ABSTRACT: In the planning and construction of high-rise-buildings the economic advantage can be utilized by improved adaptation of the load-bearing and foundation systems to the site conditions. The report presents in this context customary foundation systems for high-rise buildings such as raft and pile foundation as well as the innovative foundation system of combined pile-raft-foundation. Where piles are primarily used to reduce settlements (satisfy the serviceability) and where an adequate factor of safety against failure is provided, the innovative combined pile-raft foundation (CPRF) has been put forward in the past. Furthermore, the possibility of using geothermal energy for example by equipping the piles adequately will be presented.

1 INTRODUCTION

1.1 High-Rise-Buildings – A Challenge for Geotechnical Engineers

While architects and structural engineers are able to visually document the success of their planning efforts on each high-rise project, successful geotechnical services remain hidden underground. They are only visible or experienced when errors were made in the ground/subsoil assessment or in case of poor planning, resulting in building damage, construction delays and additional costs. Although the construction costs for the excavation pits and foundations of high-rises generally account for less than 10 per cent of the total construction costs, the ground and the subsoil are major risk factors in high-rise construction. Hence, the geotechnical engineer is faced with special challenges and responsibilities in planning and monitoring the construction of high-rises. The added value, which results from professional geotechnical services for the project and the client body, can be considerable and has a decisive influence of the overall success of the project.

2 GEOTECHNICAL TASKS FOR PROJECT PLANNING

The building ground and the location are the most important subjects in any high-rise project. The client brings the site and the ground to the project, as platform for the erection of the building. Hence, he also carries the risks associated with the conditions of the site and the subsoil. The following three aspects are important in this context:

- the subsoil incl. groundwater as material and medium for integrating the new building.
- ground and groundwater as an environmental medium.
- ground/subsoil and groundwater as material and thermal resources.

The geotechnical engineer fulfills two roles: he acts as an expert/consultant and as a planning engineer (Burland, 2004). These two roles differ in terms of legal obligations and liabilities. While planners are equally liable under private law for the accuracy, technical quality, safety and efficiency of their solution(s), the expert/consultant acts as representative of the client/investor having the task of minimizing the risk of the building ground.

2.1 Geotechnical Safety Concept

The load-bearing system of a high-rise is influenced to a great degree by the deformation behavior of the ground. In this context ‘to a great degree’ means that ground deformations determine not only the stability and serviceability of the building (elevators, transitions, watertightness, etc.), but also the internal forces of the load-bearing system (load distribution, stresses, bending moment of foundation elements) and hence the reliability and dimensioning of the entire system.

Similar conditions apply to the deep excavation
pits required for high-rise construction. Due to this complex interaction between building ground and structure and the importance of high-rise safety, all high-rise foundations and the deep excavation pits required for them are classified as especially difficult and high-risk geotechnical tasks according to European Codes EC7. This classification stipulates that geotechnical planning and stability and deformation analyses must be carried out with multistage redundancy in the form of a closed control cycle. The following two additional safety elements are included in the project process to allow for timely modification or adaptation of the systems:

- independent geotechnical checking of calculation assumptions, models, deformation and stability calculations.
- geotechnical monitoring throughout the construction allowing for modification or adaptation of the systems.

For high-rise projects, both are compulsory elements in the delivery of stability and serviceability certificates.

2.2 Subsoil and Foundation

In Germany, the client as owner of the site and the appropriate risk is obligated to provide the project planners and all executing firms and contractors with full access to all data of the site conditions. To this end, most clients contract a geotechnical expert, whose task is to perform investigation, testing and evaluation of the ground at the building site in order to furnish the information for a comprehensive profile of the ground condition at the site. This report must contain the following data:

- a clear, three-dimensional representation of subsoil strata.
- a classification of the existing subsoil and rock types, and a description of material behavior (shear strength and deformation).
- a detailed description of the groundwater conditions including long-term changes and interaction between ground and groundwater.
- a description of possible chemical content in the soil and in the groundwater, the type, concentration, distribution, other effects of this chemical content (pollution potential).

The data for this building-ground report are collected through subsoil investigations including geotechnical field and laboratory tests and environmental investigations.

2.3 Subsoil Investigation

Whereas the materials for all other disciplines of civil engineering, e.g. concrete and steel constructions, are available with standardized material parameters. Material selection is part of the dimensioning of the load-bearing systems. The geotechnical engineer must establish, investigate, test and model the material composition and the material behavior of the ground/subsoil at each new site and for each project. This is one of the recurring core tasks of geotechnical engineers. Extremely high standards and assurance of design compatibility with the project risks govern the methods and scope of data collection, especially for field and laboratory analyses for difficult geotechnical tasks such as high-rise foundations and deep excavation pits. The issue is not only the subject of covering the ground risks for the client, but also the creation of a solid basis for planning and accurate computational predictions of the load-bearing and deformation behavior of ground and building.

For a high-rise project the investigation of the ground must be facilitated through exploratory drilling (core drilling) of sufficient density to furnish a complete three-dimensional image of the stratified structure. The investigation depth is based on the assumed depth of the pile foundations. A sufficient number of piezometer must be built in order to investigate and collect data on the hydraulic and chemical conditions of the groundwater. Undisturbed soil samples have to be taken from the boreholes to investigate the material properties in the laboratory. It is vital to ensure that samples are taken from all existing strata. Depending on the conditions of building and ground. It may also be useful to carry out geotechnical field tests in the borehole (standard penetration tests, vane tests, pressiometer tests).

In addition to the standard geotechnical tests for soil classification, appropriate tests must be initiated to establish the deformation characteristics and shear strength of the soil materials. In order to achieve realistic results for soils that are sensitive to deformation, the stress courses of the soil samples in the ground must be simulated for the different load conditions of the construction in a triaxial test. Local data on comparable ground/subsoil conditions are taken into consideration both in the field and laboratory investigations to evaluate the test results and determine the characteristic soil parameters. This task is made more complex by the natural variety in type and distribution of the materials in the ground and the infinite range of material properties. A comprehensive model of the ground behavior (site model) must be designed for each building project based on the data collected during the investigation – and complemented by the practical experience of the geotechnical engineer.

2.4 Site Model

The summary of the background data on the site, the
investigation as well as the data collected in field and laboratory tests in a single, comprehensive and three-dimensional image of the subsoil condition is called a site model. The site model provides a cogent overview of all important information and data of the site including the ground and creates the basis for assessing and calculating the different interactions. The following elements are part of the site model content:

- knowledge of previous use of the site (buildings, types of use, previous loads);
- type and distribution of possible chemical burdens in ground or groundwater (pollution sources/veins/impact potential);
- existing development and infrastructure in surroundings;
- three-dimensional ground model with surface relief and stratification structure;
- hydrogeological situation (groundwater levels, current, sectional pressure levels, chemical and physical properties, changes over time);
- soil and rock mechanical properties of subsoil strata (genesis, composition, deformation behavior, and shear strength, rheological behavior).

For complex building sites, the site model may have to be supported by a geographic information system (GIS) with several information levels. The site model must go beyond the boundaries of the building site and should encompass the reach of the possible deformations induced by the building measures. It is the basis for the geotechnical consultation and planning for the entire project, in particular for dimensioning, stability and deformation calculations.

2.5 Geotechnical Planning

The geotechnical and environmental tasks during the planning phase are defined as follows:

- planning of the process environmentally preparing the site for building (demolitions and site remediation)
- design of the excavation pit and water management systems;
- design of the building foundations including securing the basement against groundwater.

The geotechnical planning sequence for the principal planning of – excavation pit, ground-water management and high-rise foundation – includes the additional elements of geotechnical checking and monitoring:

For high-rise projects in Germany the foundation plan with the corresponding stability and deformation analysis, the relevant geotechnical calculation model and material properties have to be checked by an independent expert (checking engineer) certified for earth- and foundation works. Close collaboration with the structural checking engineer is essential. The corrections/adjustments recommended by the checking engineer must be implemented as compulsory design elements.

Experience has shown that the potential tilt as a result of natural inhomogeneities in the ground accounts for 10 to 15 per cent of the total deformation. This means, that a differential settlement of 3–5 cm can occur as a result of natural geological anomalies alone for an overall settlement of roughly 30 cm. Given the additional eccentricity in the load impact, the tilt of a foundation raft can quickly surpass the tolerance threshold.

For modern high-rise buildings, the target is to limit the deformation of the foundation to the following ratios in order to minimize the risks:

- Settlement max. 10-14 cm
- Tilt max 1:800 (as leaning)
- Tilt max. 1:500 (as bending)
- Differential Settlement in joints max. 5 cm.

3 FOUNDATIONS OF HIGH-RISE BUILDINGS

The foundation is the interface between the load-bearing structure of the high-rise-building and the ground. The task is to transfer the high building loads as safely and with as little deformation as possible into the ground. Foundation systems must be designed to ensure sufficient external stability of the entire system and maintain the internal load-bearing capacity of the building components by appropriate dimensioning. The serviceability of the structure must be guaranteed without limitations for the entire life cycle of the building.

The following principal foundation options exist to transfer the heavy loads from high-rises into the ground:

- raft foundations, where the loads are transferred to ground via a foundation slab;
- deep foundations, where high-rise loads are transferred to a deeper load-bearing horizon via foundation piles or diaphragm wall elements;
- combined pile-raft foundations, where the high-rise loads are transferred to a deeper level in the subsoil partly via the foundation raft and partly via foundation piles or diaphragm wall elements beneath the raft.

The concept of combined pile-raft foundations represents a design strategy for high-rise foundations that delivers not only the stability and serviceability (minimized deformation), but also a qualitative technical and economical optimization of the building’s base. The advantages and goals of the combined pile-raft foundation can be summarized as follows:

- decrease of subsoil relaxation during pit excavation through the effect of the piles as tension piles
(negative skin friction) and hence avoidance of structural ‘softening’ in the upper layers (minimization of deformations);

– limitation of settlement, bending and tilt of foundation bodies to a scale that is tolerable for the serviceability of the buildings and technical systems (crack resistance/waterproofing elevator systems/facades);

– prevention of settlement gaps between the foundation elements of high-rises and perimeter building of differing weight as a result of settlement and thereby avoidance of high-maintenance and expensive settlement joints;

– centering of resultant reaction forces in the axis of the resultant building loads for asymmetrical foundation bodies (avoidance of tilt and settlement joints);

– centering of pile on load axes and hence avoidance of bending stress on the raft.

The option to safely transfer any eccentric building load with little risk of deformation to the subsoil by means of pile arrangement, staggered pile lengths and pile diameter opens up new possibilities for high-rise construction. Building fabrics, which are subjected to differing loads and asymmetrically arranged, can be realized on a monolithic foundation raft without settlement joint. The combined pile-raft foundation represents a complex foundation system, which requires a qualified understanding of the soil-structure interactions (Hanisch, 2001). These interactions are illustrated in Fig. 1.

The task for the geotechnical engineer is to evaluate the load distribution between the piles and the raft. The distribution of the total load between the raft and the piles is described by the coefficient:

\[
\alpha_{\text{CPRF}} = \frac{\sum R_{\text{pile},i}}{R_{\text{tot}}}
\]

(1)

whereas:

- \( R_{\text{pile},i} \): sum of the single pile bearing capacities of all piles of CPRF
- \( R_{\text{tot}} \): total bearing capacity of the foundation

The coefficient of CPRF ranges from 0 to 1, whereas the factor of 0 represents a raft foundation and the factor of 1 a pile foundation. Values in between represent a combined pile-raft foundation (Fig. 2).

4 GEOTECHNICAL MONITORING

According to Eurocode EC7, the second compulsory safety element in addition to geotechnical checking is ongoing measurement monitoring throughout the construction process (monitoring method). The deformation response of the building ground as a result of pit excavation, ground water management and new construction measures, as well as the changes in stresses within the foundation elements must be measured, monitored, evaluated and documented both during the construction phase and the subsequent building use and continue to be monitored until the ground reactions subside. This creates a real-time quality control record and evidentiary documentation and is also intended to facilitate early recognition of deviation from assumed values and critical conditions in order to initiate modifications/corrections (Arslan, 2005).

The requirements for the application of the monitoring method are

– a forecast of the load-deformation response of the building and the definition of tolerances before construction begins;

– the development of staggered structural engineering countermeasures in case the building measurements reveal critical deviations from the forecast values;

– measurement monitoring and prompt evaluation and interpretation of the measurement results during the construction.

It is differentiated in geotechnical monitoring of high-rise foundations between measurements of the excavation pit, measurements of the high-rise and...
measurements outside of the construction field. Each of these measurements is geodesic and geotechnical. The measurements outside of the building field are also used for the architectural documentation of the impact on neighbour buildings.

The measuring and monitoring of the load-bearing behavior of high-rise foundations involves the measuring and documentation of the following time variables according to construction sequence and the geotechnical and geometrical parameters:

- heave of excavation pit floor as a result of excavation;
- groundwater levels and porewater pressures in and near the excavation pit;
- settlements and deformations of the foundation raft;
- amount and distribution of base pressure and the hydraulic pressures beneath the foundation raft;
- load-bearing behavior at the top of the piles, distribution of skin friction along the pile shafts, load-bearing behavior at the toe of the piles);
- distribution of vertical displacements in the subsoil.

Sensors, characterized by a high degree of rigidity to external influences to withstand the installation work at the building site, are used to record these variables. In view of the long monitoring periods of up to 5 years and more, the sensors must also possess a high resolution and long-term functionality.

Simultaneous to the numerical modeling of the load-bearing behavior of the high-rise foundations, a measuring program compatible with the project-specific requirements should be foreseen as early as the design and planning stage. This measuring program must be verifiable and contain detailed information on the following parameters:

- type and scope of measuring program, i.e. number and placement of sensors;
- requirements and specifications (measurement range, resolution, etc.) of sensors;
- specifications of measurement sequence harmonized with construction sequence;
- notation of control and boundary values; complementary measurements or structural countermeasures must be implemented if these values are surpassed.

The following measuring devices are employed for geotechnical measurements:

In subsoil or at contact interface of subsoil/foundation raft:
- Extensometer (Fig. 6)
- Inclinometer
- Base pressure sensor (Fig. 3)
- Pore-water pressure sensor
- Piezometer (Fig. 5)

In foundation piles or at contact interface of pile/subsoil:
- Load cells at the top of the piles
- Load cells at the toe of the piles (Fig. 4)
- Strain gauges along the pile shafts (Fig. 7)

In practice the monitoring program for the pit and the foundation should be combined, so that possible interaction between the excavation and the foundation are taken into account.
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5 CASE STUDIES

5.1 High-Rise Building “Treptowers” Berlin, Germany

The Treptowers is situated in Berlin, Germany directly next to the river Spree (Fig. 8). The building reaches a height of 121 m and is founded on a combined pile-raft-foundation. The neighbour building with 10 floors is founded on a raft.

The thickness of the raft of the combined pile-raft foundation is between 2 and 3 m, while 54 piles with a diameter of 88 cm were installed. All piles were constructed with a jet grouted shaft. The lengths of the piles vary from 12.5 m to 16 m. The bottom of the raft is up to 8 m beneath the surface.

The ground and groundwater conditions were explored by boreholes up to a depth of 40 m. Up to a depth of 4 m beneath the surface fillings and organic soils were encountered underlying by loose to medium dense sands of the Pleistocene. These sands were found up to depth of approx. 19 m. Dense sands were encountered in depth of > 19 m. Locally a layer of boulder clay with a thickness of 1.5 m was found. The groundwater level is approx. 3 to 4 m beneath the surface (Fig. 8). The total load of the Treptowers adds up to approx. 665 MN, including the load of the raft of 103 MN.

Numerical analyses were carried out in consideration of the symmetry of the building. One quarter of the building was modelled by Finite-Elements. (Fig. 9). The used material law is an elastic-ideal-plastic stress-strain behaviour with the yield condition Mohr-Coulomb. The jet-grouting of the pile shaft is modelled by an expansion of the pile elements.

Fig. 8: Treptowers: Picture and cross section of the building with ground model

Fig. 9: Treptowers: Finite-Element mesh
For the verification of the bearing behaviour of the combined pile-raft-foundation a monitoring programme was installed. The piles no. 1, 17 and 49 are instrumented with measuring devices, such as pressure cells at the top and bottom as well as strain gauges within the piles (Fig. 10). Beneath the raft a total of 5 earth pressure cells were installed. The settlements of the building are monitored by 4 geodetic points in the corners of the building. The results of the measurements are illustrated in Figs 11 and 12. The maximum settlement of the building add up to 7.3 cm. The minimum settlements were encountered with 5.0 cm. This leads to a tilting of smaller than 1/2000. and causes no negative effect on the serviceability of the building. The measured pile resistances vary between 6.9 MN for pile 1 and 6.5 MN for pile 17. The results of the numerical calculations show a good agreement with the measurements. The pile resistance of pile 1 was calculated to 7.8 MN and for pile 17 to 7.5 MN. The monitoring shows that the 54 piles of the Treptowers bear approx. 55 % of the total load of the building.

Fig. 10: Treptowers: Plan view of the measuring devices

Fig. 11: Treptowers: Settlement depending on the load - calculation and measurement

5.2 High-Rise Building “Commerzbank” Frankfurt, Germany

The Commerzbank is situated in Frankfurt, Germany within the banking district (Fig. 13). The building reaches a height of 299 m. The building is founded on a pile foundation. The building was constructed directly next to an existing high-rise building. The existing building reaches a height of 103 m and is founded on a raft. The shape of the new high-rise building in the plan view is triangular. The vertical load is conducted in the corners of the triangle. The thickness of the raft within the tower is between 2.50 to 4.45 m. A total of 111 telescopic piles with diameter of 1.8 m within the first 20 m beneath the raft, followed by a diameter of 1.5 m were installed. All piles were constructed with a jet grouted shaft as well as jet grouting 10 m underneath the piles in the cavernous limestone. The length of the piles vary from 37.7 to 45.6 m.

The ground and groundwater conditions were explored by boreholes up to a depth of 105 m. Up to a depth of 5 m beneath the surface fillings were encountered underlying by quaternary sands and gravels in depth of 10 m. Underneath the ground layers of the Hydrobien (Frankfurt clay) is found up to a depth of 35 to 40 m. The ground layers of the Inflaten (Frankfurt limestone) and Cerithien (marl) were encountered beneath the Hydrobien (Fig. 13). The Frankfurt clay consists of clay interbedded with sand and limestone. The dark grey clay with stiff to very stiff consistency reaches a portion of approx. 72 % of the Hydrobien layer. The limestone within the Hydrobien layer are encountered with a thickness of a few decimetre to 2.2 m. The thickness of the Inflaten layer is approx. 25 m. The Inflaten con-
sists of limestone, sand, silt and marl. The limestone is horizontally inconsistent, sometimes made of single blocks, which can be cavernous. The limestone is encountered as moderately strong to strong. In case of weathered rock, the Inflaten are encountered as weak.

Two groundwater level were found in the project site. An unconfined groundwater level in the quaternary sands and gravels as well as a confined groundwater level circulating in the sands and limestone of the Hydrobien. The unconfined groundwater level was found 5 to 6 m beneath the surface. The confined level’s pressure head exceeds the confined level by 0.3 to 0.8 m.

The total load of the Commerzbank adds up to approx. 1800 MN, including the load of the raft of 208 MN. The total load can be split into dead load (dL) of 1355 MN and live load (LL) of 486 MN. The loads which induces settlements, that means which where used to calculate the settlements (SLS) add up approx. 1430 MN (= dL + 0.15 LL).

Numerical analysis were carried out in consideration of the symmetry of the building. A sixth part of the building was modelled by Finite- and Infinite-Elements. The extent of the model is 200 m x 180 m x 120 m (Fig. 15). Infinite elements were used to model the ground outside the tower area. The used material law for the finite elements is a elastic-plastic stress-strain behaviour with the yield conditions of Drucker-Prager with cap.

For the verification of the bearing behaviour of the pile foundation a monitoring programme was installed. A total of 30 piles are instrumented with measuring devices, such as 20 pressure cells at the top and bottom as well as 300 strain gauges within the piles (Fig. 16). Beneath the raft a total of 13 earth pressure cells and 4 piezometer were installed. Additionally 13 Extensometer up to a depth of 105 m were established. The settlements of the building are monitored by 22 geodetical points. The results of the measurements are illustrated in Fig. 17. The maximum settlement of the building add up to 2.1 cm. The minimum settlements were encountered with 1.5 cm. This leads to a tilting of smaller than 1/2000 and causes no negative effect on the serviceability of the building. The results of the numerical calculations show a good agreement with the measurements (Fig. 18).

The measured mean value of pile resistance range between 13 MN for piles in the corner of the building and 9 MN for piles in the centre of the building.
5.3 High-Rise Building “MainTower” Frankfurt, Germany

In the future, the use of the ground and of groundwater and their thermal storage capacities will gain in importance due to the increasing scarcity and cost of conventional resources and in response to growing...
environmental awareness. In high-rise projects, the following approaches are of interest for heating and cooling applications:

- Geothermal use of ground (earth) as seasonal heat/cold storage in combination with energy piles and/or energy sumps;
- Thermal use of groundwater;
- Material use of groundwater as service water.

Implementation of these types of technologies depends on the geological and hydrogeological site conditions (efficiency and permissibility). The following parameters must be investigated from a geotechnical perspective and integrated into the planning/permission process in order to develop and implement a solution that is ecologically and economically optimized:

- Hydrogeological ground properties (e.g. location and yield of groundwater streams, groundwater flow direction);
- Thermal ground properties (e.g. heat conduction and heat storage capacity);
- (Geo-)chemical and physical groundwater composition (e.g. temperature, anthropogenic and geogenic contents and their impact on the operability of the system).

Efficient solutions for the thermal and/or material use of the ground and the groundwater for heating/cooling high-rises must be developed jointly by HCV-engineers (heating/cooling/ventilation) and geotechnical experts.

The Maintower high-rise project in Frankfurt is one example of thermal use of the ground and the groundwater. In this project, the foundation piles are utilized as heat exchanger elements (energy piles) to provide intermediate storage for excess heat/cold energy and to release it when needed.

The building reaches a height of 200 m. The building is founded on a combined pile-raft foundation. The thickness of the raft within the tower is between 3 to 3.8 m. A total of 112 piles with diameter of 1.5 m were installed. The length of the piles vary from 20 m to 30 m (Fig. 19).

The ground encountered consists of quaternary sands down to 10 m below the surface where it is underlain by tertiary sediments of the Hydrobien. These sediments (Frankfurt clay) consist of clay interbedded with sands and limestone bands (Fig. 19). The ground layers of the Inflaten (Frankfurt limestone) and Cerithien (marl) were encountered beneath the Hydrobien.

To ensure an economic design of the MainTower three innovative ideas were put forward:

1. the bored piles of the retaining wall are part of the foundation system (combined pile-raft foundation). They transfer the loads in addition to the 112 foundation piles into the ground. Fig. 20 shows the position of the piles of the foundation and of the retaining wall.
2. the building pit and the first floors of the MainTower were constructed in top-down-technique to reduce construction time and to provide a pit which observe stability and serviceability of neighbouring structure. By using this technique it is possible to construct the basement floors and the upper floors at the same time (Fig. 20).
3. apart from their static function the piles of the foundations and partly of the retaining wall are used for the environmental-friendly heating and cooling of the building. For this, the piles were additionally installed with heat exchanger tubes (Fig. 21), so that the piles work as heat exchanging elements to create a closed system. Energy is transferred to the ground from the exterior (outside air) and stored until it is needed (Fig. 21). The energy piles can load and unload the seasonal storage. In winter energy can be withdrawn, thus a cooling of the ground arises. In summer the cooled down ground can be used for cooling the building through the ceilings.
6 CONCLUSIONS

The new possibilities, which have emerged through the introduction of the combined piled raft foundation for the design of high-rise foundations, can be expanded with dedicated development. Further development of special civil engineering technology will lead to more rational and hence economic production processes of piles, diaphragm wall and anchorage systems. Post-construction pre-stressing of the deep foundation elements can also optimize the utilization of the load-bearing behavior of the ground (skin and cap pre-stressing of piles). Integrated solutions allow for multiple uses of building elements. Thus, the drilled pile or diaphragm walls of the excavation pit retaining can be employed to assist in the vertical load transfer or even assume the function of a watertight external skin for the basement levels.

The foundation elements raft, piles, diaphragm walls can also be employed as heat exchangers to utilize the ground as seasonal heat/cold storage (Kaltschmitt, 1999 and VBI, 2005).

Finally, another optimization potential resides in the improvement to existing geotechnical calculation models. Standardization of three-dimensional procedures render simulation of the ground/building interaction more realistic and the calculations can be used for the option investigations for technical and economic optimization of the foundation and excavation pit designs.

The prerequisite for the design of high-rise projects that are as safe as they are economic, and for the successful use of geotechnical development potentials is a comprehensive knowledge of the interactions between ground and load-bearing elements of the structure, experience in working with geotechnical calculation models and sound strategies for foundation design. Herein lie the challenge and the unique responsibility of the geotechnical engineer for high-rise construction.

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