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Foundation of a tall building in cavernous limestone

Fondation d'une immeuble très élevé sur des roches calcaires caverneux

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ABSTRACT

In the scope of this paper the design of the foundation for a 17-storey hotel with an adjacent 4-storey office building is presented. The subsoil comprises of limestone with caverns and residual soils as a result of the leaching of gypsum and anhydrite. To ensure the serviceability of the foundation, soil improvement by means of compaction grouting has been carried out in the leaching zone. The results of geotechnical and geodetic measurements, which are carried out to monitor the performance of the foundation, are presented.

RÉSUMÉ

Le présent article présente les études techniques sur la fondation d'une immeuble à 17 étages adjoindrée à une complexe des bureaux à 4 étages. Le sol de fondation consiste en roches calcaires caverneux et des sols résiduels qui forment le résultat de la dissolution des roches gypseuses et anhydritiques. Afin de assurer l'exploitabilité de la fondation de l'immeuble, ces sols peu stable sont injectes et compactés par des injections. Les résultats des mesures géotechniques et géométrique exécutes pour observer le comportement de la fondations, sont présentés aussi.

1 INTRODUCTION

The subsoil conditions in Wuerzburg, Germany, are characterized by the Middle Triassic layers, i.e. the Muschelkalk (shell limestone) with its typical cavernous limestone banks. The caverns are the results of leaching processes in layers which contain gypsum or anhydrite. These leaching processes continue for geological time periods until nowadays. The collapse of caverns and the compression of residual soft soils result in a subsidence of the ground surface. Differential settlements may cause significant damages to buildings.

In the scope of this paper, the design of the foundation for a hotel with an adjacent office building under these challenging subsoil conditions is presented.

The building complex consists of a 17-storey hotel with an adjacent 4-storey office building (**Fig. 1**). The hotel and the office building share a 2-storey 4200 m² basement which is used as an underground car park. The load of the superstructure of the hotel amounts to approximately 290 MN (dead & live loads). Since the basement is partially below groundwater level, the hotel and the office building are founded on one monolithic raft.

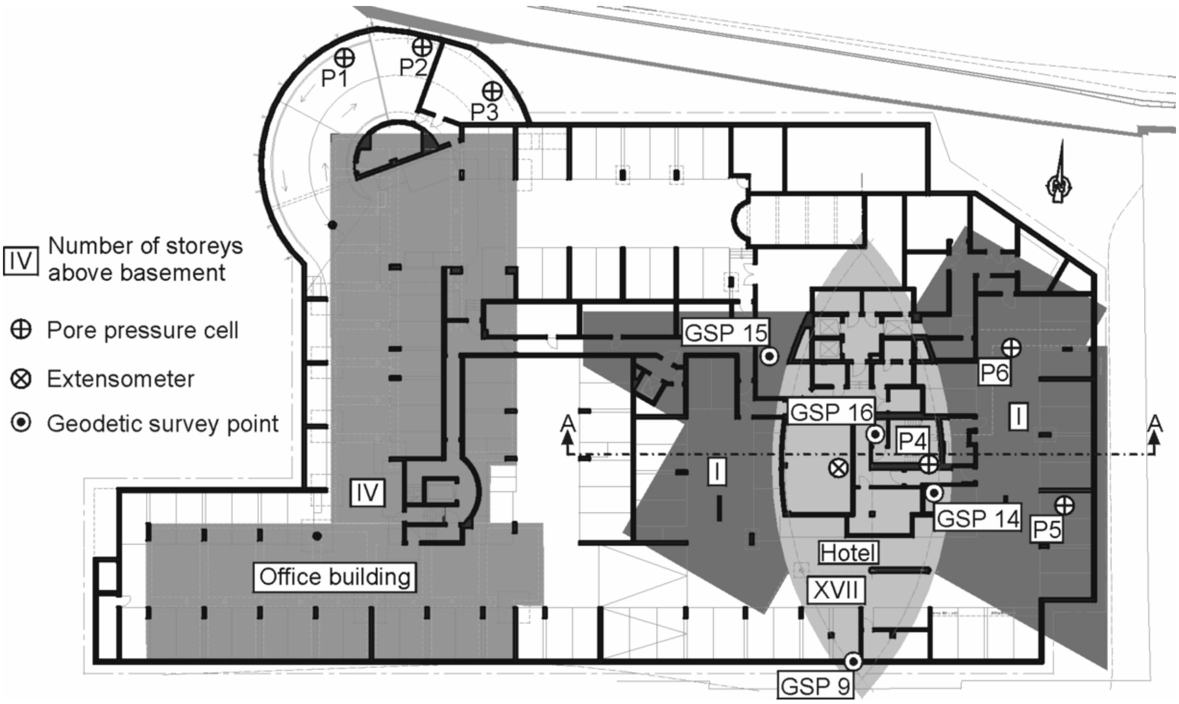

Fig. 1 Groundplan of the raft with measurement devices.

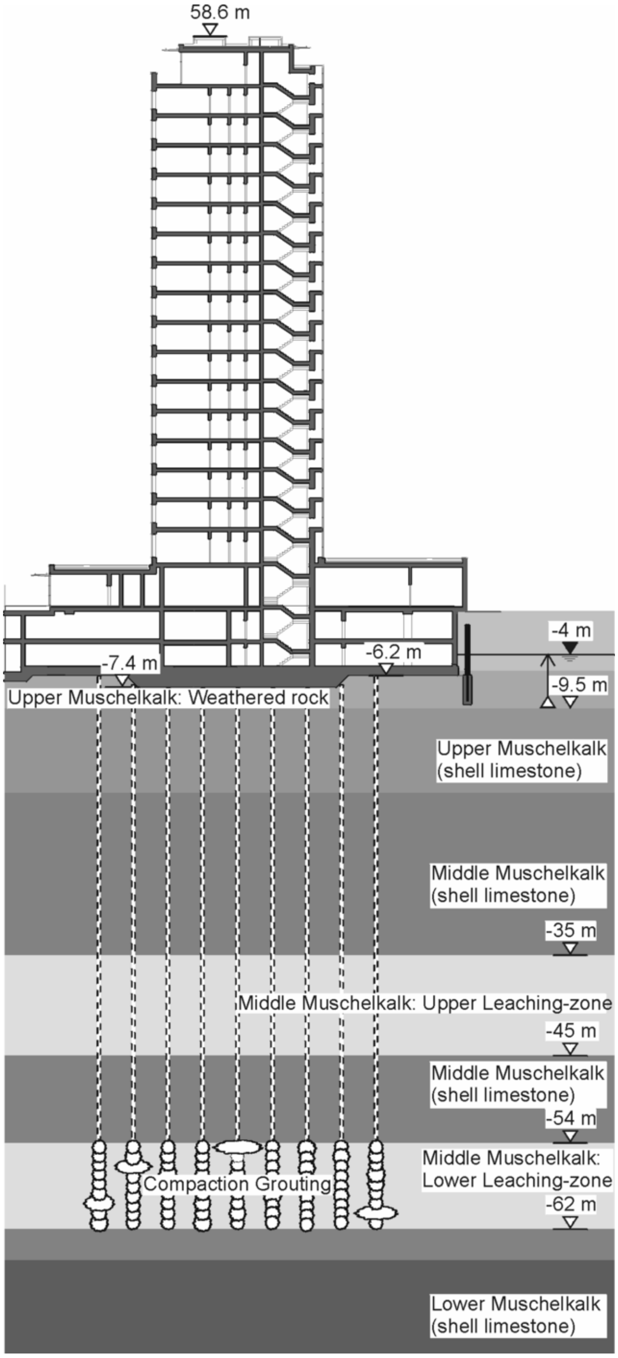

Fig. 2 Cross-section of the hotel and the subsoil

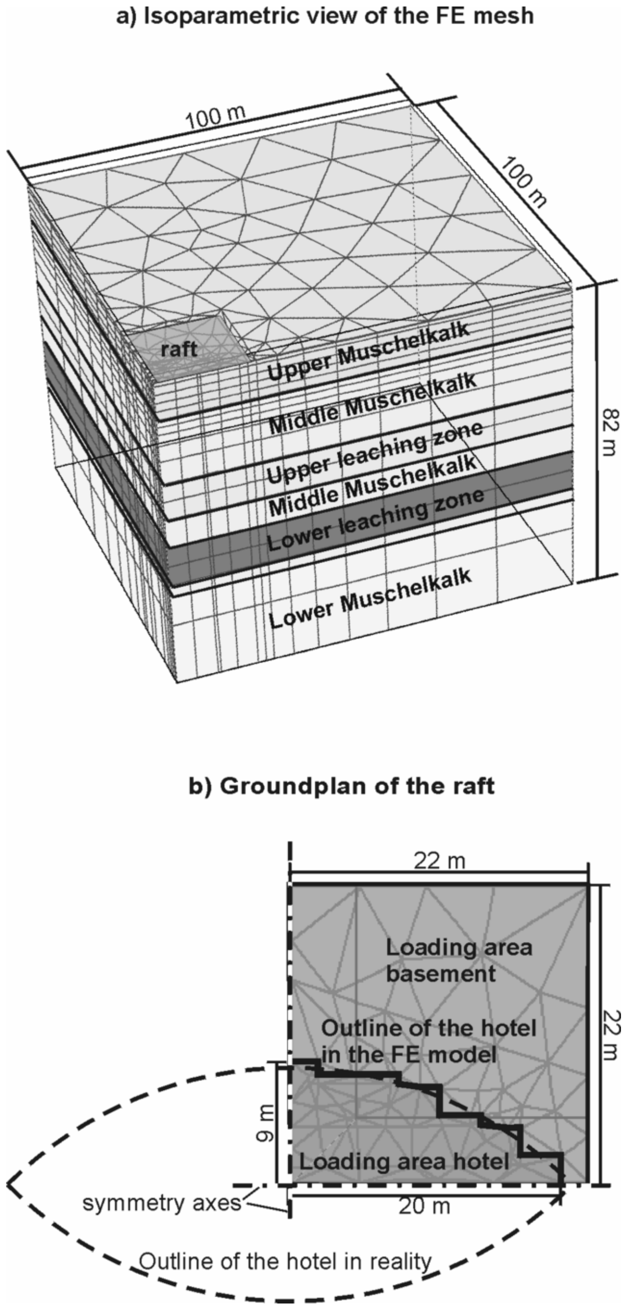

Fig. 3 Finite element model

2 SUBSOIL CONDITIONS

Fig. 2 shows a cross section of the hotel and the subsoil. The foundation level lies in a weathered zone of the Upper Muschelkalk (shell limestone), a heterogeneous layer which comprises of limestone blocks in a silty, clayey matrix. This layer is followed up to great depth by the Upper, Middle and Lower Muschelkalk (shell limestone) which consist mainly of limestone, dolomite and marlstone. However, for the design of the foundation, two layers with significantly weaker behaviour have to be considered.

The Upper Leaching-zone of the Middle Muschelkalk (shell limestone) in a depth of about 35 m to 45 m is composed of residual clay and marl with a firm to stiff consistency and embedded sand bands and limestone blocks. The Lower Leaching-zone of the Middle Muschelkalk in a depth of about 54 m to 62 m comprises of silty sands, clayey silts with a very soft consistency, columns of limestone and gypsum/anhydrite as well as small caverns partially filled with very loose silty sands. These two layers are the result of the leaching of gypsum and anhydrite. While this process is completed in the Upper Leaching-zone and the residual soils have been already consolidated under the weight of the overlying soil and rock, it is still continuing in the Lower Leaching-zone. Although the soil investigation showed only a small proportion of gypsum/anhydrite, the continuation of the leaching processes had to be considered.

The foundation level of the hotel is situated between 3.4 m and 4.0 m below the artesian ground water-level, which made groundwater-lowering necessary.

3 FOUNDATION DESIGN

The design objective for the foundation was to ensure the stability and the serviceability of the structure under the complex subsoil and groundwater conditions described above. A detailed discourse of the geotechnical aspects involved in the design and construction of high rise buildings is given by Arslan & Ripper (2003).

In a pre-design study a number of different solutions for the foundation of the hotel and the improvement of the Lower Leaching-zone, including a pile foundation with up to 60 m long bored piles or jet grouting, have been analyzed concerning their technical and economical feasibility.

The final foundation design has been based on 3D finite element analysis of the subsoil-structure deformation behaviour. **Fig. 3** shows the finite element mesh with the soil layers considered in the model. Details about the numerical modelling and the analyses results are given by Ripper & Reul (2004).

After the technical and economic assessment of the various design alternatives, a mat foundation in combination with compaction grouting of the Lower Leaching-zone in the vicinity of the hotel has been proposed.

As a result of the numerical analyses, the optimized design of the foundation comprises a monolithic raft with a thickness varying between 2 m in the area of the superstructure of the hotel and 0.8 m in the area of the office building. To ensure the uplift capacity of the foundation, approximately 100 ground anchors have been installed in areas with none or only one storey above the basement.

4 COMPACTION GROUTING

Compaction grouting is a technique which has been successfully applied for numerous applications and for a wide range of subsoil conditions. An overview of the state of the practice of compaction grouting is given for example by Bandimere (1997), Graf (1992) and Warner et al. (1992). In the present case, the aim of the compaction grouting was to densify loose and soft residual soils and to fill caverns in the Lower Leaching-zone of the Middle Muschelkalk.

The injections have been carried out in the area of the hotel in a grid of 3.5 m × 3.5 m via 102 boreholes. The depth of the boreholes was defined by the dolomite at the base of the Middle Muschelkalk. The mean depth of the boreholes amounted to 58.5 m. Based on the information gained from the drilling of the boreholes, the mean thickness of the Lower Leaching-zone was identified to be 8.8 m.

The grout consisted of a mixture of cement, bentonite and sand. From a total number of 55 grout samples taken during the compaction grouting works, a mean density of ρ = 1,86 g/cm³ and a mean horizontal slump (as defined by German code DIN 18555) of 20 cm have been established. The average values for the Young's modulus and the uniaxial compression strength after 7, 14 and 28 days are given in **Table 1**.

The injections have been carried out in the Lower Leaching-zone, only. The placement of the grout was carried out with the so called bottom-up procedure. After the final depth of each borehole, i.e. the bottom of the Lower Leaching-zone minus 0.5 m, had been reached, the borehole casing has been lifted by 0.5 m and the grout has been injected in the subsoil via the casing. The criteria for the required injection pressures and injected volumes are summarized in the flowchart of the injection process (Fig. 4). The injection process was repeated until the top of the Lower Leaching-zone has been reached.

In total, an amount of 1200 m³ of the grout has been injected into the Lower Leaching-zone. The mean injected volume per borehole amounted to 11.4 m³, equivalent to a mean diameter of 1.3 m. **Fig. 5** shows the mean injection pressure and the mean diameter of the injection columns for the 102 bore points.

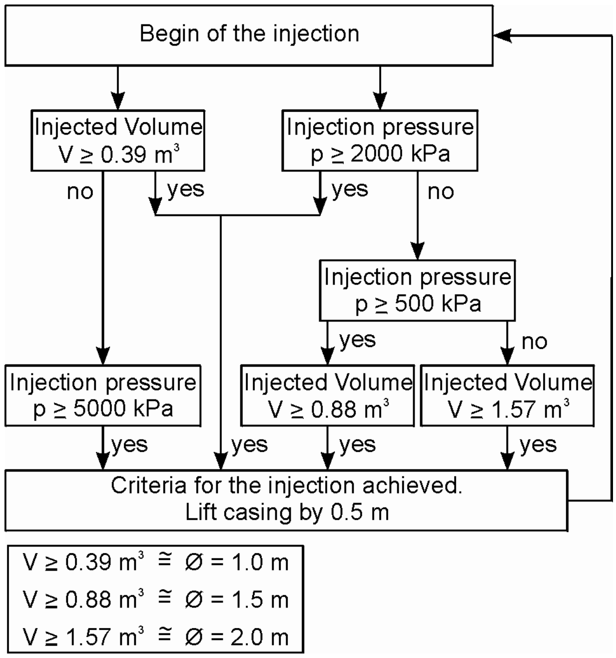

Fig. 4 Flow chart of the injection process

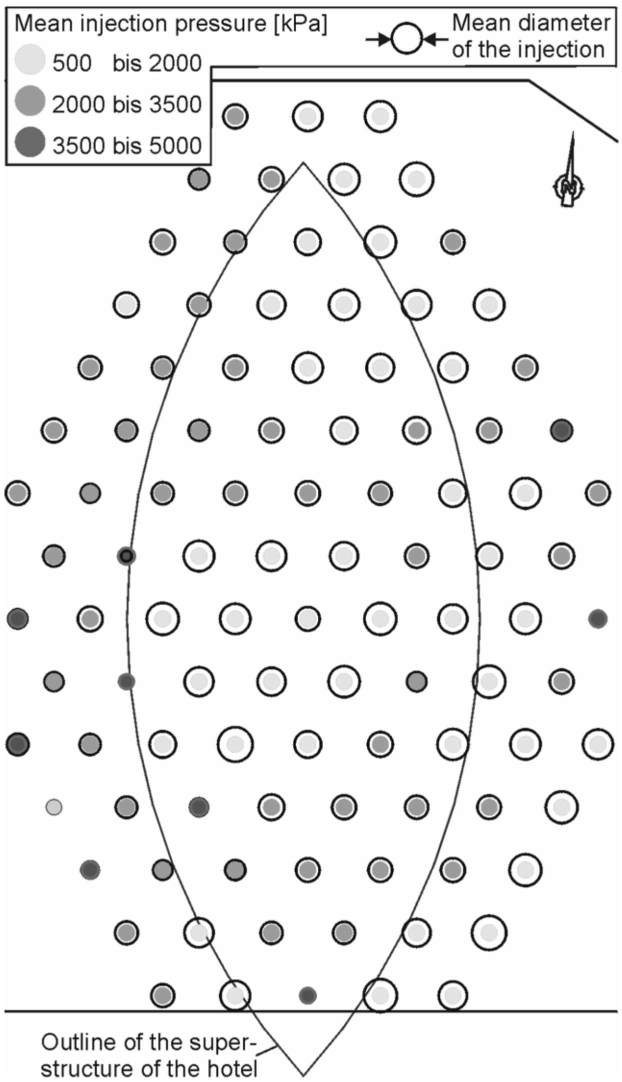

Fig. 5 Mean injection pressure and mean diameter of the injection columns

Table 1 Young's modulus and uniaxial compression strength of the grout after 7, 14 and 28 days

			7d	14d	28d
Young's modulus	E	MPa	1046	1465	1770
Uniaxial compression strength	q_u	MPa	8.9	13.5	16.1

5 IN-SITU MEASUREMENTS

According to design codes such as Eurocode EC 7 the foundations and deep excavation pits of tall buildings are usually classed with geotechnical category GK3 and the application of the observational method is recommended. 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 a total number of 18 geodetic survey points in the basement of the hotel and the office building as well as a multi-point borehole extensometer at the centre of the hotel. The pore pressure acting on the raft, resulting in an uplift, are measured with six pore pressure cells. The position of the geotechnical measurement devices and of the geodetic survey points in the area of the hotel tower are shown in **Fig. 1** in the groundplan of the raft.

Fig. 6 compares the development of the uplift acting on the hotel and the total load of the hotel consisting of the weight of the raft, the basement and the superstructure with the settlements of the hotel at four different points. The maximum settlement of 28 mm is measured at the centre of the raft. At the date of the last measurement available, when the shell of the hotel was finished, the total load amounts to approximately 235 MN. The significant increase of the settlements starting in June 2004 is a result of the construction of the superstructure of the hotel with a rate of approximately one storey per week.

The maximum measured settlement is approximately 2/3 of the value predicted for this construction stage based on the design calculations. The observed angular distortion resulting from the differential settlements between the centre of the raft (GSP 16) and the edge of the raft (GSP 9) amounts to approximately 1/1400, which has no influence on the serviceability of the building.

The uplift has been established based on the pore pressure measurements. At the date of the last measurement available, the uplift is approximately 20 MN. Please note that the uplift, i.e. the pore pressures, start to rise before the end of the groundwater drawdown because the wells were turned of subsequently one by one from the beginning of 2004.

Since the building site is situated in a water protection area, which is vital for the water supply of Wuerzburg, a city with approximately 130,000 inhabitants, extensive quality and quantity monitoring of the pumped groundwater had to be performed during the period of excavation and basement construction. The quality and quantity monitoring consisted of:

- Continuous measurement of the groundwater head at five groundwater gauges surrounding the building site.
- Measurement of the groundwater head at the wells on the building site in 3-day intervals.
- Chemical analyses on groundwater samples in 3-day intervals.

The mean pumping rate of groundwater during the period of the groundwater-drawdown amounted to approximately 72 l/s while no effect on the water quality was observed.

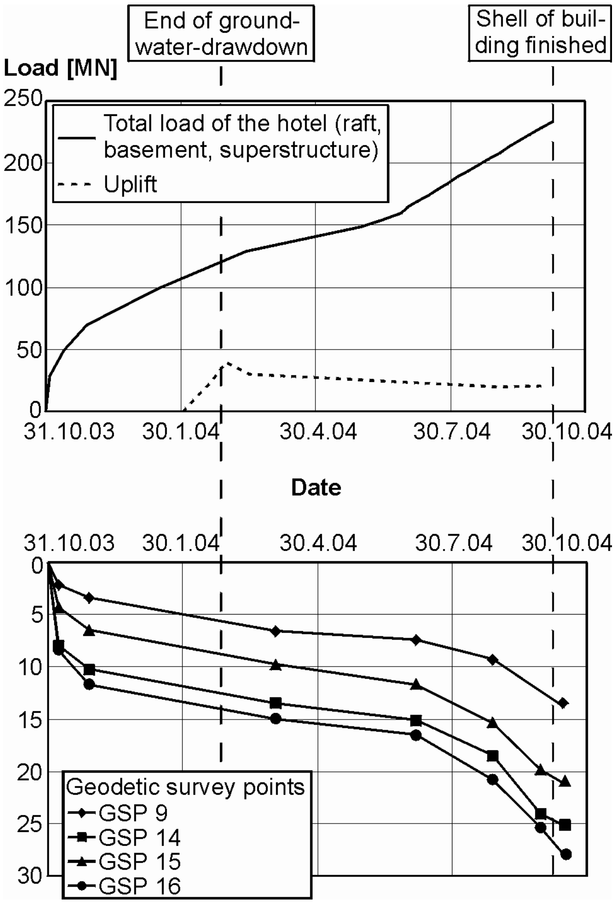

Fig. 6 Load, uplift and settlement of the hotel versus time

6 SUMMARY AND CONCLUSIONS

For the example of a 17-storey hotel with an adjacent 4-storey office building, which share a 2-storey basement, it has been shown that a safe and economic design of foundations can be achieved under challenging subsoil conditions such as the Muschelkalk (shell limestone) with its cavernous limestone banks and ongoing leaching processes.

The geotechnical and geodetic measurements show a satisfactory load-settlement behaviour of the foundation. The measured settlements do not exceed the predictions based on 3D finite element analysis of the subsoil-structure deformation behaviour, which have been carried out for the design of the foundation.

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