Chapter

Reducing Carbon Emissions by Combined Pile-Raft Foundations for High-Rise Structures

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Abstract

Regarding the impact of construction processes on the environment, the reduction of CO_2 has an important role. The production of materials e.g. reinforced concrete, and the construction of structures consume large amounts of energy, which leads to a large emission of CO_2. The target is the reduction of the amount of construction material used and of the energy consumed for construction. For this, the structures have to be optimized regarding the geometry considering the requirements of the stability, serviceability, and durability. Also, foundation systems of high-rise buildings can be optimized regarding CO_2 emission. For the optimization, three parts have to be considered. The first part is the detection of the real load-deformation behavior of a foundation element. This can be reached by large-scale load tests in situ. The second part is to use the hybrid foundation system Combined Pile-Raft Foundation (CPRF), which combines the bearing capacities of the raft and of the piles. The third part is the realistic prediction of the load-deformation behavior of the foundation. For this three-dimensional, nonlinear calculations using the Finite-Element-Method (FEM) are necessary. The contribution explains the three parts and shows the application in engineering praxis, including case studies.

Keywords: CO_2 reduction, load test, Combined Pile-Raft Foundation, high-rise building, sustainability

1. Introduction

The most important aspects for the design of any foundation system are safety, serviceability, and sustainability. The requirements for safety and serviceability are defined in standards, codes, and regulations. For sustainable construction, a reduction of construction material used and energy consumed during the construction phase and the service phase of a building/structure is important. Regarding the changing climate and the necessity to avoid CO_2 emissions, the design and construction of new buildings and structures have to be optimized. The focus has to be on the production of cement. The production of one ton of cement leads to an emission of about 800 kg of CO_2. This is about 91% of the whole CO_2 footprint of concrete and about 8% of the man-made CO_2 emission of the world [1]. This shows that the reduction of concrete for any kind of structure is an important aspect for the reduction of CO_2 emission.

Optimized foundations systems lead to a reduction of concrete. This optimization has to consider the requirements of safety, serviceability, and sustainability. For the foundation systems of high-rise buildings, the following parts are necessary:

- Large-scale load tests in situ on the construction site to detect the real load-deformation behavior of the foundation.

- Hybrid foundation systems for high-rise buildings like the Combined Pile-Raft Foundation (CPRF) [2].

- Three-dimensional, nonlinear simulations of the load-deformation behavior of the foundation system using e.g. Finite-Element-Method (FEM).

All of these three important aspects will be explained in the following chapter. Nevertheless, the precondition for any kind of safe and optimized design is a sufficient soil and groundwater investigation.

2. Large scale in situ load tests of piles

Load tests of piles, that are performed in-situ on the construction site are the best opportunity for the determination of the load-deformation behavior [3]. For the determination of the bearing capacity, the loads on test piles can have a vertical resp. horizontal direction. Vertical loads can be compression loads or tension loads depending on the construction task. The tests can be static load tests or dynamic load tests. Detailed descriptions of these different test types are given in [4, 5]. In the following, only the static pile load test for determining the vertical bearing capacity is presented.

Normally counterweights or anchors are used as an abutment for the pile load. The installation of counterweights or anchors necessitates large technical and financial input. Using hydraulic jacks like the Osterberg-cell (O-cell) is more convenient. **Figure 1** shows the variations of static pile load tests.

By using the Osterberg-method, hydraulic jacks are installed in a test pile to detect to determine the skin friction in different pile segments that correspond to different soil layers. The single pile segments serve as counterweights for the different test phases.

The result of a pile load test with vertical load is described by a resistance settlement curve $R_{c,k}(s)$ which can be used as the basis for the analyses of stability and serviceability. In **Figure 2** a qualitative trend of a resistance settlement curve is shown. Two straight reference lines help to determine the pile resistance $R_{c,k}$. These two straight reference lines draw a tangent at the beginning and at the end of the resistance settlement curve. The interaction of both lines defines the stability limit state.

Based on one or several pile load tests, the measured value $R_{c,m}$ is determined, which has to be reduced by the factor ξ taking straggling into account. According to [6] the pile resistance has to be calculated by Eq. (1) if the superstructure is not able to transfer loads from softer to stiffer piles.

$$R_{c,k} = MIN\left\{\frac{(R_{c,m})_{av}}{\xi_1}; \frac{(R_{c,m})_{min}}{\xi_2}\right\} \tag{1}$$

The superstructure is able to transfer loads from softer to stiffer piles if the superstructure has sufficient rigidity. In this case, the straggling factors ξ_i can be

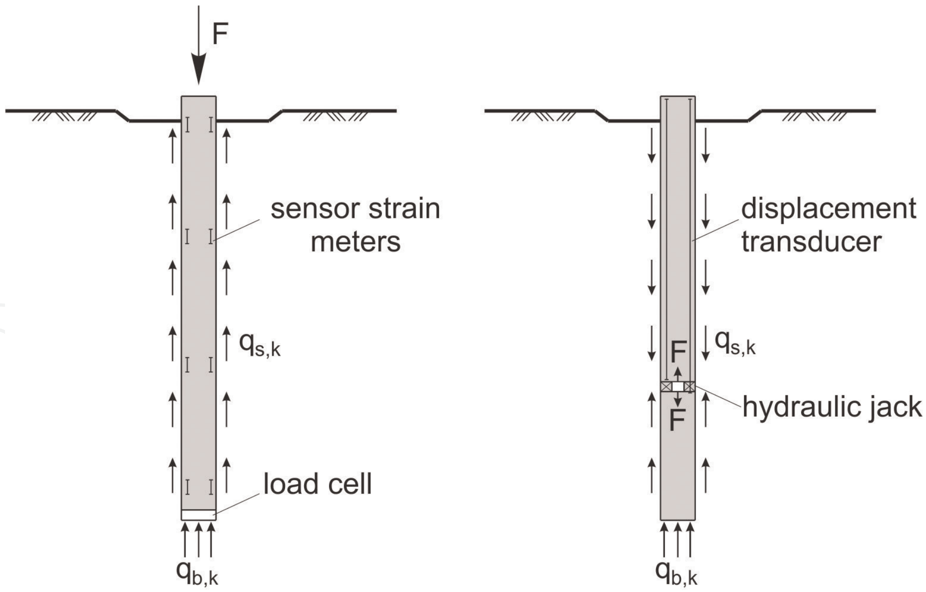


Figure 1.
Static piles load test with counterweight resp. anchor (left) and hydraulic jack (right).

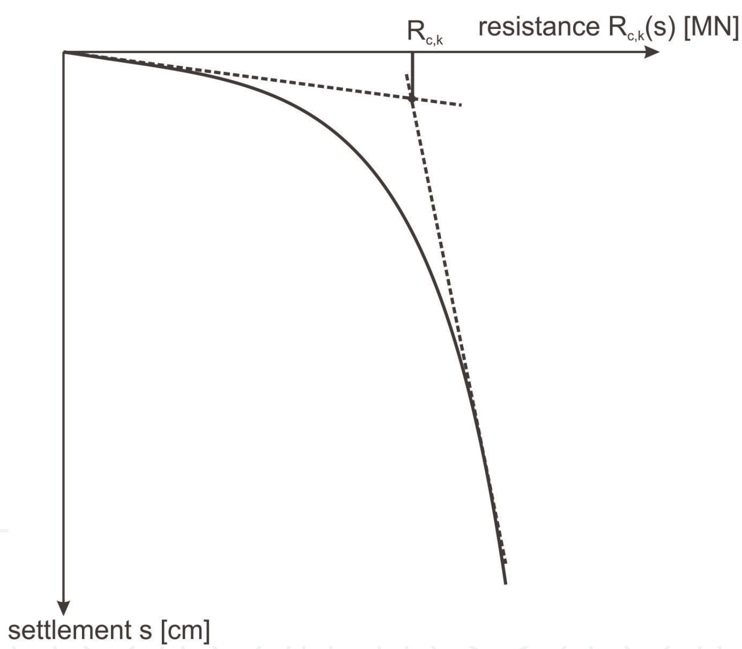


Figure 2.
Determination of the pile resistance by a resistance settlement curve.

n	1	2	3	4	≥5
ξ_1	1.35	1.25	1.15	1.05	1.00
ξ_2	1.35	1.15	1.00	1.00	1.00
n = number of pile load tests					

Table 1.
Straggling factors ξ_i for resistance of pressure piles.

divided by 1.1 (ξ_1 is always ≥ 1.0). To the measured average pile resistance belongs the straggling factor ξ_1. To the measured minimum pile resistance belongs the straggling factor ξ_2. The straggling factors for pressure piles are given in **Table 1**.

3. Combined Pile-Raft Foundation (CPRF)

3.1 Basics

A Combined Pile-Raft Foundation (CPRF) is a hybrid, technically and economically optimized foundation system. It combines the bearing capacity of a foundation raft and of piles or barrettes. For the foundation of classic high-rise buildings as well as for engineering constructions like bridges and towers CPRFs can be used.

The technical regulations for classic deep foundations prevail for CPRFs as well [4]. In addition, the Combined Pile-Raft Foundation Guideline [7] has to be considered. This internationally validated guideline reflects the individual features of a CPRF and is published by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE).

CPRFs have a very complex bearing and deformation behavior due to the interaction between the foundation elements and the subsoil. CPRFs belong to the Geotechnical Category GC 3 according to EC 7 [6].

The advantages of a CPRF, compared to a conventional spread foundation and a classic pile foundation, are the reduction of:

- Settlements and differential settlements.
- The bending moments of the foundation raft.
- Pile materials (30–40%)

3.2 Bearing and deformation behavior

The measurement data of high-rise buildings founded on spread foundations in Frankfurt am Main, Germany, showed, that 60–80% of the settlements arise in the upper third of the influenced soil volume. A part of the load on a CPRF is transferred py the piles from areas with a small stiffness under the foundation raft to a stiffer, deeper area of the subsoil without neglecting the bearing capacity of the foundation raft (**Figure 3**).

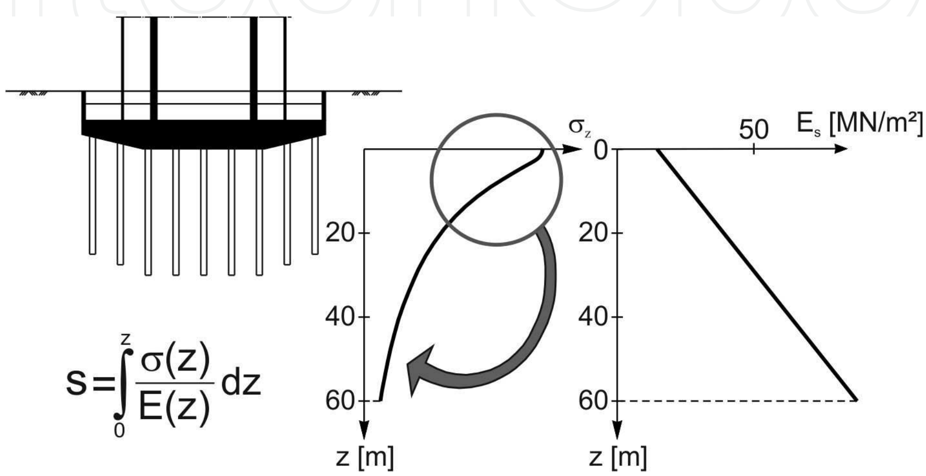


Figure 3.
Principle load transfer of a CPRF.

The bearing and deformation behavior of a CPRF is characterized by the interaction between the bearing elements (foundation raft and pile resp. barrettes) and the subsoil. **Figure 4** shows all interactions of a CPRF.

A CPRF transfers the total building load $F_{tot,k}$ to the piles and the subsoil. The mobilized resistance of a CPRF depends significantly on the settlement s, which is similar to a classic deep foundation. The resistance $R_{raft,k}(s)$ equates to the integration of the soil contact pressure $\sigma(x,y)$ under the foundation raft. The resistance $R_{tot,k}(s)$ of a CPRF equates to the resistance of the foundation piles $\sum R_{pile,k,i}(s)$ added to the resistance of the foundation raft $R_{raft,k}(s)$ (Eq. (2)).

$$R_{tot,k}(s) = \sum_{i=1}^{i=n} R_{pile,k,i}(s) + R_{raft,k}(s) \tag{2}$$

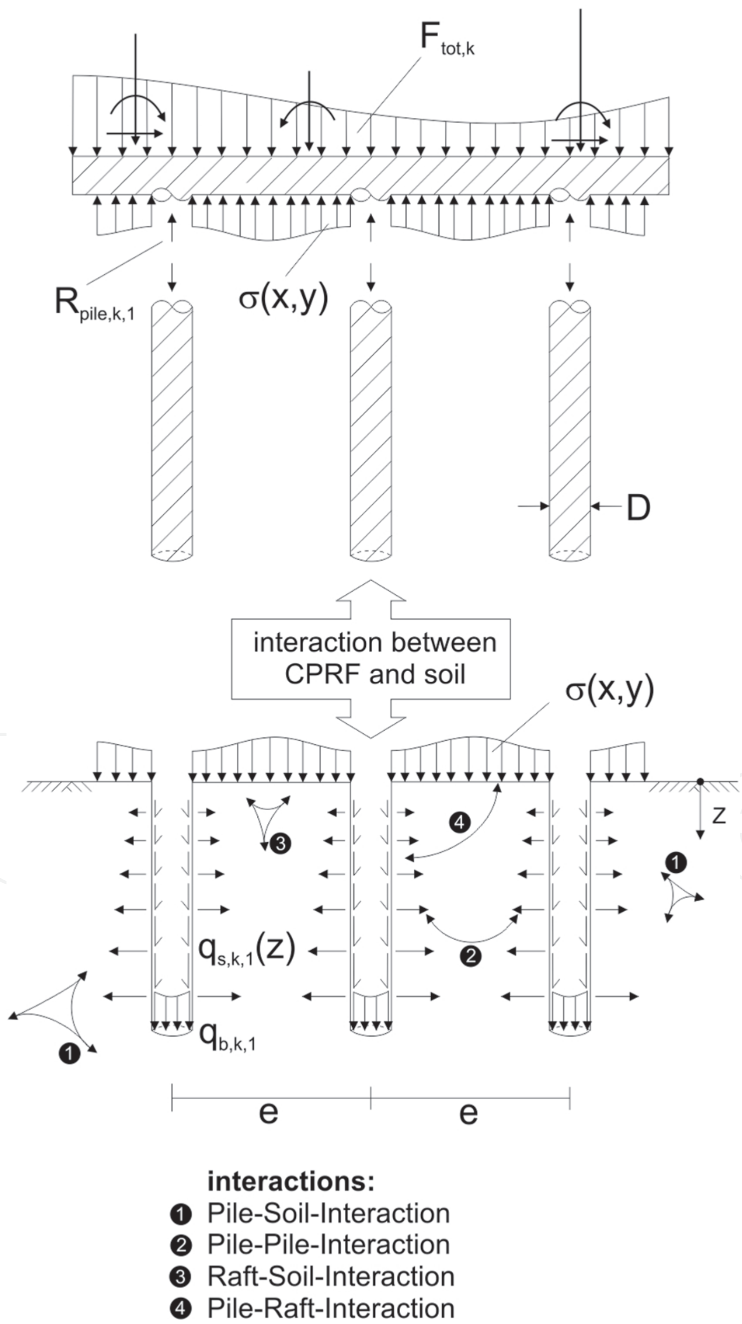


Figure 4.
Interactions of a CPRF.

As shown in Eq. (3), the total resistance of a single foundation pile consists of the skin resistance $R_{s,k,i}(s)$ and the pile base resistance $R_{b,k,i}(s)$. The skin resistance $R_{s,k,i}(s)$ can be calculated by integration of the skin friction $q_{s,k}(s,z)$, which depends on the settlement s and the depth z.

$$\begin{aligned} R_{pile,k,i}(s) &= R_{b,k,i}(s) + R_{s,k,i}(s) \\ &= q_{b,k,i} \bullet \frac{\pi \bullet D^2}{4} + \int q_{s,k,i}(s,z) \bullet \pi \bullet D \bullet dz \end{aligned} \tag{3}$$

The load-deformation behavior of a CPRF can be specified by the CPRF coefficient α_{CPRF}. This coefficient declares the relation between the resistance of the piles and the total resistance and varies between 0 and 1 (Eq. (4)).

$$\alpha_{CPRF} = \frac{\sum R_{pile,k,i}(s)}{R_{tot,k}(s)} \tag{4}$$

If the whole load $F_{tot,k}$ is carried by the foundation raft, the CPRF coefficient is $\alpha_{CPRF} = 0$. If the whole load $F_{tot,k}$ is carried by the foundation piles, the CPRF coefficient is $\alpha_{CPRF} = 1$. Related to technical and economic aspects a CPRF coefficient α_{CPRF} between 0.5 and 0.7 can be considered as optimum. For $\alpha_{CPRF} > 0.9$ additional analyses on the piles are necessary.

The effective horizontal stresses influence the mobilized skin friction of the piles. Hence the stress level of the subsoil influences the load-deformation behavior of a CPRF. The neighboring piles, the foundation raft, and the effects during the construction of the piles influence the stress level of the subsoil around every pile of a CPRF. The soil contact pressure under the foundation raft leads to an increased stress level of the subsoil. The result is higher skin friction in the upper parts of the piles.

3.3 Principle calculation method of a CPRF

For the design and calculation of a CPRF various methods can be selected [8–14]. Up to now only numerical methods, like the Finite-Element-Method (FEM) provide calculation results that are comparable to reality.

The knowledge about the load-deformation behavior of a free, single pile is necessary for a qualified design of a CPRF [4]. Otherwise, a pile load test has to be performed. Two reasons are important for the knowledge about the bearing capacity of a free, single pile:

- Evaluation of the selected geometries of the piles and to prove the plausibility of the calculation method.

- Possibility to calibrate the numerical model.

In situ pile load tests are required for complex construction projects and/or difficult soil conditions.

3.4 Monitoring of a CPRF

Regarding the Geotechnical Category GC 3 a CPRF has to be monitored [4, 6, 7]. The monitoring program consists of geodetic and geotechnical measurements of the new building and of the vicinity and covers the construction phase and the service phase of the building. The following tasks are important:

- Verification of the calculation model including the parameters used.
- Early detection of critical forces, stresses, deformations.
- Verification of the predicted deformations.
- Quality assurance and preservation of evidence.

4. Examples from engineering practice

4.1 Calibration of a numerical model

Numerical simulations using FEM have been carried out for the design of a CPRF of a new high-rise building founded in soft soil [15]. For the calibration of the numerical model a pile load test using Osterberg-Cells (O-cells) has been carried out in the project area. The test pile consisted of the upper test segment 1, the middle test segment 2 between the two O-cells, and the lower test segment 3.

In various testing phases, the O-cells were activated individually to determine the skin friction of the different layers and the pile base resistance. At test segment 3 only the lower O-cell was activated, while test segment 2 was used as an abutment to determine the skin friction and the pile base resistance. At test segment 2 the upper O-cell was activated and the lower O-cell was released to determine the skin friction. Test segment 1 was used as an abutment in this test phase. At test segment 1 the upper O-cell was activated and the lower O-cell was stiffened to determine the skin friction. Test segments 2 and 3 were used as an abutment in this test phase.

A numerical (FEM) back analysis of the pile load test was used to calibrate the numerical model of the CPRF. The FE-model of the numerical back analysis of the pile load test with the three test segments and the two O-cells is shown in **Figure 5**.

The results of the in situ pile load test and the numerical back analysis show good accordance (**Figure 6**). By this, the used soil mechanical parameters and the simplified stratigraphy, which was necessary for the numerical model, were verified.

The design of the CPRF is performed by three-dimensional, nonlinear FE-simulations. Taking into account the requirements of the load-deformation behavior the length, diameter, and the number of piles were optimized on the basis of the FE-simulations. The optimized CPRF is shown in **Figure 7**. Eighty percent of the total building load are carried by the piles and 20% of the total building load is carried by the raft. So, the CPRF coefficient is $\alpha_{CPRF} = 0.8$.

4.2 High-rise building in settlement active clay

The high-rise building Messeturm in Frankfurt am Main, Germany, is 256.5 m high and is founded on a CPRF in the settlement active Frankfurt Clay (**Figure 8**). The foundation raft has a ground view of 58.8 m × 58.8 m with a maximum thickness of 6 m in the center and a thickness of 3 m at the edges. The base of the foundation raft is about 11–14 m below the surface.

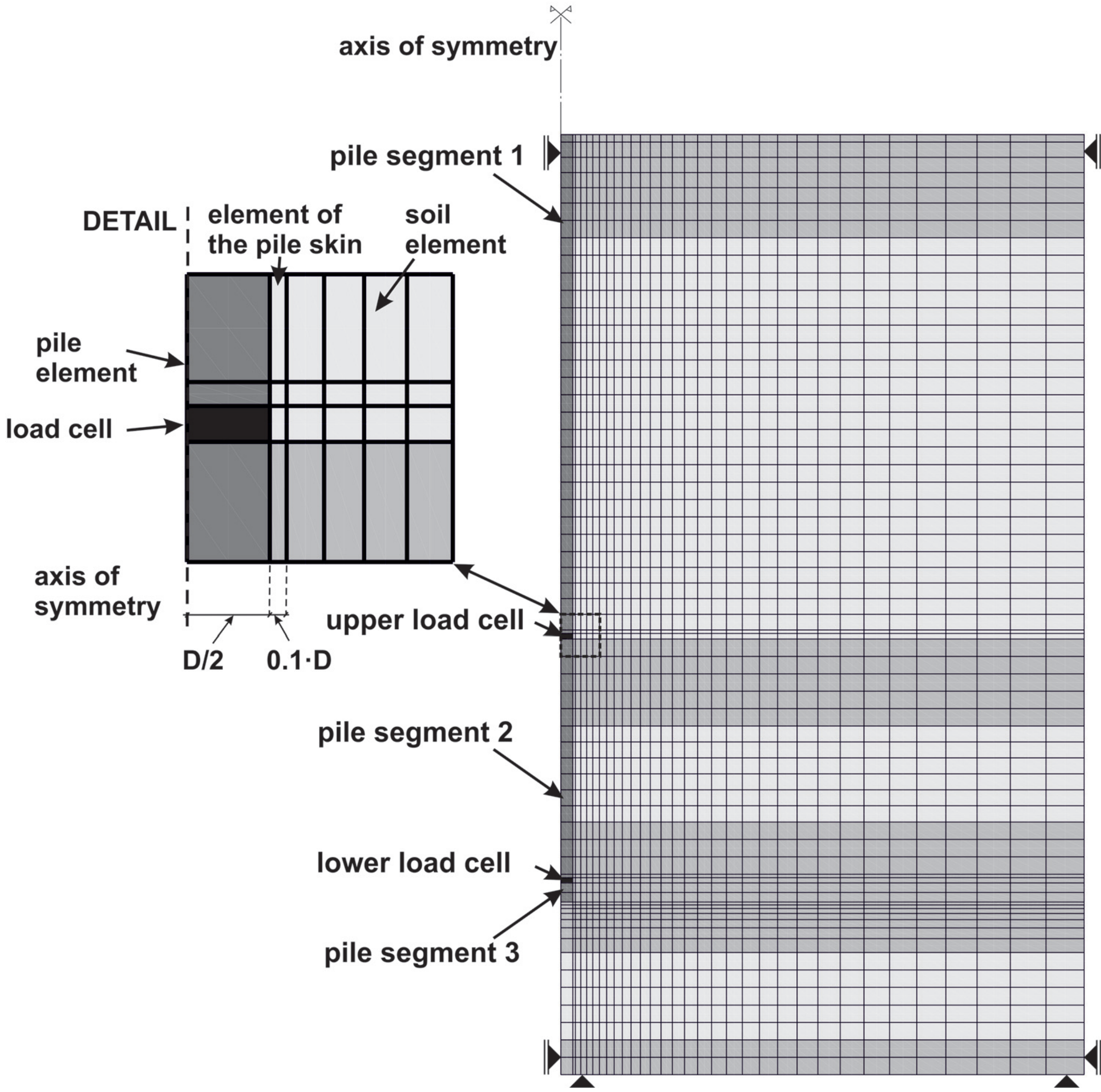


Figure 5.
Numerical simulation of the pile load test for calibration.

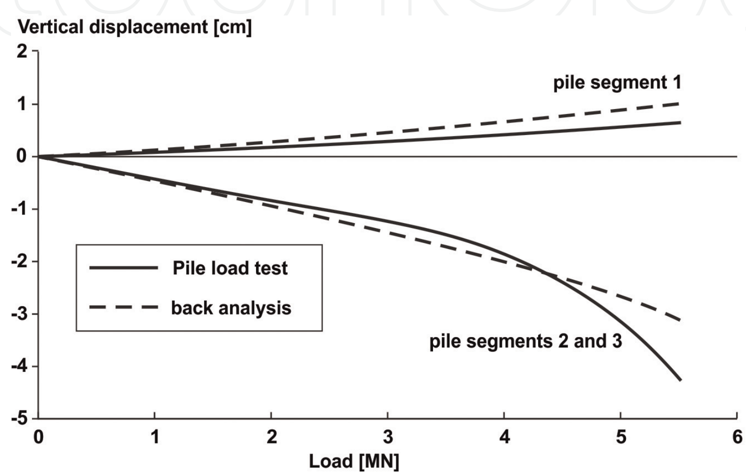


Figure 6.
Measurement and calculation of the pile load test (upper O-cell activated, lower O-cell stiffened).

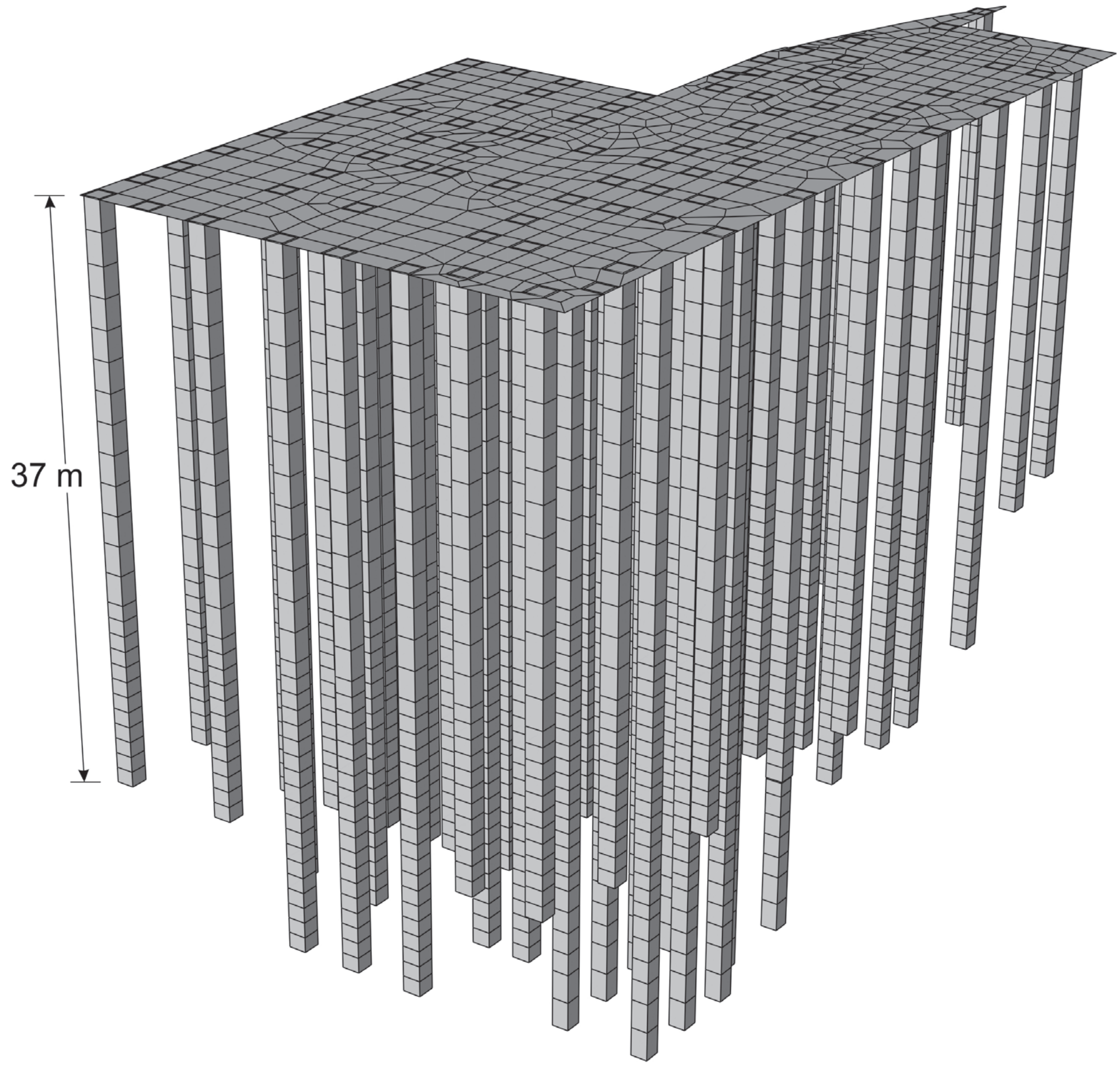


Figure 7.
FE-mesh of the optimized CPRF.

Figure 9 shows the CPRF with 64 bored piles with a diameter of 1.3 m. The length varies between 30.9 m in the center and 26.9 m at the edges. The total building load is about 1,855 MN including 30% of the live loads.

The subsoil in the project area consists of artificial fillings at the surface which are underlain by quaternary sand and gravel until a depth of 8–10 m below the surface. Below follows the tertiary Frankfurt Clay to a depth of about 70 m below the surface. At a depth of 4.5–5.0 m below the surface is the groundwater table. The maximum measured settlements of the foundation raft were 13 cm in the center and 7–9 cm at the edges.

The CPRF was calculated using the FEM. Thereby a section of the foundation was modeled, using the symmetry of the ground view (**Figure 10**).

The FE-calculation simulates the construction process step-by-step. These steps are the excavation of the construction pit, the construction of the CPRF, the groundwater lowering, the loading of the CPRF, and the groundwater re-increase.

For the optimization of the CPRF different pile configurations and pile length was analyzed as well as a pure raft foundation. **Figure 11** shows the comparison of the load-settlement curves of a pure raft foundation and of a CPRF.

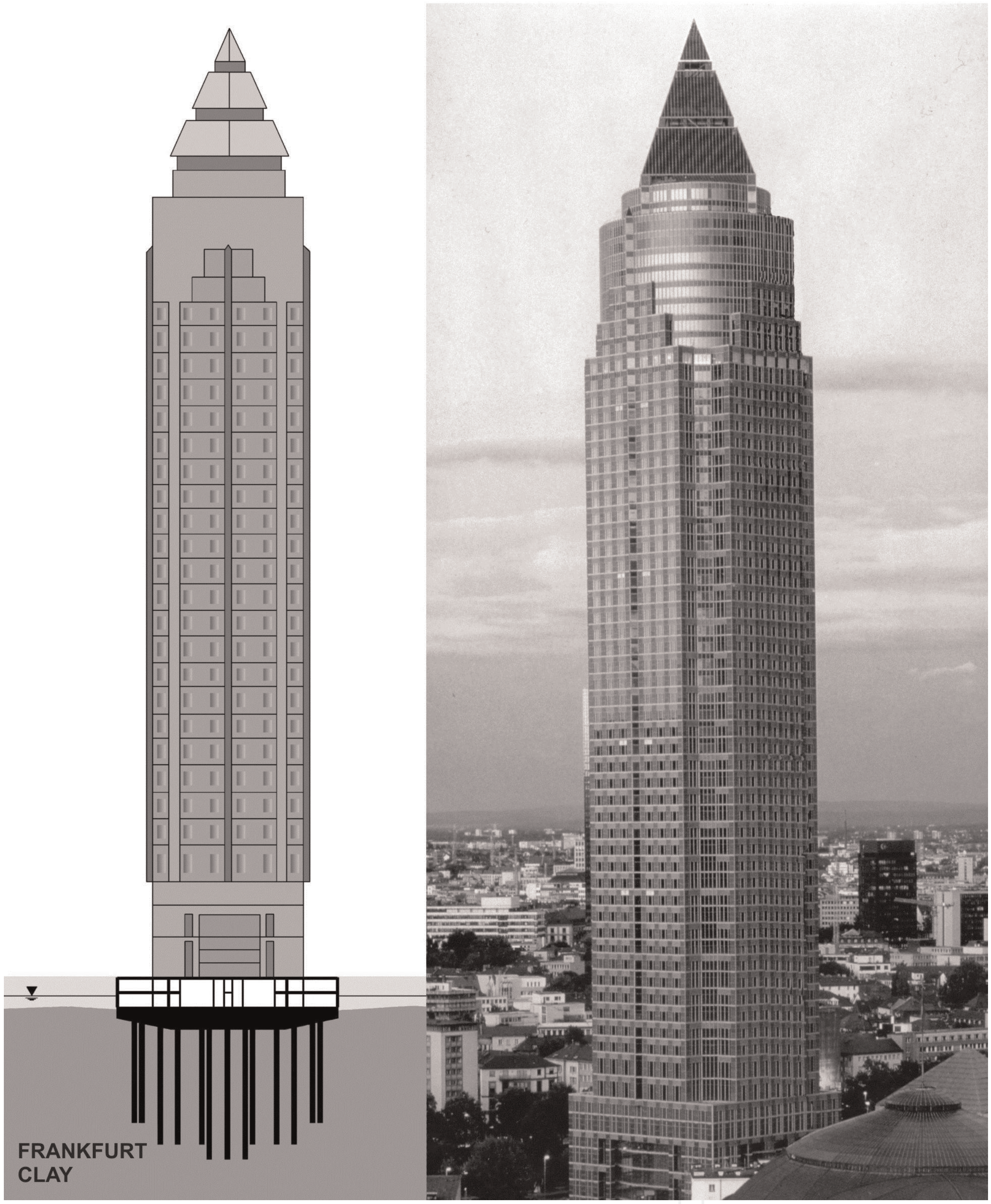


Figure 8.
High-rise building Messeturm in Frankfurt am Main, Germany.

The maximum settlements of a pure raft foundation were calculated to be 32.5 cm. The in situ measured maximum settlements of the CPRF of 13 cm correspond to the calculated maximum settlements. The calculation and the measurement data showed a CPRF coefficient of $\alpha_{CPRF} = 0.43$.

Until the construction of the Messeturm the ultimate skin friction q_s of bored piles in Frankfurt Clay was estimated to 60–80 kN/m^2 for 20 m long piles, based on pile load tests. At the piles of the Messeturm, an average skin friction q_s of 90–105 kN/m^2 was measured. At the pile toe, a maximum skin friction q_s of 200 kN/m^2 was measured.

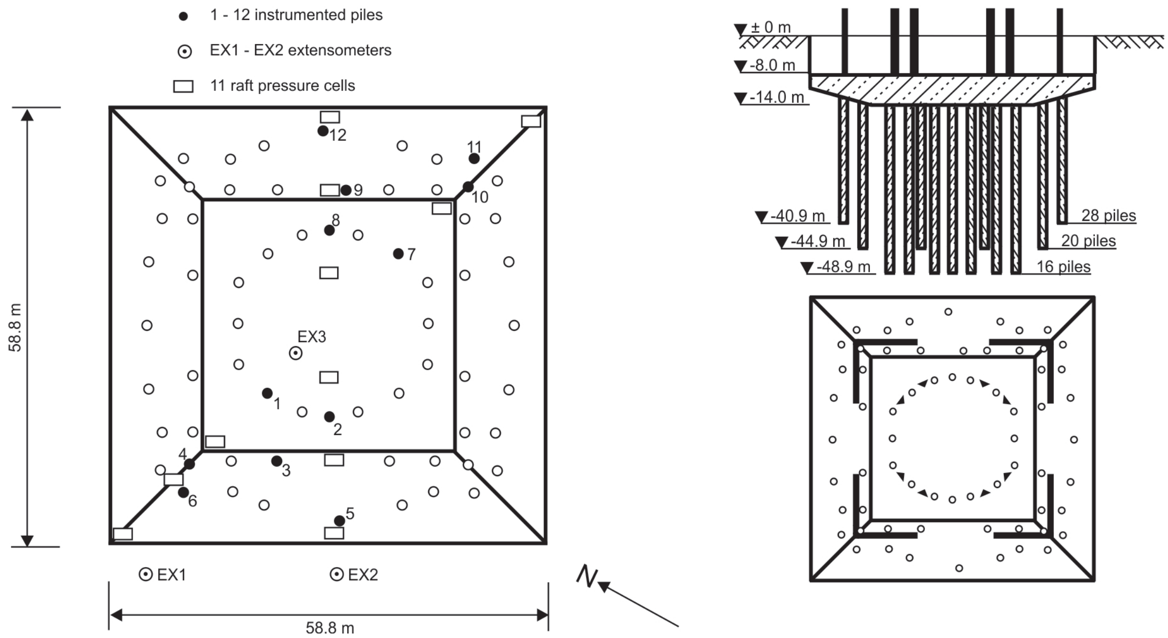


Figure 9.
Ground view (left) and cross-section (right) of the CPRF.

A pure pile foundation would have required 316 piles with 30 m in length and a diameter of 1.3 m. In comparison to the realized CPRF with 64 piles and an average length of 30 m, a pure pile foundation would have required much more material, time, and money. Regarding the CO_2 emission, the CPRF saved about 10,000 tons of concrete. With the estimation, that the average cement ratio is about 300 kg/t of concrete, the CPRF saved about 6000 t of CO_2.

4.3 High-rise building on a steep slope

The high-rise building Mirax Plaza in Kiev, Ukraine, consists of two high-rise buildings, each of them with a height of 192 m (**Figure 12**). The subsoil consists of artificial fillings to a depth of 2–3 m, which are underlain by quaternary silty sand and sandy silt with a thickness of 5–10 m. Below follow tertiary silt and sand with a thickness of 0–24 m. Then follows tertiary clayey silt and clay marl of the Kiev and Butschak formation with a thickness of about 20 m, which is underlain by tertiary fine sands of the Butschak formation. The groundwater level is about 2 m under the service. The soil conditions and a cross-section of the construction project are shown in **Figure 13**.

Two pile load tests have been carried out on the construction site to verify the skin and the base resistance of the deep foundation elements and for the calibration of the numerical simulations. The piles had a length of 10 m and 44 m and a diameter of 0.82 m. The soil properties that resulted from the back analysis were partly three times higher than indicated in the geotechnical report. The results of the numerical back analysis and the load tests show good accordance (**Figure 14**).

Tower A has a foundation raft of about 2000 m^2 and an overall load of about 2200 MN. **Figure 15** shows the calculated settlements of the three-dimensional FEM simulation.

The raft is located at a depth of 10 m below the surface in Kiev clay marl. The barrettes go through the Kiev clay marl and reach the tertiary fine sands.

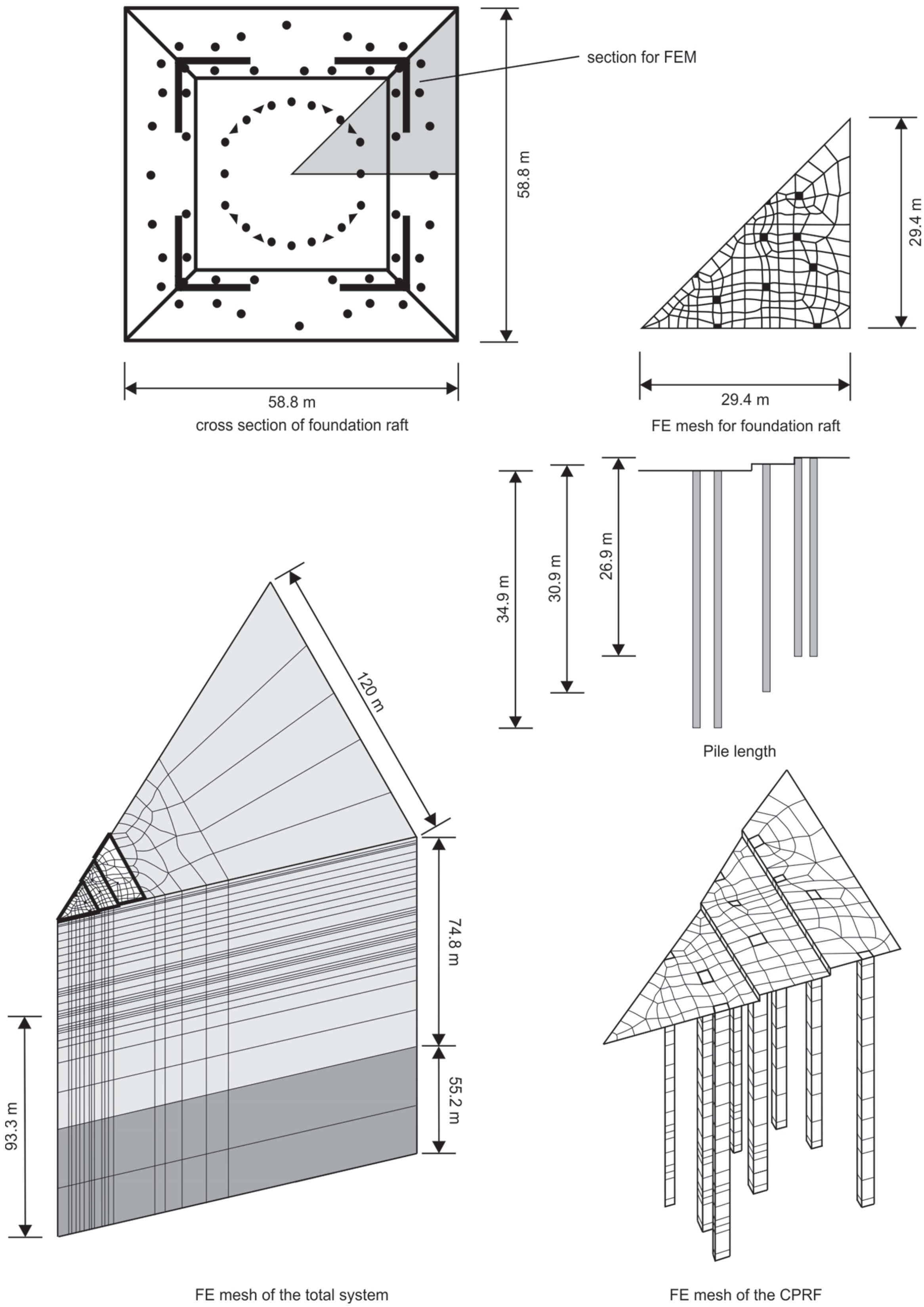


Figure 10.
FE-mesh of numerical simulation.

The outer barrettes have calculated loads between 41.2 MN and 44.5 MN. The inner barrettes have calculated load between 22.1 MN and 30.7 MN. This is typical behavior of a CPRF. The barrettes at the edge of the foundation raft have a higher

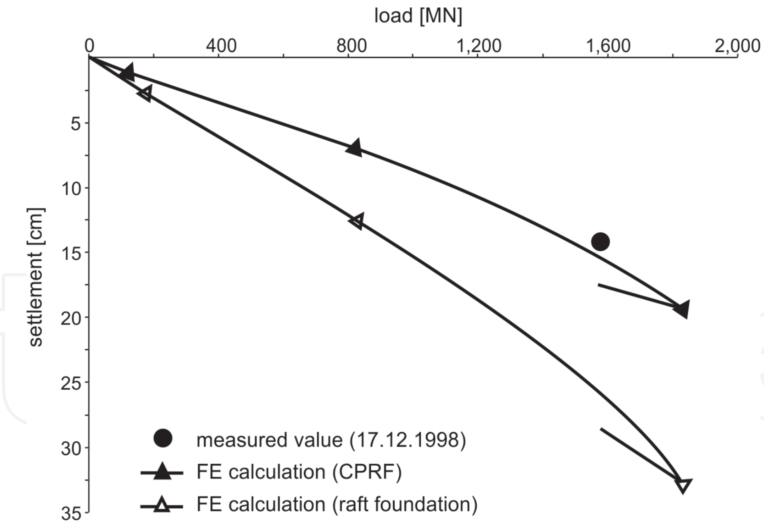


Figure 11.
Measured and calculated settlements.

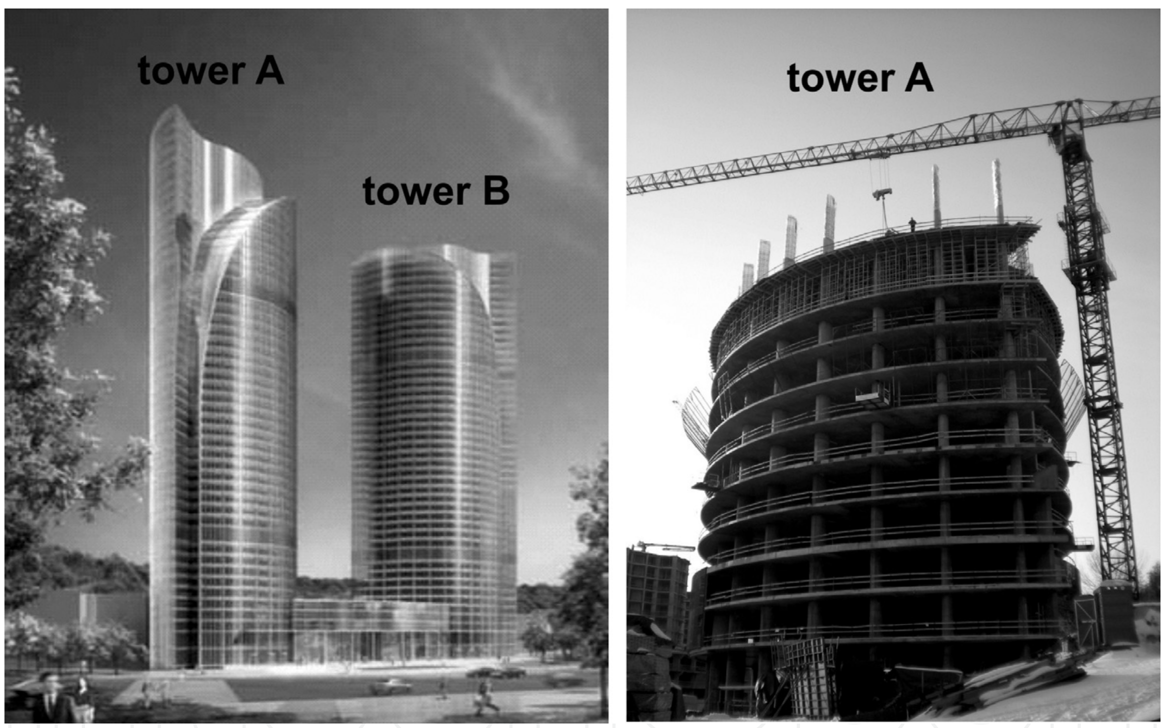


Figure 12.
Mirax Plaza in Kiev, Ukraine.

stiffness due to the bigger volume of the activated soil. They get more of the total load. The calculated CPRF coefficient is α_{CPRF} = 0.88. The settlement-relevant load of 85% of the total load will lead to maximum settlements of about 12 cm. The estimated pressure under the raft is about 200 kN/m^2 (center) and 400 kN/m^2 (edges).

The calculated base pressure under the barrettes is about 4130 MN/m^2 (center) and 5100 MN/m^2 (edges). The estimated skin friction increases with the depth reaching 150 MN/m^2 (center) to 180 kN/m^2 (edges).

The foundation of Mirax Plaza is the first authorized CPRF in Ukraine. The CPRF reduced the number of barrettes from 120 with 40 m length to 64 with 33 m length. Regarding the CO_2 emission, the CPRF saved about 15,000 tons of concrete. With the

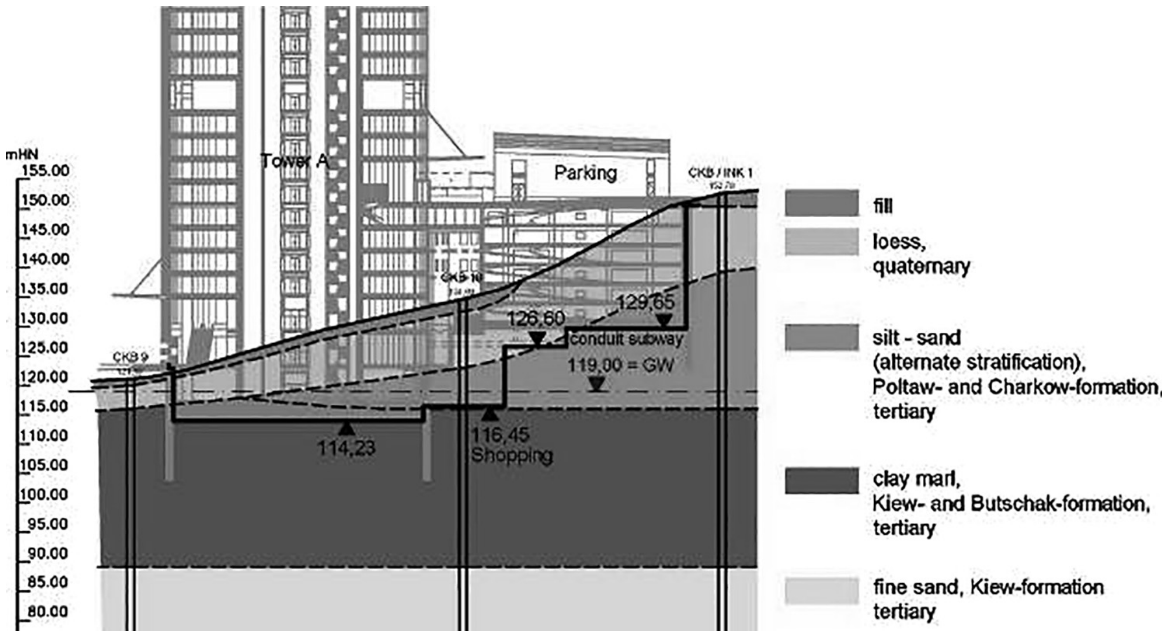


Figure 13.
Soil conditions and cross-section of Mirax Plaza.

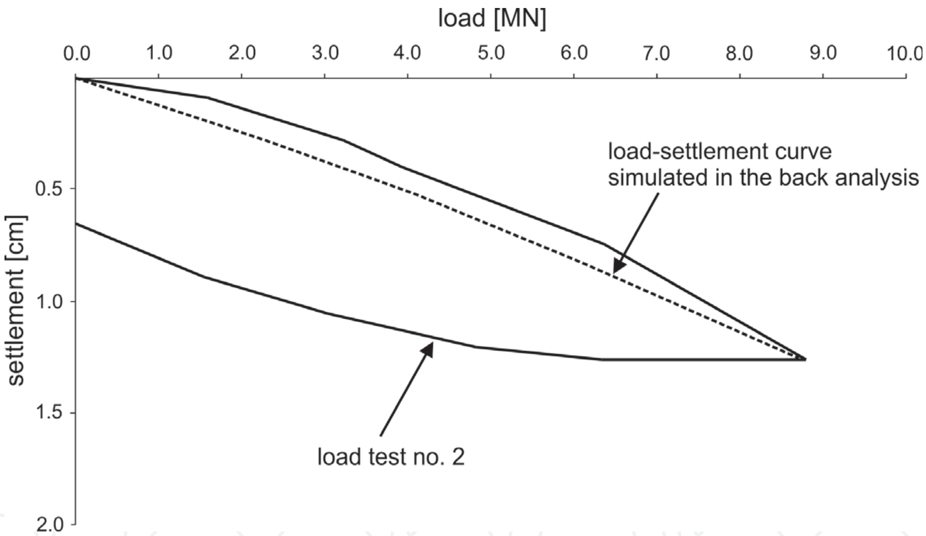


Figure 14.
Measurement and calculation of the in situ load test.

estimation, that the average cement ratio is about 300 kg/t of concrete, the CPRF saved about 9000 t of CO_2.

4.4 Settlement sensitive structure on a geological fault

The soil investigation for the science and congress center Darmstadtium in Darmstadt, Germany, showed that the planned settlement-sensitive structure is situated above the eastern fault of the Rhine Valley. The construction was finished in 2007 and is shown in **Figure 16**.

The eastern fault of the Rhine valley crosses the project area as shown in **Figure 17**. In the northern and western areas unconsolidated sediments of the Rhine Valley fault were found. In the eastern and southern area, rocks of the Odenwald crystalline were identified (granodiorite). The tectonic activities along the fault zone have not finished

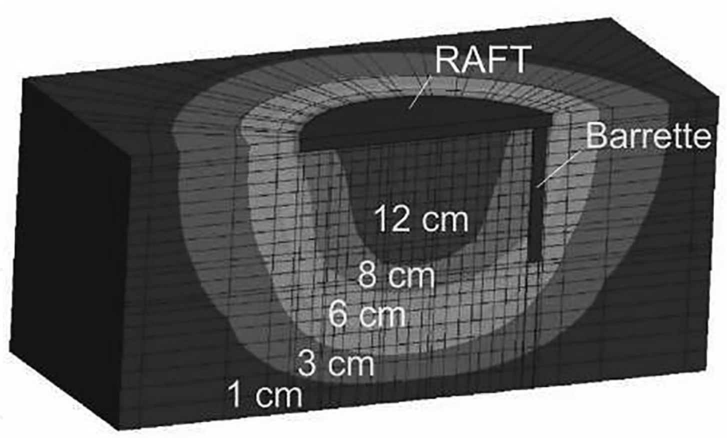


Figure 15.
FE-mesh of the numerical model and calculated settlements.

Figure 16.
Science and congress center Darmstadtium, Germany.

up to now. The area of Darmstadt that is located west of the Rhine Valley fault has an annual settlement of about 0.5 mm. These tectonic displacements hand to be considered for the design of the foundation system and the rising structure. In the area of the rock, the foundation was constructed as a spread foundation and a CPRF was constructed in the area of the Rhine Valley (**Figure 18**).

4.5 Horizontal loads on a CPRF

The Exhibition Hall 3 in Frankfurt am Main, Germany, was finished in 2001 and is one of the biggest exhibition halls in Europe. Its length is about 210 m and its width is about 130 m. The height is about 45 m. The roof is a double-curved, three-dimensional, load-bearing structure consisting of five arched compression trusses and

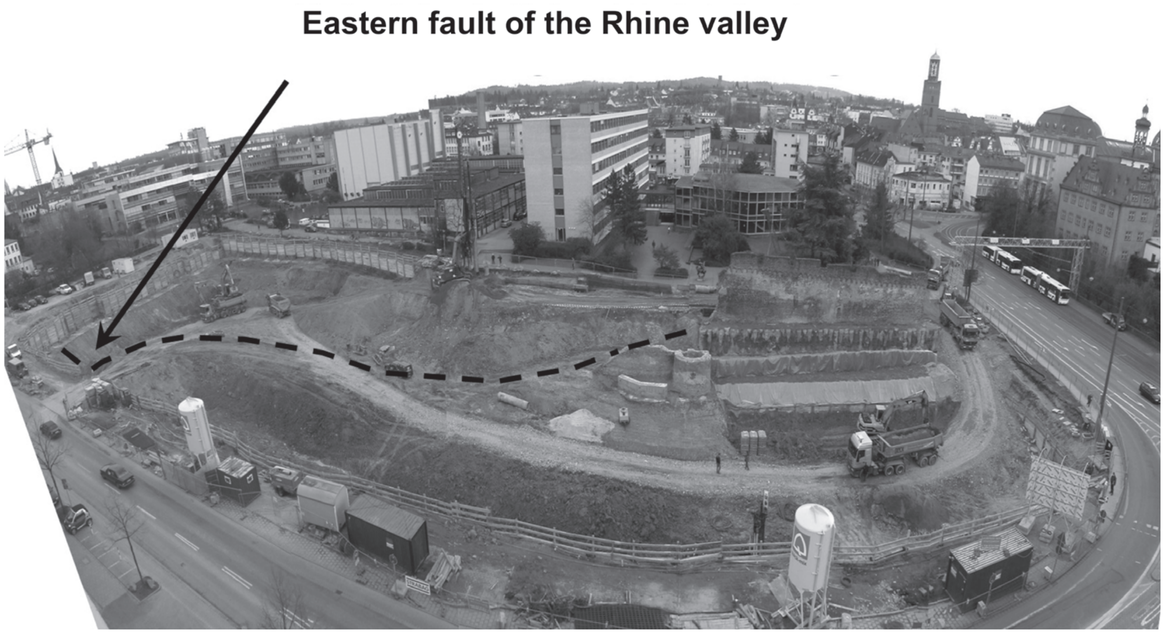
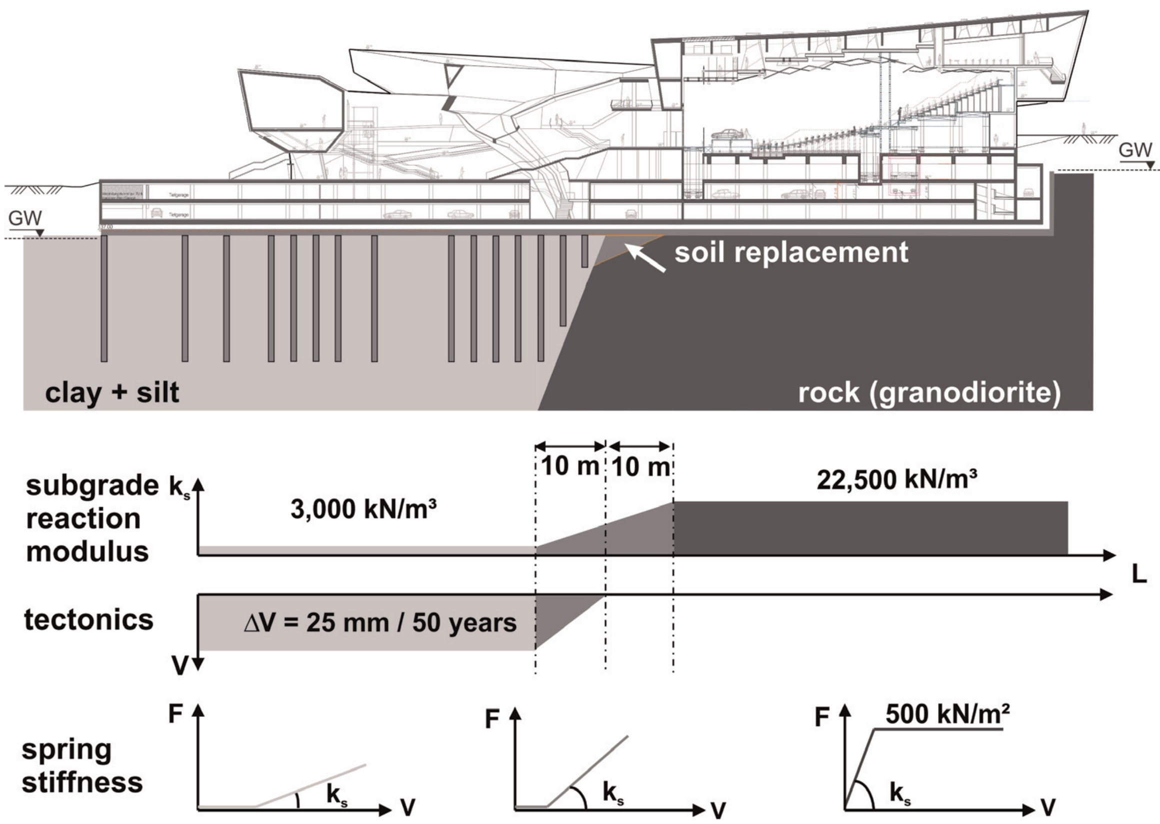


Figure 17.
Excavation pit and gradient of fault.



Figures 18.
Foundation system.

six arched tension trusses with a free span of 165 m [16, 17]. **Figure 19** shows a cross-section of the realized project and the subsoil conditions. Twelve A-frames, six on each side, carry the horizontal and vertical loads of the roof. These A-frames, with a height of 24 m, are constructed of two steel tubes (**Figure 20**). According to [6] the project belongs to the Geotechnical Category GC 3.

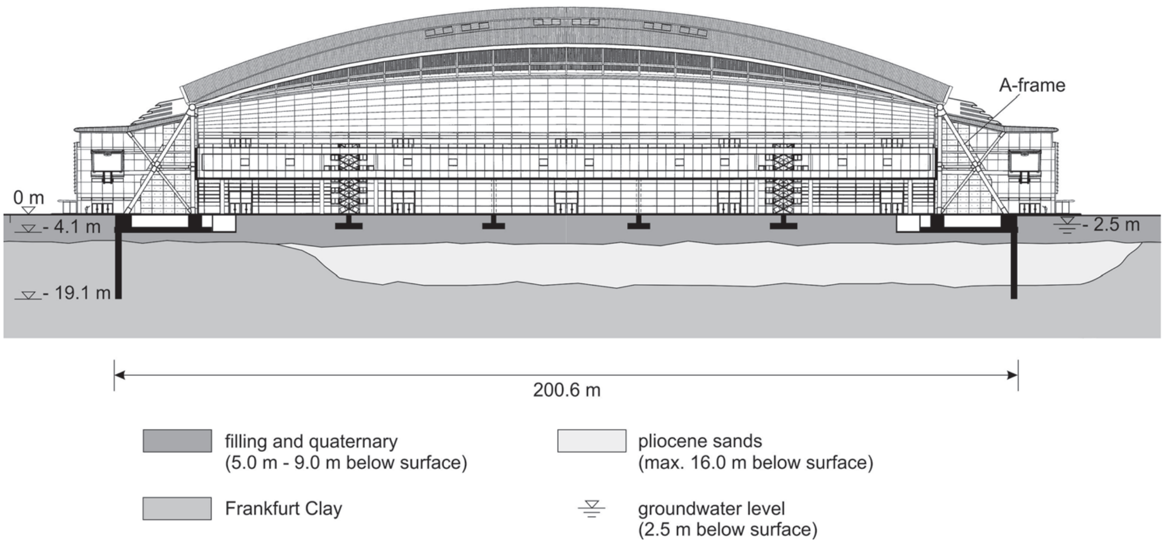


Figure 19.
Cross-section and subsoil conditions.

The soil investigation showed, that the conditions are not equal all over the project area. Under the surface is a 5–9 m thick layer of fillings and quaternary soil. Below this follows a layer of tertiary sediments. The project area is crossed diagonally by a layer of tertiary sand and gravel. The settlement active Frankfurt Clay follows until bigger depth.

A strong limitation of the displacements of the foundation is necessary due to the strong interaction between the superstructure, the foundation, and the subsoil. Three-dimensional numerical analyses were used for the design of the horizontal loaded CPRF. On each end of the hall is a CPRF which consists of a raft and 14 bored piles. The raft has a thickness of 1.4 m, a length of 127.5 m, and a width of 22.15 m. The bored piles have a diameter of 1.5 m and a length of 15 m.

According to the observational method, a geotechnical and a geodetic measurement program was installed. By four inclinometers the horizontal displacements of the CPRF were observed at a depth of 50 m under the surface. For the measurement of the vertical displacements, four extensometers were installed. In addition. pressure cells in the soil under the raft, strain gauges at A-frames, and geodetic measurement points were installed. The measurements showed horizontal displacement up to 1 cm and vertical displacements between 1.0 cm and 3.5 cm.

The example shows that the CPRF can be used for a settlement-reduced transfer of horizontal loads into the subsoil. Compared to a classic file foundation or a massive block foundation the CO_2 emission was reduced significantly.

4.6 High-rise building on cavernous subsoil conditions

The project Moscow City contains several high-rise building for business in Moscow, Russia, on an area of more than one square kilometer [18]. In this project, the Federation Tower is a complex of two single towers (**Figure 21**). Tower A is about 374 m high, or 450 m high when including the spire on the roof. The height of Tower B is about 243 m. At the start of the construction in 2003, the high-rise double-towers were planned as the highest high-rise buildings in Russia and Europe. The two towers are founded on a foundation raft, which is 4.6 m thick and has a length of 140 m and a width of 80 m. The foundation level is about 20 m below the surface.

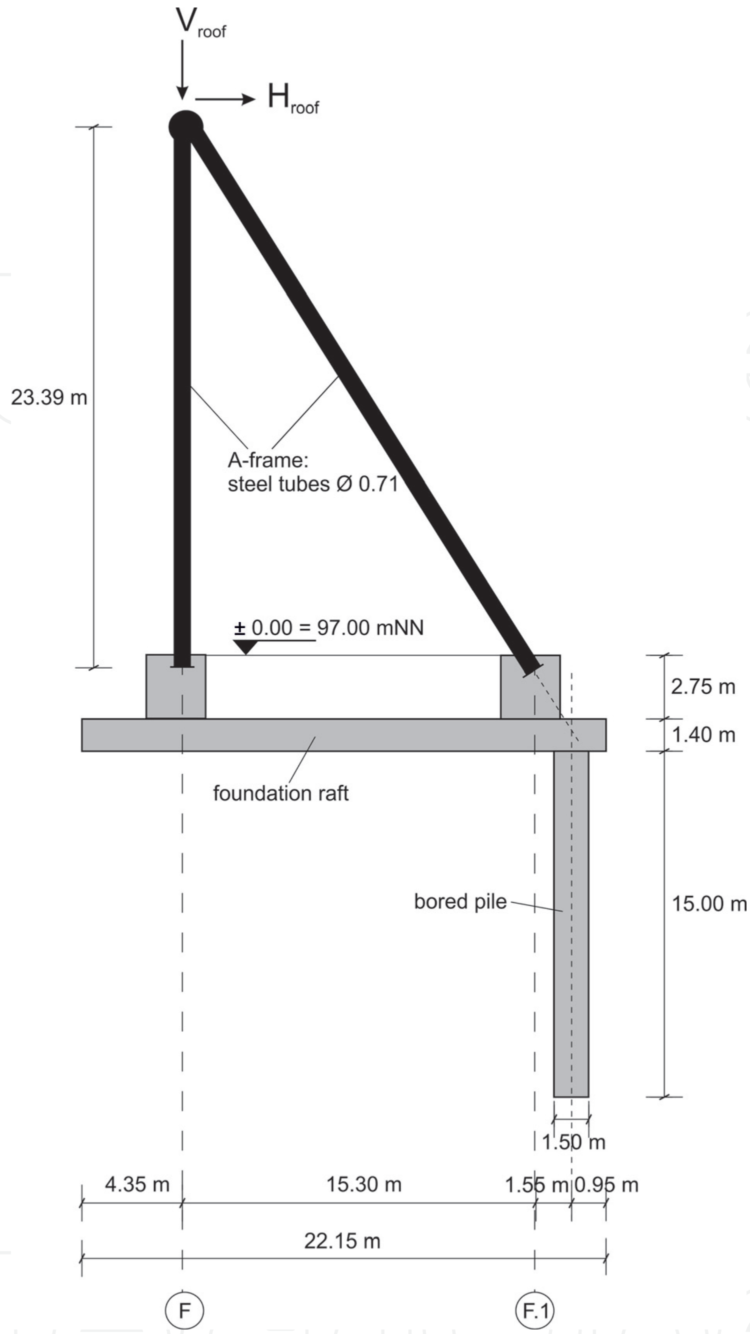


Figure 20.
Schematic visualization of the A-frames and the CPRF.

Tower A has a total load of about 3000 MN and Tower B has a total load of about 2000 MN. Including loads of about 1000 MN for adjacent buildings and the basement floors and a load of about 1300 MN for the foundation raft itself, the total load results in 7300 MN.

The project area of Moscow City is located on the left bank of the River Moskva in the west of the central district. The anthropogenic artificial fillings are followed by the quaternary accumulation of the river terrace. Below this, an alternating sequence of carbon follows. The foundation level of the Federation Tower is in a complex alternating sequence of variably intensively fissured, cavernous and porous limestone and variably hard, more or less watertight clay/marl. The thickness of the layers varies between 3 m and 10 m. The project area is located in a territory where potentially dangerous karst-suffusion processes occur.

Figure 21.
Federation Tower in Moscow City, Russia.

In the project, area exists several groundwater horizons carrying confined water which are not or just moderately corresponding with each other due to the sealing effect of the clay/marl. The pressure of the confined groundwater is up to 12 m. The groundwater mainly circulates in the fissured and karst-suffusion-affected limestone.

For the determination of the load-bearing behavior of deep foundation elements, two pile load tests have been carried out on the construction site. The test piles TP-15-1 and TP-15-2 had a diameter of 1.2 m and were instrumented with O-Cells. The pile segments in total were 6.9 m and 13.35 m long. The empty drill hole was filled with sand. The piles are completely positioned in the limestone (**Figure 22**).

The test piles had two segments with an O-cell in between. The displacements of the segments were measured with displacement transducers.

The maximum load of pile load test TP-15-1 was about 33 MN with an unloading-phase at 15 MN back to zero and a reloading-phase as shown in **Figure 23**. The upper

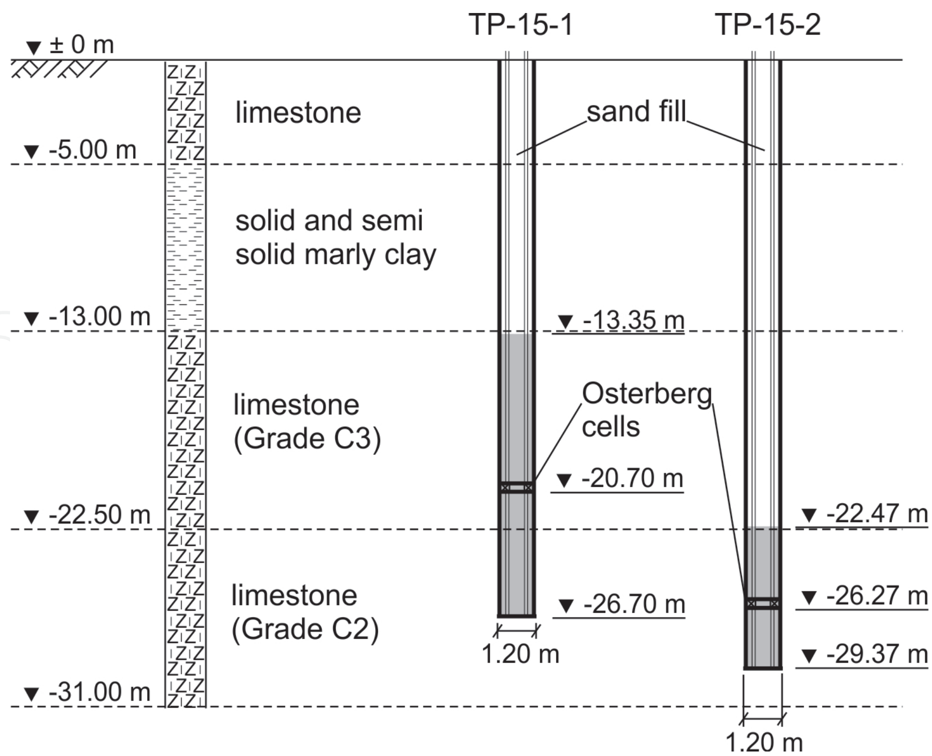


Figure 22.
Test piles TP-15-1 and TP-15-2 with O-Cells.

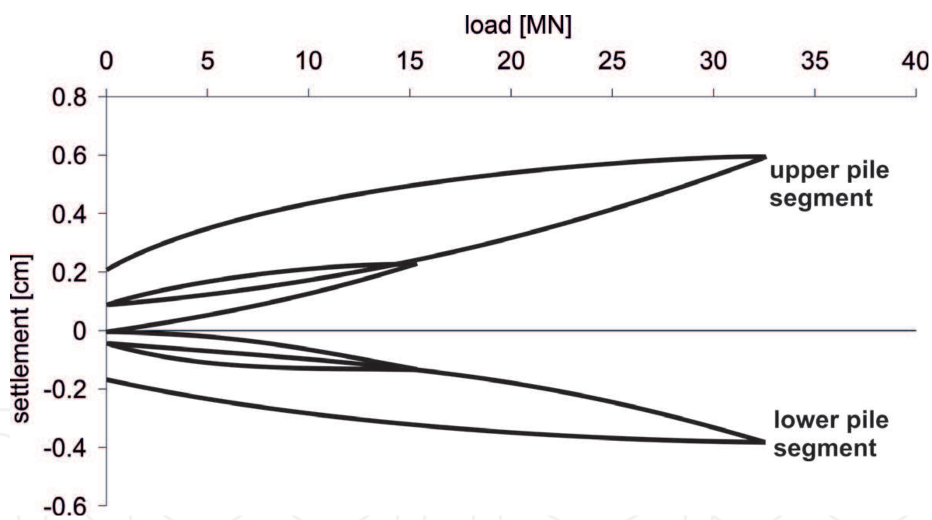


Figure 23.
Load-displacement diagram of test pile TP-15-1.

pile segment has a final displacement of 0.6 cm and the lower pile segment has a final displacement of 0.4 cm. No failure was seen and the empirically defined limit in [4, 6] of the settlement s = 0.1, D = 12 cm was not reached. The results of the pile load test TP-15-1 gives skin friction of q_s = 1140 kN/m^2 and base resistance of q_b = 5380 kN/m^2. Both values are not ultimate ones because failure criteria was not reached.

The maximum load of pile load test TP-15-2 was about 33 MN with three unloading-phases back to zero as shown in **Figure 24**. The upper pile segment has a final displacement of 4.3 cm and the lower pile segment has a final displacement of 2.2 cm. Again, no failure was seen and the empirically defined limit of the settlements of s = 0.1, D = 12 cm was not reached. The results of the pile load test TP-15-2 gives

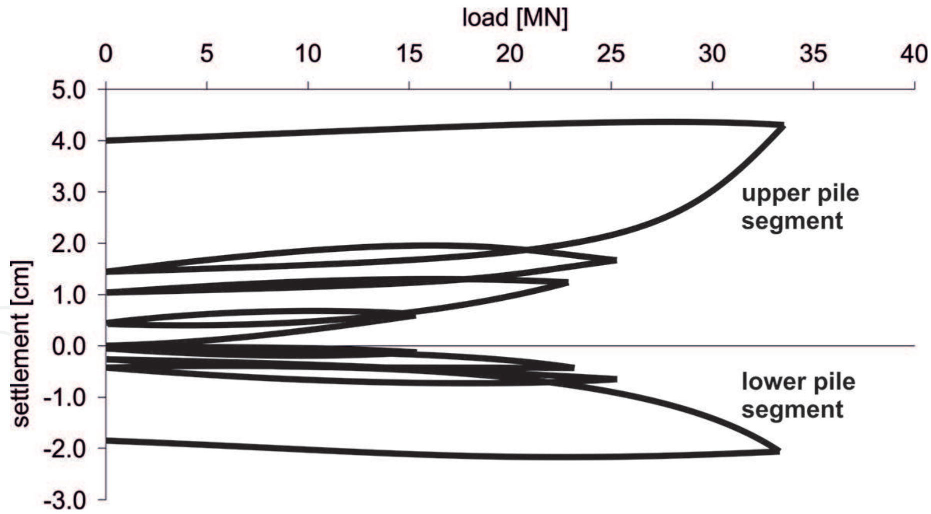


Figure 24.
Load-displacement diagram of test pile TP-15-2.

skin friction of q_s = 2310 kN/m^2 and base resistance of q_b = 5630 kN/m^2. Both values are not ultimate ones because failure criteria was not reached.

5. Summary and conclusions

The Combined Pile-Raft Foundation (CPRF) is a hybrid foundation system that combines the bearing capacity of a foundation raft and of piles or barrettes. The experiences made during the construction of several high-rise buildings show, that compared to a raft foundation a CPRF reduces the settlements by more than 50%. In addition, a CPRF reduces the necessary construction material including concrete and steel. This leads to a significant reduction of CO_2 emissions. To sum up the positive effects of a CPRF are:

- Increase of the overall stability of a raft foundation due to the reduction of the settlements, differential settlements, and tilts.

- Reduction of the inner forces and bending moments of the foundation raft using an optimized number and configuration of the piles.

- At foundation systems with an eccentricity the foundation resistance can be concentrated under the total building load; normally joints between the building elements are not necessary.

- Reduction of the uplift in the area of the excavation, because the relaxation of the soil is constrained.

- Cost optimization of the whole foundation system regarding the material used, time spent for construction, and CO_2 emitted.

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