Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-1547

Complex foundation design in inhomogeneous ground conditions for a high-rise building in Frankfurt, Germany

Conception de fondations complexes pour un gratte-ciel en conditions de sol inhomogènes à Francfort, Allemagne

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ABSTRACT
In downtown Frankfurt a new high-rise building is being constructed. According to the soil investigation inhomogeneous ground conditions were found. Different soil layers with changing thickness and stiffness, such as clay, claystone and coal were encountered. In the project site two groundwater tables were explored. The deep groundwater table is perched. The design of the foundation is carried out with help of 3D-numerical calculations which have to regard the difficult ground and groundwater conditions. Besides the results of the numerical calculations the report presents the limitation of the prognosis of the ground and groundwater conditions and hence, the difficulties for the geotechnical engineer to design such complex foundations.

RÉSUMÉ
Au cœur de Francfort la construction d'un nouveau gratte-ciel est en cours. Les résultats de l'analyse du sol affichent une géologie extrêmement inhomogène. Différentes couches d'épaisseur et de rigidité changeantes, telle que de l'argile, de l'argilolithe et du charbon ont été identifiées. Deux niveaux phréatiques, la nappe la plus profonde étant subartésienne, furent trouvées dans le domaine du terrain à bâtir. La conception des fondations fut effectuée à l'aide des calculs numériques en 3D en considérant d'une part la complexité de la géologie et d'autre part les effets des nappes phréatiques. Le rapport présente les résultats des calculs numériques, démontre les limites d'un pronostic des couches géologiques et phréatiques et souligne les difficultés pour l'ingénieur géotechnique à concevoir des fondations appropriées.

1 INTRODUCTION

Throughout the nineties a miscellaneous development of both residential and office buildings were implemented on former industrial area in the western part of Frankfurt close to the fair grounds.

Due to the urban location the 77 m high-rise office building had to be planned regarding the serviceability of the neighbouring structures. For this proof a combined pile-raft-foundation was chosen to conduct the load into the soil. Numerical calculations were carried out to guarantee the stability and serviceability.

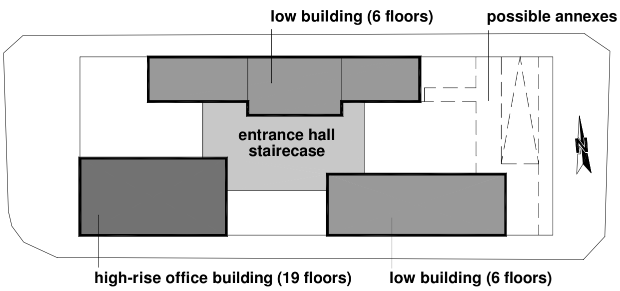

Figure 1. Site plan

2 PROJECT SITE

The building area of approx. 5400 m² consists of a 77 m high rise tower with 19 floors which is connected to surrounding low buildings with max. 6 floors like shown on the site plan (fig. 1). Below the whole area an underground parking with 3 basement floors on a continuous foundation slab will be constructed.

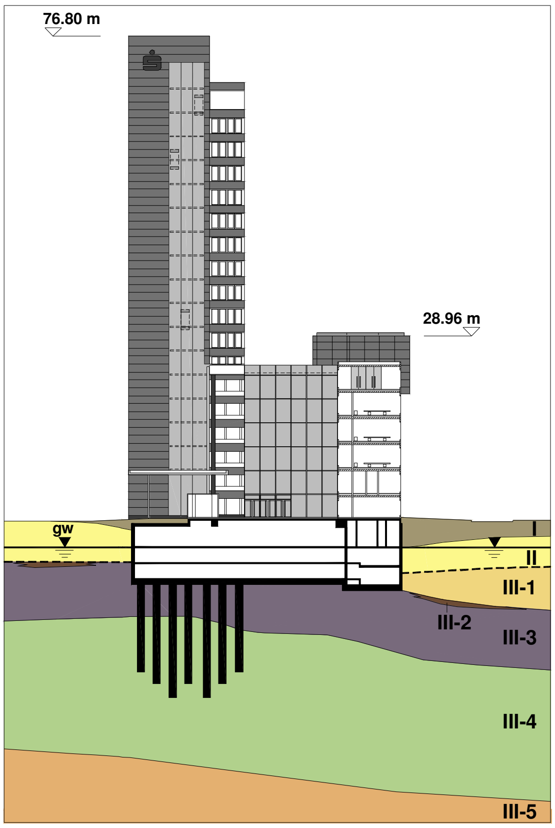

Figure 2. Projected office building (south-north)

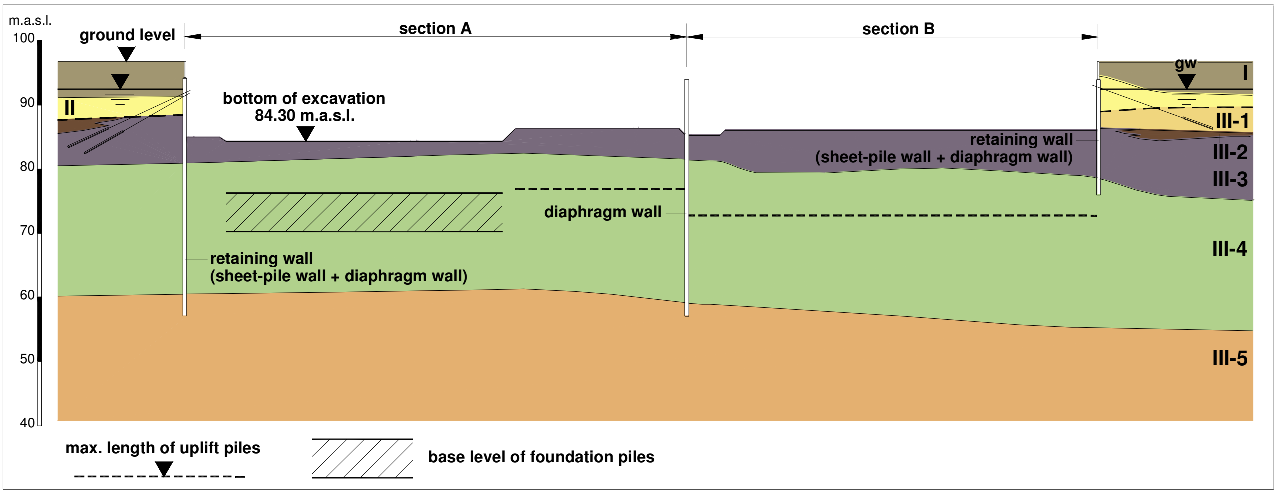

Figure 3. Geotechnical longitudinal section (west-east)

3 SOIL AND GROUNDWATER CONDITIONS

In 2003 a first soil investigation with 11 drillings up to a depth of 50 m took place. After analysing the investigation and after demolition of the former building complex a second stage of investigation was planned with additional 13 drillings. The aim of the additional investigation was to evaluate the soil layering more in detail. The explored ground conditions consisted of Quaternary fills (sand, gravel and silt) underlying by tertiary silt, clay and the fossil limestone. The tertiary sequence can be subdivided by 5 different layers as follows:

- Sand, silt and clay of the Congerien (III-1)
- Clay, organic clay and coal of the Prososthenien (III-2)
- Clay of the Prososthenien (III-3)
- Reef structures of the fossil limestone and marl (III-4)
- Clay with fine grained sand and limestone beds of the Hydrobien (III-5)

Below this sequence the limestone / clay of the tertiary Inflaten were found.

The results of the drillings show that the prevailed sequence and its thickness may vary locally. Especially the layers III-1 and III-2 are not continuous. Furthermore the inclination of the soil layers differs locally from the global known inclination.

The layer III-4 consists of an alternating sequence of layered facies of clay and silt (marl) as well as vertical extending columns (fossil reef structures). The experience in the local area gained from former projects like the construction of subway tunnels showed diameters of up to 3 m for these reef structures. The centre to centre distance can vary like shown in fig. 4. The reef structures are described as cavernous and compressible and arose of former coral reefs like shown in fig. 4 and 5.

Figure 4. Coral reef

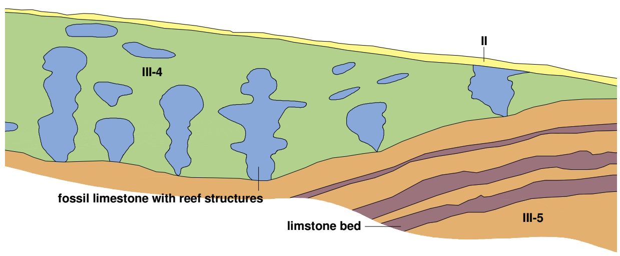

Figure 5. Fossil reef structures in layer III-4 (schematic)

The groundwater conditions are characterized by two groundwater tables. One unconfined groundwater table (gw 1) in the Quaternary fills and one subartesian table (gw 2) in the tertiary fossil limestone (III-4). The ground model is shown in fig. 6.

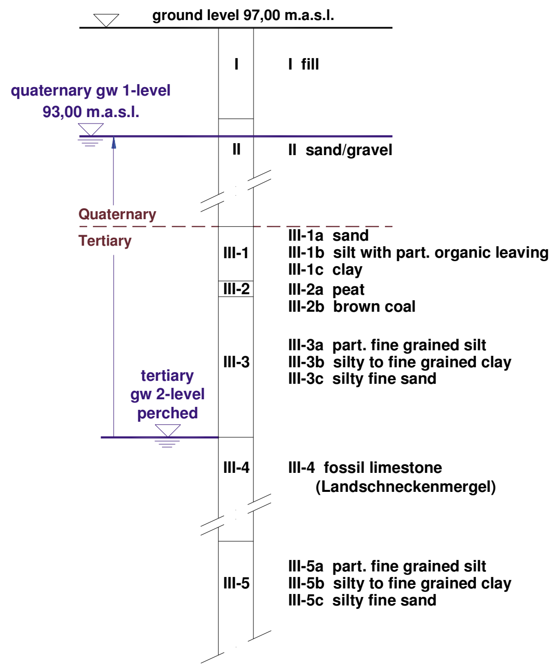

Figure 6. Ground model

4 DESIGN OF BUILDING PIT

For the construction of the underground parking and the foundation slab a building pit with a depth up to 12 m was excavated. The retaining structure consists of a diaphragm wall with additional sheet piling and up to 3 layers of grouted anchors. The watertight diaphragm wall reaches up to a depth of 45 m into layer III-5 with little permeability, the sheet piling up to 20 m depth.

Additional retaining elements are needed to secure the bottom of excavation against hydrostatic uplift. Therefore micro piles (diameter 0.3 m) with a length between 10 m and 14 m are used.

Regarding the inhomogeneous ground conditions the building pit was subdivided into two sections (section A and section B, fig. 7) in order to optimize length and grid distance of the micro piles as well as the length of the diaphragm wall in section B.

A transverse diaphragm wall between section A and section B without retaining function was constructed with a depth of 45 m.

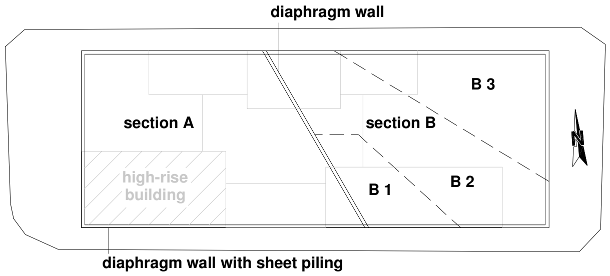

Figure 7. Building pit

A groundwater lowering of the tertiary groundwater level (gw 2) has been necessary to guarantee the safety against uplift in section A during construction.

The geological situation for section B is different. The layer III—5 with little permeability is encountered at a greater depth. Therefore the diaphragm wall was not constructed into this layer. To guarantee the safety against uplift in this section it was necessary to construct micro piles starting from a working plane above the critical uplift state. The final excavation was carried out by means of small excavation steps combined with the immediate installation of a special reinforced sub-base. According to the thickness of the clay (layer III-3) section B was subdivided into 3 zones (B1 to B3, shown in fig. 7). The size of the excavated area per excavation step was adapted to the local hydrostatic uplift conditions.

Because of the mentioned procedure for section B a groundwater lowering for the tertiary groundwater level (gw 2) as well as the embedding of the diaphragm wall into the fossil limestone (III-5) was not necessary.

5 FOUNDATION DESIGN

The slab of the whole building complex had to be designed continuously without any joints because of the groundwater situation. The eccentric loading of the building complex with a raft foundation causes large differential settlements and angular displacements. Thus a raft foundation was not advisable.

It was decided to carry out a combined pile-raft-foundation (CPRF) underneath the high-rise building. The surrounding low buildings are carried out by means of a raft foundation.

The design of the CPRF consists of a foundation raft with a thickness of 2.5 m and an area of approx. 900 m². The 31 foundation piles with a diameter of 1.2 m and length between 10.5 and 16.5 m are installed underneath the high loaded core sections of the high-rise building. The German recommendations for combined pile-raft-foundation (CPRF) require a design strategy as follows:

1. Geotechnical proof for ultimate limit state (ULS) as shown in fig. 8
2. Geotechnical proof for serviceability limit state (SLS) as shown in fig. 9

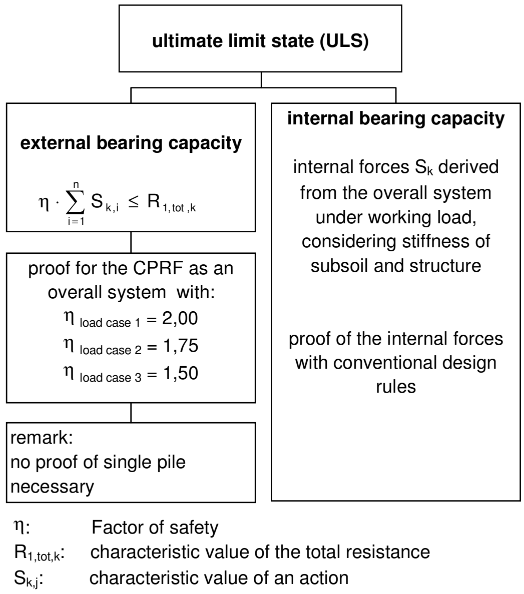

Figure 8. Geotechnical proof for ultimate limit state (ULS)

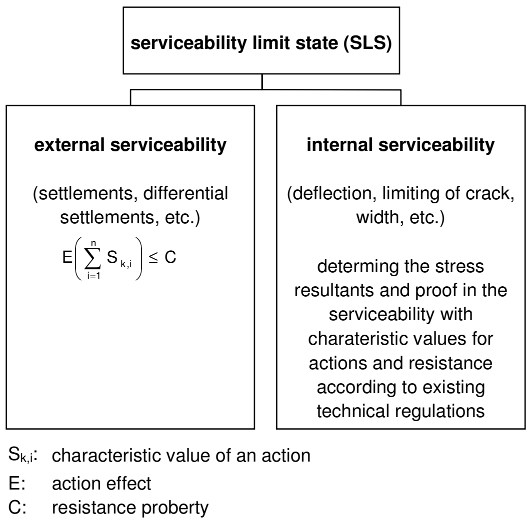

Figure 9. Geotechnical proof serviceability limit state (SLS)

6 RESULTS OF NUMERICAL CALCULATIONS

Three dimensional calculations by means of the Finite Element Method (FEM) were carried out to proof external bearing capacity (ULS) and external serviceability (SLS) as well as to determine the characteristic values of the combined pile-raft-foundation like the stiffness of the piles and the subgrade reaction of the ground between the piles.

The chosen numerical model represents the realistic geometry of the foundation raft of the high-rise building and a strip of 20 m width of the slab, the positioning of the piles as well as the pile length. The piles are modelled with rectangular shape with coextensive skin surface. The numerical model is shown in fig. 10.

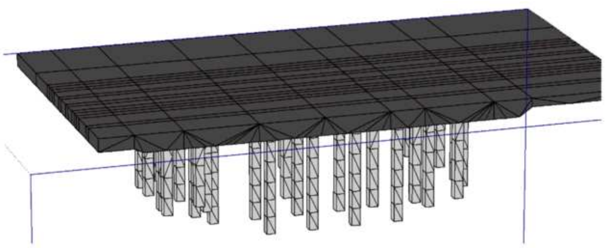

Figure 10. 3D numerical model

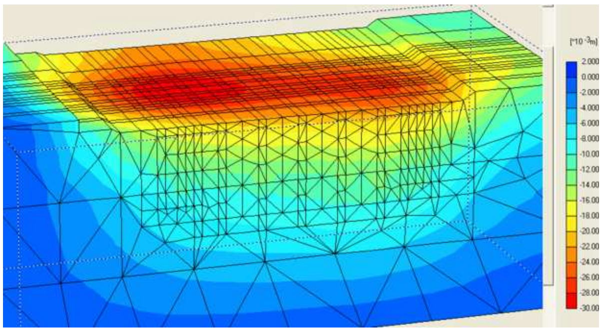

Figure 11. 3D numerical model · vertical displacements

For the modelling of the soil behavior an elastic-plastic constitutive law with isotropic hardening was implemented. The results showed a maximum settlement of the high-rise building of approx. 6 cm and max. angular displacements less than 1:700 (fig. 11 and 12).

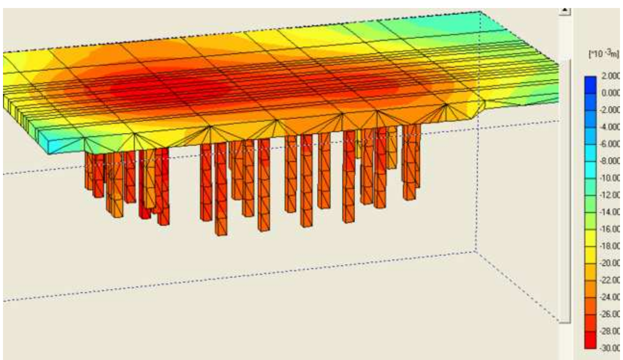

Figure 12. 3D numerical model · vertical displacements

Further considerations were made on the long term bearing capacity of the fossil limestone (III-4). The acting loads are partially transferred via skin friction and end bearing of the piles into this inhomogeneous soil layer. In case of partial failure of the weak and cavernous reef structures within the fossil limestone underneath a single pile or a group of piles the loss of bearing capacity of those pile(s) might be possible.
To ensure sufficient overall bearing capacity and serviceability of the combined pile-raft-foundation (CPRF) the mentioned scenario was analyzed numerically. Therefore various calculations were carried out deactivating a single pile and a pile group up to 3 piles. The results showed an uncritical increase of deformation up to 10 %. The stiffness of the piles nearby will increase up to 25%, and the subgrade reaction in the sector where the piles were deactivated increases up to the double.

7 CONCLUSION

For a complex foundation in inhomogeneous ground conditions the design of the building pit and the foundation itself can be optimized on the basis of a careful soil investigation.
Three dimensional calculations by means of the Finite Element Method (FEM) are capable for geotechnical approval and for determination of characteristic values of the combined pile-raft-foundation.
For the modelling of the soil behavior elastic-plastic constitutive models can be considered. Nevertheless the prediction of long term bearing capacity of the fossil reef structures requires further considerations. The task of the geotechnical engineer is the evaluation of the influence of a possible failure of the fossil reef structures concerning bearing capacity and serviceability of the combined pile-raft-foundation (CPRF).

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