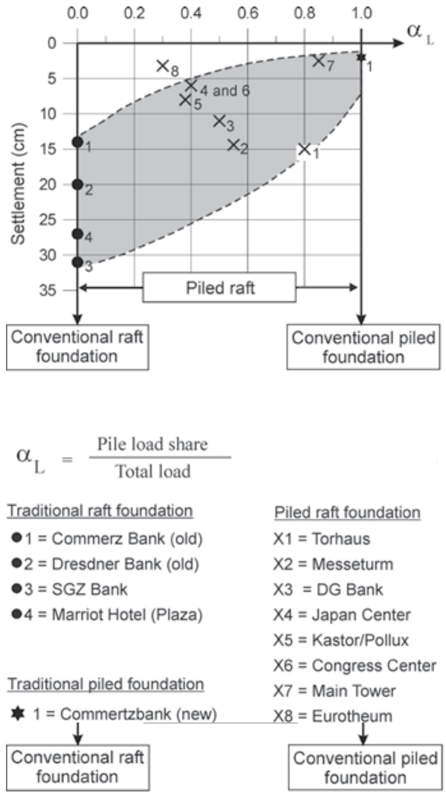
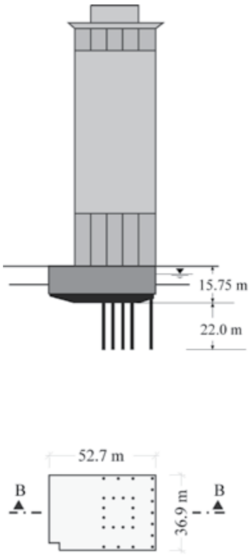
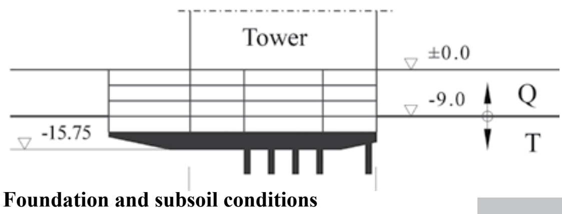


Figure 2: Settlement behavior of high-rise buildings in Frankfurt, Germany

Calculation procedures to model the behavior of such complex three-dimensional problems have been developed since the 1970s (e.g., by Butterfield and Banerjee 1971, Poulos and Davis 1980 and Randolph 1993). But some important requirements concerning the raft stiffness, the nonlinear behavior of the pile support and the slip developing along the pile shafts even under working loads were not sufficiently considered in these analyses. For these reasons improved numerical models based on three dimensional finite element method are applied taking into account all above mentioned effects (El-Mossallamy 1996).

A traditional 3D finite element technique with the appropriate soil constitutive laws presents a powerful tool to model this complex soil-structure interaction problem. Nevertheless, the main disadvantage applying the 3D FE analyses is the need of a huge number of volume elements which can exceed the available computer capacities. To cover this problem, a new technique combined the so called embedded pile model with the 3D finite element model was developed by Plaxis B.V. under the name Plaxis 3D Foundation version 2. The following sections present an example demonstrating the ability of this program to deal with a complex piled rafts. A case history in Frankfurt will be resolved applying this program.





General information	
Height (m)	114
Foundation area (m2)	1930
Raft thickness (m)	3.5 - 1.0
Foundation depth (m)	-15.75
Groundwater	- 6.0
Slenderness ratio	3.5
No of piles	25
Pile length (m)	22
Pile diameter (m)	1.3

Figure 3: General layout

Frankfurt subground and methodology to develop the piled raft

Most of the high-rise buildings in Frankfurt are founded on the so-called Frankfurter clay, which developed 2 to 10 million years ago as a result of the sedimentation in the Tertiary sea in the Mainz basin. In the town center, the clay layer measures up to 100 meters and includes limestone banks, lignite coal lenses and layers of calcareous sand. The groundwater level is mostly just above the clay surface and circulates in the fissured limestone banks and sand lenses resulting in different confined aquifer pressures. The clay is geologically overconsolidated through older, already eroded sediments and volcanic rock.

Example of a high-Rise Building on Frankfurt subsoil

The 120 m building with a 4-storey underground basement has an L shape (Fig. 3) with a load eccentricity of about 7.0 m. Applying the concept of piled raft foundation it was possible to construct the foundation without settlement joints between the tower and the adjacent 4-storey underground garage. The piles were placed eccentrically below the tower to balance the load eccentricity.

Geometry

The foundation of the building has a total area of about 1930 m². Only 25 large diameter bored piles were constructed beneath the raft as a piled raft foundation. The pile arrangements are shown in Figure 4. The rafts are 3.5 meters thick in the middle and 1.0 m at the edges. The raft base lies at a depth of 15.75 meters below the soil surface. The piles where designed with a diameter of 1.3 m and a length of 22 m. The total working loads reach about 900 MN.

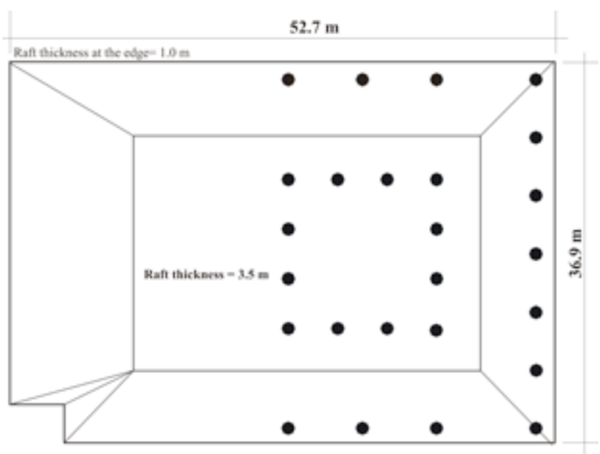


Figure 4: Foundation dimensions and pile arrangement

Modelling the behaviour of piled raft applying Plaxis 3D Foundation Version 2

Yasser El-Mossallamy, Associate Prof., Ain Shams University, Cairo, Egypt c/o ARCADIS GmbH, Berliner Allee 6, D - 64295 Darmstadt, Germany y.el-mossallamy@arcadis.de

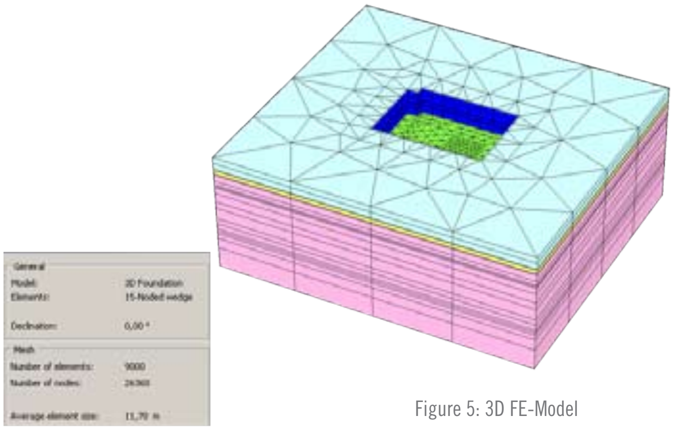


Figure 5: 3D FE-Model

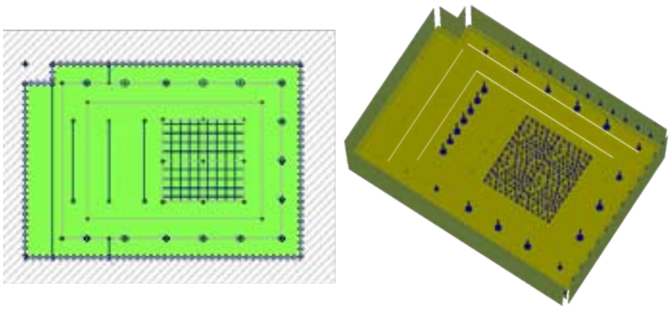


Figure 6: Applied loads

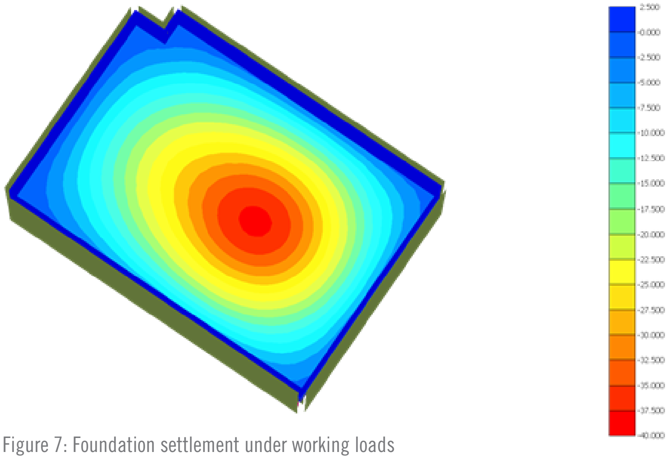


Figure 7: Foundation settlement under working loads

Numerical model

Soil Parameters

The soil stress-strain relationship was modelled applying the Hardening soil model. The main advantage of this constitutive law is its ability to consider the stress path and its effect on the soil stiffness and its behavior. For the concrete piles and raft, a linear elastic material set was applied using the concrete weight and its stiffness. The ultimate skin friction of the pile is assumed to start with 60 kPa at the pile head and increased with depth to reach 120 kPa at the pile tip. The ultimate pile base resistance was taken equal to 2.0 MPa.

3D Finite element model

Work-planes are defined. The Work-planes are needed at each level where a discontinuity in the geometry or the loading occurs in the initial situation or in the construction process. Figure 5 shows the applied three dimensional finite element mesh. The main model geometries are given in figure 6.

Inspect output

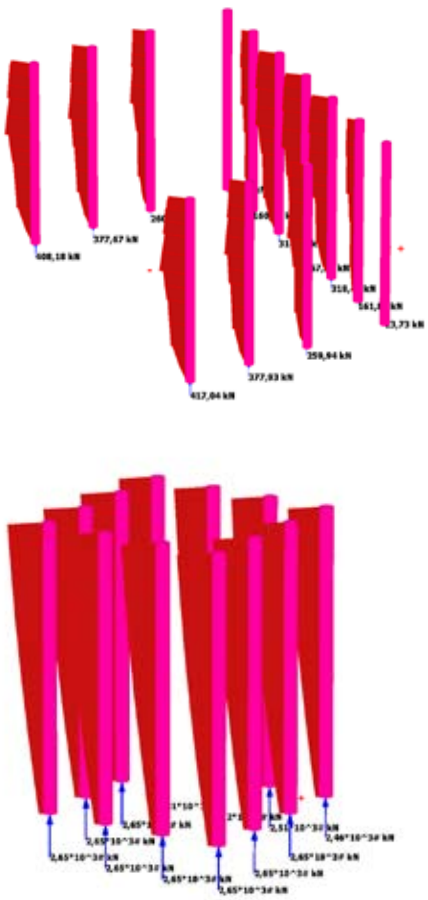
The initial conditions should be generated using the K_0-procedure. A value of $K_0 = 0.8$ is applied to consider the effect of overconsolidation. The aim of the calculation is to determine the average settlement of the rafts under working load (serviceability limit state). Figure 7 demonstrates the raft settlements under working loads.

Settlement of about 4 cm is calculated at the raft center. This value agrees well with the measured value and approves the ability of the three dimensional analyses to predict the settlement of the piled raft as a main part of the foundation design. Figure 8 shows the load distribution among the individual piles within the pile group. It can be recognized that the contribution of the edge piles by carrying the loads is very small. This is due to the presence of the outer wall that works also as shoring system, which is modelled as fully connected with the foundation raft. The effect of the outer walls can be investigated by applying a new model in which the outer walls are not modelled.

Conclusion and Outlook

The illustrated examples show that understanding of the effects of the interaction between construction and subsoil based on the appropriate theoretical knowledge and on experienced application of measurement techniques and numerical modelling are the necessary qualification for a safe and economic design for such complex foundations.

The piled raft foundation can be modelled using the embedded piles that are available in Plaxis 3D foundation. The results should be further compared with cases where the piles are modelled using volume elements. There is still need of horizontal interface elements to investigate the raft contact stresses in a direct manner. The embedded piles help to reduce the required number of elements needed to model the complex three dimensional feature of piled rafts. The experience with this model type should be gathered with time and shared among the Plaxis users. The effect of the shoring system on the behavior of piled raft needs further investigation.



Outer piles

Middle piles

Figure 8: Results of normal force distribution along all piles

Some related references

- Burland, J.B., Broms, B.B., and de Mello, V. (1977) Behaviour of foundations and structures, State-of-the- art report, Proc. 9th ICSMFE Tokyo, vol. 2, 495 - 546
- Butterfield, R., and Banerjee, P.K. (1971) "The problem of pile group-pile cap interaction." Géotechnique, Vol. 21, No. 2, pp. 135-142.
- DIN 1054-100 (2005) Baugrund: Sicherheitsnachweis im Erd- und Grundbau
- Dürrwang, R., El-Mossallamy, Y. und Reininger-Behrenroth, M.(2007) Neue Erkenntnisse zum Verformungsverhalten des Frankfurter Tones, Bautechnik, Vol.3, 190-192
- El-Mossallamy, Y. (1996) Ein Berechnungsmodell zum Tragverhalten der kombinierten Pfahl-Plattengründung., Dissertation, Fachbereich Bauingenieur-wesen der Technischen Hochschule Darmstadt
- El-Mossallamy, Y., Lutz, B., and Richter, Th. (2006) Innovative application and design of piled raft foundation. 10th International Conference on Piling and Deep Foundations, (31 May - 2 June 2006), Amsterdam, Netherlands
- El-Mossalamy, Y., El-Nahhas, F. and Essawy, A. (2006) Innovative Use of Piled Raft Foundation to Optimize the Design of High-Rise Buildings. 10th Arab Structural Engineering Conference, 13-15 November 2006, Kuwait
- El-Mossallamy, Y (2007) Piled raft foundation in Frankfurt clay. Validation manual, Plaxis 3D Foundation, Version 2
- Franke, E.; El-Mossallamy, Y.; and Wittmann, P.(2000) Calculation methods for raft foundations in Germany. Design applications of raft foundation and ground slabs, Edited by Hemsley, Published by Thomas Telford Ltd, London, 2000, p.p.283-322
- Hanisch, J., Katzenbach, R., und König, G. 2002. Kombinierte Pfahl-Plattengründung, In Zusammenarbeit mit dem Arbeitskreis „Pfähle“ der Deutschen Gesellschaft für Geotechnik e.V. (DGGT), Ernst & Sohn.
- Poulos, H.G., and Davis, E.H. (1980) Pile Foundation Analysis and Design. Wiley, New York.
- Randolph, M.F. and Clancy, P. (1993) Efficient design of piled rafts. Proc. 2nd Int. Seminar, Deep foundation, Ghent, 119-130.