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COMBINED PILE RAFT FOUNDATIONS (CPRF): AN APPROPRIATE SOLUTION FOR THE FOUNDATIONS OF HIGH-RISE BUILDINGS

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ABSTRACT

In urban areas, the principle question related to the design of high-rise buildings on settlement-sensitive soils is the cost-optimised reduction of settlements to prevent possible damage and to minimise deformations of adjacent structures and the high-rise building itself. A conventional method for a reduced settlement-foundation on settlement-sensitive soils is to design and build a pile foundation based on a stiff layer like rock or dense sand. In the case of a stiff deep-seated layer, a pile foundation is connected with a large amount of long and large diameter piles respectively with enormous construction costs. To handle problems encountered in the design of foundations for high-rise buildings on settlement-sensitive soils, the development of new technical and economically optimised foundation designs has to be advanced. One method is to combine conventionally bored piles with a raft foundation resulting in a combined pile raft foundation (CPRF). This paper gives an overview of the theoretical and practical development of CPRF foundations.

KEY WORDS

1. INTRODUCTION

The city with the tallest high-rise buildings in Germany is Frankfurt am Main. The construction of these buildings is a demanding and complicated task for all areas of civil engineering, especially for geotechnical engineers when considering settlement-sensitive Frankfurt clay. Due to the high loads of the new structures, the risk of a high degree of settlements and tilts of not only the new buildings themselves, but also of the adjacent structures have to be taken into account.

The subsoil of Frankfurt am Main mainly consists of non-homogeneous, stiff and overconsolidated tertiary "Frankfurt clay" with embedded limestone bands of varying thicknesses. This layer is underlain by "Frankfurt limestone", which consists of limestone and dolomite layers as well as algal reefs, marly calcareous sands and silts and marly clay. The rather thin top layer consists
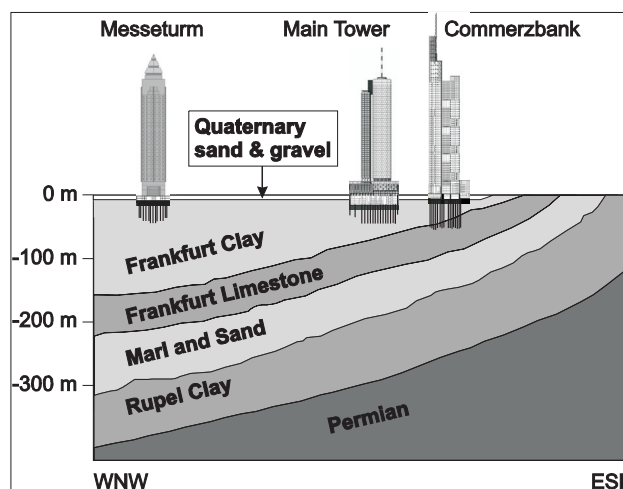

Fig. 1. *Subsoil of the area of Frankfurt am Main*

of quaternary sand and gravel. The various soil layers slightly dip 3° to 5° in a northwest direction (Fig. 1); the thickness of the settlement-sensitive Frankfurt clay layer varies beneath the foundation structures.

The aim during the design and construction process of high-rise building foundations in urban areas is to ensure the lifelong safety and serviceability of the new and existing buildings in the neighbourhood. In order to realise this aim in a cost-optimised manner, the combined pile raft foundation (CPRF) was developed. The CPRF is a approach accepted worldwide that during the last two decades has successfully been used for foundations in the Frankfurt am Main area, elsewhere in Germany and the rest of the world (Conte et, al. 2003; Poulos 2001; Russo & Viggiani, 1998; Poulos, et al., 1997; Randolph & Clancy, 1993; Randolph, 1983; Cooke, 1986).

2. FIRST GENERATION OF HIGH-RISE BUILDINGS IN FRANKFURT AM MAIN

For the first high-rise buildings, which were built on shallow foundations (2-4 m thick rafts), settlements of between 20 cm and 34 cm have been observed (Katzenbach, et al., 2001). Due to the problems of deflection and tilting, considerable efforts had to be spent to correct the settlement behaviour of these buildings during their construction stages and later on. One example, as seen in Fig. 2, are the 158 m high towers of the Deutsche Bank with measured settlements of 10 to 22 cm until 1985 and resulting differential settlements of 12 cm. The towers were built on a 80 m x 60 m large raft with a thickness of 4 m.

It was attempted during construction to keep the towers from drifting out of plumb, and it was finally accepted - although not recognizable - to have two not exactly vertical towers. The method of dealing with the differences in settlement between the towers and the adjacent lower building parts included hydraulic pumping devices in all the load-carrying columns of the lower building parts close to the towers. With this measure the lower building parts could be regulated ± 8 cm in their altitude in comparison to the two towers. The differential settlement and their effects on the serviceability of the structures in the towers were overcome by assembly regulations for the facade and the elevators.

This method of pre-installing hydraulic devices was also used when constructing the shallow foundation Dresdner Bank. As depicted in Fig. 3, 5 m x 5 m pressure cushions were located under the northwest corner because of the eccentric load. The pressure cushions were initially filled with water. After the completion and vertical adjustment of the structure, the water was replaced by mortar.

These complicated correction measures, which to some degree caused considerable problems, were insufficient and became unnecessary when using CPRFs some years later.

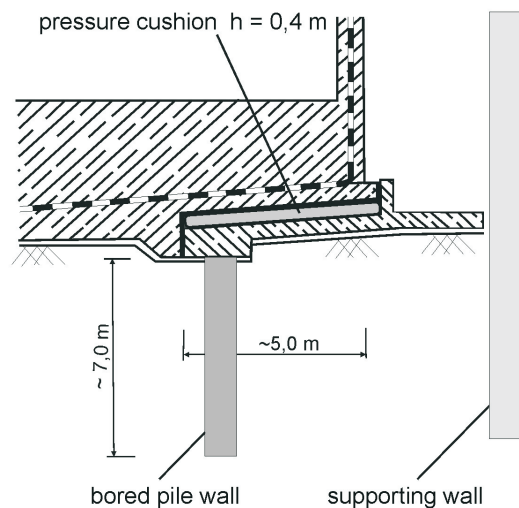**Fig. 2.** *Deutsche Bank: towers & settlement isolines*
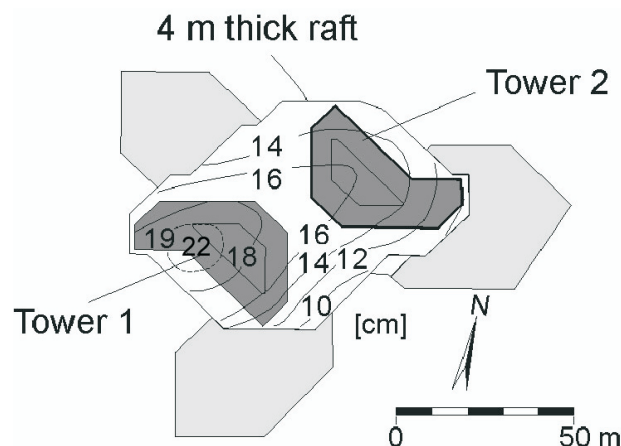
Fig. 3. *Dresdner Bank, tower & hydraulic devices used to adjust settlement behaviour*

3. COMBINED PILE RAFT FOUNDATIONS

3.1 Definition and Concept

The highest building in Frankfurt am Main which is built on a CPRF is the 256 m high Messeturm, which was constructed between 1988 and 1990 (Fig. 4). The initial settlements, which were calculated for a shallow foundation, were about 40-50 cm with a differential settlement of about 15 cm. The settlement observed for the CPRF was about 13 cm until 2000 (Reul 2000).

Designing CPRFs requires the qualified understanding of the different interactions as presented in Fig. 5.
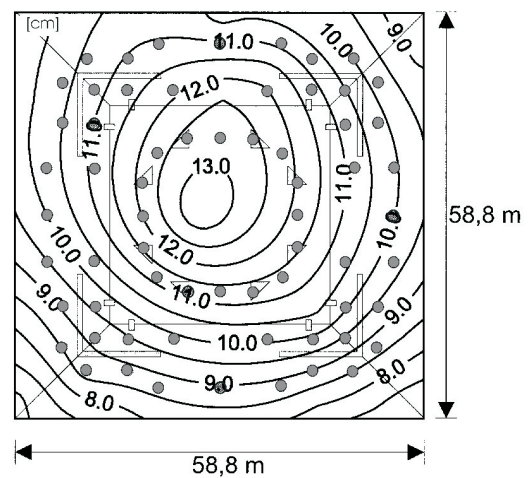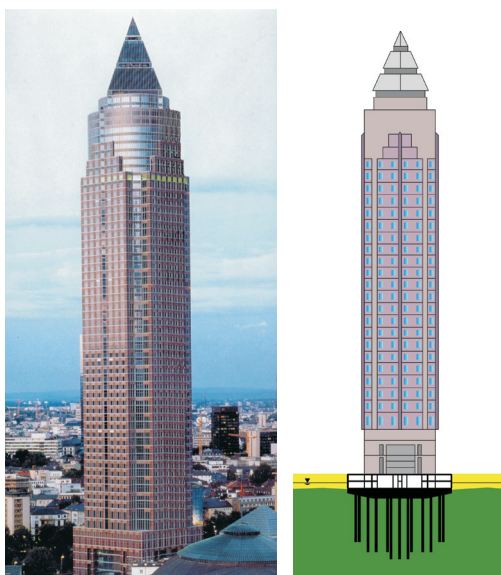

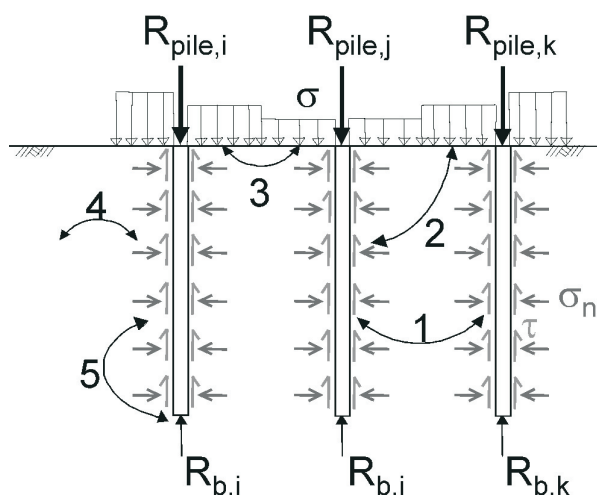Fig. 4. *Messeturm, tower & settlement isolines*

Fig. 5. *Interactions of a CPRF*

1 – Pile - Pile Interaction, 2 – Pile - Raft Interaction, 3 – Raft - Raft Interaction, 4 – Pile - Soil Interaction, 5 – Pile base - Pile shaft interaction

According to its stiffness, a CPRF transfers the total vertical load of a structure R_{tot} into the subsoil by contact pressure of the raft R_{raft} as well as by the piles $\Sigma\, R_{pile,i}$ (Equation 1).

$$R_{tot} = \sum R_{pile,i} + R_{raft} \tag{1}$$

In comparison with a conventional foundation design of a pile group, a new design philosophy has been applied for CPRFs. Piles are now used up to a load level which is much higher than the permissible design values for the bearing capacities of comparable single piles. The performance of the entire foundation system has to therefore be evaluated, taking into account the different effects of soil-structure interaction.

The distribution of the total building load between the different bearing elements of a CPRF is described by the CPRF coefficient α_{CPRF} (Equation 2), which defines the ratio between the amount of load carried by the piles $\Sigma\, R_{pile,i}$ and the total load of a building R_{tot}.

$$\alpha_{CPRF} = \frac{\sum R_{pile,i}}{R_{tot}} \tag{2}$$

For the large number of high-rise buildings which have been instrumented by the Institute and Laboratory of Geotechnics of the Technical University of Darmstadt, the load share observed between the raft and piles is depicted in Fig. 6 (Katzenbach, et al., 2001).
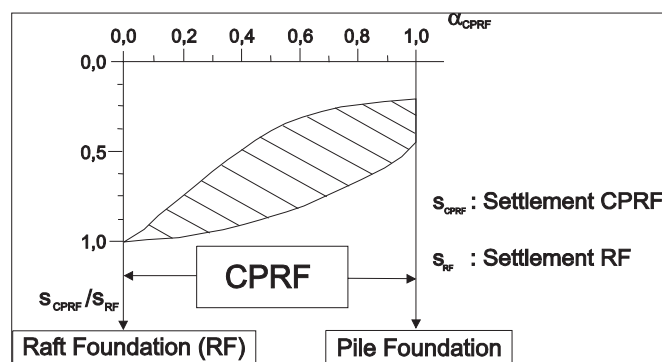

Fig. 6. *CPRF coefficient*

A CPRF coefficient of zero describes a raft foundation without piles; the coefficient of one represents a freestanding pile group, ignoring the existence of the raft.

In order to investigate the bearing behaviour of a CPRF, the aforementioned interactions as depicted in Fig. 5 have to be considered in the design process. Starting in the early 1980s, CPRFs were first used for high-rise office buildings in Frankfurt am Main (Fig. 7), mainly to reduce settlements to practicable dimensions and ensure their serviceability by reducing differential settlements to a minimum. Compared to traditional pile foundations, CPRFs allow for a saving of construction time and, consequently, a considerable reduction in costs.
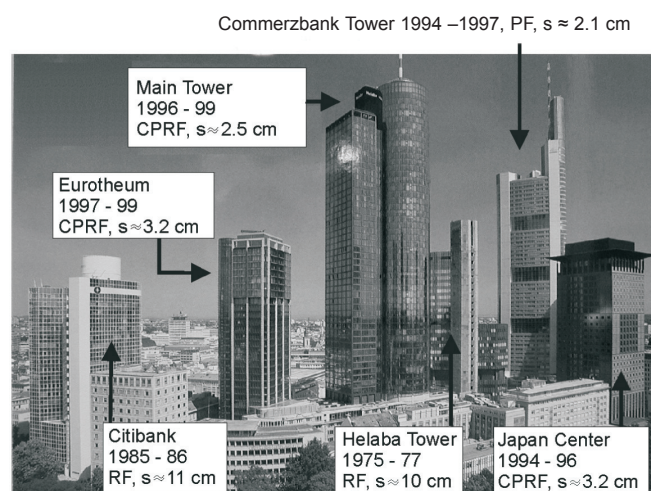

Fig. 7. *Examples of foundations of high-rise buildings in Frankfurt am Main*

RF – Raft Foundation, PF – Pile Foundation, CPRF – Combined Pile Raft Foundation

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However, it has become clear that the design and forecasting of settlements requires, in general, the application of a powerful numerical tool. The finite element method has been used to exemplarily predict settlement behaviour and the performance of a high-rise building foundation.

3.2 A Guideline for Combined Pile Raft Foundations

Based on a large variety of parametric studies with numerical simulations and extensive experience with CPRFs gained by long-term monitoring of foundation behaviour, a guideline for combined pile raft foundations was developed (Hanisch, et al., 2002). The CPRF guideline provides guidance on several aspects regarding the design, the safety concept, the limits of application, the use of the observational method and the construction of CPRFs. It also gives guidance for an engineer concerning an adequate soil investigation program and also includes pile drilling and pile tests (Hanisch, et al., 2000; Katzenbach & Moormann, 2001). Furthermore, the guideline points out the requirements for an appropriate calculation method within the CPRF design process.

The guideline distinguishes between the external and internal bearing capacity and follows the limit state design philosophy. Within the limit state design method, the performance of a whole structure as well as the different parts of the structure is described with reference to a set of limit states beyond which the structure fails to satisfy fundamental requirements. In Eurocode EC 7, a distinction between the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS) is made. Ultimate limit states comprehend different kinds of collapses, failures and excessive deformations prior to failure, the risk of casualties and the danger of severe economic loss.

The ULS (Fig. 8) is separated into two parts. Proofing the external bearing capacity ensures that the overall system consisting of soil and foundation elements like raft and piles are appropriately and safely supporting the working load of the building. The applied global safety factor is $\eta=2$ for load case 1 (applicable for dead loads and regular working loads, including wind loads).

In the formula depicted in Fig. 8, $S_{k,i}$ is the characteristic value of action i, and $R_{1,tot,k}$ is the characteristic value of the total resistance of a combined pile raft foundation, which can be derived from the calculated load-settlement curve of the CPRF. The internal bearing capacity is defined by the bearing capacity of the different parts of the reinforced concrete structure itself. Attention is drawn to the fact that, compared to classical pile foundations, no proof for the external bearing capacity of each individual pile is necessary.

The serviceability limit state (SLS) corresponds to conditions beyond which specified requirements for the structure and its use are no longer given. This applies to deformations, settlements and vibrations in normal use under working loads, such that the serviceability of the structure is no longer guaranteed.

The SLS condition (Fig. 9) requires that the design value of the action effect E be less than the limiting value of the deformation of the structure at the serviceability limit state, where C is the resistance property for the SLS. Corresponding to the ULS, the internal serviceability is related to the construction materials used for different foundation parts.
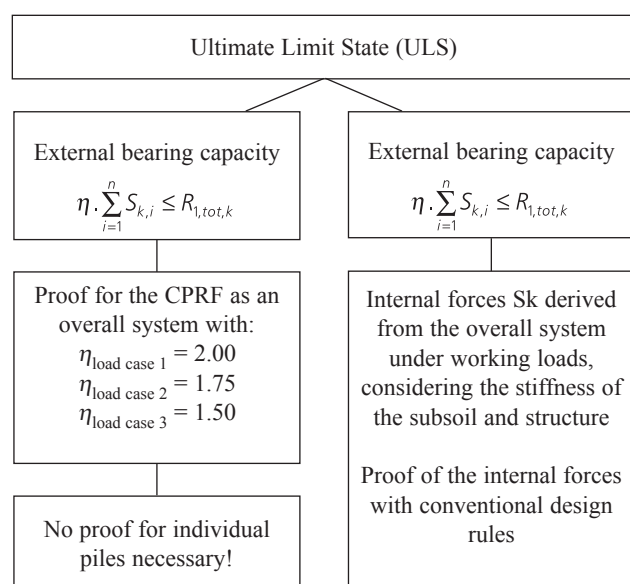
Ultimate Limit State (ULS)

External bearing capacity $\eta \cdot \sum_{i=1}^{n} S_{k,i} \leq R_{1,tot,k}$	External bearing capacity $\eta \cdot \sum_{i=1}^{n} S_{k,i} \leq R_{1,tot,k}$
Proof for the CPRF as an overall system with: $\eta_{\text{load case 1}} = 2.00$ $\eta_{\text{load case 2}} = 1.75$ $\eta_{\text{load case 3}} = 1.50$	Internal forces Sk derived from the overall system under working loads, considering the stiffness of the subsoil and structure Proof of the internal forces with conventional design rules
No proof for individual piles necessary!	

Fig. 8. *CPRF guideline: Ultimate Limit State (ULS)*

Serviceability Limit State (SLS)

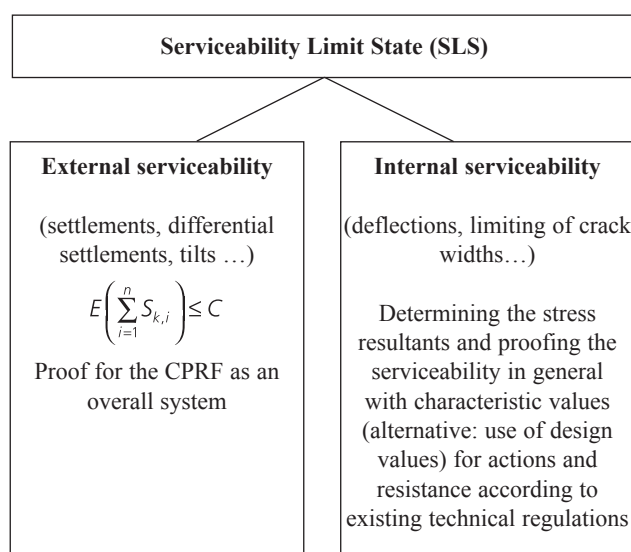| **External serviceability** (settlements, differential settlements, tilts …) $E\left(\sum_{i=1}^{n} S_{k,i}\right) \leq C$ Proof for the CPRF as an overall system	**Internal serviceability** (deflections, limiting of crack widths…) Determining the stress resultants and proofing the serviceability in general with characteristic values (alternative: use of design values) for actions and resistance according to existing technical regulations

Fig. 9. *CPRF guideline: Serviceability Limit State (SLS)*

4. THE OBSERVATIONAL METHOD

According to Eurocode EC 7, the observational method has to be applied when the prediction of geotechnical behaviour is difficult. The observational method is much more than pure monitoring. On the one hand, it is a combination of the usual geotechnical investigations and calculations, and on the other hand, the geotechnical measurement program during the construction process and – if necessary – even after the construction has ended (Fig. 10).
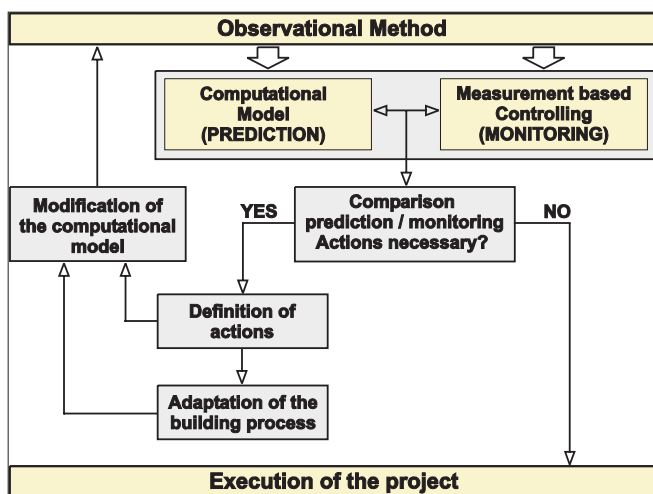

Fig. 10. *Flow chart for the application of the observational method*

The following requirements have to be met before the construction begins:
- Acceptable limits of behaviour have to be established.
- An assessment of the scope of the possible behaviour has to be performed. The predicted behaviour should occur within the acceptable limits by an acceptable probability.
- A plan of the measurements has to be set up to monitor the actual behaviour and control if it is within the acceptable limits.
- The response time of the instruments and the procedures for analysing the results should be sufficiently rapid in relation to the possible evolution of the system.
- A plan of contingency actions has to be devised, which may be adopted if the monitoring reveals behaviour which is outside the acceptable limits.

The observational method should be applied to:
- Constructions with a high degree of difficulty (buildings classified as Geotechnical Category 3)
- Constructions with a distinct soil-structure interaction, especially when adjacent buildings are affected
- Constructions with strong and alternating water pressure loading
- Constructions on slopes, and
- Constructions whose stability is affected by pore water pressure changes.

The application of the observational method is not aimed at compensating for mistakes during design and construction, but at revealing a sufficient degree of safety with respect to any difficulty in describing the subsoil and the complex interactions between the structure and soil. Furthermore, the observational method can be used as an instrument for the construction process with special regard to alternative solutions.

The observational method is an essential part of the safety concept for CPRFs and must always be applied during the construction process of a CPRF.

5. MONITORING OF COMBINED PILE RAFT FOUNDATIONS

Installing measuring devices and monitoring the performance of foundation structures only serves not safety and stability aspects, but also serves to document movements that occur and guarantee serviceability throughout all the construction stages, including the phase of operation.

The monitoring of a CPRF might comprise the excavation, foundation and surrounding area. The type and quantity of instrumentation and measurements depend on the requirements defined by the complexity of the CPRF, its geotechnical and geometric boundary conditions and the subsoil situation. The following parameters might be measured by geotechnical and geodetic measurements within the context of the observation of a CPRF:

- The load-settlement behaviour of the foundation: Settlements are usually measured by geodetic measurements, whereas in order to determine the time-dependent load developments, a careful analysis of the actual weight of the building is necessary (e.g., by analysing the delivery notes for concrete and steel).
- The load share between the raft and foundation piles: It can only be measured indirectly by measuring the effective contact pressure and the pile forces as well.
- The value and distribution of the total contact pressure and the water pressure below the foundation raft.
- The bearing behaviour of the foundation piles comprising the pile forces at the pile heads within the pile group, the distribution of skin friction along the pile shaft and the remaining pile forces at the pile toe (tip resistance).

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• The variation in depth of the settlements in the subsoil.
• Any impact on the adjacent area and structures next to the CPRF (e.g., vibrations).

In simple cases geodetic measurement of the foundation settlements might be sufficient, whereas in more difficult cases, geodetic and geotechnical measurement devices have to be devised for an ingenious monitoring system.

Simultaneously with the design process of a CPRF, a monitoring program should be planned and specified by a geotechnical expert. The monitoring program should be fixed to the project-specific situation and boundary conditions. The content of such a monitoring program should include at least:

• The type and quantity of instrumentation, i.e., the kind of sensors, the amount and the location planned for its installation.
• The requirements and specifications for the measurement sensors planned to be installed.
• Specifications of a time-dependent measurement program with defined dates for measurements correlated to the building process.
• Specifications of any values, which act as a limit, that will raise alarm and require counter-measures if they are reached.
• Based on long-term experience, it should be pointed out that it is very important to use two sensors or two instrumented sections for any essential measurement task that means to take care of redundancy.

6. CASE STUDIES IN FRANKFURT AM MAIN

The design, instrumentation and monitoring of CPRFs can be illustrated in more detail by two case histories of combined pile raft foundations that serve as foundations for high-rise buildings in Frankfurt am Main, Germany. At the same time the two case histories selected elucidate developments in designing CPRFs and observing their load-bearing behaviour.

6.1 Messe-Torhaus

The construction of the Messe-Torhaus from 1983 to 1985 was the first application of a Combined Pile Raft Foundation in Frankfurt am Main and in Germany as well (Fig. 11). Due to an adjacent triangular intersection of railway bridges, a settlement-reduced foundation was required for the 30-floor building.

The CPRF of the Messe-Torhaus consists of two separate rafts, each with 42 bored piles with a length of 20 m and a diameter of 0.9 m. The 6 x 7 piles are arranged uniformly under each raft with a pile spacing of 3 to 3.5 times the pile diameter. Both rafts have planned dimensions of 17.5 m x 24.5 m. Each raft is forced by an effective structural load of 200 MN. As there had not been any earlier experience with CPRFs in Germany, the bearing behaviour of the CPRF was carefully monitored by a geotechnical measurement program during construction. As shown in Fig. 11, for the northern CPRF, 6 piles were instrumented with strain
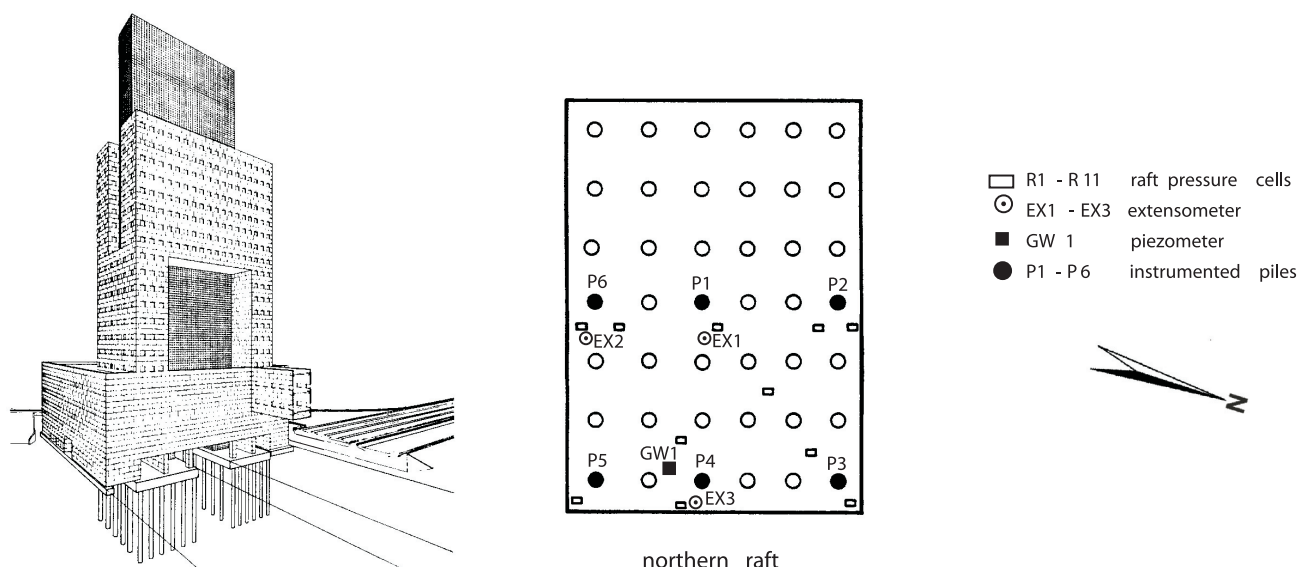

Fig. 11. *Messe-Torhaus, ground plan with measurement devices*
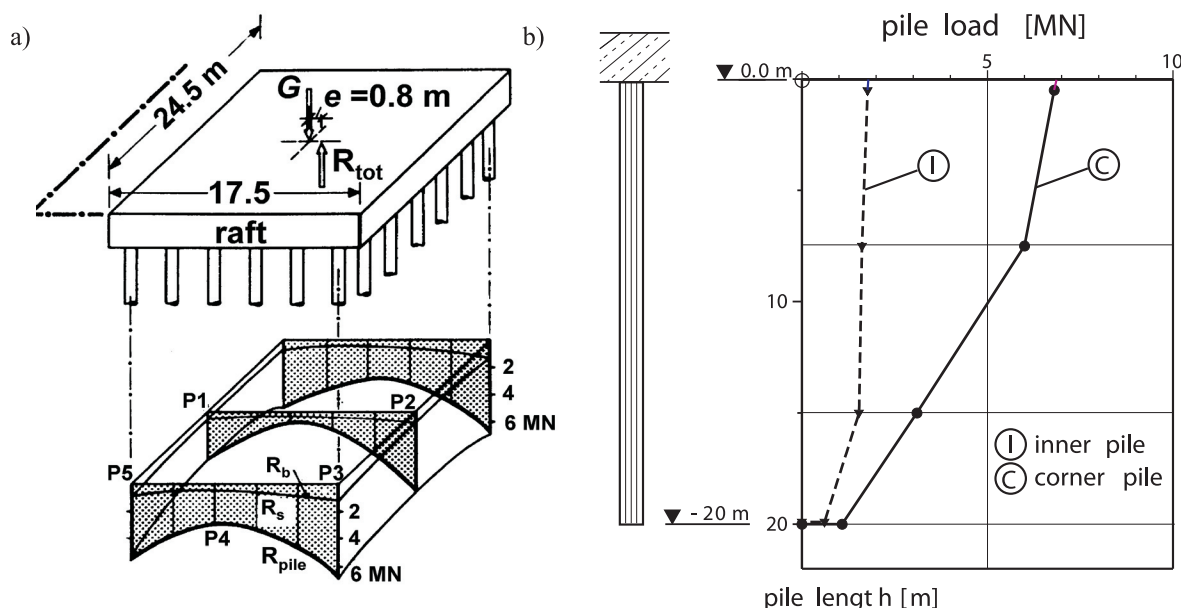
Fig. 12. *Messe-Torhaus building.*
a) Measured pile loads at northern CPRF, b) Measured distribution of pile force with depth for a corner pile and an inner pile

gauges and a load cell at the pile toe, 11 earth pressure cells were installed beneath the raft and 3 extensometers led down to a depth of 40.5 m below the raft.

The measured load sharing indicates that only a rather small part of the structural load has been transferred by the raft to the soil as indicated by a CPRF coefficient α_{CPRF} equal to about 0.8. The distribution of the measured pile loads under the northern raft is illustrated in Fig. 12a, where the total resistance of the pile (R_{pile}) is separated into its shaft resistance (R_s) and its base resistance (R_b). Its pile loads decrease from the corner piles (P3, P5) to the edge piles (P2, P4, P6) and, significantly, to the inner piles (P1). The different pile loads are a consequence of the dependency of the mobilised skin friction on the position of a pile within the group. Figure 12b shows the distribution of the pile forces for the corner pile P3 and the inner pile P1 measured by the strain gauges. The corner pile can mobilise an average skin friction of 140 kN/m in the lower two thirds of the pile shaft; the inner piles mobilise only a skin friction of 60 kN/m in the lowest third of the pile shaft.

These measured results in combination with the rather high α_{CPRF}-value of 0.8 indicate a quite conservative design of the CPRF of the Messe-Torhaus. The aim of reducing the settlements of the foundation in comparison to the shallow foundation has been achieved, but the distribution of the pile loads with very small pile loads carried by the inner piles indicates that there is the potential to optimise the design of CPRFs. The maximum settlement measured was about 12 cm.

6.2 Messeturm

By its completion in 1991, the 256-m high Messeturm was the tallest office building in Europe. The building has a basement with two underground floors and a 60-storey core shaft (41 m x 41 m in the plan). The overall load of the building was calculated at 1,880 MN. The site of the Messeturm contains Frankfurt clay to a depth of more than 100 m below the surface. The construction of a conventional pile foundation was therefore more or less impossible.

The foundation system comprises a 3 m to 6 m thick raft, which is supported and stabilized against tilting by 64 bored piles with a diameter of 1.3 m arranged in three concentric circles under the raft. The pile length varies from 26.9 m for the 28 piles of the outer circle to 30.9 m for the 20 piles of the middle circle and 34.9 m for the 16 piles of the inner circle (Fig. 13). The pile spacing varies between 3.5 and 6 times the pile diameter. The improved pile spacing is greater than 3 times the pile diameter, and the increasing pile length from the edge to the centre of the raft is the result of experience gained by monitoring the CPRF of the Messe-Torhaus. The monitoring of the bearing behaviour of the CPRF in accordance with the observational method was an important part of the design.
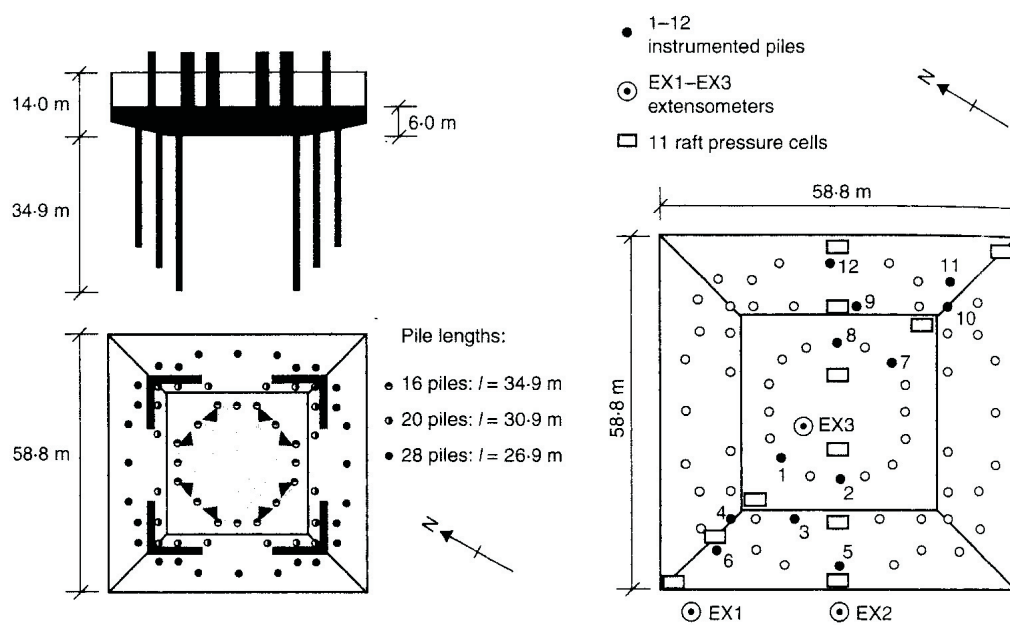
Fig. 13. *Messeturm building: ground plan and cross section of the CPRF*

Figure 13 shows the measurement devices installed under the raft and inside the pile shafts. Twelve foundation piles were instrumented by load cells at the pile head and strain gauges along the pile shaft. Thirteen earth pressure and 10 pore water cells were installed below the raft as well as 3 extensometers 70 m below the surface.

As a summary of the measured results, the CPRF coefficient was determined to be $\alpha_{CPRF} = 0.55$. Following completion of the shell, the average effective stresses beneath the raft were measured by the earth pressure cells to be about 160 kN/m². The bored piles transfer the load into the subsoil mainly by skin friction (Fig. 14a). From the upper section of the pile shaft down to 15 m below the raft, the skin friction was remarkably low with measured values of 25 kN/m² - 70 kN/m². In the deeper section of the pile shaft, the inner piles mobilise a skin friction of up to 110 kN/m², while the piles in the middle and outer pile circles mobilise a skin friction of 160 kN/m². In comparison with the Messe-Torhaus, the inner piles of the Messeturm mobilise a significantly higher skin friction. This measured distribution of the skin friction clearly demonstrates the effect of the pile-raft interaction on the load-bearing behaviour of the piles as part of the CPRF.

The distribution of the settlements with some depth beneath the Messeturm was measured by extensometers at a corner (EX1), at an edge (EX2) and at the centre (EX3) of the raft (Fig. 14b). The EX1 and EX2 extensometers show a uniform distribution of settlements along the depth measured, whereas EX3 indicates superproportional decreasing settlements with depth. The measurements show that 20 - 30 % of the settlements occur below a level of 70 m under the surface. The results of the field measurements indicate that the load-bearing behaviour of the Messeturm CPRF has been optimised in comparison to the CPRF of the Messe-Torhaus. However, the original design assumption, that the piles would reach their ultimate bearing capacity at the settlements generated by the structural load and thereafter transfer any additional load increments to the raft could not be proved by field observation. The measured pile loads show that a much higher skin friction has been mobilised than was determined for a single isolated pile.

7. CONCLUSIONS

By using CPRFs as a foundation for high-rise buildings in the settlement-sensitive Frankfurt clay, a considerable settlement reduction of more than 50% compared to raft foundations can be achieved. Due to its enhanced design philosophy, a CPRF reduces the costs for piles by more than 60 % compared to a conventional pile foundation.

During the design process of a CPRF based on finite element analysis, strong co-operation between the geotechnical and structural

engineers is necessary to guarantee a safe and economic construction (Katzenbach, et al., 1999). In this context, an important part of the design work of the geotechnical engineer is also to review and assess the effects of the results of the geotechnical analysis of the structural design.

The observational method is an important tool of the safety concept of complex geotechnical constructions like the CPRF. In order to evaluate the bearing behaviour of a CPRF, extensive measurements should be performed during the construction process.
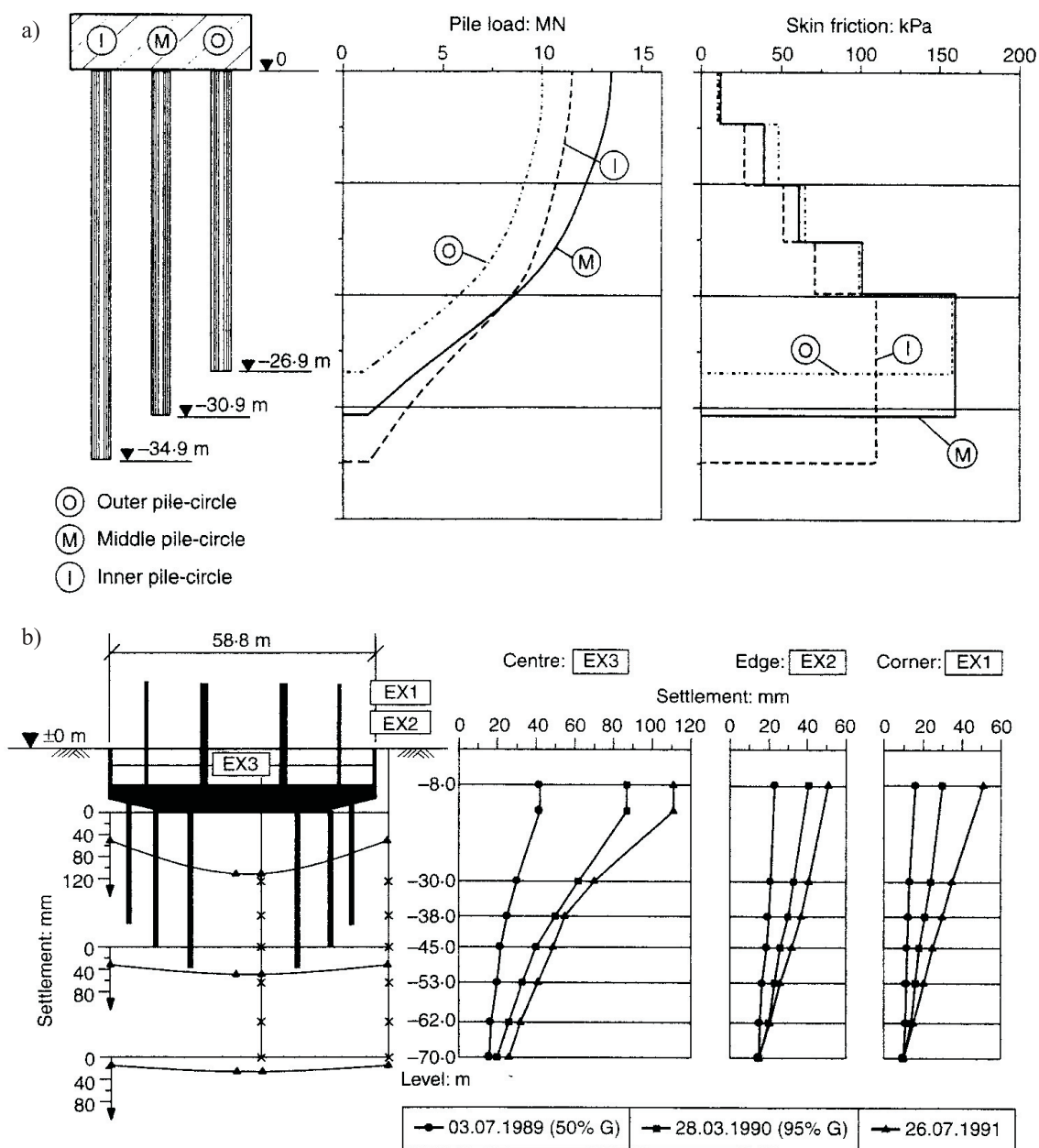

Fig. 14. *Measured behaviour of the CPRF of the Messeturm: a) Distribution of pile load and skin friction, b) Distribution of settlement with depth*

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