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EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS: Lecture 24: Geotechnical and Seismic Analyses of CPRF

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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. CPRF – 2nd Lecture

- ❖ Geotechnical Analysis of CPRF
- ❖ Seismic Analysis 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.

Geotechnical Analysis of CPRF

- **Ultimate Limit State (ULS)**
- **Serviceability Limit State (SLS)**
- **Pile load tests**

Ultimate limit state (ULS)

The CPRFs have to be analyzed in accordance to the internal and external bearing capacity. The analysis of the internal bearing capacity is conducted according to the corresponding standards. The analysis of the external bearing capacity is conducted under consideration of the time-dependent material behavior of the subsoil and the rigidity of the rising structure.

The external bearing capacity is sufficient, if the design value of the loads E_d is smaller or equal to the design resistance $R_{\text{tot},d}(s)$ i.e. $(E_d \leq R_{\text{tot},d}(s))$.

The design value of the resistance $R_{\text{tot},d}(s)$ is defined by Eq. 1. Where $\gamma_{R,v}$ is safety factor for base failure resistance.

$$R_{\text{tot},d}(s) = \frac{R_{\text{tot},k}(s)}{\gamma_{R,v}} \quad (1)$$

Ultimate limit state (ULS) (Continued...)

The total resistance of a CPRF is calculated for the whole foundation system, which consists of the foundation raft and the piles. A separate geotechnical analysis of the single piles is not necessary.

The characteristic resistance must be calculated by using a validated model, for example, numerical methods. In simple cases, the application of other methods, for example, analysis of the base failure, is possible.

Criteria of simple cases are

- Simple geometry (similar pile length and diameter; constant pile spacing; rectangular, quadratic, or round foundation raft)
- Homogenous subsoil (no major differences of the stiffness)
- Centric loads
- No predominating dynamic loads

Serviceability Limit State (SLS)

- For the assessment of the suitability of a CPRF, a maximum settlement and a maximum settlement difference, must be specified.
- In the context of the verification of the serviceability, the specified limit values must be proved under characteristic loads.
- The specified limit values for the deformation are defined by the rising structure as well as by neighboring buildings and structures on the surface and under the surface.
- The analysis of the internal bearing capacity of SLS is conducted according to the corresponding standards and regulations.

Pile Load Tests: Basics

- For the design and the calculation of a CPRF, knowledge about the load deformation behavior of a free, single pile is necessary.
- If there is no knowledge of the bearing capacity of piles for a special pile type in comparable soil conditions, a pile load test has to be performed.
- If a pile load test is not performed, the bearing capacity of a single pile can be estimated on the basis of empirical values, whereby this simplification and transferability has to be proved.
- Knowledge about the bearing capacity of a free, single pile is important for two reasons. On the one hand, it is the only way to evaluate the selected geometries of the piles in accordance to the technical and environmental aspects. On the other hand, it is possible to calibrate the numerical models.
- For complex construction projects and/or difficult soil conditions, *in-situ* pile load tests are strongly advised.

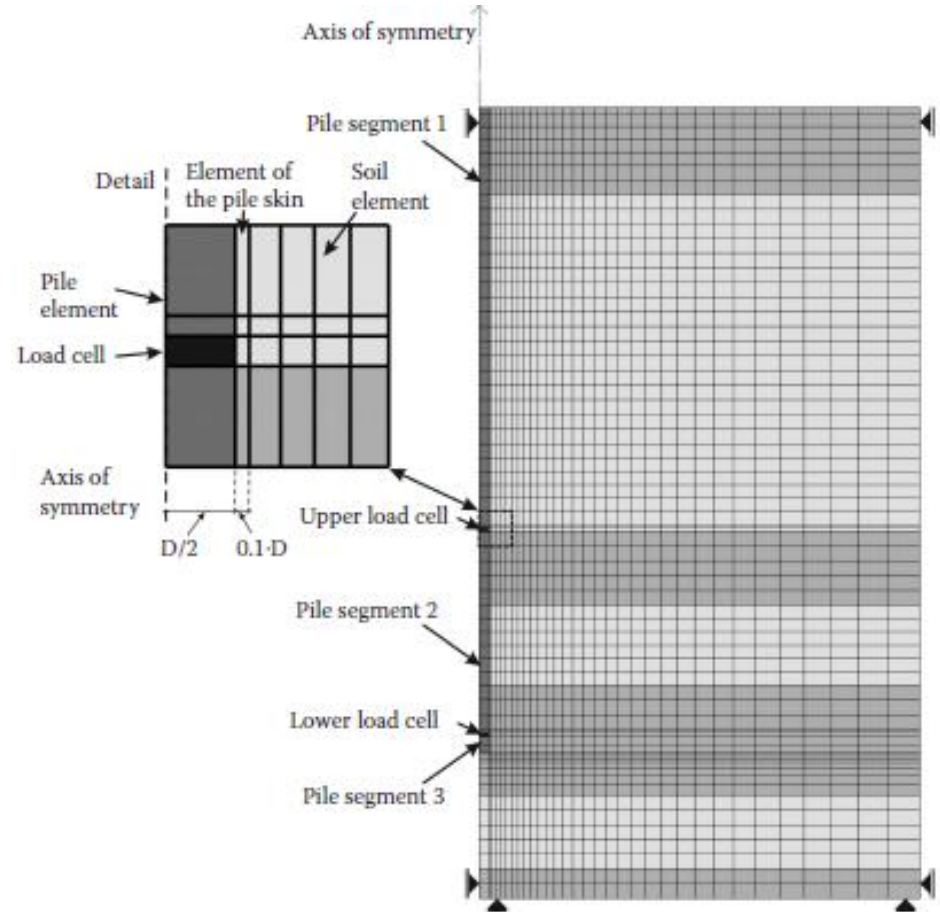
Pile Load Tests: Example

For the new construction of a high-rise building in soft subsoil, numerical simulations have been carried out for the design of a CPRF. The calibration of the numerical simulations is based on the results of a pile load test, which has been carried out on the project area. For the loading mechanisms, Osterberg-cells (O-cells) were used. The test pile consisted of three segments: The upper test segment 1, the middle test segment 2 between the two O-cells, and the lower test segment 3.

For the determination of the pile base resistance and the skin friction of the different soil layers, the individual O-cells were activated in various testing phases.

- For the test segment 3, only the lowest O-cell was activated, while test segment 2 was used as an abutment.
- For the test segment 2, the upper O-cell was activated, while the lower O-cell was released. In this test phase, test segment 1 was used as the abutment.
- For the test segment 1, the upper O-cell was activated and the lower O-cell was stiffened. The test segments 2 and 3 were used as abutments.

Pile load tests (Continued...)



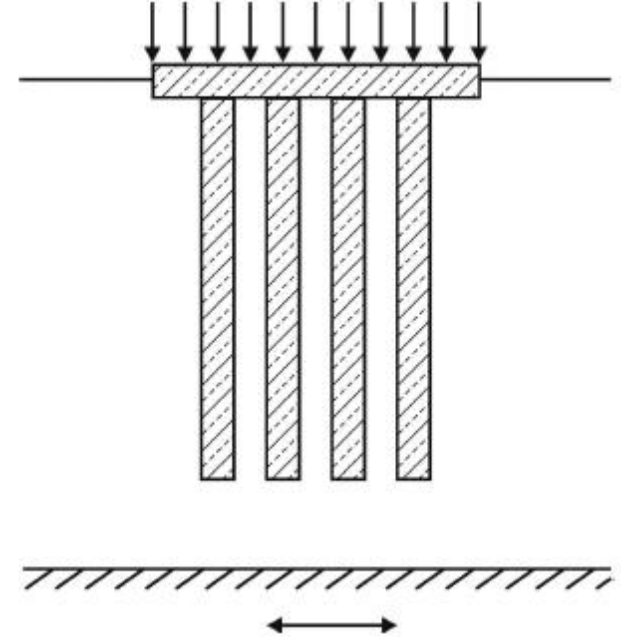
Seismic Analysis of CPRF

- **Introduction**
- **Advantages of CPRF under Dynamic Condition**
- **Numerical Dynamic Analysis**
- **Steps for the Design of CPRF**
- **Dynamic Centrifuge Tests on Piles and CPRF**

Introduction

Seismic analysis of a CPRF is very complex and needs proper understanding of pile–soil–raft interaction.

- The lateral load induced on a CPRF during earthquake motion is jointly shared by raft and pile component.
- Hence, the stiffness parameter and connection condition between pile and raft has to be defined carefully by performing sensitivity analysis.



The generalized CPRF model subjected to seismic excitation

Introduction (Continued...)

It is observed by various researchers that

- The horizontal stiffness of a CPRF is larger than that of a pile group with the same configuration as a CPRF, because a raft acts efficiently as a horizontal displacement reducer.
- The bending moment of piles in a CPRF is less than that of piles in a pile group. The rotation of a CPRF increases as the rigidity of connection condition increases.
- The horizontal load carried by a CPRF does not have significant influence on the pile head connection, whereas it has significant influence on the horizontal load proportion, where the raft shares a larger proportion of the load as the connection condition rigidity increases.
- The seismic analysis and design of the CPRF is done by using the results obtained by centrifuge modeling, numerical simulations, and case studies.

Advantages of a CPRF under Dynamic Conditions

- Improvement of serviceability of shallow foundations by reducing settlement, differential settlements, and tilt, and avoiding eccentricities and making loads centric, by concentrating piles around highly loaded area.
- Lateral load induced during dynamic condition will be shared by raft and pile.
- If a pile passes through liquefiable soil deposit, raft provides buckling stability to pile foundation in case pile is subjected to excessive axial load.
- Depending upon the loading condition, lateral load shared by the CPRF may be governed by designing the proper connection either as rigid, semi-rigid or hinged.
- Various case studies show that CPRF performs better than other foundation systems in cases of seismic loading.
- In summary, CPRF is the most suitable foundation in seismically vulnerable areas.

Numerical Dynamic Analysis

- The purpose of numerical dynamic analysis is to simulate in situ soil condition and to analyze the influence of dynamic loading on the various geotechnical structures with the help of an available numerical computer program.
- With the advances in the computers, the finite element analysis and finite difference analysis are gaining popularity and being applied more in the design of geotechnical structures.
- The invention of high-speed computers is encouraging geotechnical engineers to apply the finite element analysis for solving complicated dynamic problems.
- Different researchers have used different approaches for dynamic analyses of pile, pile group, and pile raft foundations, which include the application of seismically induced lateral loads to the top of the pile head, or applying the acceleration, force, or displacement time history at the base of a soil model to capture the response of such structures.

Steps for the Design of CPRF

- Soil investigation data has to be properly checked before selecting any soil parameters and constitutive soil model to simulate realistic soil behavior.
- If stiffness parameters of soil are constant values, which is normally for the case of sand, then the Mohr-Coulomb model is the preferred choice, but if stiffness parameters of soil are depth dependent or the soil is soft clay, care has to be taken in choosing the constitutive model to simulate actual field condition. The hardening soil model and the soft clay constitutive model can be chosen.
- To model the liquefaction condition, Finn and Byrne models can be chosen, which are dependent upon the relative density and penetration resistance of soil.

Steps for the Design of CPRF (Continued...)

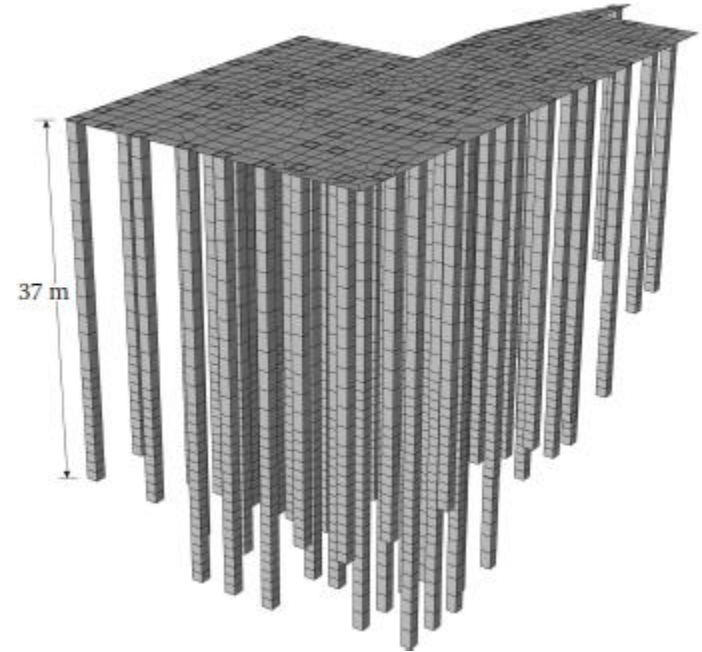
- The size of the numerical model should be greater than about 2.5 times the length of longest pile for a static case and should be increased further for lateral loading and seismic loading cases, based on engineering judgment, to eliminate the boundary effects.
- Pile spacing, pile diameter, and pile position may be decided on the basis of procedure and parametric variation. Feasibility of CPRF must be checked based on settlement and differential settlement responses observed and compared with the conventional raft and pile foundation responses.
- For structural components, that is, raft and piles, high stiffness value has to be chosen as per the characteristic strength of raft and pile material.

Steps for the Design of CPRF (Continued...)

- Consideration of uniformly distributed loads may be useful for preliminary design and proportioning of foundation components.
- Seismically induced loads can be replaced by equivalent static horizontal load, which is equal to the seismic acceleration coefficient times the maximum load of superstructure acting on to the foundation unit. Else, the real acceleration-time history may also be applied at the base of the soil model and the response of the CPRF can be observed.
- Suitable CPRF codes like ISSMGE combined pile-raft foundation guidelines has to be followed properly for static design and can be updated further for seismic loading conditions.

Design of CPRF

The design of the CPRF is performed by three-dimensional, nonlinear FE-simulations. The length, diameter and the number of the piles were optimized on the basis of the FE-simulations taking into account the requirements of the load deformation behavior. Fig. illustrates the optimized CPRF in the FE-simulation. The CPRF coefficient $\alpha_{\text{CPRF}} = 0.8$, which means that 80% of the total building weight is carried by the piles and 20% of the total buildings weight is carried by the raft.



Dynamic Centrifuge Tests on CPRF

- Full-scale pile and CPRF testing are very cumbersome and time-consuming, and simulation of an earthquake event in such tests makes it more complex.
- To simulate the behavior of deep foundations under seismic loading, the numerical technique is one of the options, but to validate the numerical analysis data, one must have some field-measured result, hence the need for dynamic centrifuge tests arises, which can simulate not only the state of stress, but also the event of liquefaction during the seismic event.
- Many researchers have done extensive tests on piles and CPRF to understand their behavior during an earthquake event.

Examples from Engineering Practice

A CPRF is a technically and economically optimized foundation system, which is established in engineering practice, but it is still an open research topic. Numerous examples show its excellent applicability. The scope of application includes not only vertical loaded CPRFs, but also horizontal loaded CPRFs. The following example demonstrate a construction project where CPRFs were applied to realize an economical and reliable basis for high-rise structures.

Examples from Engineering Practice (Continued...)

Meseturm

The Meseturm in Frankfurt am Main, Germany, is 256.5 m high. It is founded on a CPRF in the Frankfurt Clay (Fig.). The foundation raft has a ground view of $58.8 \text{ m} \times 58.8 \text{ m}$ 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.



Thank You

