VILNIUS TECH
Vilnius Gediminas Technical University

12th International Conference
ENVIRONMENTAL ENGINEERING

April 27–28, 2023, Vilnius, LITHUANIA

eISSN 2029-7092
eISBN 978-609-476-342-7
Article ID: enviro.2023.899
https://doi.org/10.3846/enviro.2023.899



# ENVIRONMENTALLY OPTIMIZED FOUNDATION OF A RAILWAY BRIDGE

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Received 16 January 2023; accepted 20 February 2023

**Abstract.** The production of materials, e.g. reinforced concrete, and the construction of structures consume large amounts of energy, which lead to a large emission of $CO_2$. Regarding the resulting impact of construction processes on the environment, the reduction of $CO_2$ has an important role. The target is the reduction of the amount of the construction material used and of the energy consumed for construction. For this, the structures have to be optimized regarding the geometry considering the requirements on the stability, the serviceability, and the durability. Bridges are significant rather expensive and complex infrastructural structural units of roads and railways. Foundations for bridges in many cases designed in complicated soil profiles and should resist long-term permanent and variable loadings. General aim in rational foundation design for bridge structures is in maximum evaluation of total bearing capacity of foundation structure, distributing bridge loadings to soil mass in most rational way, id. est. both in shallow and deep layers. The hybrid foundation system Combined Pile-Raft Foundation (CPRF) is a high-tech solution for the transfer of big loads even in settlement active soil. The CPRF combines the bearing capacities of the raft and of the piles. For the design of a CPRF three-dimensional, non-linear calculations using the Finite-Element-Method (FEM) are used. In the first part of the contribution the load-bearing behaviour of a CPRF and the design principles are explained. In the second part, the application in engineering practice is shown by a real case study of a railway bridge with a width of about 110 m. To demonstrate the optimization process, alternative foundation systems were calculated. At the end of the contribution, all foundations systems are compared and evaluated by the savings of $CO_2$ emission.

**Keywords:** railway bridge, Combined Pile-Raft Foundation, foundation systems, FEM, $CO_2$ emission.

## Introduction

Bridges are very important road and railway infrastructural units. In many cases they located in complicated geotechnical conditions (soil profile, water influence, complex loading history of permanent and variable loads). Therefore, usual foundation design usually corresponds high level of reserve (overdesign factor). All factors, met during exploitation term, can be grouped to reasons of 1) factors, complicated to evaluate directly (dynamic effects, coupling effects to soil, ground water level changes, construction in vicinity of bridges, etc.), 2) choosing conservative system of foundation structure. Combined Pile-Raft Foundation (CPRF) in bridge design is smart foundation system solution allowing transmitting bridge loads to soil mass in most efficient and rational way with minimum volume and intervention to environment. Developed methods and techniques for CPRF contribute minimizing overdesign factor in evaluation raft (shallow soil layers) and piles (deeper soil layers) bearing capacity and deformation. Numerical simulation via proper discretization and application of advanced mathematical modelling is the proper approach in CPRF rational design. More exact modelling techniques, based on CPRF stress and strain evolution analysis in concert with validation of test results allows minimizing overdesign result.

Safety, serviceability and sustainability are the most important aspects for design of any foundation system. The requirements for safety and serviceability are defined in standards, codes and regulations. For a 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 has to be optimized. The focus has to be on the production of cement. The production of one ton of cement lead to an emission of about 800 kg of $CO_2$. This is about 91% of the whole $CO_2$-footprint of

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concrete and about 8% of the man-made $CO_2$ emission of the world (Aldrian & Bantle, 2021). This shows that the reduction of concrete for any kind of structures is an important aspect for the reduction of the $CO_2$ emission.

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

– large scale load tests in-situ on the construction site to detect the real load-deformation behaviour of the foundation,
– hybrid foundation systems like the Combined Pile-Raft Foundation (CPRF) (Katzenbach et al., 2016),
– three-dimensional, non-linear simulations of the load-deformation behaviour of the foundation system using e.g. Finite-Element-Method (FEM).

## 1. Combined Pile-Raft Foundation (CPRF)

### 1.1. 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. CPRFs can be used for both traditional high-rise buildings and engineering structures such as bridges and towers.

The technical regulations for classical deep foundations also apply to CPRFs (Deutsche Gesellschaft für Geotechnik e.V., 2018). In addition, the Guideline for Combined Pile-Raft Foundation (Katzenbach & Choudhury, 2013) must 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 behaviour due to the interaction between the foundation elements and the subsoil. According to DIN EN 1997-1 Eurocode 7: Geotechnical design – Part 1: General rules (European Standard, 1997; Deutsches Institut für Normung e.V., 2014), CPRFs belong to the Geotechnical Category GC 3. This category includes very challenging constructions.

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

– settlements and differential settlements,
– the bending moments of the foundation raft,
– pile materials (30–40%).

### 1.2. Bearing and deformation behavior

Measurement data from high-rise buildings founded on spread foundations in Frankfurt am Main, Germany, showed that 60% to 80% of the settlements occur in the upper third of the influenced soil volume. Part of the load on a CPRF is transferred by the piles from areas of low stiffness under the foundation raft to a stiffer, deeper area of the subsoil, without neglecting the bearing capacity of the foundation raft (Figure 1).

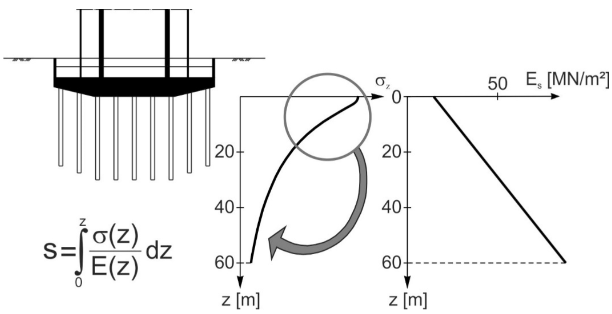


Figure 1. Principle load transfer of a CPRF

The bearing and deformation behaviour of a CPRF is characterized by the interaction between the bearing elements (foundation raft and pile or barrettes) and the subsoil. Figure 2 shows all the interactions of a CPRF.

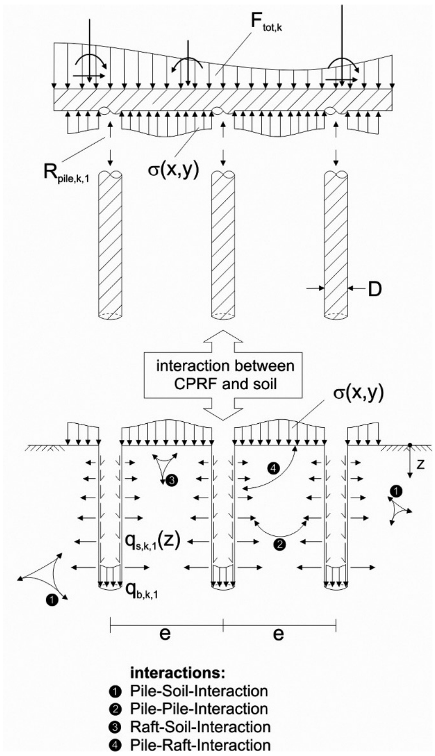


Figure 2. Interactions of a CPRF

A CPRF transfers the total building load $F_{tot,\,k}$ to the piles and the soil. The mobilized resistance of a CPRF depends significantly on the settlement $s$, which is similar to a classical 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 $R_{raft,\,k}(s)$ 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. (1)).

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

As shown in Eq. (2), 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.

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

The load deformation behaviour of a *CPRF* can be specified by the *CPRF* coefficient $\alpha_{CPRF}$. This coefficient declares the relation between the resistance of the piles and the total resistance and varies between 0 and 1 (Eq. (3)).

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

If the entire load $F_{tot,\,k}$ is carried by the foundation raft, the *CPRF* coefficient is $\alpha_{CPRF} = 0$. If the entire 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 $\alpha_{\mathrm{CPRF}}$ between 0.5 and 0.7 can be considered as optimum. For $\alpha_{CPRF} > 0.9$ additional analysis on the piles are required.

The effective horizontal stresses influence the mobilized skin friction of the piles. Hence the stress level of the subsoil influences the load deformation behaviour of a CPRF. The neighbouring 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 increasing stress level of the subsoil. The result is a higher skin friction in the upper parts of the piles.

### 1.3. Principle calculation method of a CPRF

For the design and calculation of a CPRF various methods can be selected (Cooke, 1986; Horikoshi & Randolph, 1998; Katzenbach & Reul, 1997; Leppla & Norkus, 2020; Randolph, 1994; Poulos, 1989; Poulos et al., 1997; Russo & Viggiani, 1998). Up to now only numerical methods, like the Finite-Element-Method (FEM) provide calculation results that are comparable to the reality. The knowledge about the load deformation behaviour of a free, single pile is necessary for a qualified design of a CPRF (Deutsche Gesellschaft für Geotechnik e.V., 2018). 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.

For the detection of the real load-deformation behaviour in-situ pile load tests are required for complex construction projects and/or difficult soil conditions.

### 1.4. Monitoring of a CPRF

Regarding the Geotechnical Category GC 3 a CPRF has to be monitored (Deutsche Gesellschaft für Geotechnik e.V., 2018; Katzenbach & Choudhury, 2013), DIN EN 1997-1 Eurocode 7: Geotechnical design – Part 1: General rules (Deutsches Institut für Normung e.V., 2014). The monitoring program consists of geodetic and geotechnical measurements of the new structure and of the vicinity and covers the construction phase and the service phase. The following tasks are important:

- verification of the calculation model including the soil parameters used,
- early detection of critical forces, stresses, deformations,
- verification of the predicted deformations,
- quality assurance and preservation of evidence.

## 2. Environmentally optimized bridge foundation

### 2.1. Bridge foundation

To illustrate the advantages of a CPRF, a bridge abutment of a real railway project is analysed by numerical simulations using FEM. The bridge will have a width of approximately 110 m. The foundation raft of the bridge abutment is about 13 m long, about 11 m wide and 1.5 m thick. In addition to the foundation geometry, the 1 m thick base of the abutment wall is considered in the numerical model. All other loads on the foundation, such as the abutment walls, the fill and the bridge are represented by surface loads. The base of the foundation is 2.75 m below ground level. The subsoil consists of dense sand and gravel. The three-dimensional finite element model is shown in Figure 3.

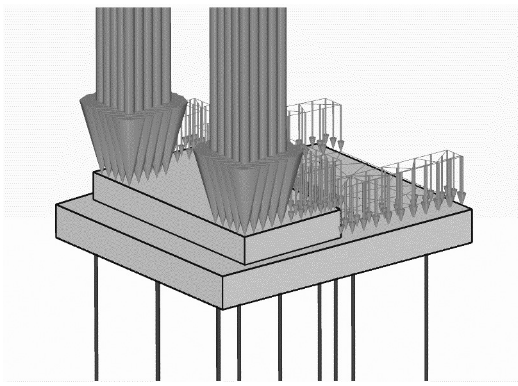

Figure 3. Three-dimensional finite element model

To illustrate the advantage of the CPRF, in the following the bridge abutment is calculated as a raft foundation, as a classical pile foundation and as a CPRF. In the calculations of the classical pile foundation and the

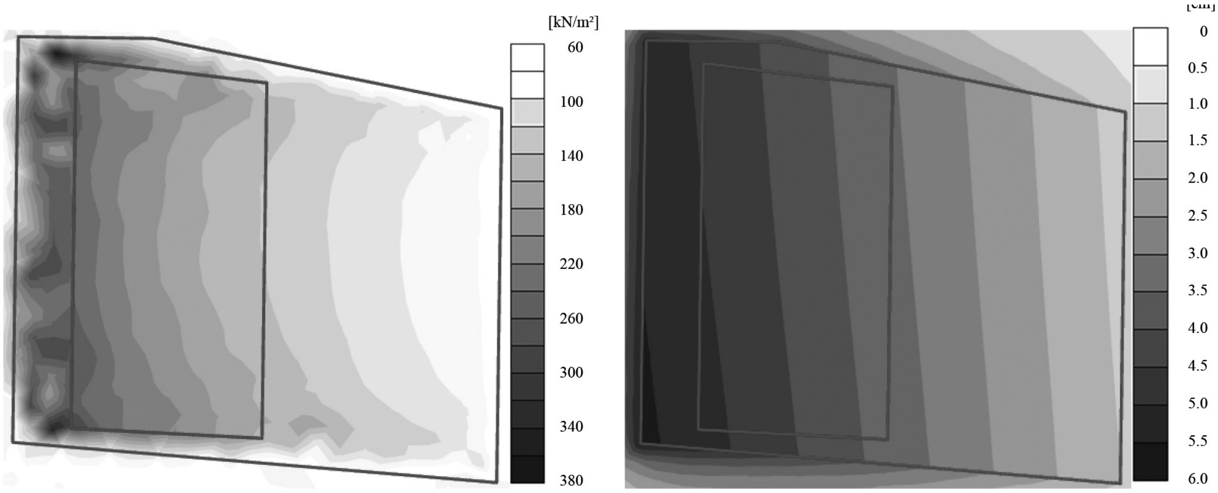


Figure 4. Contact pressure (left) and settlements (right) under the foundation raft

CPRF, the pile lengths are varied so that the maximum settlement under the bridge abutment is $s_{max} = 2$ cm.

### 2.2. Raft foundation

In the first numerical simulation the foundation consists only of a raft. In the calculation the excavation and the construction of the foundation raft were modelled first. Then all loads were applied to the foundation. Figure 4 shows the settlements under the foundation raft. The contact pressure under the raft is up to 380 kN/m$^2$ and the maximum settlement is $s_{max} = 6$ cm.

### 2.3. Classic pile foundation

The CPRF resistance for different load levels is conditioned by stress and strain state evolution of foundation. The contribution of pile base and skin resistances to total pile resistance depends on the pile settlement, spacing of piles, installation type (Mandolini et al., 1992), installation sequence of piles in their groups (Norkus & Martinkus, 2019) and connection of pile to cap. These effects influence contribution of CPRF total load to piles and raft. In the second numerical simulation, the bridge abutment is founded on a classical pile foundation. Therefore, a thin non-load-bearing soil layer with very low stiffness was modelled directly under the foundation raft. This means that the loads are only transferred into the soil through the piles. Eleven piles were also placed under the raft. The centre distance of the bored piles is approximately 3.3 m. The diameter of the bored piles is D = 1.2 m.

The pile length was varied to limit settlement of the bridge abutment. All piles were modelled with the same length. Varying the length of the bored piles has shown that the piles need to be 13.5 m long to limit the settlement of the bridge abutment to $s_{max} = 2$ cm. Figure 5 shows the settlements under the foundation raft of the pile foundation.

Table 1 shows the calculated pile forces, the pile settlements and the pile stiffnesses. The sum of all pile forces is 23.8 MN.

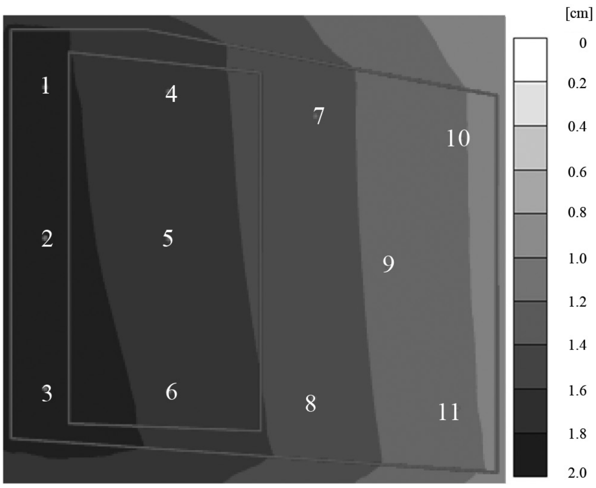


Figure 5. Settlements under the foundation raft of the classic pile foundation

Table 1. Pile forces, pile settlements and pile stiffnesses of the classic pile foundation

| No. pile | Pile force [MN] | Settlement [cm] | Pile stiffness [MN/m] |
|---|---|---|---|
| 1 | 3.65 | 1.84 | 199 |
| 2 | 2.58 | 1.86 | 139 |
| 3 | 3.75 | 1.91 | 197 |
| 4 | 2.26 | 1.69 | 134 |
| 5 | 1.02 | 1.71 | 60 |
| 6 | 2.52 | 1.75 | 144 |
| 7 | 1.80 | 1.47 | 122 |
| 8 | 1.98 | 1.52 | 131 |
| 9 | 0.77 | 1.36 | 57 |
| 10 | 1.58 | 1.21 | 130 |
| 11 | 1.86 | 1.25 | 150 |
| Σ | 23.8 | | |

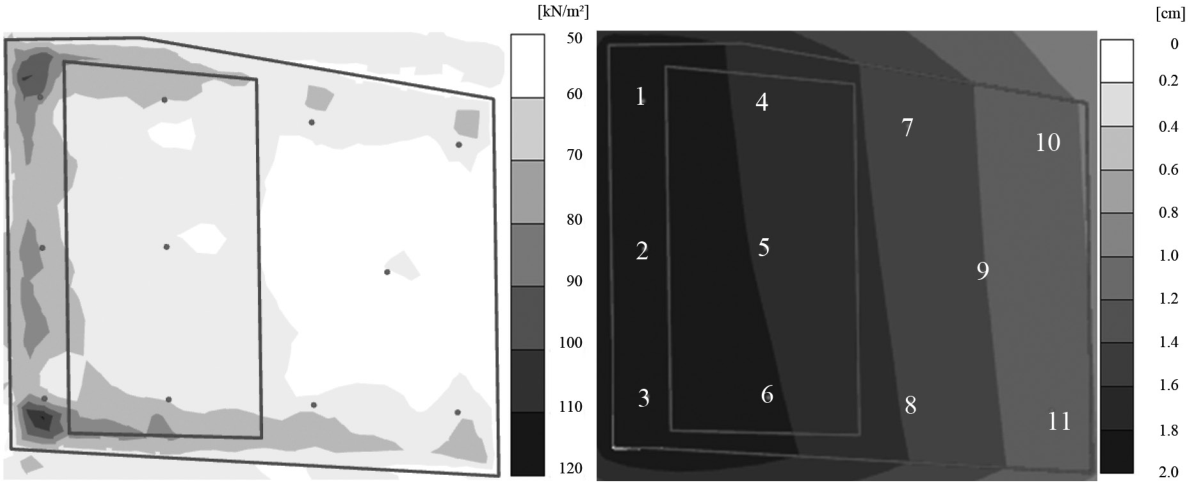


Figure 6. Contact pressure (left) and settlements (right) under the foundation raft of the CPRF

### 2.4. Combined Pile-Raft Foundation (CPRF)

In the third numerical simulation the bridge abutment is founded on a CPRF. The foundation raft is placed directly on the dense sand and gravel. To limit the settlements to $s_{max}$ = 2 cm, the pile length was varied.

The variation of the bored pile length showed that the piles need to be 11.5 m long. Figure 6 shows the contact pressure and the settlements under the foundation raft of the CPRF. The contact pressure under the raft is up to 120 kN/m$^2$.

The total pile volume of the CPRF was reduced by 15 % compared to the conventional pile foundation. In this case study the number of piles was not reduced. Further calculations would show that the piles No. 5 and No. 9 could be removed without any significant increase in settlement. Table 2 shows the pile forces, the pile settlements and the pile stiffnesses. The sum of all pile forces is 20.5 MN.

Table 2. Compilation of pile forces, pile settlements and pile stiffnesses of the CPRF

| No. pile | Pile force [MN] | Settlement [cm] | Pile stiffness [MN/m] |
|---|---|---|---|
| 1 | 2.95 | 1.91 | 154 |
| 2 | 2.38 | 1.94 | 123 |
| 3 | 3.07 | 1.99 | 154 |
| 4 | 1.96 | 1.75 | 112 |
| 5 | 0.96 | 1.78 | 54 |
| 6 | 2.06 | 1.83 | 113 |
| 7 | 1.66 | 1.53 | 109 |
| 8 | 1.74 | 1.58 | 110 |
| 9 | 0.79 | 1.41 | 56 |
| 10 | 1.34 | 1.26 | 106 |
| 11 | 1.56 | 1.29 | 121 |
| Σ | 20.5 | | |

### 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. Experience gained during the construction of several high-rise buildings shows that a CPRF reduces settlements by more than 50 % compared to a raft foundation. In addition, a CPRF reduces the necessary construction material including concrete and steel. This leads to a significantly reduction of the $CO_2$ emission.

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 structure 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 material used, time spend for construction and $CO_2$ emitted, as shown by the case study.

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