Recommendations for the design and construction of piled rafts

Recommandations pour le dimensionnement et la construction de fondations mixtes radier-pieux

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ABSTRACT: The bearing behaviour of piled rafts is characterized by a complex soil-structure interaction between structure, piles, raft and subsoil. Since there have been neither standards nor definite design strategies available for the design and computation of piled rafts so far, a 'Guideline for design, computation and construction of piled rafts' has been worked out in Germany on basis of parametric numerical studies and experiences gained by monitoring various piled rafts. Beside a short summary of these investigations the main aspects of the 'Piled-Raft Guideline' will be presented.

RÉSUMÉ: Le comportement de l'appui des fondations mixtes radier pieux est caractérisé par l'interaction entre ouvrage, pieux, radier de fondation et sous-sol. Comme il n'y ait ni modèle ni stratégies de conception définitives disponibles pour la réalisation et le calcul des fondations mixtes radier pieux jusqu'à présent, un „Manuel pour la conception, le calcul et la construction des fondations mixtes radier pieux" a été rédigé en Allemagne basant sur des études numériques de paramètre et des expériences acquis par la surveillance en technique de mesure de certains fondations mixtes radier pieux. Outre une courte sommaire de ces recherches les aspects principaux du „Manuel des fondations mixtes radier pieux" seront présentés.

1 INTRODUCTION

1.1 *Soil-structure interaction of piled rafts*

Piled rafts are composite foundation constructions which use both bearing elements, the piles and the raft, to transfer structural loads into subsoil (Burland et al. 1977). The application of piled rafts implies an effective concept to minimize settlements and differential settlements, to improve the bearing capacity of a shallow foundation and to reduce in an economic way the bending moments of a raft. The bearing behaviour of a piled raft is characterized by a complex soil-structure interaction between structure, piles, raft and subsoil. In detail there are the following interaction effects, which should be considered in design (Figure 1):

- soil-pile interaction,
- pile-pile interaction,
- soil-raft interaction,
- pile-raft interaction.

By conventional foundation design it has to be proofed that the building load is transferred either by the raft or the piles in the ground. The concept of piled rafts indicates a new understanding of soil-structure interaction because the contribution of the raft as well as of the piles is taken into consideration to satisfy the proof of the ultimate bearing capacity and of the serviceability of a piled raft as an overall system. Besides this the interaction between raft and piles makes it possible to use the piles up to a load level which is higher than the permissible design value for the bearing capacity of a comparable single standing pile (Katzenbach & Moormann 1997).

1.2 *Definitions and concept*

According to its stiffness the raft distributes the load of the structure S_{tot} over contact pressure, represented by $R_{raft}(s)$, as well as over the piles, generally represented by the sum of pile resistance $\Sigma R_{pile,k,j}(s)$ in the ground (Figure 1), so the total resistance of the piled raft is:

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

whereby the particular pile resistance is:

$$R_{pile,k,j}(s) = R_{b,k,j}(s) + R_{s,k,j}(s) \qquad (2)$$

The bearing behaviour of a piled raft can be characterized by the piled raft coefficient α_{pr}, which describes the load sharing between piles and raft. The piled raft coefficient α_{pr} is defined as the ratio between the sum of pile resistance $\Sigma R_{pile,i}$ and the total resistance of the piled raft R_{tot}:

$$\alpha_{pr}(s) = \sum_{j=1}^{m} R_{pile,k,j}(s) \Big/ R_{tot,k}(s) \qquad (3)$$

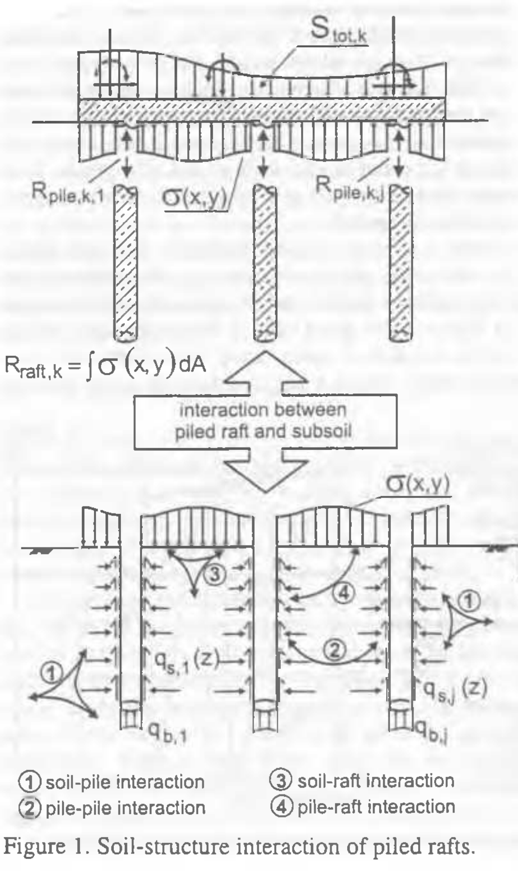

Figure 1. Soil-structure interaction of piled rafts.

A piled raft coefficient of $\alpha_{pr} = 0$ indicates the case of a shallow foundation and $\alpha_{pr} = 1$ indicates the case of a piled foundation without contact pressure beneath the raft.

2 PEFORMANCE OF PILED-RAFTS

2.1 *Behaviour of piles depending on stress level in situ*

The stress level in the subsoil significantly influences the bearing behaviour of piles. Figure 2 shows the results of a numerical analysis of two single bored piles with the same geometric properties. One pile is located concerning its pile head on the actual ground level while the other pile is located in an excavation pit with a depth of 20 m under the ground level. In consequence of the higher residual stresses of the soil in greater depth the second pile can mobilize a significantly higher value for the ultimate shaft resistance $R_{s,k}$. So the ultimate skin friction $q_{s,k}$ of a pile is not only a function of the strength of soil, but also a function of the residual stresses in the soil continuum.

2.2 *Influence of pile-pile interaction and pile-raft interaction*

For the piles the pile-raft interaction causes a similar effect as the demonstrated influence of the residual stress level. Due to the contact pressure beneath the raft, a higher stress level is caused in the soil between the pile group. A higher vertical and horizontal stress level allows the mobilization of a higher skin friction along the pile shafts avoiding a shear failure. In consequence the bearing behaviour of piles as part of a piled raft varies from its typically known behaviour as single standing pile. Figure 3 impressively demonstrates the influence of the pile-pile interaction and especially of the pile-raft interaction on the load-settlement behaviour of bored piles. The five load-displacement curves describe the numerically determined load-settlement behaviour of a single standing pile ①, of a pile as part of a simple 1-pile-1-raft model ② and of a corner pile ③, an edge pile ④ and an inner pile ⑤ of a piled raft with 25 piles. Although all piles are embedded in same subsoil and have same length and diameter their load bearing capacity is significantly different. The variation of the bearing behaviour of the piles of the piled raft in function of their position inside the pile group is a consequence of the pile-pile interaction, which leads to a block deformation of the soil and the piles. Thus especially in the upper part of their shaft the inner piles can mobilize a lower skin friction as the piles located at the edge of the pile group. In a piled foundation or a piled raft the pile loads decrease from outside to inside the pile group.

For piled rafts the load sharing between raft and piles, represented by the piled raft coefficient α_{pr}, depends on the magnitude of the structure loads respectively on the settlement of a piled raft. In Figure 4 two piled rafts in Frankfurt Clay, which differ only by the number of piles, have been examined by a numerical spatial study. Model A has 64 piles with a pile spacing

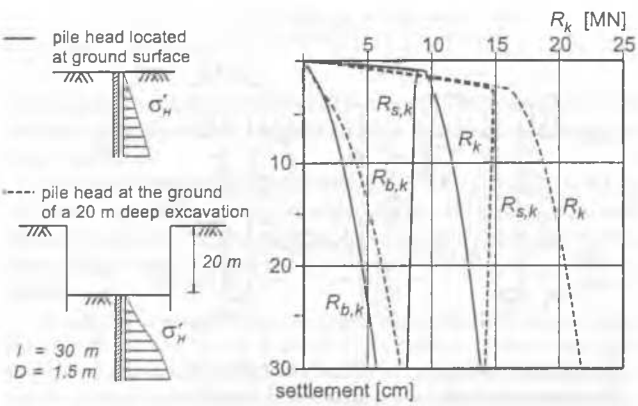

Figure 2. Influence of residual stress level on pile behaviour.

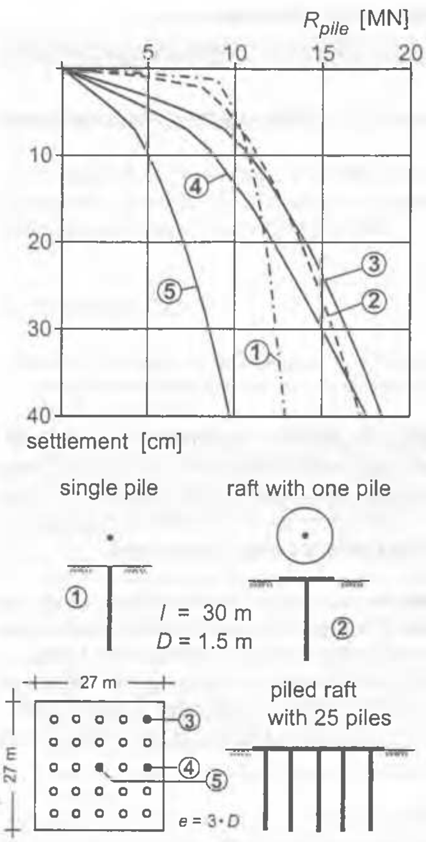

Figure 3. Influence of pile-pile and pile-raft interaction on load-settlement behaviour of piles.

of $e = 3 \cdot D$ while model B has 16 piles with $e = 6 \cdot D$. The length of all piles is $l = 30$ m, the diameter is $D = 1.5$ m. The piles are combined with a square raft with 45 m as length of side. Under an increasing total load the piled raft coefficient of model M1 remains with 80 % quite constant, that means the resistance of piles and rafts increases with the same percentage. For model M2 an increasing total load and settlement of the piled raft leads to a significant increase of the resistance of the raft as the piles can mobilize only a small growth of resistance.

2.3 *Consequences for a design and safety concept of piled rafts*

The results of the numerical study illustrate the following main effects influencing the soil-structure interaction of piled rafts:

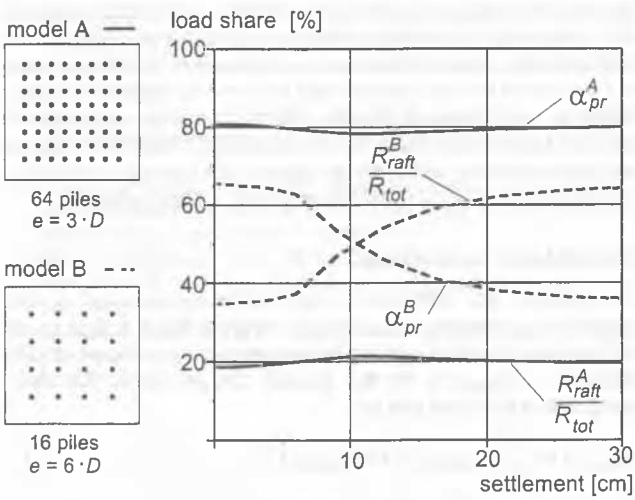

Figure 4. Influence of pile-pile and pile-raft interaction on load-settlement behaviour of piles.

- The skin friction depends on the stress level within the subsoil.
- In most cases a bearing resistance failure of a piled raft as overall system doesn't occur for a manifold of the working load. So usually deformations are the main design criteria for piled rafts, also the overall stability of a piled raft should be considered with an adequate calculation model in any case.
- The load sharing between piles and raft depends on the settlement of a piled raft. There is no linear relation between α_{pr} and the settlement.
- For a piled raft the bearing behaviour of the piles is significantly different from the bearing behaviour of a comparable single standing pile depending on (1) the position of the pile in the pile group and (2) the pile spacing.
- The pile-raft interaction leads to increasing vertical and horizontal stresses in the subsoil. So an increasing load on the piled raft can mobilize an increasing resistance mainly of the shaft resistance of the piles. The consideration of the piles as an action on the raft of constant value is unrealistic.

These characteristic effects determining the bearing behaviour of piled rafts have been taken into consideration by defining recommendations for the design of piled rafts.

3 GERMAN 'PILED-RAFT GUIDELINE'

3.1 *Recommendations by European codes*

In Eurocode EC7 coming award as framework for geotechnical design in Europe (Gudehus & Weißenbach 1996) there are no explicit guidelines given for the design of piled rafts. Chapter 7 of EC7 deals with pile foundations. In clause 7.6.3(3) it is mentioned that for pile groups two failure mechanisms should be considered: (1) the bearing resistance failure of the piles individually and (2) the bearing resistance failure of the piles and the soil contained between them acting as a block. Contrary to this recommendation, for a piled raft the proof of the bearing resistance for single piles individually is unnecessary, because this proof is inconsistency to the concept of piled rafts.

An advice especially to piled rafts is given by EC7 in clause 7.6.3(4), where it is outlined, that: 'when the piles are used to reduce the settlement of a raft, their resistance corresponding to the creep load may be used in analysing the serviceability states of the structure'. The application of this advice may be difficult in practice, as inside a pile group a clear bearing resistance failure of a pile or a creep load as known from a single pile does not longer exist (Fig. 3). Besides this the advice only deals with the serviceability, so that additional recommendations concerning the bearing resistance of piled rafts are necessary.

3.2 *Content of the German 'Piled-Raft Guideline'*

Due to the fact, that so far neither national or international standards nor definite design-strategies for the design of piled rafts exists, a working group of geotechnical and constructional experts supported by the German Institute for Building Research · Berlin (DIBt) has worked out within the last four years (1996-2000) a 'Guideline for design, computation and construction of piled rafts'. Basis for the recommendations are parametric studies with numerical models and extensive experiences gained by the monitoring of various piled rafts. In detail the following topics are treated by this 'Piled-Raft Guideline':

- definitions and classifications for piled rafts,
- demands on soil investigations for piled rafts,
- requirements for reliable calculation methods,
- definition of a design and safety concept,
- definition of limits for the applicability of piled rafts,
- demand for an independent check of the design of piled rafts,
- recommendations concerning the construction and the quality assurance concept on site,
- demand for application of the observational method.

In the following some main aspects of the recommendations will be presented.

3.3 *Demands on soil investigation campaign*

One main precondition for the design of a piled raft is a careful soil investigation campaign by laboratory and field methods, which satisfies concerning quality and extent all requirements of the design concept. In any case drillings down to same depth as for conventional piled foundations are required. With samples taken from the drillings laboratory tests have to be performed in order to investigate soil strength and deformability. The kind and extent of laboratory tests have to coincide with the chosen constitutive law in the calculation model for the piled raft. As a second important precondition for the design of a piled raft the bearing behaviour of a single standing pile in the same soil conditions and with similar geometric dimensions should be known. Otherwise a static axial pile test is required.

3.4 *Requirements for calculation methods to design piled rafts*

For the safe and economic design of a piled raft it is necessary to have a calculation method which have the capacity to consider all relevant pile-raft-soil interactions as outlined in chapter 1 and 2. An appropriate calculation model should be able to predict reliably the following:

- the load-settlement behaviour of the piled raft as an overall system loaded progressively up to ultimate loads.
- the load sharing between piles and raft as a function of the settlement of the piled raft.
- the bearing behaviour of the individual piles depending on their particular position inside the pile group.
- the internal forces and bending moments for the structural design of the piles and raft.

The calculation model applied to design a piled raft should consider the characteristics of the soil and the stress level in situ. The models should be able to predict the behaviour of piled rafts depending on the geometric configuration of the foundation as varying number and position of piles with different lengths or diameters.

Over the last decades a great number of different calculation methods have been developed to analyse the bearing behaviour of piled rafts (Horikoshi & Randolph 1998, Poulos et al. 1997). Concerning their basic assumptions and models these calculation methods can be divided up into empirical methods, methods based on equivalent foundation systems, simplified analytical methods and numerical methods (Randolph 1994).

By choosing a calculation method for a certain project it should be taken into account that the type and the quality of the obtainable results depends extremely on the capabilities of the applied calculation model. The German Guideline requires that the suitability of the chosen calculation method has to be proven in a preliminary step by (1) the back-analysis of the investigated load-settlement behaviour of a single pile and by (2) the back-analysis of the measured behaviour of existing foundations with similar conditions.

3.5 *Proof of the ultimate limit state (ULS)*

Figure 5 shows the safety concept for the ultimate limit state (ULS). The 'external bearing capacity' is the bearing capacity of the subsoil; the 'internal bearing capacity' is the structural bearing capacity of the reinforced concrete structure of the foundation. For all calculations and proofs the characteristic values for properties and actions should be used.

Concerning the external bearing capacity it has to be proofed that the piled raft as an overall system will support the working load of the building with an adequate safety against loss of overall stability and against bearing resistance failure. For load case 1 (dead loads and regularly recurring working loads) the global safety factor is $\eta = 2.0$. There is no proof for an individual pile necessary, that is important and the main difference to conventional pile foundations. For 'simple' cases (geometrically regular configuration of the piled raft, homogenous soil condition, only vertical loads) the external bearing capacity of the piled

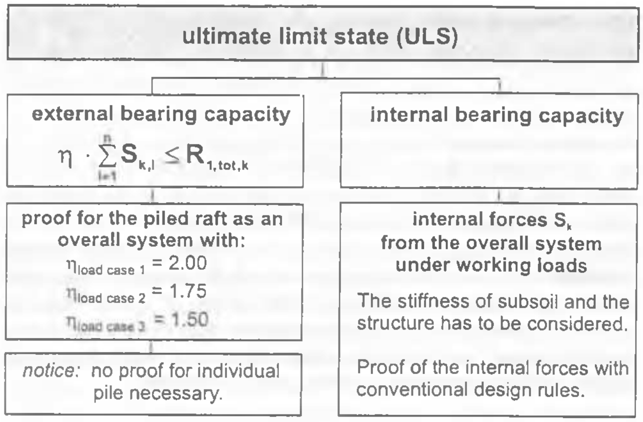

Figure 5. Proof of the ultimate limit state of piled rafts.

raft may alternatively be calculated as the base failure of an equivalent shallow foundation neglecting the piles.

For the proof of the internal bearing capacity of the piled raft the initial forces S_k inside the piles and the raft have to be calculated from the overall system under working loads. Then the internal forces have to be proofed in accordance to conventional design rules like Eurocode EC2.

3.6 *Proof of the serviceability limit state (SLS)*

The verification of the serviceability limit state (SLS) shall be considered in the common way as shown in Figure 6. The piled raft is calculated using characteristic values for the resistance and the actions.

3.7 *Limits for the applicability of piled rafts*

Outside the scope of the guideline are cases in which the applicability of piled rafts as foundation concept is limited. The application is limited in cases of stratified subsoil with large differences in the stiffness of the particular layers especially if a soft layer like organic soil or a filling is located immediately below the raft. Figure 7 represents such an example. The simplified piled raft consists of a circular raft and one pile. The load-settlement curve in Figure 7.a shows the bearing behaviour of the system in homogenous subsoil ($E_1/E_2 = 1$). The load carried by the raft increases with increasing total load and improves the bearing capacity of the overall system. In the second case shown in Figure 7.b the upper layer below the raft has only 1 % of the stiffness of layer two. In this case the failure of the piles leads to a bearing failure of the piled raft as overall system. In cases of layered subsoil with $E_1/E_2 \leq 1/10$ and in all cases with $\alpha_{pr} > 0.9$ the validity of the guideline ends and another kind of foundation like a piled foundation is recommended.

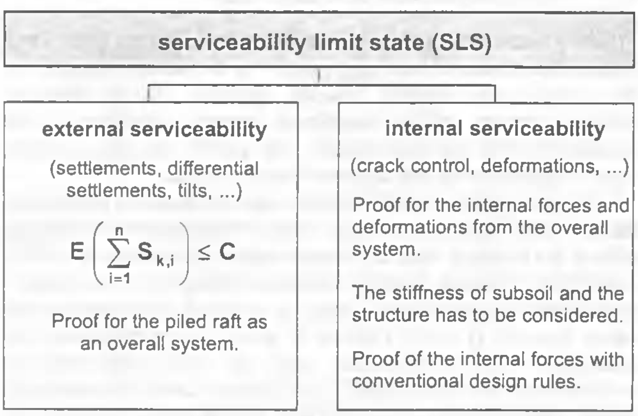

Figure 6. Proof of the serviceability limit state of piled rafts.

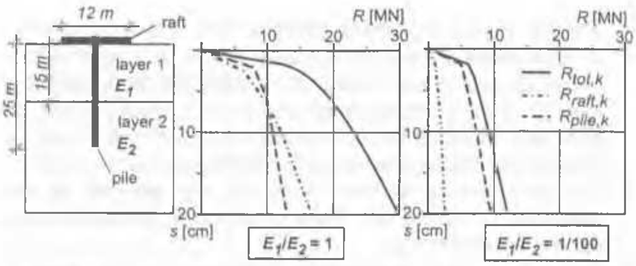

Figure 7. Bearing behaviour of a piled raft on layered subsoil.

3.8 *Further safety relevant requirements of the guideline*

Further important requirements of the German ´Piled-raft Guideline´ concern the following aspects:

- The design of a piled raft has to be supervised and checked by an independent expert in the field of soil mechanics and foundation design. The expert has to check the extent and the results of the soil investigation campaign, the suitability of the calculation method used for the design and the predictions for the influence of the new piled raft on adjacent buildings.
- A quality assurance concept on site is required to guarantee the integrity of the construction process for piles and raft. The foundation level for the raft has to be prepared with high diligence avoiding any loosening or softening of the soil.
- Part of the safety concept is the stringent application of the observational method (EC 7). The load-settlement behaviour of a piled raft should be monitored by geodetic and geotechnical measurement devices. The results have to be compared with the calculated values in time.

4 CONCLUSIONS

1. The bearing behaviour of a piled raft is substantially influenced by a complex soil-structure interaction. In consequence the load-settlement behaviour of a pile as part of a piled raft differs significantly from its known behaviour as a single standing pile.
2. An economic and safe design of piled raft foundations is only possible, if this soil-structure interaction is considered with adequate and reliable calculation methods.
3. In Germany a new ´Guideline for design, computation and construction of piled rafts´ was developed to give a consistent practical guideline and frame to all designers.
4. The German ´Piled-Raft Guideline´ may be an essential contribution for developing standardized recommendations for the design and construction of piled rafts at international level.

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