Environment-friendly and economically optimized foundation systems for sustainable high-rise buildings

Systèmes de fondations respectueux de l'environnement et optimisés économiquement pour des gratte-ciel durables

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ABSTRACT: According to the technical and environmental standards and requirements all types of foundation systems of high-rise buildings have to be analysed regarding stability, serviceability, environmental impact and sustainability. Therefore, environment-friendly and economically optimised foundation systems have to be designed. For safety and quality assurance an independent peer review and the observational method have to be applied. By using technically optimised load tests or advanced numerical simulations, hybrid foundation systems like the Combined Pile-Raft Foundation (CPRF) or re-used existing foundation elements can be environment-friendly and economically designed and optimised. Based on these global requirements regarding sustainability, CO_2-reduction and environmental compatibility the paper presents the basics and the application of advanced and challenging foundation concepts by an outstanding example from engineering practice in Germany.

RÉSUMÉ: Conformément aux normes et exigences techniques et environnementales, tous les types de systèmes de fondation de gratte-ciel doivent être analysés en termes de stabilité, aptitude au service, impact environnemental et durabilité. Cela nécessite de concevoir des systèmes de fondation respectueux de l'environnement et optimisés économiquement. Un examen indépendant par des pairs et la méthode observationnelle doivent être appliqués afin d'assurer la sécurité et la qualité de l'ouvrage. En utilisant des essais de chargement optimisés techniquement ou des simulations numériques avancées, les systèmes de fondations mixtes de type radier sur pieu (Combined Pile Raft Foundation - CPRF) ou la réutilisation d'éléments de fondation déjà existants peuvent être à la fois respectueux de l'environnement et optimisés économiquement. Basé sur ces exigences globales en matière de durabilité, de réduction des émissions de CO_2 et de compatibilité environnementale, cet article présente les bases et l'application de concepts de fondation avancés et complexes avec un exemple exceptionnel de la pratique de l'ingénierie en Allemagne.

KEYWORDS: Combined Pile-Raft Foundation, environment-friendly construction, observational method, peer review

1 INTRODUCTION

For sustainable construction an economic and environment-friendly design is necessary (Vaniček 2008, Katzenbach et al. 2011). The World Commission on Environment and Development defined sustainability as follows: "Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). A scheme of the main constituent parts of sustainable development is shown in Figure 1.

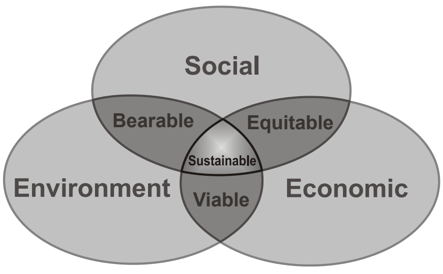

Figure 1. Scheme of sustainable development.

For reaching sustainability economical, environmental and social aspects have to be considered. The design of sustainable geotechnical structures leads during construction and service time to a reduction of materials, time, money and energy (Katzenbach et al. 2010b, 2010c). Therefore, a systematic planning and design method for the optimization between technical and financial efforts to reach the biggest benefit and social acceptance with the smallest environmental impact is needed. Regarding these goals, in geotechnics and other construction fields, the following basic aspects for a successful design of complex foundation systems have to be considered:

- qualified experts for planning, design and construction
- interaction between architects, structural engineers and geotechnical engineers
- adequate soil investigation beforehand
- consideration of the soil-structure interaction during the design phase, using the Finite-Element-Method (FEM) in combination with enhanced in-situ load tests for calibrating the soil parameters used in the numerical simulations
- quality assurance by an independent peer review process (4-eye-principle) combined with the observational method if necessary (Katzenbach et al. 2010a)

For any type of construction, the optimization process has to consider the efforts of construction and the efforts during the period of operation.

In the following a challenging large construction project is presented to explain the development and the construction of an environment-friendly and economical optimized foundation system.

2 ENVIRONMENT-FRIENDLY AND ECONOMICALLY OPTIMIZED FOUNDATION SYSTEM - EXAMPLE FROM ENGINEERING PRACTICE

2.1 *Project overview*

In Frankfurt am Main, Germany, a new building complex is realized on a construction site with 21,000 m². An overview of the project area is given in Figure 2. The new building complex is situated nearby a historic monastery in the east, the river Main in the south, a metro tunnel in the west and a street and metro tunnel in the north. The building complex consists of 6 parts, 4 of them are high-rise buildings. Regarding the complex construction process in several steps and the soil-structure-interaction between existing buildings, new buildings, the metro and street tunnels and an existing sewer line the project has to be classified into the Geotechnical Category 3 according to EC 7 (CEN 2008, DIN 2014). The Geotechnical Category 3 is the category with the highest factor of complexity.

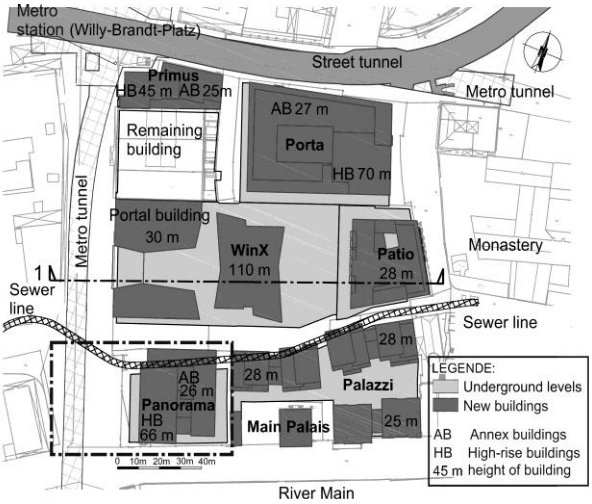

Figure 2. Project overview with Panorama building in the south-west.

2.2 *Soil and groundwater conditions*

The soil conditions can be summarized as follows:

- fillings with a thickness of 2 m to 10 m
- quaternary sand and gravel down to 11 m under surface with a thickness of 1 m to 9 m
- tertiary Frankfurt Clay, consisting of alternating layers of clay, limestone and sand, down to 35 m under surface
- Frankfurt Limestone

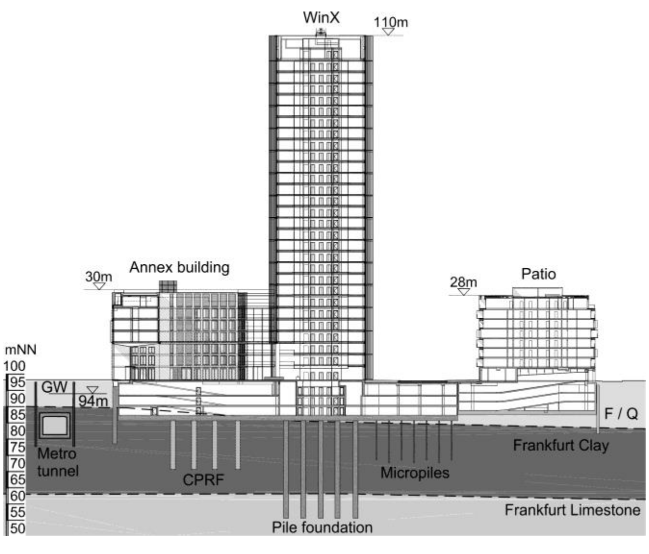

Figure 3. Cross section 1-1 of Figure 2.

The upper groundwater level is in the quaternary sand and gravel layer between 4 m and 6.5 m below the surface. The lower groundwater level is in the tertiary limestone and sand layers. The lower ground-water level is normally confined. The cross section in Figure 3 shows the soil and groundwater conditions as well as the new structures.

2.3 *Foundation system*

Depending on the loads of the building complex the foundation systems vary in relation to the loads:

- spread foundations
- classic pile foundations
- micropiles
- Combined Pile-Raft Foundation (CPRF)

For the optimization of the deep foundation elements, two pile load tests were carried out on the construction site. Using the results of the pile load tests the distribution of the stiffness of the soil model was calibrated by numerical back-analysis using the Finite-Element-Method (FEM). The test set up of Test-Pile1 (TP1) is shown as an example in Figure 4.

TP 1 ends in the Frankfurt Clay. TP 2 ends in the Frankfurt Limestone. The load on the piles was given by Osterberg Cells (O-Cell). The test piles consist of three segments: the upper, the middle and the lower one. These are divided by the upper and the lower O-Cell. Additionally, to measure stress and deformation values, the test piles were equipped with the following measurement devices:

- strain gauges in the upper, the middle and the lower pile segment
- stack extensometer from surface to the pile top, to the upper O-Cell, to the lower O-Cell and to the pile toe
- extensometer between the O-Cells
- displacement transducer inside the O-Cells

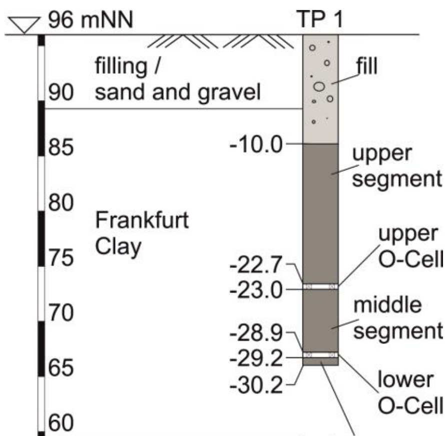

Figure 4. Test set up of pile load test TP 1.

According to Eurocode EC 7 resp. DIN EN 1997-1 the results of the pile load tests were reduced by the factors of variation (Seip et al. 2014). Table 1 shows the characteristic skin friction and base resistance under consideration of the factors of variation.

Table 1. Characteristic values for skin friction and base resistance.

Skin friction Frankfurt Clay	0.16 MN/m²
Base resistance Frankfurt Clay	1.80 MN/m²
Skin friction Frankfurt Limestone	1.30 MN/m²

Using the back-analysis of the pile load tests the developed numerical soil model was calibrated. As an example, Figure 5 shows the measured displacements of the pile load test in-situ and the calculated displacements of the back-analysis in one of the test phases.

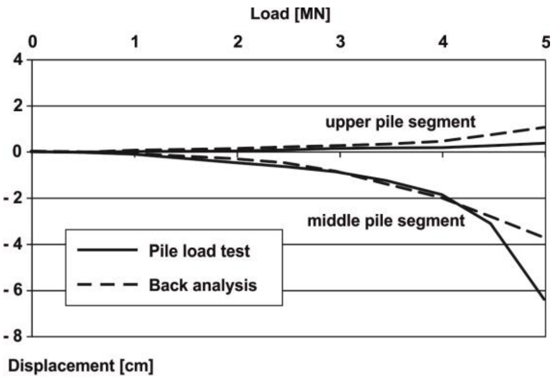

Figure 5. Measurement and back-analysis of one phase of a pile load test.

The soil mechanical parameters detected during the soil investigation were updated according to the results of the back-analysis. The results of the back-analysis were the basis for the following 2-dimensional and 3-dimensional numerical analysis.

2 .4 *Numerical analysis*

For the determination of the complex soil-structure-interaction between existing buildings, new buildings, the metro and the street tunnels and the sewer line, several 2-dimensional and 3-dimensional, non-linear numerical analysis using FEM have been carried out. For example, the numerical model of the south-west of the project area is shown in Figure 6.

The foundation system of this part of the project area combines a CPRF and a classic pile foundation. It has to be guaranteed that the existing sewer line does not get any load from the new buildings. For the reduction of the deformation of the sewer line the retaining structure does not get any vertical loads from the superstructure. For the settlement relevant loads the predicted settlements of the building is up to a maximum of 3 cm. The predicted settlements of the sewer line are smaller than 1.5 cm. The piles of the CPRF have a diameter of 1.5 m and a length between 14 m and 20 m. The CPRF-coefficient is $\alpha_{CPRF} = 0.6$ according to the CPRF-Guideline (ISSMGE 2013). This means, that 60 % of the total building loads are carried by the piles and 40 % of the total building load is carried by the raft. The piles of the classic pile foundation have a diameter of 1.5 m and a length of 24 m.

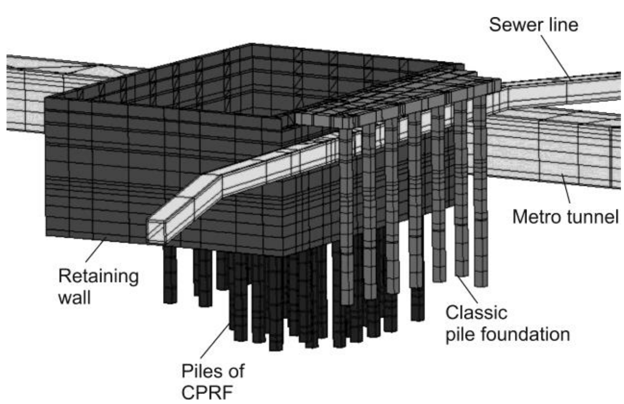

Figure 6. Numerical model of the south-west of the project area, Panorama building, view direction south-west.

In the area of the metro tunnel a 2-dimensional numerical analysis has been carried out in order to get more detailed information about the deformations, the variation of stresses during the different construction phases and the influence on the sealing system of the metro tunnel caused by the excavation and the construction of the retaining system.

The soil mechanical parameters have been varied for the study of the sensitivity of the metro tunnel. According to the results of the numerical simulations and the experiences made in the region of the project area, horizontal displacements of the metro tunnel of less than 1 cm are expected. Differential displacements of the tunnel blocks at the joints will be in the range of only a few millimeters. Based on the 2-dimensional and 3-dimensional numerical analysis no limitation of the serviceability and of course no damage of the metro tunnel are expected. The measured displacements of the tunnel blocks were less than 0.5 cm and the maximum differential displacement at the joint between the tunnel blocks was 0.1 cm.

2 .5 *Retaining system*

For the retaining system of the excavation in most cases bored pile walls have been used. The bored pile walls have been stabilized by struts or by anchors.

The maximum depth of the excavation in the south-west of Panorama building (Figure 2) for up to 4 basement floors is 14.3 m.

In order to adapt the retaining structure to the underground structures (sewer line and basement floors and retaining structures of the existing building) the piles with a diameter of 88 cm were combined with jet grouting columns to ensure a watertight pit and a maximum of flexibility regarding the difficult geometry.

Planning and design have been significantly influenced by the following aspects:

- sewer line directly beside the retaining wall
- existing underground parking with up to 3 basement floors north of the sewer line
- excavation for the buildings Palazzi (Figure 2) in the east
- several cables and sewer lines in the south
- metro tunnel in the west with a distance of about 20 m
- several remaining basements and former retaining systems

In areas with existing basements behind the retaining system the upper level of anchors has been carried out with a back anchoring into the existing, back-filled basement.

2 .6 *Construction phase*

For the construction of the excavation in the south-west of the project area the following special geotechnical constructions have been carried out:

- 3,700 m piles for retaining wall, d = 88 cm
- 10,500 m anchors for retaining wall
- 290 m special bars for anchoring into the existing, back-filled basements
- 36 t of steel for struts and girder beams
- 790 m foundation piles, d = 150 cm
- 415 m jet grout columns

Due to the tight time schedule, up to 4 big drilling rigs have been used by the contractor for the construction of the retaining walls (Figure 7).

After reaching the depth of the existing foundation raft, this reinforced concrete element with a thickness of up to 1.5 m was deconstructed. After tensioning the anchor in the upper and the middle level the foundation piles were constructed.

Figure 7. Construction of the bored pile wall.

To keep the tight schedule the installation of the anchors was carried out with up to 4 anchor drilling rigs parallel to the excavation works (Figure 8).

Figure 8. Anchor installation during excavation.

After the construction of the blinding concrete layer for preparation of the reinforcement of the foundation raft, the excavation including the retaining system and the foundation piles have been finished (Figure 9).

Figure 9. Construction of the blinding concrete layer.

3 CONCLUSION

The principle of a sustainable construction is not only based on standards and regulations but also on the newest technical developments of design, construction and control mechanisms. For safety reasons an independent peer review has to be applied. To explain how to apply an environmental-friendly, economically optimized and safe foundation a challenging large construction project with a very high complexity was presented in this paper.

For the optimized design an adequate soil investigation program, in-situ pile load tests and 2-dimensional and 3-dimensional numerical analysis have been carried out. The results of the soil investigation have been adapted by numerical back-analysis of the pile load tests.

The construction works for the retaining systems and the foundation systems have been carried out in a very tight time schedule, at last in less than 5 months. Regarding the categorization of the project into the Geotechnical Category 3 the observational method has been applied according to EC 7 (Katzenbach et al. 2010a). The measured displacements of the neighbouring buildings and underground structures have been at any time less than the predictions. No harmful situations have been detected. The monitoring will be carried out until the end of the construction works and during the first month of the service phase.

4 REFERENCES

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DIN Deutsches Institut für Normung e.V. 2014. *DIN EN 1997-1 Eurocode 7 - Geotechnical design - Part 1: General rules*. Beuth Verlag, Berlin, Germany.

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