On Application of Combined Pile-Raft Foundations for Road Structures

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Abstract. Roads and road infrastructure systems are designed to satisfy ultimate and serviceability conditions under long-term actions caused by transport loadings and environmental effects. Selected design solutions must be safe and rational in terms of construction and maintenance costs. In cases when weak or soft soil layers of natural soil profiles are shallow and/or the traffic loads are very large, the Combined Pile-Raft Foundation (CPRF) is the economical road and railway structure design solution. Application of CPRF is cheaper geotechnical solution comparing with soil change or usual piled foundation alternatives. The development of this system is based on the analysis of relevant mechanical properties of soil layers and the evaluation of the soil-structure interaction. The soil-structure interaction is of highest importance allowing proper evaluation of load bearing resistance and deformation transmitted by raft and piles to soil layers. The soil and foundation system usually is subjected by loadings, resulting elastic-plastic resistance range. Therefore, relevant nonlinear physical laws due to the stress levels are used. The paper purpose is summarizing the experience of application of Combined Pile-Raft Foundations used in road and railway construction and bridge engineering.

Keywords: road structure, soil-structure interaction, Combined Pile-Raft Foundations, performance analysis.

Introduction

Road infrastructure (road and railway pavement structure, foundations for bridges, embankment stability, other) must be designed to ensure stable codified stability and deformation requirements, formulated in terms of ultimate and serviceability limit state conditions. An employment of the proper soil-structure interaction model is the principle approach to realize a rational and economical design. It ensures a precise evaluation of the workloads transmission to the soil, e.g. via raft and piles. In the case when soil profiles include weaker shallow soil layers, the Combined Pile-Raft Foundation (CPRF) can be successfully serve a rational design solution. Using the CPRF, the soil is the stabilizing element from one hand and the loading element from other hand. The soil-structure interaction during the service period is subjected to different loadings, including construction and deconstruction stages, changes of site conditions in the vicinity of structures. The construction stage causes structural and load changes, as e.g. changes of stiffness and stress level of the soils, shifting of load application points, temporal excavations, construction of retaining walls with permanent or temporal anchors, pile installation effects to soil resistance. Changes of soil and construction material as creep, primary consolidations, shrinkage and other should be properly evaluated for predicting CPRF response measures during exploitation period. Analysis and design methods of a CPRF are under fast development, because the usual design procedures applied for piles and piled groups give conservative design solutions. The reason is that the proper contact and interaction of piles, raft and soil usually is neglected. Due to the complexity of the problem, there is no single approach of the analysis of the bearing resistance of a CPRF (Poulos et al., 2001) and the development of rational methods is under continued development. Amongst many investigations (Viggiani et al., 2012; Katzenbach et al., 2017) the main aspects, challenges and trends in design and application of CPRFs, are based on experiences as well. The general principles of CPRF application based on research and design projects, developed during last decades and also related to road and railway infrastructure constructions are presented.

1. General procedures of Combined Pile-Raft Foundation (CPRF) design

Due to high level difficulties for evaluating the soil-structure interaction of the CPRF is assigned to highest, Geotechnical category 3 according EC 7 (EN 1997-1:2004 (European Committee for Standardization [CEN], 2004)).

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It relates most complex requirements for soil investigations, discretization and development of the design model. Modelling of a CPRF includes three main parts:

- Modelling of soil profile and its mechanical behavior under various loading levels;
- Modelling of piles and raft;
- Modelling the interaction between pile-raft; pile-soil, pile-pile; raft-soil.

Construction (road, bridge superstructure, etc.) loads transmitted to a CPRF should ensure satisfaction of the ultimate limit state requirements of constructional elements and the soil as well. From the other hand, the deformations of CPRF in concert with soil deformations should satisfy serviceability requirements of the system. The soil is the load-bearing element, but in certain cases it serves as complimentary loading to other soil layers.

Modelling of the soil resistance is related to evaluation of the ground (soil mass in vicinity of geotechnical structure). It depends on the selection of the relevant physical model for the soil related to the predicted load levels and load variation. The relevant time-dependent effects have to be required in the model. Determining the parameters of the mechanical properties via routine procedures is insufficient as proper interpretation is based on practical experience. The principle difficulties for the interpretation of the investigation results e.g. analyzing soil profiles of two borings is shown in Figure 1. The real gradient between two borings has to be detected, taking into account actual variation of soil types and their properties between borings.
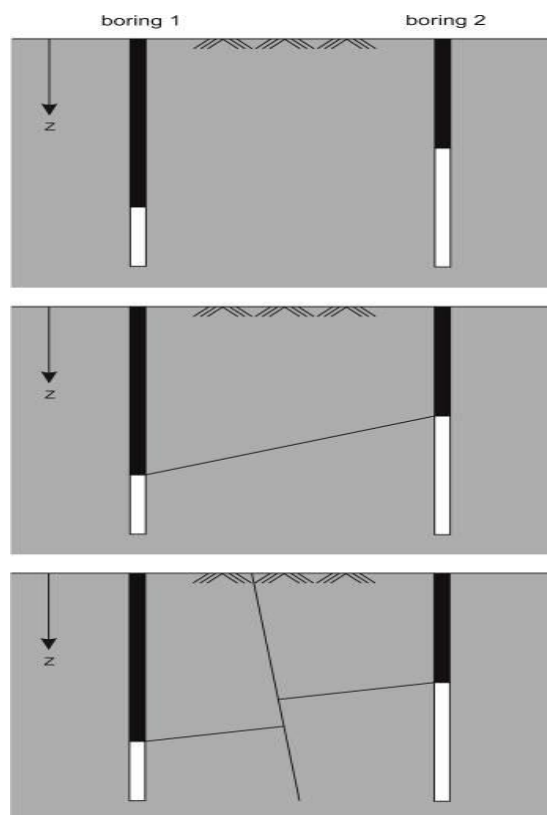

Figure 1. Soil profile discretization per depth using 2 borings (source: after Katzenbach et al., 2017)

2. Combined Pile-Raft Foundation (CPRF) design

2.1. Characterization

A Combined Pile-Raft Foundation (CPRF) is the hybrid foundation system that combines separate bearing resistances of piles and raft. It can be characterized as technically and economically optimal system, applied in many constructional schemes of geotechnical engineering (structural engineering, bridge engineering, road and railway engineering). According to the technical regulation, it is a special type of deep foundations EC 7 (CEN, 2004). The specialized technical regulations for this type of foundation in form of guidelines are presented in (Hanisch et al., 2002; International Society for Soil Mechanics and Geotechnical Engineering [ISSMGE], 2013). To ensure the quality and safety of design the independent geotechnical engineer expert in concert with checking engineer should be involved for expertizing CPRF to guarantee the four–eye principle, described in (Hanisch et al., 2002). The advantages of CPRF against conventional shallow and classic pile foundations can be summarized by:

1. Reduction of absolute and differential settlements;
2. Increasing bearing resistance of shallow foundations;

3. Reducing of bending moments and torsion moments transmitted to raft;
4. Reduction the number and size of piles (around 50% of concrete according Katzenbach et al. (2006)).

2.2. Resistance definition

CPRF includes 3 elements contributing to total bearing resistance (raft, piles and soil). The principle of load transfer scheme is illustrated in Figure 2.
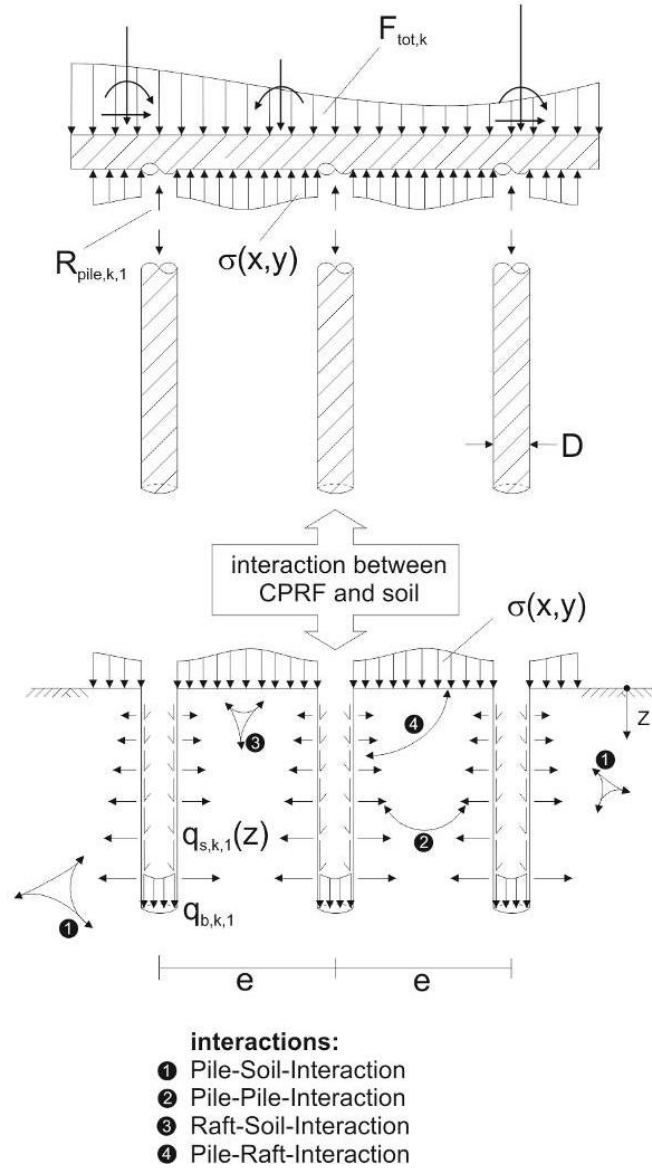

Figure 2. Interaction scheme of CPRF elements (source: after Katzenbach et al., 2017)

The deformation behavior of the soil is elastic-plastic, id. est. it is related to loading level or deformation value.

External loads $F_{tot,k}$ due the raft stiffness are transmitted to the piles and soil. External loads are equilibrated by CPRF total resistance $R_{tot,k}(s)$, which consists of the raft resistance $R_{raft,k}(s)$ and the joint resistance of the n number of piles $R_{pile,k,i}(s)$:

$$R_{tot,k}(s) = R_{raft,k}(s) + \sum_{i=0}^{n} R_{pile,k,i}(s).$$ (1)

Raft bearing resistance $R_{raft,k}(s)$ is obtained via integration of the raft base contact pressure $\sigma(x,y)$.

The resistance of the piles $R_{pile,k,i}(s)$ consists of the constant pressure $q_{b,k}$ (obtained by integrating the contact pressure of pile base) and of the shaft pressure $q_{s,k}(s,z)$ along the length of the pile z.

For CPRF with n piles the total resistance $R_{tot,k}(s)$ is:

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

The CPRF resistance performance is described by the coefficient α_{CPRF}, characterizing resistance contribution of piles to total resistance of CPRF, namely:

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

Bound values of α_{CPRF} are 0 and 1. Zero value of α_{CPRF} means that external total load is resisted only by the raft; one means that it is resisted only by foundation piles.

2.3. Bearing resistance and deformation peculiarities

As it was mentioned above, the bearing resistance and deformation of a CPRF depend on many factors conditioned by stress and strain state of the ground at certain load levels. The contribution of pile base and shaft resistances to total pile resistance depends on the pile settlement, spacing e of piles (see in Figure 2), installation type (Mandolini et al., 1992) and even installation sequence of piles in their groups (Norkus & Martinkus, 2019). These effects influence contribution of CPRF total load to piles and raft. Pile raft connection rigidity is also an important factor. Detailed analysis of above mentioned and other factors is not the aim of this paper and detailed description therefore omitted. Below are presented peculiarities of CPRF deformation behavior and resistance peculiarities, based on experiences of calculation and design practice, construction and monitoring applications:

1. In Hanisch et al. (2002) the performance of CPRFs described by $0.3 \leq \alpha_{CPRF} \leq 0.9$ was analyzed. The analysis showed that the optimal bounds correspond to the range of $0.5 \leq \alpha_{CPRF} \leq 0.7$.

2. The arrangement of the piles, of the length l and of the diameter D is described via the coefficient e/D and coefficient pile of pile slenderness l/D. The arrangement of the piles influence the α_{CPRF} magnitude and settlement s.

   2.1. For small values of e/D or large number of piles n, the load distribution amongst piles and foundations is almost constant for different total load magnitudes. Only insignificant increase of pile loads may be recognized for larger total load magnitudes.

   2.2. For large values of e/D the contribution of raft to total resistance of CPRF increase, the contribution of the piles to the total resistance of the CPRF increase. This increment influenced by soil-pile-soil changes of stress and strain state and depends on spacing e (see e.g. in Norkus & Martinkus, 2019). Settlement s of CPRF decrease.

   2.3. Bearing resistance of a single pile acting in the pile group depends on spacing e (Norkus & Martinkus, 2019). For coefficient $e/D \geq 3$ the bearing resistance of a pile essentially depends on its location of pile under the raft.

   2.4. Resistance of single piles acting in group increase from center to the edges of the raft. Thus inner piles are less loaded comparing to outer ones. The edge piles, especially at the corner receive the main portion of loading.

   2.5. The skin resistance of piles depends on pile spacing e, while its base resistance practically is not sensitive to e.

3. Increment of spacing e for CPRF resistance reduce, id. est. the pile group effect reduces as it is in case of classic pile foundations. For $e/D \geq 6$ all piles resist almost analogously, id. est. no group effect recognized.

4. For classic pile groups foundations the pile shaft resistance of upper part is significantly smaller comparing to the deeper ones (see e.g. in Norkus & Martinkus, 2019). The opposite situation is for CPRF due to larger stresses transmitted to soil by the raft.

2.4. Calculation methods and limit states

EC 7 (CEN, 2004) and other codes allow the application of various methods, techniques and approaches in foundation calculation and design (analytical, empirical, numerical modelling, testing, etc.) related to deep foundations and hybrid ones (Poulos et al., 1997; Horikoshi & Randolph, 1998; Russo & Viggiani, 1998; de Sanctis & Mandolini, 2002;

Hanisch et al., 2002; Randolph, 1994; Mandolini, 1994; Viggiani et al., 2012; Katzenbach et al., 2017). The numerical modeling is the most real tool to predict deformation behavior of deep foundations and CPRFs as well. The currently applied CPRF calculation methods briefly can be summarized (Hanisch et al., 2002) by:

1. Analytical. Applying the methods, the raft resistance against applied external load determined. If loads are larger than the raft resistance, required resistance portion is distributed to piles. Pile resistance is calculated as for single piles. CPRF settlement is determined as for a raft loaded by load magnitude contributed to raft. Obviously, it is very approximate method, recommended for first assessment only.
2. Alternative. Simplified schemes applied. Analyzing CPRF behavior by means of deep spread foundation (soil mass reinforced by piles) or as one thick single pile. Obviously, it is very approximate method, applied also as alternative for first assessment.
3. Empirical. Methods, analogously as for pile foundations, are based on field or laboratory (e.g. various scale prototypes) tests. Relevant correlations and empirical equations are developed on the basis of experiences, measurements and classical laws.
4. Numerical. The Finite-Element-Method (FEM), Discrete-Element-Method (DEM) or their combinations applied. Actually numerical methods allows to evaluate all types of nonlinearities (physical, geometrical) of ground, coupling effects and geotechnical structure and interaction, as well.

Ultimate limit state (ULS) cases must be specified. The total bearing capacity of CPRF should be the main ultimate case mode. The most reliable method is the numerical modelling to determine CPRF characteristic magnitude of resistance. Analysis of the bearing capacity of single piles generally is not necessary. In case the base failure method is applied, the resistance is checked for the lower edge of the raft. GEO ultimate states of foundation structures and their connections also analyzed. Recommendations for ULS analysis of CPRF is given in (ISSMGE, 2013).

Serviceability limit state (ULS) cases must be specified. The check against limiting values of structural deformation and foundation movement must be specified. They include maximum settlements, relative (differential) settlements, relative rotation and other values of deformation to check in respect of limiting values. Actually, numerical methods or measurements can be applied for evaluating design values of deformation.

Conclusions

The paper presents general principles of the Combined Piled-Raft Foundation (CPRF) design applications in geotechnical engineering, including application for road and railway infrastructure. They are based on experiences of modelling, implementing and monitoring of design projects.

1. CPRF is a fast developing foundation system alternatively used against conventional shallow and classic pile foundations. This hybrid foundation system advantages against afore mentioned systems as following:
   1. Better reduction of absolute and differential settlements;
   2. Larger increment of bearing resistance compared with shallow foundations;
   3. Reducing of bending moments and torsion moments transmitted to raft;
   4. Reduction the number and size of piles (saving around 50% amount of concrete).
2. Due to complexity of stress and strain state and soil-structure interaction significance for CPRF the deformation behavior should be analyzed by numerical simulation methods. Long-term and coupling effects can be implemented if required as well.
3. CPRF fits (technically and economically) well for strengthening road structures in sectors where relatively week or soft layers. This system mobilize bearing resistance of shallow layers via raft, the rest is mobilized by piles. This foundation system is much more effective against soil changing and/or strengthening methods (injection, reinforcement by geosynthetics, other) and it is more effective against classic piled foundations alternatives for complicated sectors of road and railway as well.
4. Application of CPRFs is recommended for wide usage for various road structures and infrastructural units.

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