Foundation design for the extension of an existing high-rise building

Dessin de la fondation pour l'agrandissement d'un gratte-ciel existant

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ABSTRACT

In Frankfurt, Germany, the existing 97 m high rise building SGZ-Bank has been heightened and extended to become the 111 m high Parktower. Based on foundation design by means of threedimensional elastoplastic finite element analysis, the extension of the high rise has been founded on a piled raft in the Frankfurt clay. The results of geotechnical and geodetic measurements, which are carried out to monitor the performance of the foundation, are presented.

RÉSUMÉ

À Frankfurt en Allemagne l'immeuble existant de la banque SGZ d'une hauteur de 97 m a été rehaussé et agrandit pour devenir le Parktower d'une hauteur de 111 m. Le dessin de la fondation et basé sur calculs tridimensionnels élastoplastiques des éléments finis. L'agrandissement est fondé sur une combinaison dalle-pieux dans l'argile de Frankfurt. Le résultat des calculs géotechniques et mesurages géodésiques obtenus pour la qualité de fonctionnement de la fondation sont présentés ci-dessous.

Keywords : extension of a high-rise building, piled raft, overconsolidated clay, 3D finite element analysis, measurements

1 INTRODUCTION

In Frankfurt, Germany, the existing 97 m high rise building SGZ-Bank has been heightened and extended to become the 111 m high Parktower (Figure 1). During the construction works the existing building has been stripped to the load-bearing system and the storeys No. 22 to No. 24 have been completely demolished. On the north-eastern side of the building 28 new storeys have been constructed and tied monolithically with the existing structure resulting in the challenging task to synchronize the deformations of the existing and the new foundation. A detailed discussion of the structural aspects of the construction is given by Remmel et al. (2005).

The extension of the building has been founded on a piled raft foundation in the Frankfurt clay. The piled raft comprises 16 piles with a length of L_p = 33.5 m and a diameter of d_p = 1.38 m and a raft with a thickness of t_r = 2.5 m.

In the scope of this paper the settlement history of the existing SGZ-Bank, the design analysis and the results of the geotechnical and geodetic measurements during the construction process will be presented.

2 SUBSOIL CONDITIONS

The subsoil condition on the project site is characterised mainly by tertiary soils and rock with artificially filled soils and quaternary sand and gravel with a thickness of approx. 5 m just below the ground surface. The tertiary soils consist of Frankfurt clay with a thickness of 64 m at the top underlain by the rocky Frankfurt limestone. The Frankfurt clay is a stiff, overconsolidated clay with liquid limit, plastic index and natural moisture content very similar to the London clay (Butler 1975). Sand and limestone bands of varying thickness are embedded in the Frankfurt clay, which results in a nonhomogenous appearance of the layer as a whole. The compressibility of the Frankfurt limestone, which is composed of massive limestone and dolomite layers, algal reefs, marly calcareous sands and silts and marly clay, is small compared to the Frankfurt clay. Since the boundary between Frankfurt clay and Frankfurt limestone is dipping slightly to northwest, the thickness of the clay layer on the project site is smaller than for the well known case histories Messeturm, Westend 1 and Torhaus (e.g. Reul & Randolph 2003).

The groundwater circulates in the quaternary sand and gravel as well as in the tertiary sand and limestone bands while the tertiary clay is practically impermeable. The quaternary and tertiary groundwater layers are connected. A groundwater drawdown in the tertiary layers may result in a reduction of the hydraulic head within an area with a radius of several hundred meters. Measurements showed the groundwater level in a depth of approx. 6.8 m at the project site.

3 SETTLEMENT HISTORY OF THE SGZ-BANK

In the 1970s the 24-storey high rise building and a 2-storey building have been constructed. The whole building complex SGZ-Bank has 2 basement storeys. The structure of the old high rise building consists of a reinforced-concrete skeleton construction. The foundation comprises a raft with a thickness of t_r = 2.7 m with the foundation level situated in a depth of 10.8 m below ground level. The core of the high rise building which is located at the north-western edge of the building, had been built in advance using the slip-form construction method.

Due to the asymmetric position of the core, non-uniform settlements of the raft occurred from the beginning of the construction process, resulting in an increasing tilt towards the northern corner (Leonhardt 1972). As a consequence, the measures shown in Figure 2 were taken during the construction process to reduce the tilting, namely:

- Undercuttings had been dug out along two strips at the south-western and south-eastern edge of the raft of the high rise. According to Leonhardt (1972) the undercutting at the south-western edge closed during the construction process as soon as March/April 1971.
- Application of additional dead weight on the eastern extension of the raft, which had been constructed as a cantilever beam.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2072

- The raft of the 2-storey building is founded on two strip foundation, one of them located on the south-western edge of the raft of the high-rise.

The cavities under the eastern extension of the raft and under the 2-storey building had been created with the help of a styrofoam layer which had been dissolved by means of the injection of an organic solvent. As a result, a CHC-pollution of the groundwater was noticeable during all construction activities which took place on the site in the meantime.

The various measures mentioned above showed no long term improvement of the settlement performance of the high rise building. For the last available settlement measurement of this construction phase in 1980, the settlements amounted to s = 20.9 cm at the south-eastern corner (MP2) and s = 30.6 cm at the north-western corner (MP4) resulting in a deflection ratio (Burland et al. 1977) of the raft of Δ/L = 1/340 (Figure 2). However, there were no reports of damage to the structure of the high rise or to impairments of technical installations such as elevators caused by the significant deformations (Ripper & El Mossallamy 1999).

In 2000-2001 the 2-storey building was demolished and replaced by the new 6-storey Atrium building. To prevent heaves and as a result an increase of the tilting, caused by the removal of the strip foundation on the raft, 18 pre-stressed vertical anchors (length L_A = 46.5 m; diameter d_A = 36 mm) had been installed at the south-western edge of the high-rise building (Stahlmann et al. 2001).

The construction of the new Atrium building yielded only relatively small settlements of the high rise building, i.e. s = 1.2 cm at the south-eastern corner (MP2) and s = 0.3 cm at the north-western corner (MP4) related to the beginning of this construction phase.

4 FINITE ELEMENT ANALYSIS FOR THE FOUNDATION DESIGN OF THE NEW PARKTOWER

4.1 *Finite element model*

The foundation design of the new Parktower has been based on threedimensional elastoplastic finite element analysis. In the finite element model the soil, the piles and the raft are represented by first order solid finite elements of hexahedra (brick) shape. The finite element mesh is shown in Figure 3. The bottom of the finite element mesh corresponds with the bottom of the Frankfurt clay. The mesh comprises approx. 12,000 elements with a number of degrees of freedom of approx. 38,000. For the modelling of the contact zone between soil and raft and soil and the large diameter bored piles, thin solid continuum elements have been applied instead of special interface elements. The contact between structure and soil was described as perfectly rough. This means that no relative motion between the nodes of the finite elements that represent the structure and those of the finite elements that represent the uppermost layer of soil takes place. The material behaviour in the contact area was simulated by the material behaviour of the soil.

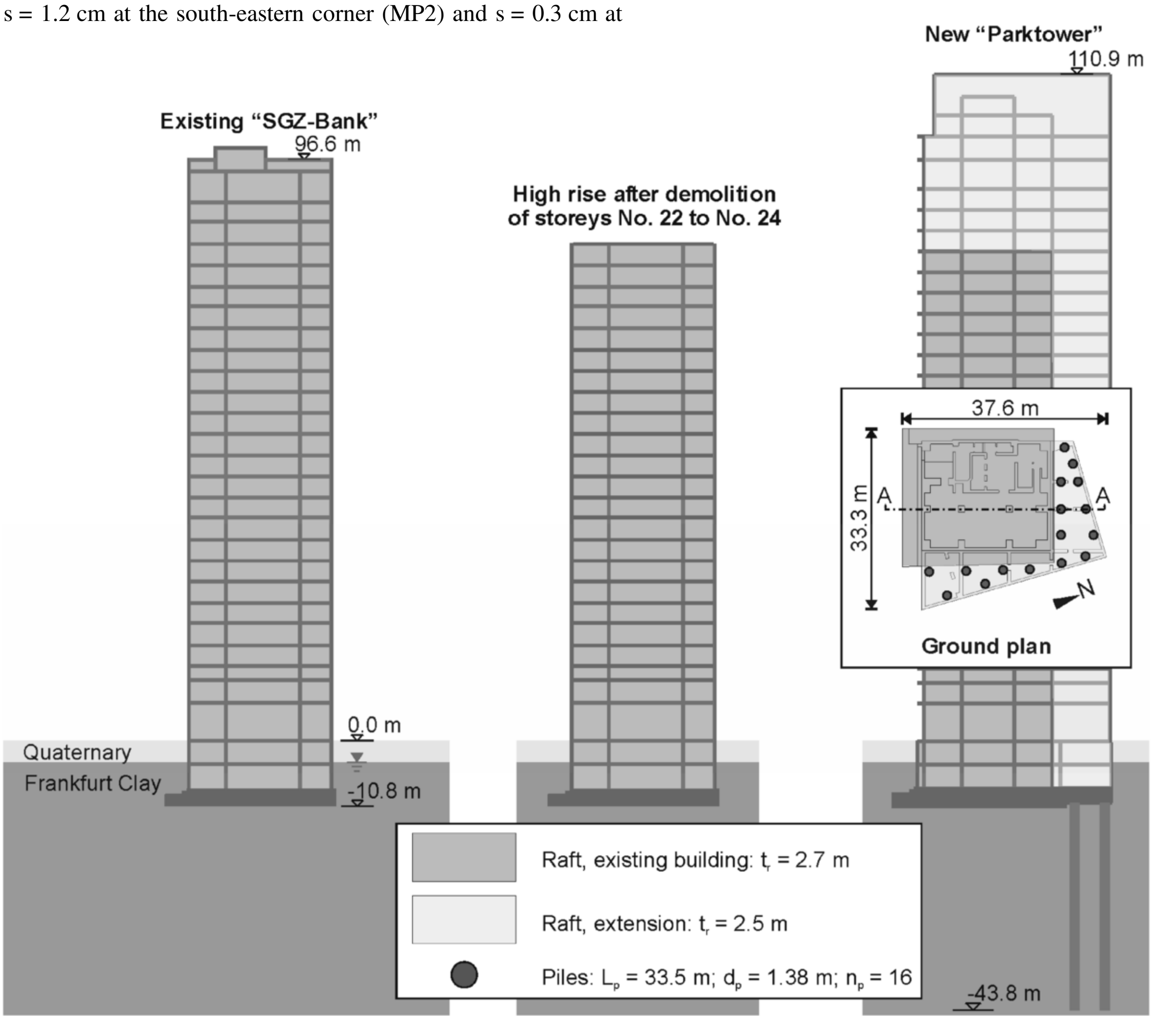

Figure 1. Cross-section and ground plan of the existing SGZ-Bank and the new Parktower

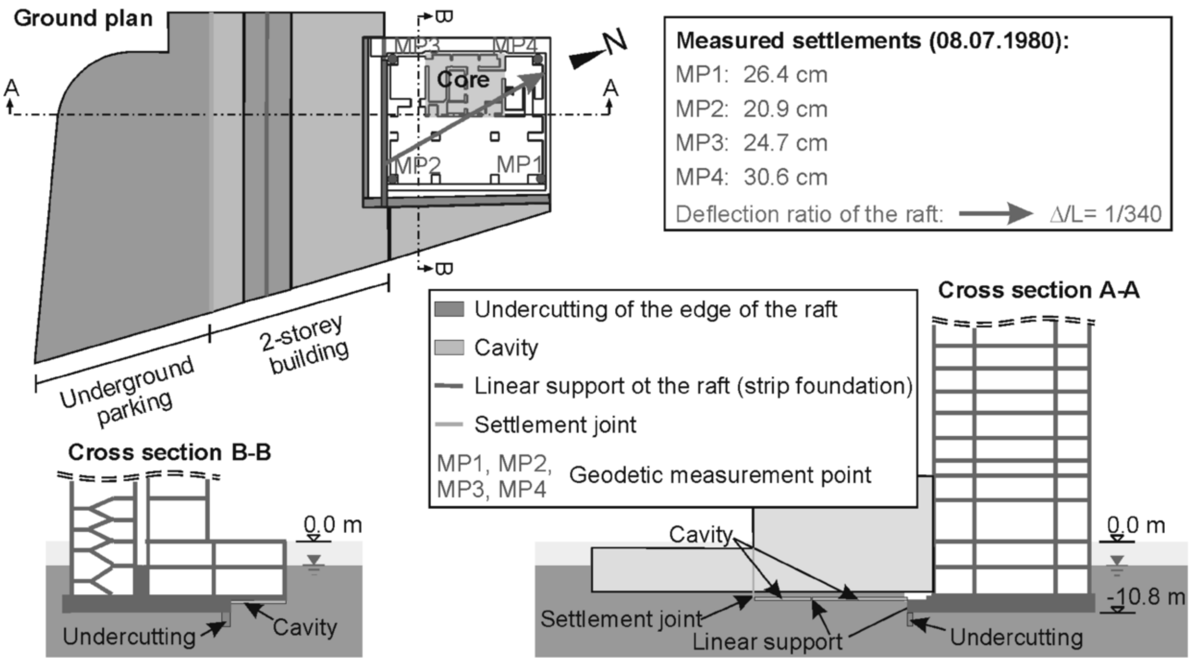

Figure 2. Constructions to reduce the non-uniform settlements of the SGZ-Bank

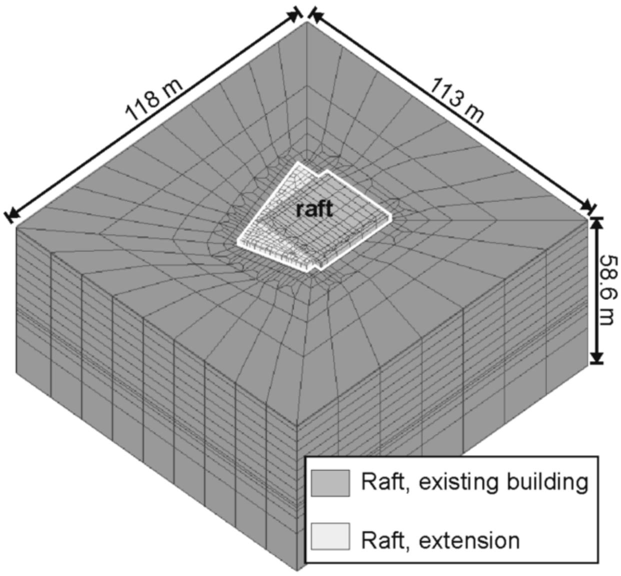

Figure 3. Finite element mesh

The material behaviour of the soil, i.e. the Frankfurt clay, is modelled with a Hardening-Soil (HS) model (FEAT 2005) where the relationship between strains and deviatoric stresses is approximated with a hyperbolic function. Shear hardening is used to model irreversible strains due to primary deviatoric loading. The raft and piles are considered to behave linear-elastically. A detailed description of the material model applied in the finite element analyses is given by Reul et al. (2007).

4.2 *Results*

The applied parameters for the Frankfurt clay as documented by Reul et al. (2007) have been calibrated based on the back analysis of the measured load-settlement behaviour of the existing SGZ-Bank. The undercuttings of the edge of the raft as described in section 3 have not been taken into account in the finite element model. Figure 4a shows the calculated settlement contours for the loading stage when the SGZ-Bank had been finished. There is a good agreement for the maximum settlement at the northern corner of the building while the settlement at the southern corner is underestimated due to the simplification mentioned above. Therefore the differential settlements and the deflection ratio of the raft are overestimated.

Figure 4b shows the calculated settlement contours for the piled raft (number of piles n_p = 16; pile length L_p = 33.5 m; pile diameter d_p = 1.38 m) for the loading stage when the new Parktower has been finished. The settlements are related to the stage when the storeys No. 22 to No. 24 of the existing high rise had been demolished.

Table 1 compares the main results of the finite element analysis for the piled raft and a hypothetical unpiled raft. The piled raft coefficient, α_{pr}, describes the ratio of the sum of all pile loads, ΣP_{pile} ,to the total load on the foundation, P_{tot} A piled raft coefficient of unity indicates a freestanding pile group whereas a piled raft coefficient of zero describes an unpiled raft.

The finite analysis shows that an unpiled raft would yield maximum deflection ratios of Δ/L_B = 1/150 and Δ/L_N = 1/220, respectively, which could not be tolerated. With the piled raft the deformations can be significantly reduced and the serviceability of the foundation can be ensured.

5 IN-SITU-MEASUREMENTS

According to design codes such as Eurocode EC 7 the foundations of high rise buildings are usually classed with geotechnical category GK3. Therefore in-situ measurements are an essential aspect of the safety concept. Furthermore they are used for the quality control and the documentation of deformations of the foundation and of neighbouring structures. In the present case, the deformations of the foundation and the subsoil are monitored with geodetic survey points in the basement as well as a multi-point borehole extensometer. The foundation has been equipped with strain gauges, contact pressure cells and pore pressure cells to establish the load transfer to the subsoil (Reul et al. 2007).

The measured settlements and pile loads in October 2007 after the building has been finished are documented in Figure 5. The measured pile loads show a significant bandwidth between P_p = 1.3 MN and P_p = 8.6 MN.

The maximum settlements amount to s = 1.6 cm in the area of the building extension and to s = 1.3 cm in the area of the existing building. The initial settlements of the raft, which are not included in the values documented above, can be estimated from other case histories to approx. $s_{initial} \leq 0.5$ cm.

Table 1. Results of the finite element analysis for the new Parktower: Comparison of the piled raft with a hypothetical unpiled raft

	$s_{max,B}$ [cm]	$s_{MW,B}$ [cm]	$s_{max,N}$ [cm]	$s_{MW,N}$ [cm]	Δ/L_B [-]	Δ/L_N [-]	α_{pr} [-]
Hypothetical unpiled raft	19.6	9.5	25.0	17.2	1/150	1/220	-
Piled raft (n_p = 16; L_p = 33.5 m; d_p = 1.38 m)	2.7	2.1	3.6	2.7	1/2250	1/8390	0.72

$s_{max,B}$ maximum settlement in the area of the existing building
$s_{MW,B}$ mean settlement in the area of the existing building
$s_{max,N}$ maximum settlement in the area of the extension
$s_{MW,N}$ mean settlement in the area of the extension
Δ/L_B deflection ratio of the raft in the area of the existing building
Δ/L_N deflection ratio of the raft in the area of the extension
α_{pr} piled raft coefficient

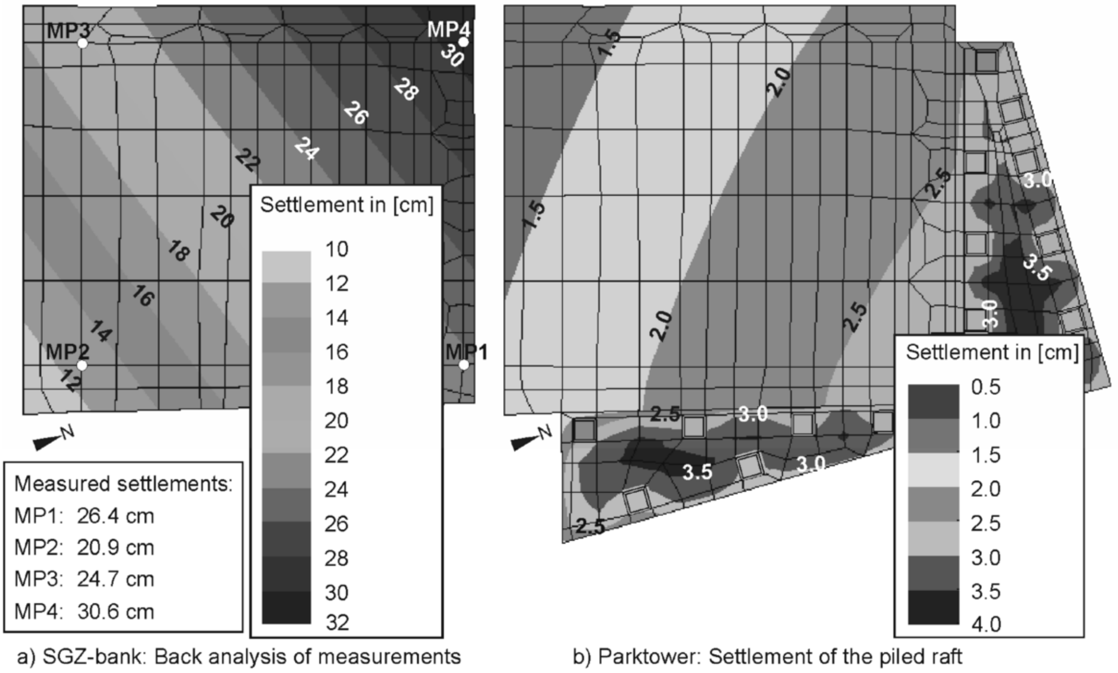

Figure 4. Calculated settlement contours

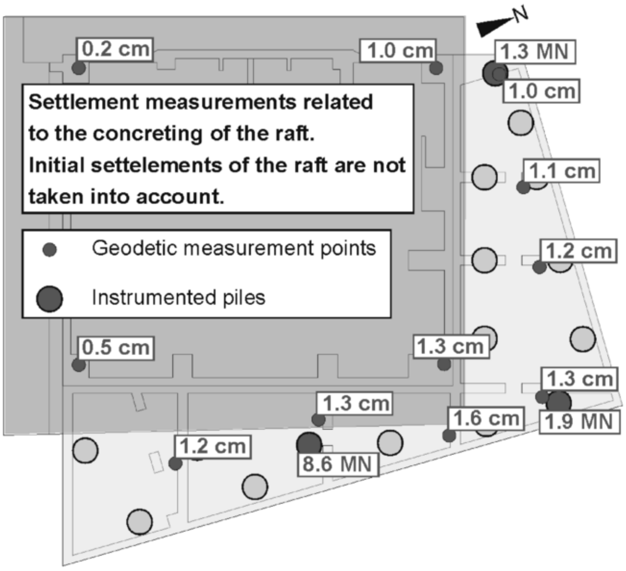

Figure 5. Measurements after the building has been finished

6 SUMMARY AND CONCLUSIONS

In the design process of the new Parktower the interaction between the existing high rise building and the extension had to be considered as well as the remarkable settlement history of the SGZ-Bank which shows maximum settlements of 31 cm and a deflection ratio of the raft of 1/340.

The settlements measured after the Parktower has been finished do not exceed the predictions based on 3D finite element analysis, which have been carried out for the design of the foundation.

For the revitalization of existing buildings in urban environments advanced numerical analysis for the prediction of deformations will be of major importance in the future.

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