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Challenging demands on the geotechnical design and first monitoring results of the T185 in Frankfurt

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ABSTRACT: The foundation system for the high-rise building TOWER185 is an excellent example to show the specific considerations undertaken to design the building pit and the piled-raft foundation. On the basis of experiences made during the past 20 years in the design, the construction and the back-analysis of the load-settlement behavior of numerous high-rise buildings in Frankfurt and consequently the well known soil and groundwater conditions, a realistic soil-structure-interaction-behavior in combination with numerical methods could be applied to design an optimized foundation system for the TOWER185. Since the center of area does not correspond to the center of mass certain considerations had to be taken into account in order to reduce the tilting of the tower and to guarantee the serviceability.

1 GROUND INVESTIGATIONS

The ground investigations are essential preliminary to the construction of high-rise buildings. The objectives of a ground investigation are to obtain reliable information to generate an economic and appropriate design, to evaluate all conditions associated with the ground and the groundwater as well as to meet the requirement for the tendering, the construction, the time and the cost schedule. The results and the interpretation of the investigations are crucial factors for the stability and serviceability of the structure. Especially when designing high-rise buildings the ground and groundwater conditions as well as all relevant geological data must be investigated in detail. The ground conditions have to be worked out by a geotechnical engineer. The investigation can consist of:

– Direct investigations (drillings, trial pits)
– Geophysical methods (crosshole seismic)
– Field and laboratory tests (geotechnical / geothermal)
– Load tests (plate or pile)

In order to evaluate the ground conditions within the area of the project T185 properly, 11 boreholes with length up to 110 m were interpreted. The ground encountered consists of Quaternary sands down to 5 m below the surface followed by the so called Frankfurt clay which was formed 2 to 10 million years ago as a result of the sedimentation in the Tertiary sea in the Mainz basin (Fig. 1). This clay includes limestone banks and layers of calcareous sand. The clay is geologically overconsolidated through older, already eroded sediments. Therefore, the subsoil is highly horizontally stressed.

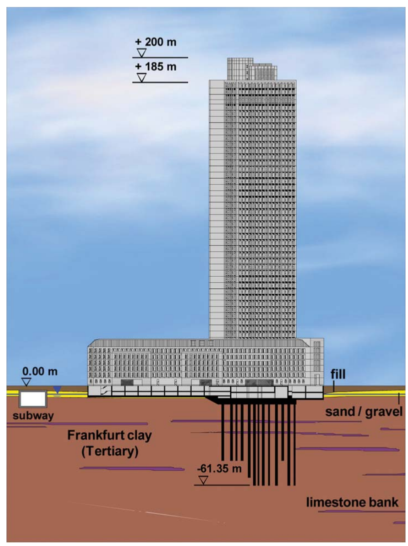

Figure 1. Ground model.

The first groundwater level in the Quaternary sands is approximately 3 m below ground surface. The second groundwater level is perched and circulates in the fissured limestone banks and sand lenses. The energy level of the perched groundwater level in the Tertiary reaches the level of the Quaternary groundwater level.

2 PIT CONSTRUCTION

Due to the above mentioned ground conditions, the influence on adjacent structures (subway, buildings etc.) and the presence of ground/groundwater contaminations in some areas, the lowering of the groundwater tables had to be prevented. This could be achieved by applying an impermeable retaining wall around the excavation area. In order to reduce the energy level in the Tertiary sediments it is necessary to install pressure relief wells distributed over the pit area. The length of these relief wells is governed by the uplift situation of the excavation level.

The retaining wall consists of secant pile walls as well as of diaphragm walls (Fig. 2). To optimize construction time the excavation area was divided into two areas. The excavation level within the tower area is 85.75 mNN (–11.5 m) and for the low-rise complex 90.0 mNN (–7.0 m). The areas are divided by a diaphragm wall without reinforcement. By means of the pit division the two areas were treated accordingly regarding the length of the retaining walls, dewatering situation and excavation process, which led to optimization in terms of buildings costs and construction time. The bottom of the retaining wall for the tower area reaches down to 75.50 mNN (–21.5 m) respectively down to 85.5 mNN (–11.5 m) for the low-rise complex (Fig. 3).

The serviceability of the adjacent subway and the sewage channel directly next to the retaining wall had to be guaranteed at all times. Since a conventional anchoring system could not be applied, the retaining wall was supported by struts with temporary pressure cells to pre-stress the retaining wall and additional piles with anchoring system (Fig. 3). In order to prove the serviceability of the adjacent subway plane numerical simulations were carried out. The construction phases were simulated in detail. The calculated deformations are presented in Figure 4. In consequence of the high-qualified construction works in this cross section the monitored deformations added up only to 0.5 cm and were in good agreement with the calculated deformations.

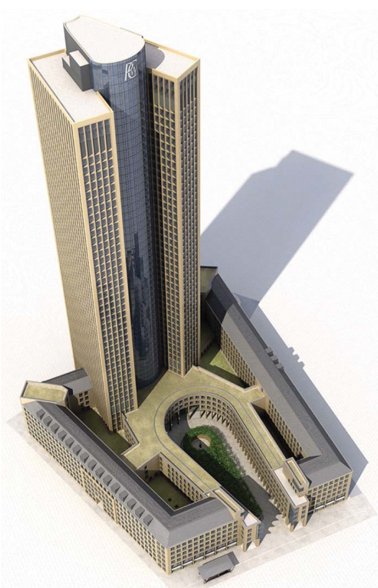

Figure 2. Animation picture.

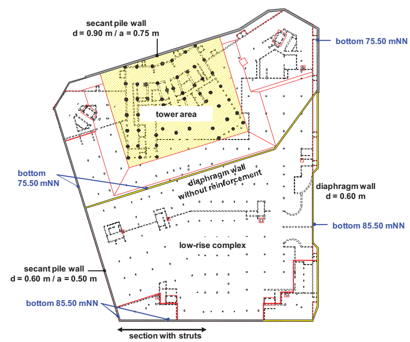

Figure 3. Layout plan building pit.

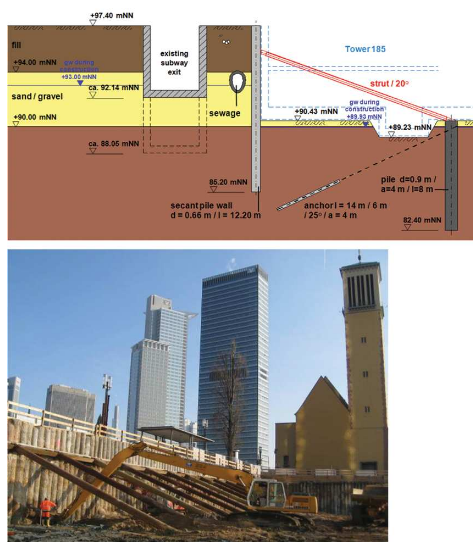

Figure 4. Building pit—cross section subway.

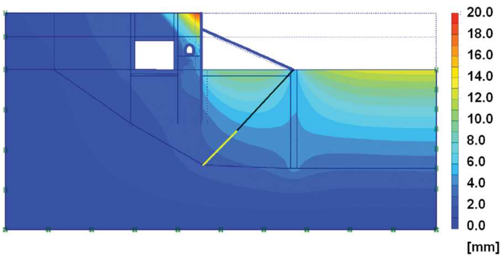

Figure 5. Building pit—Numerical simulation.

3 FOUNDATION SYSTEM

Design of a foundation has to satisfy always the following conditions:

– Factor of safety against failure of the foundation and of the supporting soil has to be adequate at Ultimate Limit State (ULS)
– Settlement of the foundation, as a whole and in particular differential settlements under working loads, should not be so large as to affect the serviceability of the structure at Serviceability Limit State (SLS)
– Safety and stability of nearby buildings and services must not be put at risk at Ultimate Limit State (ULS)/Serviceability Limit State (SLS)

With increasing height of buildings respectively increasing loads a raft foundation is not suitable to transfer the loads properly into the ground. Therefore a pile foundation is often used. The main function of a pile foundation is to transfer all loads by piles to a lower level of the ground which is capable of sustaining the load with an adequate factor of safety (ULS).

In addition to the often used raft or pile foundation, the innovative piled-raft foundation is nowadays often used to transfer the loads into the ground. In comparison to a pile foundation, in the piled-raft foundation, both the piles and the raft transfer the loads into the ground. The loads are transferred by skin friction and end (toe) bearing as well as contact pressures of the raft with the ground (bearing pressure). The piles are used up to their ultimate bearing capacity (load level) which is higher than the allowable design value for a comparable single pile. The piled-raft foundation represents a complex foundation system, which requires a qualified understanding of the soil-structure interactions.

The task for the geotechnical engineer is to evaluate by means of numerical calculations the load distribution between the piles and the raft as well as the pile stiffness parameter and the subgrade modulus. The distribution of the total load between the raft and the piles is described by the coefficient of the piled-raft foundation.

The piled-raft foundations system can lead to the following advantages in comparison to a raft or pile foundation:

– Reduction of settlements and differential settlements of structures
– Reduction of tilt in consideration of eccentric loading or inhomogeneous soil conditions
– In case of hybrid foundation it is possible to avoid joints in the raft
– Reduction of number of piles and pile length in comparison to a pile foundation
– Reduction of forces, stresses within the raft in case of an optimal position of the piles

In case of the high-rise building T185 various three-dimensional numerical simulations with the Finite-Element-Method were carried out in order to obtain an optimized foundation design. The following geotechnical idealizations were considered for the mesh generation:

– Tower area: modeling under consideration of the symmetries (raft: 3.5 m)
– Location of the piles
– Piles with diameter of 1.5 m (piles are modeled quadratically with the same skin area)
– Relevant areas of the connected low-rise buildings (raft thickness: 0.9 m)

The three-dimensional numerical model consists of continuum wedge elements with 15 nodes and 6 integration points for each element. Simulations with the Finite-Element-Method are always based on material laws. A material law can be depicted as the mathematical relation between stress and strain. A number of material laws for soil mechanical applications are available. The appropriate law has to be used in respect of the particular problem and the scientific objective. In this case the elastoplastic Hardening Soil model was used. The yield surface of the Hardening Soil model consists of two parts in the principal stress space (conus and cap). They can expand due to plastic straining. Furthermore it is distinguished between different stiffness of the material for loading, unloading and reloading. The deformation behavior can be simulated with a hyperbolic relationship between the vertical strain and the deviator stress. Both the shear conus and the yield cap have the hexagonal shape of the classical Mohr-Coulomb failure surface. The cap expands as a function of the pre-consolidation stress. The Hardening soil model involves six parameters.

Due to the eccentric loading situation of the overall system various numerical simulations were carried out to find the optimal pile length and to minimize the tilting of the tower. Piles within the core of the tower area as well as at one edge of the tower had to be longer (l = 50 m). The calculated settlements under serviceability loads add up to nearly 10 cm (Figs. 6 and 7).

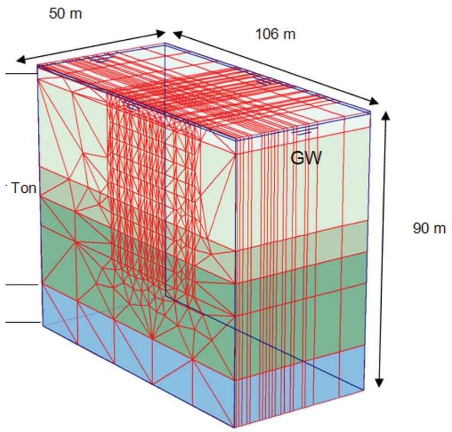

Figure 6. Numerical model.

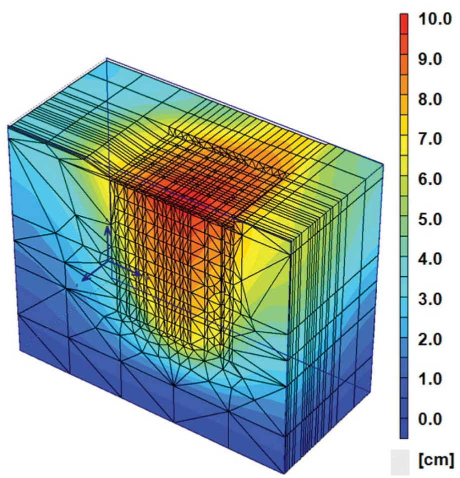

Figure 7. Calculated settlements.

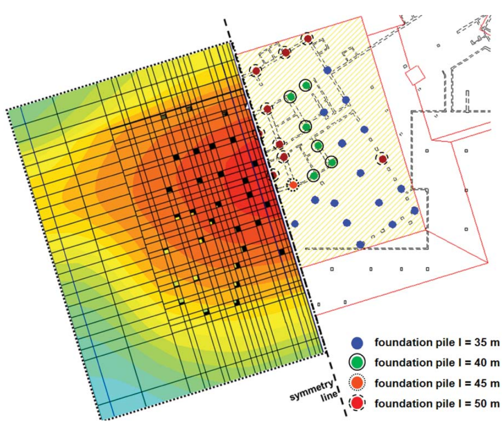

Figure 8. Settlement plot (layout) and pile layout plan.

4 MONITORING PROGRAM (OBSERVATIONAL METHOD)

A monitoring program to proof the quality of the foundation system is always recommended, so for the aforementioned high-rise buildings on a piled-raft foundation. With help of the program it is possible to compare the prognosis with the in-situ behavior of the foundation. The monitoring program must be worked out by a geotechnical expert in consideration of the foundation system, ground conditions, loading, construction phases, etc. The geotechnical expert has also to interpret all data obtained by the program. A typical monitoring program should consist of pile load cells, earth pressure cells, porewater pressure cells, extensometers and geodetical (gauging) bolts. The data can be collected for decisive construction phase or continuously.

In case of the T185 the monitoring program consists of 3 instrumented piles with load cells, 9 earth pressure cells, 2 porewater pressure cells underneath the tower raft and 20 geodetical (gauging) bolts on the raft.

5 MONITORING RESULTS

5.1 *Building pit*

The geodetical measurements of the retaining wall showed a maximal head displacement of 23 mm within the tower area and 15 mm within the low-rise area. Within the section with struts the displacements added up to only 5 mm. The adjacent subway construction showed displacement of smaller than 3 mm. All measured results were within the prognosis.

While dewatering works were carried out, the withdrawn amount of (ground)water was documented as well as 12 groundwater standpipes within the area of the pit. Figure 9 shows that ca.

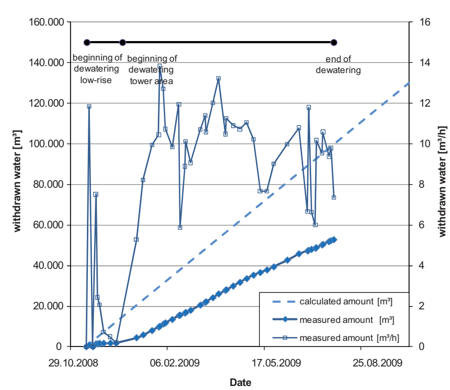

Figure 9. Dewatering: calculated/measured comparison.

53.000 m³ of (ground)water has been withdrawn. This is approximately 40% of the calculated amount. The groundwater standpipes showed nearly no influecne due to the lowering of the groundwater within the pit.

5.2 *Foundation*

Figures 9 and 10 illustrate the so far measured settlements of the construction. These results show a good correspondence with the calculated settlements. The maximum settlements so far add up to 4.1 cm. The calculated settlement for the final state is around 10 cm.

Figure 10. Measured settlements (09.07.2010).

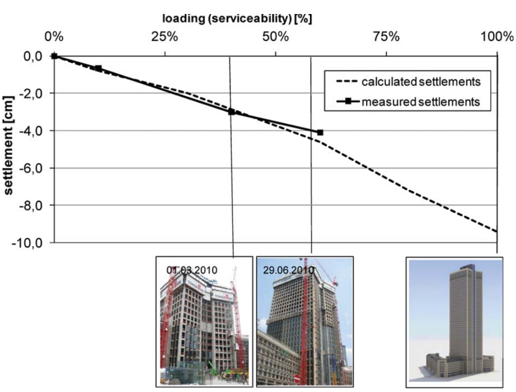

Figure 11. Settlement behavior: calculated/measured settlement.

6 CONCLUSIONS

On the basis of an extensive ground investigation and a detailed description of the ground, the foundation of high-rise buildings can be planned in an economic and safe manner. The choice of the adequate building pit and foundations system is often depending on the proof of the serviceability of the high-rise building and/or neighboring structures.

The conventional design of a pile foundation assumes that the load acting on the piles must be carried by the piles alone with a margin of safety against failure. This approach can be considered as conservative especially when piles are acting mainly as friction piles.

Where friction piles are primarily used to reduce settlements (satisfy the serviceability) and where an adequate factor of safety against failure is provided, the innovative piled-raft foundation has been put forward in the past. The essence of the piled-raft foundation is to employ piles so that settlements are reduced to an acceptable amount. The successful design and construction has been verified by many structures including many high-rise buildings.

Based on the theoretical knowledge and a qualified understanding of the soil-structure interaction numerical simulations can be used especially to optimize buildings pits and foundation systems and to evaluate deformations of the structure and neighboring structures.

By carrying out a monitoring system it is possible to verify the assumptions made and to improve the design methods for future projects.

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