Design of the retaining structure and piled raft foundation for a shopping centre

Conception de la structure de conservation et de la fondation de pieu pour un centre commercial

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ABSTRACT

This publication deals with the construction of a five-storey shopping centre in the city of Offenbach/Main, Germany. The building has two basement floors with a base area of about 7.200 m². The subsoil consists of a sand and gravel layer with a thickness of 5-7 m, followed by a high plastic clay of tertiary age. The groundwater level is about 3-4 m below surface. Up to 12.6 m deep excavation pit was built using a wall of staggered bored piles supported by grouted anchors. To reduce the water pressure on the wall only the high permeable quaternary layers were sheeted by the secant pile wall. In the tertiary layer every second pile only was installed with the required length. The gap between the bore piles was closed using shotcrete. The load of the shopping centre is carried by a piled raft foundation consisting of 130 bored piles with a diameter of 1.2 m. Pile length varies between 20 m and 30 m. The load-settlement behavior of the foundation was calculated using a 3D finite element analysis. The calculated bearing behavior was controlled by an extensive measurement program. The 130 piles are also used to extract and store geothermal energy.

RÉSUMÉ

Cette publication traite la construction d'un centre commercial á cinq étages dans la ville d'Offenbach/Main, Allemagne. Le bâtiment a deux étages de sous-sol avec une surface de base de 7.200 m². Le sous-sol se compose d´une couches de sable et gravier de 5-7 m d´epaisseur au-dessus d'argile tertiaire avec une plasticité fondamentalement haut. La nappe phréatique se trouve environ 3-4 m au-dessous de la surface. L´excavation d´une profondeur de 12.6 m est construit en utilisant un mur des pieux forés soutenues pardes tirants d´ancrages. Pour optimiser la distribution de pression de l'eau sur l'extérieur du mur les couches quaternaires perméables seulement sont blindées par des pieux sécant. Dans la couche tertiaire chaque deuxième pieux a été fabriqué jusqu'à la longueur nécessaire. L'espace entre les pieux est fermé avec le béton projeté perméable. La charge du centre commercial est supportée par une fondation sur radier combinée aux pieux se composant de 130 pieux forés d´un diamètre 1.2 m. Le longueur des pieux varie entre 20 m et 30 m. Le comportement de charge-tassement de la fondation a été calculé en utilisant une analyse élément fini 3D. Le comportement au chargement calculé était vérifié par un programme de mesure étendu. Les 130 pieux sont utilisés comme pieux-énergie thermique.

Keywords : piled raft foundation, retaining structure, finite element analysis

1 INTRODUCTION

Due to the increasing shortage of open space in the centre of the cities and the good possibilities and prospects for commercialisation shopping centres inhabit a great attractiveness for financial investors and project developers in Germany. The shopping centres are mostly multi-storey buildings with one and more basements. If the adjacent buildings are settlement sensitive constructions there are high requirements and restrictions concerning the horizontal and especially vertical deformations introduced by the construction process and the effective load of the structure. This will be more important if the ground consists mainly of over-consolidated and settlement active silt and clay like in the Rhein/Main area.

The above mentioned requirements and restrictions usually result in massive and rigid retaining structures such as a secant pile wall or diaphragm wall combined with pre-stressed anchors or struts. The vertical loading is mostly transferred into the deeper ground by means of a pile foundation.

Since a pile foundation as well as a secant pile wall or diaphragm wall are expensive geotechnical constructions, there is a high demand on improving and optimizing the design of these construction elements. The paper shows how this goal has been realised with smart engineering constructions like a partial waterproof retaining system and the application of the concept of piled raft foundation for the building.

2 SHOPPING CENTRE

The construction site of the shopping centre is situated in the city of Offenbach/Main in a distance of about 600 m to the Main River. In Figure 1 the cross section and in Figure 2 the plan views are shown. The base area of the excavation pit is about 7.200 m². The building consists of 5 stories, one basement floor in the western part and two basement floors in the eastern part of the plan view. So the maximum depth of the pit varies between 7.1 m in the western part and 12.6 m in the eastern part.

In the future the shopping centre will be connected at two levels with the existing parking deck situated at the eastern boarder of the construction site.

Figure 1. Cross section through the planed shopping centre.

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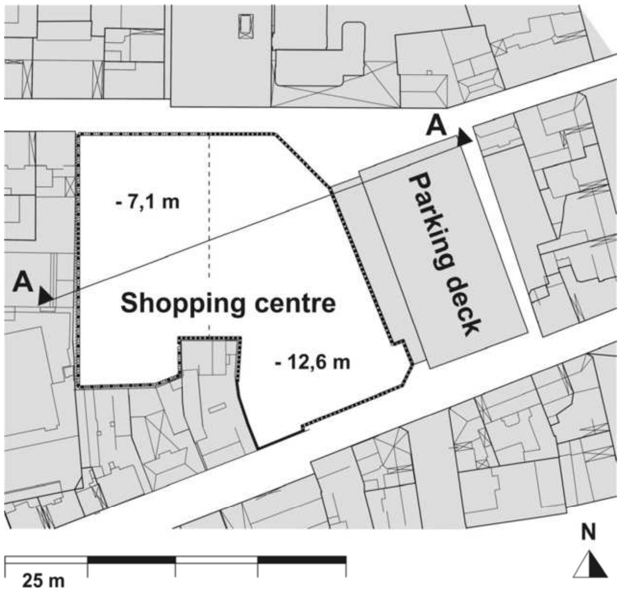

Figure 2. Ground plan of the planed shopping centre.

3 SUBSOIL AND GROUNDWATER CONDITIONS

3.1 *Subsoil conditions in Offenbach/Main*

To investigate the subsoil conditions 7 boring with a maximum depth of 40 m and 10 dynamic probing tests (DPH) were executed. According to the results the subsoil in the area of the planed shopping centre consists of an upper zone of fill with a thickness of about 1 m to 2 m. The fill is composed of sand and gravel with silt and has a loose density.

The fill layer is followed by a quaternary layer with a good bearing capacity of sand and gravel. The total depth of this layer varies between 4 m and 5 m. According to the results of the dynamic probing tests the quaternary layer is middle-dense to dense.

The base of the quaternary layer is formed by the tertiary clay layer. The clay (so-called “Rupelton”) is a high plastic clay without any sand layers or sand inclusions. The plasticity index I_P of the retained soil samples varies between 30 and 40% and the consistency index between I_C between 0.9 and 1.1. The average natural water content of the clay is about w_n = 25%. The toe of the tertiary clay layer is approximately between 80 m and 100 m below surface.

To investigate the stress dependant stiffness of the clay layer a series of compression tests were performed with samples taken at different depth. The result showed that there was a secondarily dependence of the stiffness from the samples depth. The bulk modulus varies between E_S = 20-30 MN/m² for the primary loading and E_S = 50-70 MN/m² for reloading.

3.2 *Groundwater conditions in Offenbach/Main*

In the city of Offenbach/Main the groundwater circulates in an upper and lower groundwater system. The upper system is formed in the quaternary sand and gravel and the lower in the karstified lime- and mudstone below the tertiary clay.

To monitor the ground water level in the area of the construction site 6 groundwater observation points were installed in the surrounding of the excavation pit. The measurements indicated that the groundwater level was about 3 m to 4 m below the surface. The hydraulic conductivity of the quaternary layer was estimated by the grain distribution and pumping tests in the immediate vicinity and is between about $k = 10^{-3}$ m/s and $k = 10^{-4}$ m/s. The conductivity of the clay is lower than $k < 10^{-9}$ m/s.

4 RETAINING SYSTEM

To excavate the pit a partial waterproof retaining wall has been installed (Figure 3).

The upper part between the surface and 1.5 m below the bottom of the quaternary sand and gravel layer consists of a secant pile wall with a pile diameter between 0.6 m and 1.2 m. Below this level every second pile only was extended. The gap between the two piles had been closed by shotcrete. To construct a water permeable system the shotcrete has been perforated with drainage holes.

The secant pile wall was supported by up to three levels of grouted anchors. The anchors are extended up to the tertiary clay layer and had a length of maximum 18 m including an injection body with a length of about 6 m. A characteristic anchor force of 350 kN was determined by suitability tests.

The design advantage of the partial impermeable system was the reduction of the water pressure acting on the wall. Compared to a totally impermeable system (e.g. secant pile wall over the whole height) the resulting water pressure could be reduced from 750 kN/m to 100 kN/m.

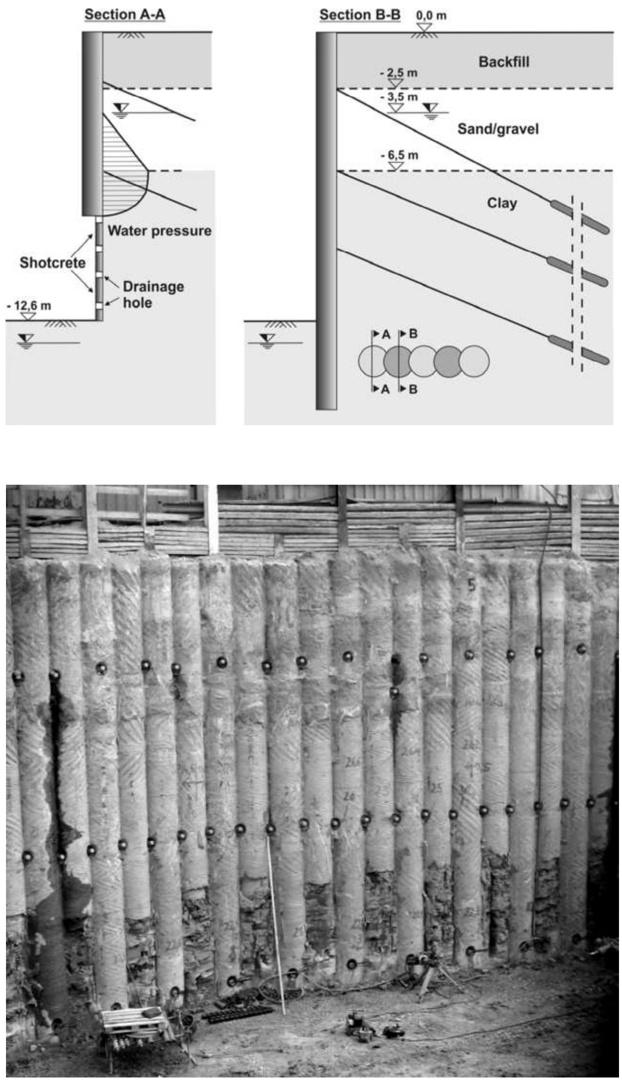

Figure 3. Photo and cross section through the retaining system.

The picture in Figure 3 shows the partially excavated pit before the shotcrete has been applied. The detail demonstrates that there is almost no water ingress from the clay.

5 PILED RAFT FOUNDATION (PRF)

5.1 *Concept*

The piled raft foundation is used to transfer the load to the underground both through the piles and the raft (Katzenbach et al. 2001). A piled raft foundation is an effective concept to reduce the load- induced vertical deformations, to decrease the differential settlements and to increase the bearing capacity of a comparable shallow foundation. The bearing behaviour is indicated by the different interactions between the pile, the raft and subsoil (Figure 4).

To characterise the bearing behaviour of a piled raft foundation the piled raft coefficient α_{pr} is used. α_{pr} is defined as the ratio of the load transferred through the piles (R_{pile}) to the total load (R_{tot}) applied to the foundation.

$$\alpha_{pr} = R_{pile} / R_{tot} \quad (1)$$

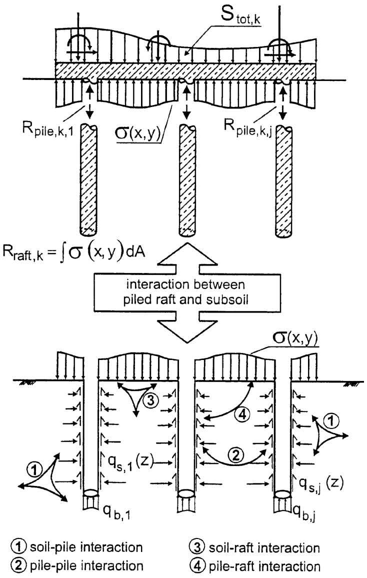

Figure 4. Soil-structure interaction of piled rafts.

To design a piled raft foundation it is necessary to use an appropriate calculation model that can simulate all the relevant interactions between the soil, the raft and the piles. The model should also consider the characteristics of the soil and the insitu stress level. For this purpose a numerical 3D model is used based on the finite element method (FEM) with an elastoplastic constitutive law is used.

5.2 *Calibration of the calculation model*

To calibrate and verify a numerical model the back-analysis of an existing piled raft foundation in the surrounding of the planned building is an appropriate method. In this case the HdW-building in a distance of about 250 m to the site was used. The calculations were carried out using the Plaxis 3D FOUNDATION (Ver. 2) program (Brinkgreve 2007). The piles were modelled using the embedded pile element. For the clay the hardening soil model with isotropic hardening was used.

The HdW-building has a height of 65 m and was founded on a piled raft with about 50 bored piles (Figure 5, 6). 18 month after the end of the structural works the measured settlements of the HdW-building were in the range of 2-3 cm (Reul 2000). The imposed load was about 850 MN.

The comparison in Figure 6 shows a good agreement between the measured and the calculated settlement and so the gained elastoplastic material parameters are used to calculate the load-settlement behavior of the planned shopping centre in Offenbach/Main.

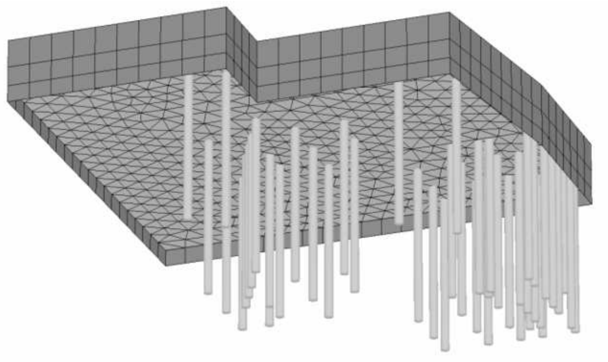

Figure 5. Finite element model of the piled raft inclusive the retaining system of the HdW-building.

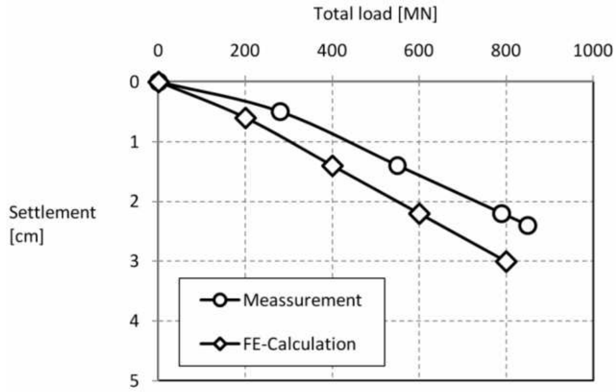

Figure 6. Comparison of measured and calculated load-settlement behaviour for the HdW-buildung.

5.3 *Numerical model*

Figure 7 shows the pile configuration and Figure 8 the numerical model of the piled raft of the shopping centre inclusive the retaining system. The whole model has the dimension of 178 m × 206 m and a height of 60 m. The piled raft consists of 36 bored piles (length 30 m) in the western part and 94 bored piles (length 20-25 m) in the eastern part of the building.

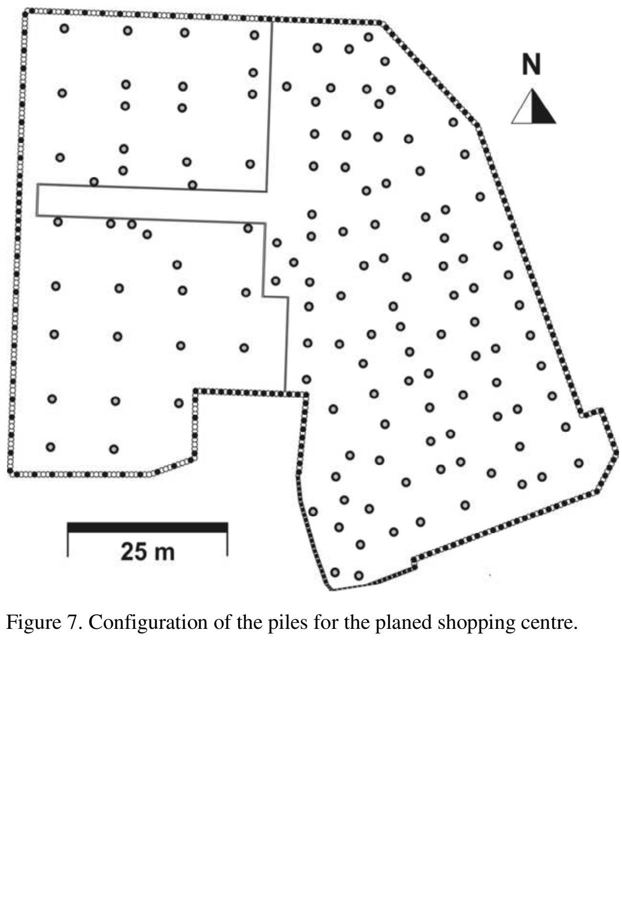

Figure 7. Configuration of the piles for the planed shopping centre.

The number of piles was specified by the public requirement that they should be used as energy piles for heating and cooling after completion of the building. So the task was not to optimize the pile quantity or pile length but to predict the settlements and calculate the piled raft coefficient α_{pr} and the vertical spring stiffness for the design of the base slab.

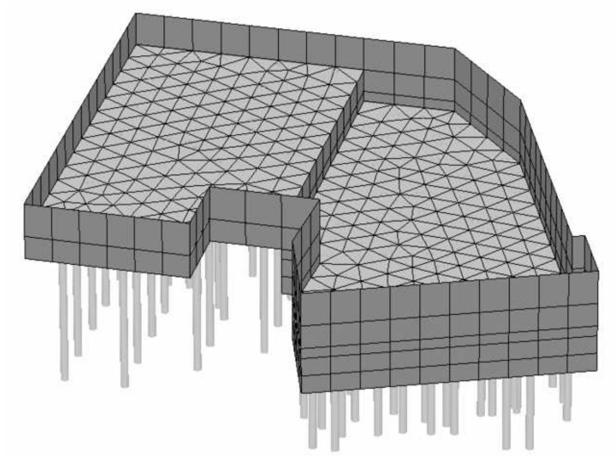

Figure 8. Numerical model of the piled raft and the retaining system of the planned shopping centre

The elastoplastic material parameters for the hardening soil model for the clay are represented in the following Table 1. For the quaternary sand and gravel layer a linear elastic model was used. Time dependency has not been considered.

Table 1. Elastoplastic material parameters used for the clay

Parameter	Symbol		Unit
Unit weight	γ / γ'	20 / 10	kN/m³
Secant stiffness (triax.)	E_{50}^{ref}	40	MN/m²
Tangent stiffness (oedo.)	E_{oed}^{ref}	30	MN/m²
Unload./reload. stiffness	E_{ur}^{ref}	80	MN/m²
Angle of internal friction	φ'	20	°
Cohesion	c'	35	kN/m²
Poisson ratio	v	0,2	-
Power (stress dependency)	m	0,750	-
Angle of dilatancy	ψ'	0,1	°

5.4 *Results*

According to the safety concept of the German ´Piled Raft Guideline´ (Hanisch et al. 2002) two evaluations have to be done :

- verification of the ultimate limit state (ULS)
- verification of the serviceability limit state (SLS)

In the present case the verification of the ULS was done by the calculation of the bearing capacity (base failure) of an equivalent shallow foundation neglecting the piles because they are primary necessary to extract and store energy from the subsoil. But the piles cannot be neglected by the calculation of the spring stiffness and the subgrade modulus included in the dimensioning of the slab and the calculation of the piled raft coefficient α_{pr}.

Figure 9 chows the comparison of the calculated settlement for a piled raft and a pure raft foundation without piles. The calculations were done using characteristic values for the properties and the loading was increased up to 200% of the dead and live load of F_d = 910 MN according to the 'piled raft guideline'.

The calculated settlement demonstrates the positive effect on the deformations when the building is founded on a piled raft foundation compared to a slab. Because the piles are primary installed to extract and store geothermal energy and not to reduce the settlement the reduction effect is quite at 100% of the total load. The 100% load corresponds to a pressure of 135 kN/m². But the positive effect becomes apparent when the design load is increased for example to 200 %.

The pile force varies between 2 MN and 9 MN and the piled raft coefficient was about α_{pr} = 0.75.

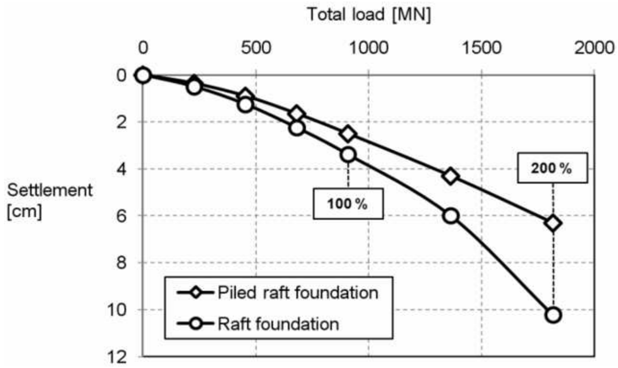

Figure 9. Comparison of the calculated settlement for a piled raft and a pure raft foundation

6 CONCLUSIONS

In order to extract and store geothermal energy the shopping centre was founded on 130 bored piles. The piles are used to reduce the settlements of the building and the adjacent structures. So the foundation was verified by the concept of a combined piled raft foundation. In comparison to the piled raft foundation a conventional pile foundation would require 230 piles instead of 130 piles according to the European standards.

Moreover, a partial impermeable retaining system was shown. By alternation of short and long piles combined with shotcrete and drainage holes the resulting water pressure to the wall could be reduced from 750 kN/m to 100 kN/m.

Thus both methods, the piled raft foundation and the partial waterproof retaining system, are smart and economical solutions.

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