ARI The Bulletin of the Istanbul Technical University
Communicated by Derin Orhon VOLUME 53, NUMBER 2

Reducing the Costs for Deep Foundations of High-Rise Buildings by Advanced Numerical Modelling

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(Received 10 May 2003)

When considering foundations for high-rise buildings in urban areas a mayor task is the reduction of settlements and differential settlements of new structures and adjacent buildings to ensure their safety and serviceability. In many cases the soil conditions can lead to deep foundations in order to transfer the high loads of the building into deep soil strata with higher bearing capacities. Compared to traditional piled foundations where building loads are assumed to be transferred to the soil only by piles, the combined piled raft foundation (CPRF) is a rather new approach. A CPRF is consisting of the three bearing elements piles, raft and subsoil. The load share between piles and raft is taken into consideration and the piles can be used up to a load level equal or greater than the bearing capacity of a comparable single pile. This design concept can lead to a considerable cost reduction for foundations of more than 50 % compared to the traditional piled foundation.

Keywords: Combined pile-raft foundation, numerical modelling, observational method, guideline CPRF

1. Introduction

The CPRF as a composite bearing structure consists of three bearing elements which are piles, raft and surrounding subsoil. In contrast to widely used traditional foundation design where building loads are either transferred by rafts or by piles, CPRFs are a new approach to reduce vertical and especially differential settlements as they play an important role in connection with the serviceability of a steadily growing number of high rise buildings planned and constructed in modern cities. The design concept for CPRFs is based on a consideration of the complicated interaction between the components of the bearing system. It is possible to meet this requirements by performing three-dimensional Finite Element simulations [1, 2]. An indispensable part of the design concept of CPRFs is the Observational Method with its controlling function ensured by geotechnical measuring devices. So far CPRFs have been used successfully for the foundation of high-rise buildings [3, 4] and foundations of bridges [5] and for power plants [6]. A commonly accepted and standardised designing and approval concept for CPRFs in Germany now is available and will be shortly presented in the following. The foundation type itself with its economical advantages is already in use with an undoubtedly outstanding success. Moreover an economical design requires the basic knowledge and experience of the bearing interactions of all contributing elements [7].

2. Bearing Behaviour of a Vertical Loaded CPRF

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

$$R_{tot} = \Sigma R_{pile,j} + R_{raft} \tag{1}$$

In comparison with a conventional foundation design of a pile group for CPRFs a new design philosophy with different and more complicated soil-structure interaction, where piles are used up to a load level which can be even higher than permissible design values for bearing capacities of comparable single piles, is applied. The distribution of the total building load between the different bearing structures of a CPRF is described by the CPRF coefficient α_{CPRF} which defines the ratio between the amount of the pile loads $\Sigma R_{pile,j}$ and the total load of the building R_{tot}.

$$\alpha_{CPRF} = \frac{\Sigma R_{pile,j}}{R_{tot}} \tag{2}$$

In order to investigate the bearing behaviour of a CPRF a number of different interactions as

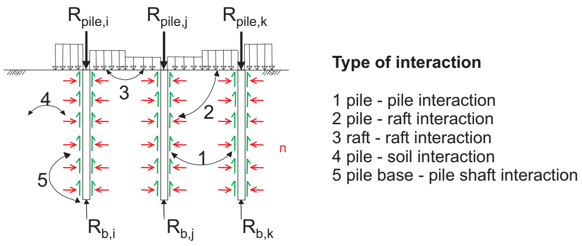

Figure 1. Soil-structure interaction between raft, piles and subsoil.

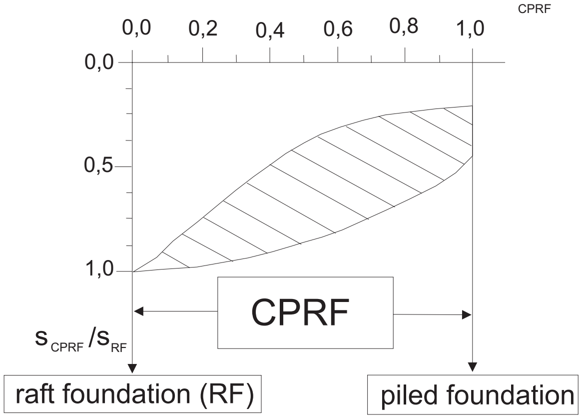

Figure 2. Example for the settlement reduction of a CPRF as a function of α_{CPRF}.

depicted in Fig. 1 have to be considered. A suitable modelling technique has to include all these different types of interactions.

In Fig. 2 the obtainable settlement reduction s_{CPRF}/s_{RF} is given as a function of the combined piled raft coefficient α_{CPRF}. Where s_{CPRF} and s_{RF} are the settlements of the CPRF and the comparable raft foundation (RF). In general the value of α_{CPRF} varies between 0.4 and 0.7 [8]. For a value of $\alpha_{CPRF} = 0$ the load is transferred only through the raft whereas for $\alpha_{CPRF} = 1.0$ the load is transferred only through the piles.

3. Experience gained on CPRFs

The experience gained is based on settlement and load measurements on projects carried out so far, as well as on numerical computations and their validation on model and field tests. The use of numerical simulations has become an essential part of research performed in order to find a suitable design concept and a capable explanation of interactions. The reason is rather not the restricted number of high-rise buildings being built on CPRFs but more likely the fact that only less than 0.1 % of the effected area of these buildings can be investigated by installing measurement devices.

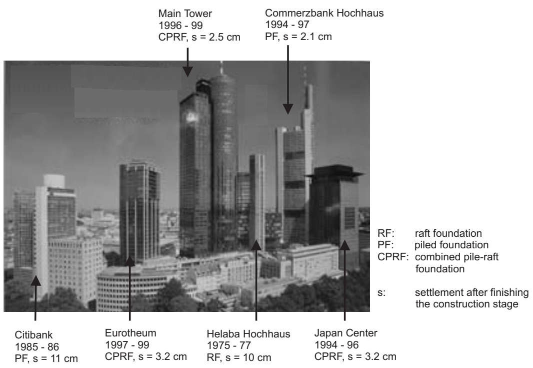

Figure 3. Examples of deep foundations for high-rise buildings in Frankfurt am Main.

Starting in the early 80s first piled raft foundations came under use mainly for high-rise office buildings in Frankfurt am Main Fig. 3 to reduce settlements to practicable dimensions and to ensure serviceability by reducing differential settlements to a minimum in an economical way. This undoubtedly would not have been possible to achieve with a simple raft. Compared to traditional piled foundations the cost reduction was immense.

In the following the example of the office tower CITY-TOWER in Offenbach with its geometrical model of the continuum and the constitutive modelling is described. The material behaviour of the piles and the raft have been simulated as linear-elastic in the finite element analysis, whereas for the simulation of the material behaviour of the soil an elasto-plastic model was used.

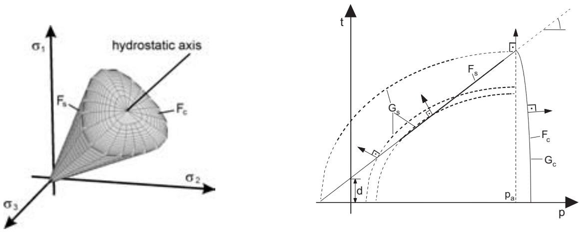

Figure 4. Yield surfaces in the principal stress space and in the p-t-plane.

4. Constitutive Model

Within the frame of the research work undertaken, an elasto-plastic constitutive model is used for simulating the non-linear elasto-plastic material behaviour of soil in numerical analysis (Drucker-Prager Cap Model). The constitutive model consists of two main yield surface segments, a pressure dependent, perfectly plastic shear failure surface F_s and the compression cap yield surface F_c (Fig. 4).

The hardening/softening behaviour of the cap yield surface is a function of the volumetric plastic strain, the hardening function is derived from hydrostatic triaxial tests. This yield surface may change in size, position or shape as the soil is loaded successively to higher stress levels. On the Drucker-Prager shear failure surface F_s the material dilates while on the cap surface it compacts. The plastic flow on the Drucker-Prager shear failure surface F_s produces plastic volume increase, which causes the cap to soften. The constitutive model gives the possibility for a reasonable good simulation of the stress-strain behaviour of soils and depends on the stress path and the previous stress history.

The Drucker-Prager failure surface can be written as

$$F_s = t - d - p \tan\beta = 0. \tag{3}$$

The cap surface with it‘s elliptical shape is written as

$$F_c = \sqrt{(p-p_a)^2 + \left(\frac{Rt}{1+\alpha-\frac{\alpha}{\cos\beta}}\right)^2} - R$$

$$(d + p_a \tan\beta) = 0. \tag{4}$$

The plastic flow is defined by a flow potential which is associated on the cap area and nonassociated on the failure yield surface. It consists of an elliptical portion in the cap region defined by

$$G_c = \sqrt{(p-p_a)^2 + \left(\frac{Rt}{1+\alpha-\frac{\alpha}{\cos\beta}}\right)^2} \tag{5}$$

and a second elliptical part in the failure region given by

$$G_s = \sqrt{\left[(p-p_a)\tan\beta\right]^2 + \left(\frac{t}{1+\alpha-\frac{\alpha}{\cos\beta}}\right)^2} \tag{6}$$

with:

$$t = \frac{1}{2} q \left(1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\cos(3\Theta)\right) \tag{7}$$

d = intersection of the yield surface F_s with the t-axis (derived from cohesion c‘)
p = hydrostatic stress
q = Mises equivalent stress
K = shape parameter of yield surface F_s
R = shape parameter of yield surface F_c
p_a = initial cap position
p_b = compression yield stress
α = shape factor for a transition surface (not applied here)
b = slope of yield surface F_s in the p-t plane (derived from internal angle of friction φ‘)
Θ = Lode angle

The constitutive model used at the Darmstadt University of Technology was widely verified by numerical simulations of static pile load tests as well as by back analysing existing settlement data.

5. An Example for the Design Procedure of a CPRF for a High-Rise Building

The principle design procedure for a high-rise building foundation is described exemplarily for the office building CITY-TOWER Fig. 6 which is presently under construction. The tower in the outskirts of Frankfurt is about 121 m high and founded in settlement active clay on a CPRF with large diameter bored piles. In a distance of about 4 m from the foundation of the tower a railway tunnel is situated 3 m below ground surface. An

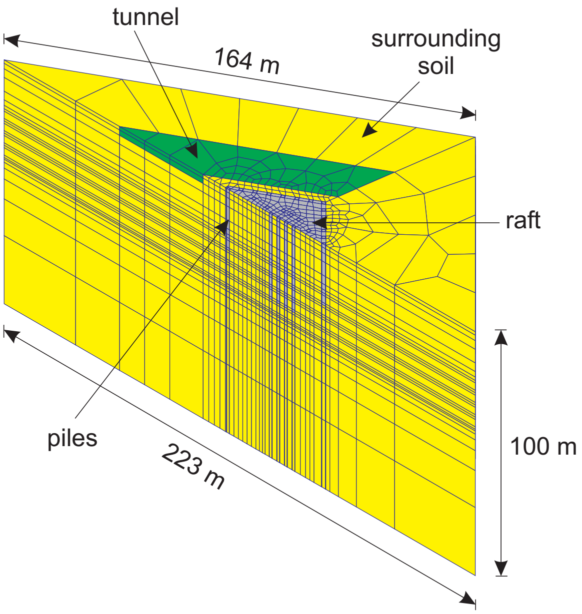

Figure 5. Finite Element mesh of CITY-TOWER foundation.

important task was to guarantee the serviceability of the tunnel during the whole construction process and further on.

The numerical analysis for the foundation design have been performed with a three-dimensional Finite Element (FE) model at the Institute of Geotechnics in Darmstadt.

Based on the load distribution obtained from the structural engineer and the symmetry of the geometry the finite element mesh could be reduced to a half of the area to be considered with a total number of 10365 elements Fig. 5. Several simulations have been performed to optimise the foundation design and to assess the appropriate pile length, diameter and location of each pile under the raft. These simulations also consider the preloading of soil by old buildings which have been demolished before the construction process of the CITY-TOWER had started. The final foundation design consists of 36 piles with a pile length between 25 m and 35 m. The pile length increases from 25 m for the outer piles to 35 m for the piles located in the centre of the raft. The diameter of all piles is 1.50 m, the thickness of the raft is about 3 m.

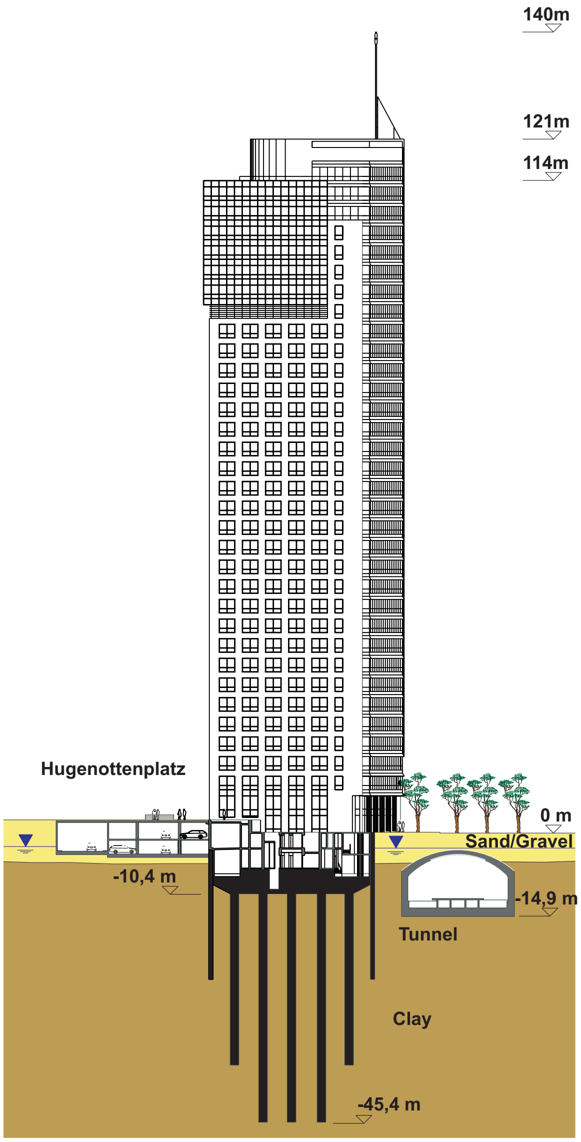

Figure 6. Cross section of CITY-TOWER.

The total load (dead load G + service load P) of the building considered within the simulation is about 600 MN. The settlement calculated for $G+1/3 \cdot P$ reaches a maximum of about 6 cm at the center of the piled raft foundation. The differential settlement is about 1 cm between the center of the CPRF and it's outer borders. The horizontal displacement of the adjacent tunnel was predicted with 0.5 cm - 1.4 cm. In Fig. 7 the load-settlement curves derived from one of the Finite Element simulations for the CPRF are given for the entire foundation structure, the piles and the

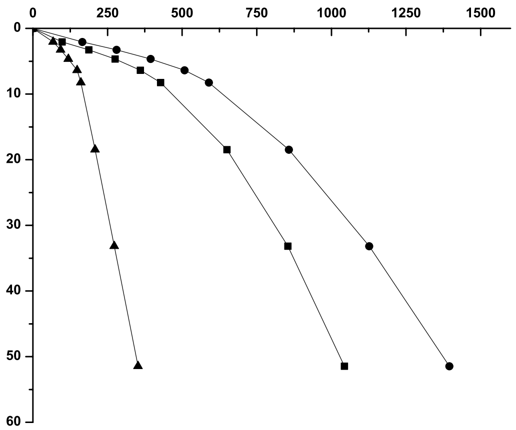

Figure 7. Load-settlement curves derived from Finite Element simulation.

raft. The letters A-D describe different loading levels of the foundation.

6. The Observational Method - Monitoring the Foundation

As a matter of the rather extraordinary geometrical conditions and the special situation of the foundation adjacent to an existing tunnel the CITY-TOWER required an comprehensive measuring program according to regulations of Eurocode 7.

With the results of the geotechnical measuring program as an indispensable part of the safety concept also a verification of the numerical model that had been used to predict the settlement behaviour of the foundation will be possible. The bearing behaviour of the piles is observed by 6 piles equipped with different measuring devices Fig. 8.

The general assembly consists of load cells at the pile bottom and on the pile top as well as 8 strain gages in four different depths along the pile length. The settlements adjacent to the new building are monitored with two multi point borehole extensometers up to a depth of about 70 m. The vertical displacement of the adjacent tunnel is monitored by geodetic levelling whereas the horizontal displacement is observed by an inclinometer installed behind the new bored pile wall Fig. 8.

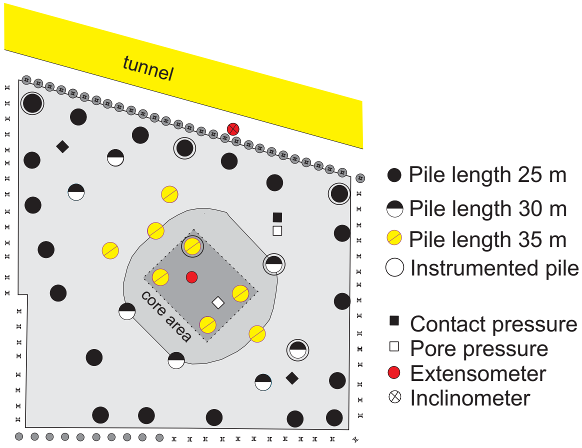

Figure 8. Ground plan CITY-TOWER including geotechnical measurement devices.

7. The New German CPRF-Guideline

Based on a large variety of parametric studies with numerical simulations and the extensive experience on CPRFs gained by long term monitoring of the foundation behaviour, the new German guideline for Combined Piled-Raft Foundations was developed by Prof. Katzenbach (TU Darmstadt, Geotechnics) and Prof. König (University Leipzig, Structural Engineering) under the leadership and the financial support of "Deutsches Institut für Bautechnik (DIBt)", Berlin [9]. The new CPRF-guideline (German name: KPP-Richtlinie) gives guidance to several aspects regarding the design, the safety concept, the limits of application, the use of the observational method [10] and the construction of CPRFs. It does also give a guidance for the practising engineer on an adequate soil investigation program including also the matter of drilling and the question in which cases are static axial pile tests required [7, 9]. Furthermore the guideline gives clearance on the questions what is required and expected from an appropriate calculation method and which requirements a calculation method applied to design a combined piled raft foundation should fulfil.

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 the whole structure as well as a part of it is described with

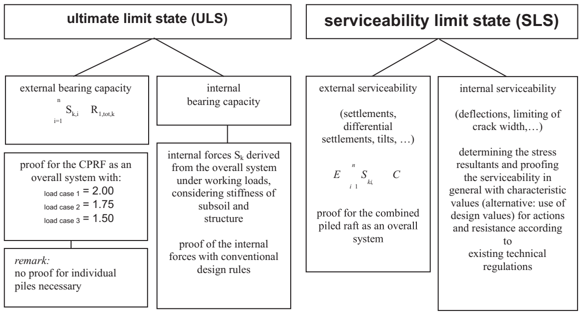

Figure 9. CPRF-guideline: Ultimate limit state and serviceability limit state approach.

reference to a set of limit states beyond which the structure fails to satisfy fundamental requirements. In the Eurocode a distinction is made between ultimate limit state (ULS) and serviceability limit state (SLS). Ultimate limit states are situations involving different kind of collapse, failure and excessive deformations prior to failure, situations where there is a risk of danger to people and/or severe economic loss.

The ULS Fig. 9 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 supporting the working load of the building with a global safety factor η. In the formula depicted in Fig. 9 $S_{k,i}$ is the characteristic value of action i and $R_{1,tot,k}$ gives the characteristic value of the total resistance of a piled raft which can be derived from the calculated load-settlement curve of the whole system. 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 piled foundations no proof for the external bearing capacity of each individual pile is necessary which leads to the enormous economic advantages of CPRFs.

The serviceability limit state (SLS) corresponds to conditions beyond which specified requirements for the structure and it‘s use are no longer met. This applies to deformations, settlements and vibrations in normal use under working loads such that the serviceability of the structure is not guaranteed. The SLS condition to be satisfied is that the design value of the action effect E is less than the limiting value of the deformation of the structure at the serviceability limit state, where C is the resistance property for SLS Fig. 9. Corresponding to ULS the internal serviceability is related to the construction materials used for different foundation parts.

8. Conclusions

The CPRFs of high-rise buildings completed during the last years have shown that by choosing the foundation concept of a CPRF, a considerably settlement reduction of more than 50 % compared to a simple raft foundation can be achieved. During the design process of a CPRF based on Finite Element calculations as described before, a strong co-operation between geotechnical and structural engineer is necessary to guarantee a safe and economic construction [11]. An important part of the design work of the geotechnical engineer is reviewing and assessing the effects of results on the structural design. A European CPRF-Guideline would be desirable in terms of harmonisation of construction codes within Europe.

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