



IIT ROORKEE



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CERTIFICATION COURSE

EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS:

Lecture 23: Combined Pile-Raft Foundations (CPRF) - General

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ERD of Foundations - Modules

1. Introduction
2. Shallow Foundations
- 3. Pile Foundations**
4. Well Foundations
5. SSI for Deep Foundations



Module - 3

Pile Foundations

Module -3: Chapters

Combined Pile-Raft Foundation (CPRF)

1. CPRF - General
2. Geotechnical Analysis and Guidelines of CPRF

Acknowledgement - Reference

Most of the contents of this lecture are taken from following literature.
This is gratefully acknowledged:

Katzenbach, R., Leppla, S. and Choudhury, D., (2016). Foundation systems for high-rise structures. CRC press.

CPRF - General

- **Introduction**
- **Advantage of CPRF**
- **Bearing and Deformation Behavior**
- **Calculation Method**

Introduction

A CPRF is a special form of deep foundation. A CPRF is a hybrid foundation system that combines the bearing capacity of a foundation raft and the piles. CPRF is a technically and economically optimized system. CPRFs can be used for the foundations of classic high-rise buildings as well as for engineering constructions like bridges and towers.

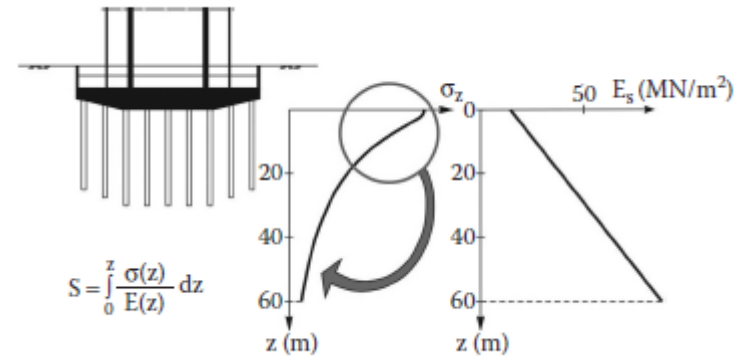
Due to the interaction between the foundation elements and the subsoil, CPRFs have a very complex bearing and deformation behavior. Therefore, CPRFs have to be classified into the Geotechnical Category 3 according to **Euro Code 7**. For safety and quality assurance, an independent geotechnical engineer has to be involved to guarantee the four-eye principle. This requires a check by certified independent experts in the area of geotechnical eng., structural eng., fire prevention and technical facilities.

Advantage of a CPRF

- Increase in the bearing capacity of spread foundations
- Reduction of total and differential settlements
- Reduction of the bending moments of the foundation raft
- Reduction of pile materials (30%–50%)

Bearing and Deformation Behavior

Measurement data of high-rise buildings with spread foundations in Frankfurt am Main, Germany, showed that during the load transfer into the subsoil, 60% to 80% of the settlements arise in the upper third of the influenced soil volume. A CPRF transfers a part of the stress from areas with a small stiffness under the foundation raft to a stiffer, deeper area of the subsoil. This transmission is effected via the piles of the CPRF without neglecting the bearing capacity of the foundation raft.



Bearing and Deformation Behavior (Continued...)

a CPRF can be constituted as a geotechnical composite structure, which consists of the following, interacting bearing elements:

- **Foundation raft**
- **Piles**
- **Subsoil**

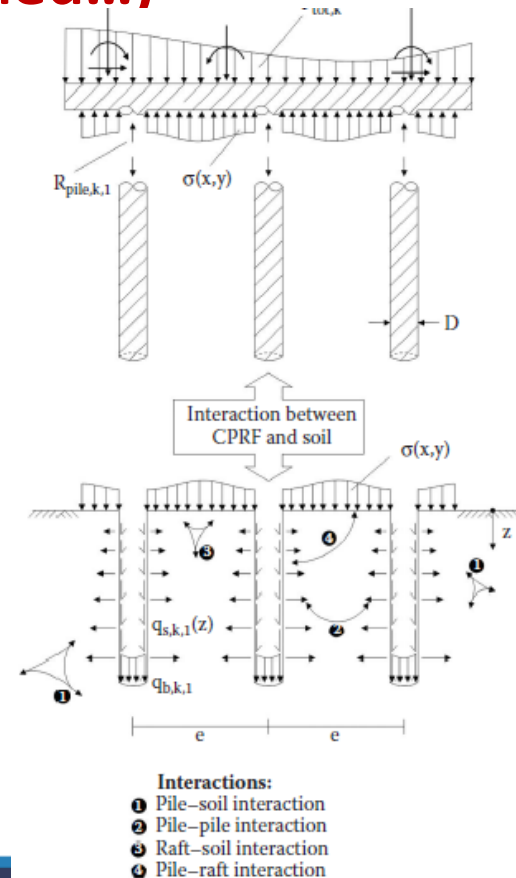
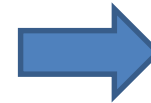
Bearing and Deformation Behavior (Continued...)

The bearing and deformation behavior is characterized by the interaction between the bearing elements and the subsoil. Figure shows all interactions of a CPRF. Due to the stiffness of the foundation raft, the loads $F_{tot,k}$ of the rising structure are transferred to the piles and the subsoil. Similar to a classic deep foundation, the mobilized resistance of a CPRF depends significantly on the settlement s . The integration of the soil contact pressure $\sigma(x,y)$ under the foundation raft is the resistance $R_{raft,k}(s)$. The resistance of the foundation piles $\Sigma R_{pile,k}(s)$ added to the resistance of the foundation raft $R_{raft,k}(s)$ delivers the total resistance $R_{tot,k}(s)$ of a CPRF (Eq. 1).

$$R_{tot,k}(s) = \Sigma R_{pile,k}(s) + R_{raft,k}(s) \quad (1)$$

Bearing and Deformation Behavior (Continued...)

Different Interactions Effects for a CPRF



Bearing and Deformation Behavior (Continued...)

Using Eq. 2, the resistance of a single foundation pile i can be determined. The resistance of a single pile of a CPRF 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 .

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

Bearing and Deformation Behavior (Continued...)

The load deformation behavior of a CPRF can be specified by the CPRF coefficient α_{CPRF} . The coefficient declares the relation between the resistance of the piles and the total resistance (Eq. 3). The CPRF coefficient varies between 0 and 1. A CPRF coefficient $\alpha_{\text{CPRF}} = 0$ means that the whole load $F_{\text{tot},k}$ is carried by the foundation raft. A CPRF coefficient $\alpha_{\text{CPRF}} = 1$ means that the whole load $F_{\text{tot},k}$ is carried by the foundation piles.

$$\alpha_{\text{CPRF}} = \frac{\sum R_{\text{pile},k,i}(s)}{R_{\text{tot},k}(s)} \quad (3)$$

CPRFs with a CPRF coefficient α_{CPRF} between 0.3 and 0.9 have been realized. Related to technical and economic aspects, a CPRF coefficient α_{CPRF} between 0.5 and 0.7 can be considered as optimum.

Bearing and Deformation Behavior (Continued...)

The load deformation behavior of a CPRF depends on the stress state of the subsoil. The value of the mobilized skin friction of the piles is influenced by the effective horizontal stresses. The stress level of the subsoil around a pile of a CPRF is influenced by the neighboring piles, the foundation raft, and the effects during the construction of the pile itself. Due to the soil contact pressure under the foundation raft, the stress level of the subsoil increases, which leads to considerably higher skin friction that can be mobilized in the upper parts of the piles, depending on the settlements. Conversely, the piles reduce the soil contact pressure under the foundation raft.



Bearing and Deformation Behavior (Continued...)

The load deformation behavior of a CPRF is influenced by the pile–raft interaction as well as by the pile–pile interaction. For the same geometric dimensions of a raft, the CPRF coefficient α_{CPRF} depends on the arrangement of the piles. The arrangement of the piles is described by the ratio e/D (pile spacing e to pile diameter D) and the ratio L/D (pile length L to pile diameter D), as well as by the load and settlement state of the CPRF.

- If the **ratio e/D is low**, or if the construction has a high number of piles n , the proportional load distribution between the piles and the foundation raft **remains nearly constant**, even if the total load is multiplied. The load component, which is carried by the piles, can increase slightly because of a rising load level.
- If the **ratio e/D is high**, the load component carried by the foundation raft as well as the settlements is rising in connection with a higher load level. Concurrently, the load component carried by the **piles decreases**. The reason for this is the different load-bearing behavior of the piles, which is influenced by the pile spacing e .

Bearing and Deformation Behavior (Continued...)

- If the pile spacing e between the piles of a CPRF decreases, the deviation of the load bearing of a single pile increases. If the ratio $e/D \geq 3$, the load-bearing behavior of a pile of a CPRF essentially **depends on the position** within the foundation system.
- Analogically to classic pile foundations, at the same settlements, the pile resistance of a CPRF increases from the center to the edge of the raft. Due to the neighboring piles, the **inner piles receive significantly smaller loads**. The edge piles, especially **the corner piles, receive the majority of the loads**.
- With growing pile spacing e between the piles, at a CPRF the influence of the neighboring piles gets smaller, analogue to a classic pile foundation. If the **ratio $e/D \geq 6$** , all piles of a CPRF have the same load deformation behavior **independent of their position**. There is no group effect.

Calculation Methods

The results of the different methods depend on the modeling schemes and the simplified assumptions and boundary conditions. Only for a preliminary design or in very simple cases, these methods are sufficient to develop a technically and economically optimized CPRF. Only the numerical methods provide calculation results that are comparable to the reality.

The following calculation methods are available

- **Empirical methods:** Based on the results of laboratory and field tests, the bearing capacity of a single pile can be determined via correlations and the use of tabular values. Using further correlations, the bearing capacity of a pile group is determined. The correlations and empirical equations are based on experiences made at in situ measurements and model tests.

Calculation Methods (Continued...)

- **Methods with equivalent alternative models:** The CPRF is seen as an alternative model, such as a deep spread foundation or a thick single pile.
- **Analytical methods:** For example, at first, the bearing capacity of the foundation raft is determined, neglecting the piles. If the loads are higher than the bearing capacity of the raft, the surplus loads are allocated to the piles. The piles are regarded as single piles whose resistance can be fully activated. The settlements are determined for the foundation raft and its respective load. Due to its disregard of all interactions, this approach is only convenient as a first assessment.
- **Numerical methods:** The finite element method (FEM) is generally used for numerical methods, being able to consider and solve complicated geometries and nonlinear constitutive equations. In three-dimensional simulations, the foundation elements are modeled with linear elastic material behavior, while the subsoil is modeled with elastoplastic material behavior.

Thank You

