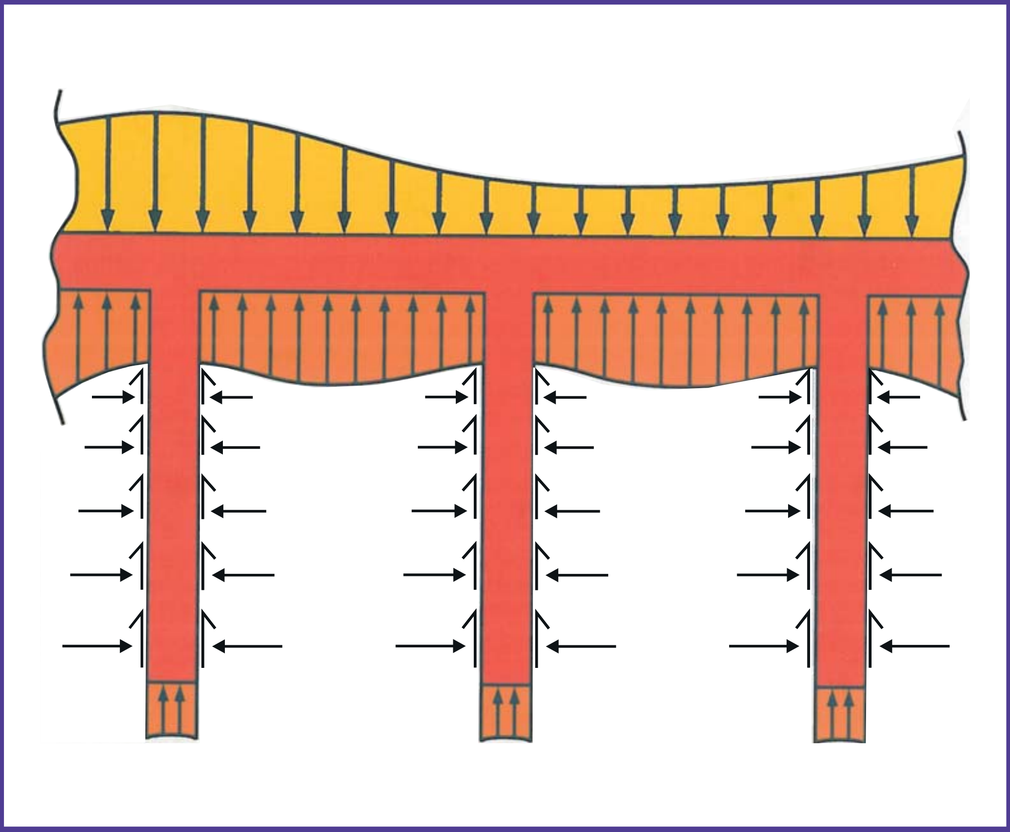
Combined Pile Raft Foundations



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1 Terms and Definitions

The Combined Pile Raft Foundation (CPRF) is a geotechnical composite construction that combines the bearing effect of both foundation elements raft and piles by taking into account interactions between the foundation elements and the subsoil shown in figure 1.1.

The characteristic value of the total resistance $R_{tot,k}$ (s) of the CPRF depends on the settlement s of the foundation and consists of the sum of the characteristic pile resistances $\sum_{j=1}^{m} R_{pile,k,j}$ (s) and the characteristic base resistance $R_{raft,k}$ (s). The characteristic base resistance results from the integration of the settlement dependant contact pressure $\sigma(s, x, y)$ in the ground plan area A of the raft.

$$R_{raft,k}(s) = \iint \sigma(s,x,y)\,dx\,dy \qquad (1.1)$$

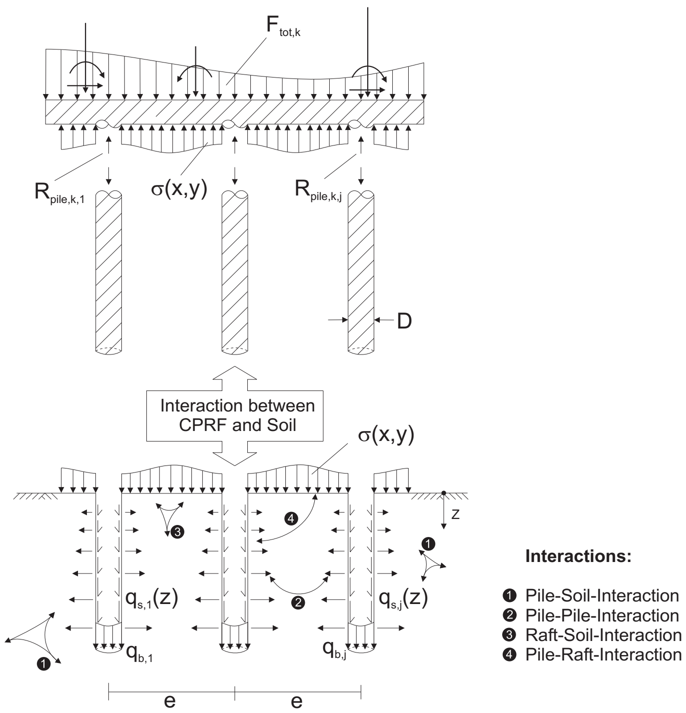

Fig. 1.1 Combined Pile Raft Foundation (CPRF) as a geotechnical composite construction and the interactions coining the bearing behaviour

$$R_{tot,k}(s) = \sum_{j=1}^{m} R_{pile,k,j}(s) + R_{raft,k}(s) \quad (1.2)$$

$$R_{pile,k,j}(s) = R_{b,k,j}(s) + R_{s,k,j}(s) \quad (1.3)$$

The bearing behaviour of the CPRF is described by the pile raft coefficient α_{pr} which is defined by the ratio between the sum of the characteristic pile resistances $\sum_{j=1}^{m} R_{pile,k,j}(s)$ and the characteristic value of the total resistance $R_{tot,k}(s)$:

$$\alpha_{pr} = \frac{\sum_{j=1}^{m} R_{pile,k,j}(s)}{R_{tot,k}(s)} \tag{1.4}$$

The pile raft coefficient varies between $\alpha_{pr} = 0$ (spread foundation) and $\alpha_{pr} = 1$ (pure pile foundation). Figure 1.2 shows a qualitative example of the dependence between the pile raft coefficient α_{pr} and the settlement of a CPRF s_{pr} related to the settlement of a spread foundation s_{sf} with equal ground plan and equal loading.

The pile raft coefficient α_{pr} depends on the stress level and on the settlement of the CPRF.

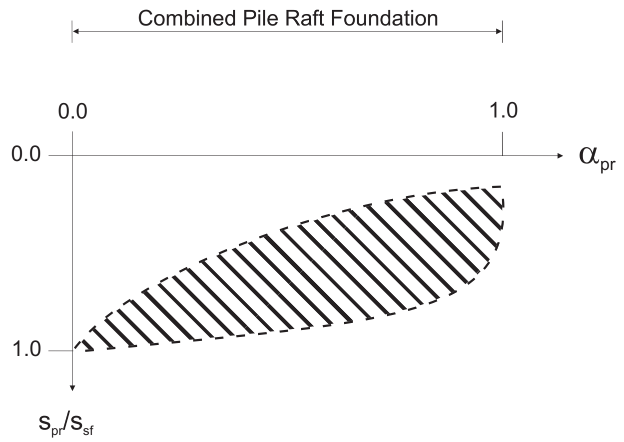

Fig. 1.2 Qualitative example of a possible settlement reduction of a CPRF in function of the pile raft coefficient α_{pr}

2 Scope

The CPRF guideline applies to the design, dimensioning, inspection and construction of preponderant vertically loaded Combined Pile Raft Foundations.

Note: The CPRF guideline can also be applied to other deep foundation elements than piles such as diaphragm walling elements (barrettes) respectively diaphragm walls, sheet pile walls etc.

The CPRF guideline shall not used in cases in which layers of relatively small stiffness (e.g. soft cohesive and organic soils) are situated closely beneath the raft. It also shall not applied to layered soil with a stiffness ratio between the top and bottom layer of

$$\frac{E_{s,top}}{E_{s,bottom}} \leq \frac{1}{10}$$

as well as to all cases in which the pile raft coefficient is $\alpha_{pr} > 0{,}9$.

3 Geotechnical Category

In Europe (CEN states), the Combined Pile Raft Foundation has to be assigned to Geotechnical Category 3 according to EC 7.

4 Symbols

Number	Symbol	Explanation	Unit	Chapter
1	C	resistance property for SLS		8
2	D	pile diameter	m	1
3	e	pile spacing	m	1
4	E	action effect		8

5	E_s	stiffness modulus	MN/m²	2
6	F	Action	MN	1
7	$F_{k,i}$	characteristic value of an action i	MN	7
8	$F_{tot,k}$	sum of characteristic values of all actions	MN	1
9	H	sum of horizontal actions	MN	2
10	i	index for an action	-	7
11	j	index for a pile	-	1
12	k	index for characteristic value	-	1
13	n	number of actions	-	7
14	m	number of piles of a CPRF	-	1
15	q_b	base pressure of a pile	MN/m²	1
16	$q_s(z)$	skin friction of a pile	MN/m²	1
17	R	resistance	MN	1
18	$R_{b,k}(s)$	characteristic value of the base resistance of a pile as a function of settlement	MN	1
19	$R_{tot,k}$ (s)	characteristic value of the total resistance of a CPRF as a function of settlement	MN	1
20	$R_{1,tot,k}$	characteristic value of the total resistance of a CPRF for ULS	MN	7
21	$R_{pile,k,j}$	characteristic value of the resistance of the pile j of a pile group	MN	1
22	$R_{raft,k}$	characteristic value of the resistance of a CPRF mobilised by contact pressure	MN	1

23	$R_{s,k}(s)$	characteristic value of the skin friction resistance of a pile	MN	1
24	s	settlement	m	1
25	s_{pr}	settlement of a CPRF	m	1
26	s_{sf}	settlement of shallow foundation	m	1
27	s_2	allowable settlement for SLS	m	8
28	Δs_2	allowable differential settlement for SLS	m	8
29	V	sum of vertical actions	MN	1
30	x,y,z	cartesian coordinates	m	1
31	α_{pr}	pile raft coefficient	-	1
32	γ	partial safety factor	-	7
33	$\sigma(x,y)$	contact pressure	MN/m²	1

Tab. 1 Symbols

5 Soil investigation and evaluation

Soil investigation on site and in laboratory is necessarily required for the design and the dimensioning of a CPRF and the basis for all analysis. The quality and quantity of the geotechnical investigations and the performance of the field and laboratory tests have to be designed and controlled by geotechnical experts and also have to be evaluated under the consideration of the Soil-Structure-Interaction.

The results of field and laboratory investigation have to be compared with values experienced for the local soil conditions.

5.1 Field investigation

Direct soil investigations are necessarily required for the design of a CPRF even if local experiences are given. Depending on project related circumstances and the local soil conditions the investigation program has to be reviewed concerning the necessity of further investigations.

5.2 Laboratory investigation

The design of a CPRF requires a sufficient knowledge of the deformation and the strength properties of the subsoil. Additional to classification tests, a sufficient number of laboratory tests on soil samples are to be performed in order to determine the stiffness and shear strength of the soil. Quality and quantity of the laboratory tests have to be defined with regard to the constitutive laws used within the analysis of the CPRF.

5.3 Tasks within the construction process

Exposures during the constructing process of a CPRF have to be examined and evaluated by a geotechnical expert and have to be compared to the results of the actual soil investigation. The data achieved during the construction of the bored piles have to be recorded in a protocol and displayed graphically by diagrams. The usage of driven piles or other deep foundation elements requires a corresponding procedure.

If the soil and groundwater conditions encountered during the construction process deviate relevantly from the expected soil and groundwater conditions additional investigations of subsoil and groundwater have to be carried out. The updated geotechnical data is the basis for a reviewed design and construction process of the CPRF.

6 Requirements to the computational methods for the design of a CPRF

6.1 Prefaces

The bearing effect of a CPRF is influenced by the interactions of the particular bearing elements (fig. 1.1).

Beside the pile group effect, i.e. the mutual interactions of the piles within the pile group, the contact pressure considerably influences the bearing behaviour of the foundation piles of the CPRF.

Therefore, the prerequisite for a safe design of a CPRF is the realistic modelling of the interactions between the superstructure, the foundation elements and the subsoil. This requires the use of a computational model which is able to simulate the interactions determining the bearing behaviour of the CPRF due to the system configuration in a reliable and realistic way.

The computational model used for the design of a CPRF shall contain a realistic geometric modelling of the foundation elements and the soil continuum as well as a realistic description of the material behaviour of both structure and subsoil and of the contact behaviour between the soil and the foundation elements. The choice of the constitutive laws and the applied material parameters used within the analysis has to be justified.

6.2 Bearing behaviour of a single pile

For the design of a CPRF the knowledge of the bearing behaviour of a stand-alone single pile under comparable soil conditions is required (chapter 6.3, paragraph 1).

As far as no experiences are given for the bearing behaviour of a single pile by test loadings a static pile test under axial loading has to be performed for a corresponding pile type under comparable soil conditions.

As far as no static load pile tests are performed, the bearing behaviour of a single pile can be defined by using the empirical values indicated in the concerned standards. The transferability of the standardised empirical values on the soil conditions explored on site and on the planned CPRF has to be proven.

6.3 Requirements for a computational model

The used computational model shall be able to simulate the bearing behaviour of an appropriate single pile according to chapter 6.2. The shearing at the pile shaft and the compression process at the pile base has to be modelled correctly.

The computational model used for the design of the CPRF shall also be able to transfer the bearing behaviour of a single pile to the bearing behaviour of the CPRF including the pile-pile-interaction and the pile-raft-interaction. Furthermore the computational model has to be able to simulate all relevant interactions including their effects on the bearing behaviour of the CPRF (fig. 1.1).

For the design of a CPRF different computation methods are available which are based on different computation and modelling approaches. The computation method used for the design of a CPRF has to be documented within the design process.

7 ULS – Ultimate Limit State

The proof of the external and internal bearing capacity has to be carried out for a CPRF. The external bearing capacity describes the bearing capacity of the soil interacting with the foundation elements. The internal bearing capacity describes the bearing capacity of the single components like the piles and the foundation raft.

The bearing behaviour of the CPRF is computed based on characteristic soil and material parameters. Time-dependant properties of the soil and the structure have to be considered if necessary.

The stiffness of the superstructure and its influence on the bearing behaviour of the CPRF has to be considered within the computational investigation and the proofs of limit states.

Figure 7.1 shows the concept for the proof of ultimate limit state schematically.

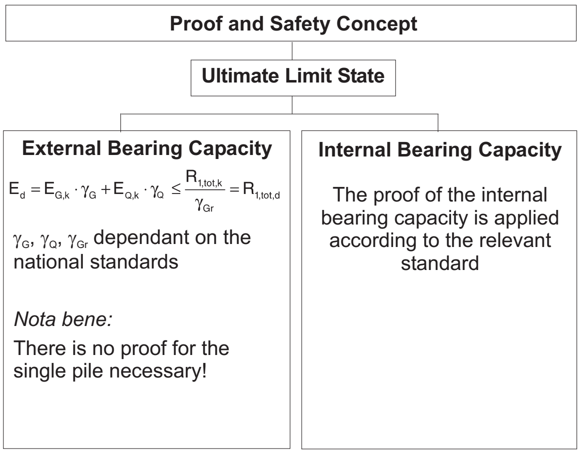

Fig. 7.1 Proof and safety concept in the ultimate limit state

7.1 Proof of the external bearing capacity (ULS)

A sufficient safety against failure of the overall system is achieved by fulfilling the following inequation:

$$E_d = E_{G,k} \cdot \gamma_G + E_{Q,k} \cdot \gamma_Q \leq \frac{R_{1,tot,k}}{\gamma_{Gr}} = R_{1,tot,d} \qquad (7.1)$$

The characteristic value of the total resistance of the CPRF in the ultimate limit state $R_{1,tot,k}$ has to be determined by an analysis of the CPRF as an overall system based on a computational model including all relevant interactions according to chapter 6.2. The characteristic values of the soil and the structure properties shall be used within the analysis. The characteristic value of the total resistance $R_{1,tot,k}$ has to be derived from the load-settlement relation for the overall system. The characteristic value of the total resistance $R_{1,tot,k}$ is equal to the load at which the settlements of the CPRF visibly increase. In the load-settlement curve the characteristic value of the total resistance $R_{1,tot,k}$ represents that point at which the flat section, after a transition region with increasing settlement, passes into the steeply falling section.

If the proof is not performed by a realistic computational model according to chapter 6.3 in simple cases it is permissible to calculate the characteristic value of the total resistance $R_{1,tot,k}$ alternatively by means of the characteristic value of the base resistance of the foundation raft of the CPRF.

"Simple cases" are given if the following conditions are fulfilled:

- A geometrically uniform configuration of the CPRF:
  - identical pile length and pile diameter
  - constant distance between the pile axes *e*
  - rectangular or round raft foundation
  - projection of the raft foundation beyond the outer pile row $\leq 3 \cdot D$ (D = pile diameter)
- Homogeneous subsoil (no layering):
  - no distinct difference in stiffness between the individual layers (see chapter 2)
- Actions
  - centrically loaded raft foundation i.e. the resulting action is concentrated in the centre of gravity of the raft
  - no predominantly dynamic effects

The bottom line of the raft defines the foundation level for the calculation of the base resistance.

The vertical bearing effect of the piles has to be neglected within the base resistance calculation of the raft.

The horizontal bearing effect of the piles may be applied as dowel resistance within the base resistance calculation of the raft. The calculation of the base resistance has to be carried out according to the relevant national standards.

The proof of the external bearing capacity of a CPRF saves the proof of all single piles.

7.2 Proof of the internal bearing capacity (ULS)

A sufficient safety against material failure has to be proven for all foundation elements according to the specific standards. The proof of the internal bearing capacity shall be carried out for all relevant combinations of actions. The following stress states have to be proven:

- Piles: Tension (construction stages), compression combined with bending and shearing.
- Raft: Bending, shearing, punching at the areas of punctual loading of the superstructure elements (columns) as well as of the foundation piles.

The calculation of the internal forces shall be performed for two cases because of the non-linear relation between the settlement and the partial resistances of raft and piles. The pile raft coefficient αpr shall be calculated for both limit states, the ultimate limit state (chapter 7.1) and the serviceability limit state (chapter 8.1). The internal forces of the raft and the piles have to be computed due to the distribution of the characteristic actions on raft and piles determined by the pile raft coefficient. The more unfavourable results have to be used for the design of the foundation elements.

The proof of the internal bearing capacity of the foundation elements has to be carried out according to the relevant standards.

If no detailed proof is performed, the piles have to be reinforced to the minimum amount respectively the amount calculated within the design process on their total length.

8 SLS – Serviceability Limit State

The proof of the serviceability limit state comprises of two different examinations analogously to the proof of the ultimate limit state (figure 8.1).

8.1 Proof of the external serviceability

A sufficient safety of the serviceability is achieved by fulfilling the following inequation:

$$E_{2,d} = E_{2,k} \leq R_{2,tot,d} = R_{2,tot,k} = f(C_k) \tag{8.1}$$

The effects E dependant on the actions $F_{k,i}$ have to be computed by a computational model according to chapter 6.2 based on characteristic values for the material properties. The effects E are computed on the overall system subjected to onefold actions.

During the service of the building the effects E expressed by the relevant settlements or differential settlements have to be smaller than the allowable value C_k for the resistance property within the serviceability limit state.

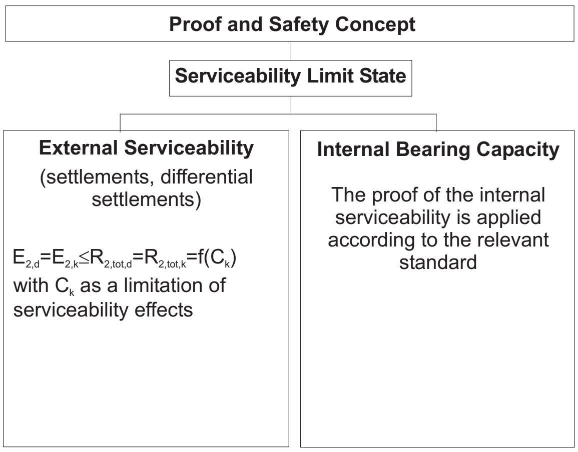

Fig. 8.1 Proof and safety concept in the serviceability limit state

The value of the resistance property C_k is defined by the requirements deriving from the characteristics of the planned CPRF and the adjacent buildings possibly affected by the construction of the CPRF. For the allowable settlements s_2 respectively the allowable differential settlements Δs_2 limit values have to be defined due to the structures sensitivity of deformations and especially of differential settlements and due to the sensitivity of the adjacent subterranean and superficial buildings and infrastructural installations.

8.2 Proof of the internal serviceability

For the foundation elements a sufficient safety for the serviceability limit state has to be proven according to the material specific standards. The following stress states have to be proven:

- Piles: Restriction of the crack width
- Raft: Restriction of the crack width, allowable deflections and/or differential settlements with respect to the requirements the superstructure is subjected to

The internal forces have to be determined for the serviceability limit state.

9 Proof of design and construction of a CPRF

The examination of the design and the construction of a CPRF should be controlled by an geotechnical expert particularly qualified on this subject with respect to the subsequent aspects:

- Examination of the extent, the results and the evaluations of the soil investigation (field and laboratory tests).
- Evaluation of the plausibility and suitability of the characteristic values of the soil properties used in the computational models for the CPRF.
- Examination of the computational model used for the design of the CPRF and the computation results by using independant comparative calculations.
- Examination of the evaluation of the effects on the adjacent buildings.
- Examination of the measuring program and of the soil exposures attained within the construction process of the CPRF.
- Examination of the protocol of the acceptance procedure and the measured values.

10 Construction of a CPRF

The construction of a CPRF has to be supervised by a geotechnical expert particularly qualified on this subject assigned by the owner respectively the supervising authority with respect to the ground engineering aspects. This applies to the construction both of the piles and the foundation level. The protocols of the acceptance procedure and the measured values have to be included into the examination.

11 Monitoring of a CPRF

The bearing behaviour and the force transfer within a CPRF have to be monitored by a geotechnical expert particularly qualified on this subject due to the requirements deriving from the soil, the superstructure and the foundation according to the concept of the observational method on the basis of the measuring program set up in the design phase. The monitoring comprises geotechnical and geodetic measurements at the new building and also at the adjacent buildings. The monitoring of a CPRF is an elementary and indispensable component of the safety concept and is used for the following purposes:

- the verification of the computational model and the computational approaches,
- the in-time detection of possible critical states,
- an examination of the calculated settlements during the whole construction process and the
- quality assurance respectively the conservation of evidence

both during the construction process and during the service of the building.

The monitoring program has to be designed by a geotechnical expert in the design phase. The measurements shall give information about the load distribution between the raft and the piles.

In simple cases the arrangement and regular levelling of settlement measuring points can be sufficient.