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Effects of actions due to group effect on the superstructure on pile groups

Les Actions à cause de l'effet de group sur la superstructure fondée sur une groupe de pieux

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ABSTRACT
An approach based on design charts for the effects of actions due to group effects on the superstructure on pile groups is presented. Therefor an extensive numerical paramtetric study was carried out. A description of the numerical model and comparisons with field load tests and theoretical results are presented. The proposed computer-independent approach is a simplified analytical approach for practical cases to predict the average settlement of a pile group and the different pile resistances including the consideration of non-linear pile behaviour. Finally, a design example is illustrated in order to demonstrate the applicability of this approach.

RÉSUMÉ
On a présenté une approche avec des abaques de dimensionnement pour tenir compte les actions à cause de l'effet de group sur la superstructure fondée sur une groupe de pieux. Pour cette raison une étude étendue, paramétrique et numérique a été effectuée. Une description du modèle numérique, la comparaison avec des essais sur le terrain et des résultats théoriques sont donnés. L'approche proposée représente une méthode analytique simplifiée sans besoin d'utiliser l'ordinateur pour prédire le tassement moyen de la group de pieux et aussi bien pour évaluer la résistance de chaque pieu concernant le comportement non linéaire de pieu. Finalement, un exemple de conception est présenté afin de démontrer l'applicabilité de cette approche.

1 INTRODUCTION

Pile foundations are one of the common used type of deep foundations. Thereby piles are used to reduce the settlements and displacements of the structure or to increase the bearing capacity.

So far it is German practice to design pile groups based on the German standard DIN 4014 for bored piles. In connection with the unification of design with the European standards (European Codes - EC) the general German standard for geotechnical design DIN 1054 has been recently developed based on the partial safty concept of the European Code EC 7. This new standard DIN 1054:10-2004 regulates et alii the design of piles.

The general new philosophy of design which includes new regulations and a different saftey concept may arise several questions for its application. The new design concept attaches more importance to the settlements of the piles, both to the total settlements and to the differences of settlements between piles. It is matter of common knowledge that caused by group effect the behaviour of group piles differ from the behaviour of single piles. In general, for the considered range of serviceability limit state the bearing capacity of group piles is less than for single piles. As a consequence of the different settlements in a pile group the superstructure can be effected.

The degree of interaction of the piles depends among others on the group geometry. Normally the interaction of piles is coupled with the ratio of the pile distance to the pile diameter D. An often declared limit value of the pile spacing is 8·D. The proposed investigations have also assessed a dependency of the limit value of the pile spacing to the pile length.

At present no satisfactory approach for the design of pile groups which considers the group effect and the nonlinear pile behaviour is available except pile software developed based on analytical analysis or the finite and boundary elements method.

Therefor, the aim of this paper is to develop a simple approach with the help of design charts for the design of pile groups which consider the group effect. With this approach the user should be able to design standard situations of pile foundations without using computer programs. The basis of this new approach is an extensive parametric study using the finite-elemets-method. It was carried out varying among others the pile group geometry, the soil parameters and the actions.

2 METHOD OF ANALYSIS

2.1 *Numerical Model*

The numerical investigation of pile groups are carried out using the finite elements program ABAQUS.

The requirements of the used models is to describe correctly the resistance-settlement-behaviour of the group. In other words, the model should reasonably predict the distribution of the pile resistances in the group and the base and shaft resistance-settlement-graphs of each pile separately.

In order to consider cohesive and noncohesive soils and to minimise the soil parameters required for this investigation the Mohr-Coulomb constitutive equation was elected.

The generated FE-models are three dimensional composed of brick and triangular prism solid elements. The piles are idealised as quadratic piles having the same shaft area as the assimiable round pile. The contact between pile and soil is modeled by direct contact without introducing contact or interface elements. Therby, shear failure occurs in the soil elements touching the pile shaft. Preliminary studies and the investigations by Holzhäuser (1998) prove the numerical applicability of this approach. A detailed description of the numerical models is given in Rudolf (2005).

2.2 *Comparison with field load tests and theoretical results*

The applicability of the finite models is verified by back analysis of several documented pile load tests (e.g. Fig. 1, Kempfert, 1982) and by comparison with numerical investigations of pile groups (e.g. Fig. 2, Hanisch et al., 2002).

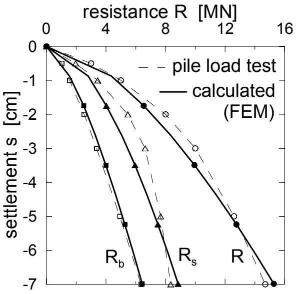

Figure 1. Calculated and measured resistance-settlement-graph of a pile test.

For all studied load tests of single piles the numerical calculations show a close agreement with the load test results. Comparing the results of the numerical computation with that of Hanisch et al. (2002) shows a very good agreement of the base resistances while the shaft resistances are a bit underestimated. This difference in the shaft resistance comes mainly from the different constitutive equations used in both computations. In genral, the used model is able to describe the behaviour of pile groups very applicable.

Moreover, in order to validate the model and the presented results, a parametric study is also performed by an analytical method, which is a modified form of the approach by Randolph /Wroth (1979). This analytical approach is not part of this paper and it is described in Rudolf (2005). In general, both methods shows a good agreement.

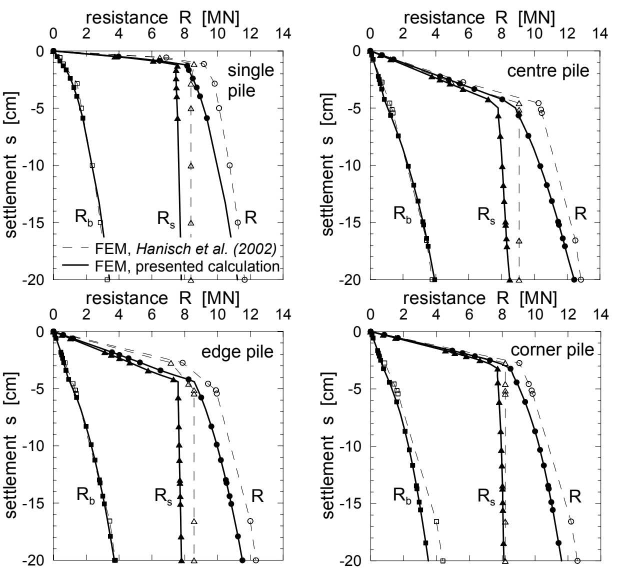

Figure 2. Comparison of computed resistance-settlement-graphs of group piles.

3 PARAMETRIC STUDY OF PILE GROUPS

3.1 *General*

The general idear of the presented approach is to define a standard pile group geometry, see Sec. 3.2. The considered geometrical parameters are:

- the pile length L or pile length in bearing soil d,
- the pile spacing a,
- the soil parameters.

For this standard geometry design charts for the group effect are developed based on the resistance-settlement-graph of a comparable single pile. Other influencing parameters considered by other design charts are:

- the pile diameter D,
- the stiffness of the pile cap EI,
- the dimension of pile group (n_G = n·n piles),
- the pile type.

The factor for the group effect $G_{R,i}$ considering the pile resistances is defined by the ratio of the resistance of a group pile $R_{G,i}$ to the resistance of a comparable single pile R_E with the same settlement. The value for the group effect factor results from the product of the values of all design charts (F_1 to F_5, see Sec. 3.3):

$$G_{R,i} = \frac{R_{G,i}}{R_E} = F_1 \cdot F_2 \cdot F_3 \cdot F_4 \cdot F_5 \qquad (1)$$

Because of the nonliner pile behaviour, the design charts are dependent on the settlement value. In accordance with DIN 4014, the state of settlement at 2%, 3% and 10% of the pile diameter are accounted. The first two values should consider the serviceability limit state, the third one the ultimate limit state.

Before the above discribed design charts can be applied, first the settlement must be predicted. For this propose design charts for the estimation of the settlement are developed as well.

3.2 *Standard pile group*

In general, square groups are analysed in this parametric study. Thereby, the standard pile group is defined as a quadratic pile group with 25 piles, the pile diameter constitutes D = 0,90 m. The pile length is variied between 9 and 24 m, pile spacing is assumed to vary between 3 to 9·D.

In this paper the stiffness of the pile cap was assumed to be absolutly rigid.

To include a representative spectrum of underground conditions, several soil parameter sets are compiled. It turned out that the oedometric modulus is the controlling parameter. In general, nine values of the oedometric modulus varying from 3 to 70 MN/m² are defined and corresponding soil parameters are elected representing normal consolidated and overconsolidated cohesive soils as well as non cohesive soils.

In all cases the bearing soil is overlaid by a non bearing layer of soft soil with a thickness of 3 m. In this paper only vertically loaded pile groups of bored piles are examined.

For the defined boundary conditions calculations are carried out using different combinations of the parameters. The aim is to find a simple way to illustrate the results in the charts. First of all the piles are divided in positions with comparable pile behaviour. They are classified as corner, edge and centre piles.

In the design charts the ordinate values are defined as the ratio of the resistance of a group pile to the resistance of a comparable single pile with the same settlement. On the abscissa the ratio of the pile spacing to the pile length embebbed in the bearing soil is illustrated. Using this axis-definitions the calculation data results in a continious set of curves, see Fig. 3.

3.3 *Distribution of the pile resistances*

Fig. 3 correspond to the design charts of the factor F_1 of Eq. 1 for the standard group. In the following sections, the other factors in Eq. 1 will be discussed.

The pile diameter is varied between 0,4 to 1,50 m. In the past the pile diameter was taken as one of the most controlling parameter for the interaction of group piles. However, the study demonstrates that the pile diameter has no influence on the developed design charts. Fig. 4 illustrates the different calculation results of varying pile diameters. The results are significantly concentrated at points, showing that the influence of the pile diameter is negligible.

But at all it should be mentioned that the influence of the pile diameter is only inconsiderable for the characteristics of the relativated design charts. Despite of the corresponding design charts for different pile diameters the absolute values of the group effect differ with the pile diameter.

Examplarily corresponding design charts of the factor F_1 for pile diameters from 0,4 to 1,50 m are pictured in Fig. 3.

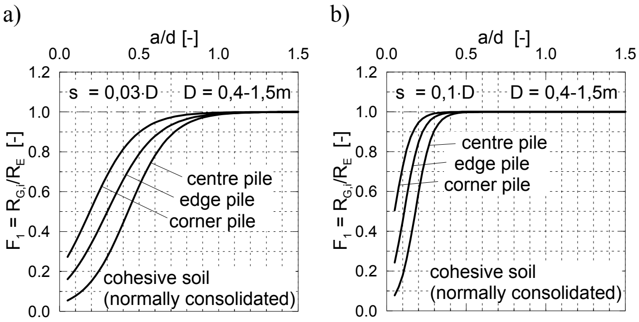

Figure 3. Design charts for the factor F_1 (standard group) with a settlement of a) s= 0,03·D and b) s= 0,1·D.

It was expected that the group dimension has an significant influence on the group effect, but the results show that the influence on the corner and edge piles appear to be marginal. Only the centre piles are affected essential by the group dimension. Pile groups with a lower number of piles than the standard pile group have a lower group effect, i.e. the resitance of the centre piles are higher than that of the standard group. An example of the design charts of the factor F_2, which express the influence of the group dimension is given in Fig. 5.

The factor F_3 considering the pile diameter and the factor F_4 considering the cap stiffness are set to 1,0.

More parameters are conceivable affecting the group effect, e.g. the pile type see Eq. 1 factor F_5. But in this paper other parameters are not discussed.

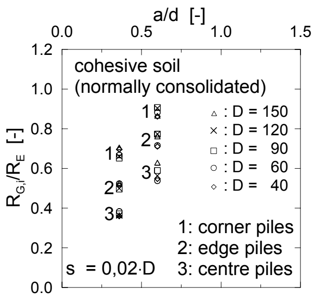

Figure 4. Independency of the design charts from the pile diameter.

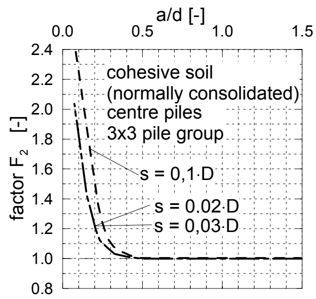

Figure 5. Design charts for the influence of the group dimension.

3.4 *Settlement prediction*

The design charts desribed in the privious sections can only be used, if the avarage settlement of the pile group is known. For this reason design charts for the prediction of the settlement of the pile group are developed.

Similar to Eq. 1 the finally value for the group effect factor G_s considering the settlement is defined as the ratio of the avarage settlement of the pile group s_G to the settlement of a single pile s_E with the same resistance. The value for the group effect factor results from the product of the factors S_1 and S_2:

$$G_s = \frac{s_G}{s_E} = S_1 \cdot S_2 \tag{2}$$

In Fig. 6a the factor S_1 for the increasing of the group settlement with the ratio a/d is illustrated for the standard group. The abscissa value is the resistant of a group pile relaited to the ultimate bearing resistance of a comparible single pile. Fig. 6b shows the influence of the pile dimension on the pile group effect of the settlement expressed as the factor S_2.

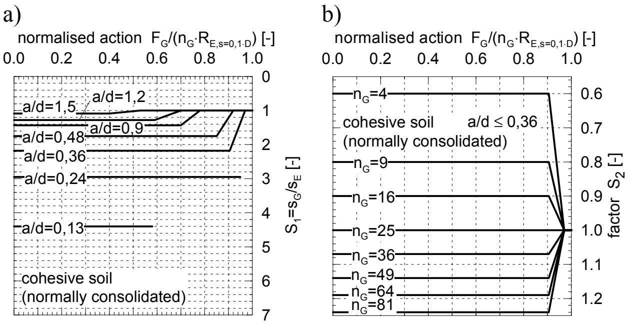

Figure 6. Design charts for the prediction of settlement a) the factor S_1 (standard group) and b) the factor S_2 considering the group dimension.

4 PILE FOUNDATION OF A PIER

4.1.1 *Application of the design charts*

To illustrate the application of the design charts, the design of a pile-foundation of a pier is selected as discussed below.

The geometry of the construction, the soil parameters and the resistance-settlement-graph of a considerable single pile from a pile load test are given in Fig. 7.

First the average settlement of the foundation must be estimated using Fig. 6. The input parameter a/d ratio and the normalised total action can be calculated as follows:

$$a/d = 5{,}2/14{,}5 = 0{,}359 \tag{3}$$

$$F_G/(n_G \cdot R_{E,s=0,1\cdot D}) = 14/(9 \cdot 2{,}56) = 0{,}61 \tag{4}$$

From Fig. 6a the first settlement factor is found to be $S_1 = 2{,}2$. The second settlement factor $S_2 = 0{,}8$ can be obtained from Fig. 6b. With the average pile action $F_G/n_G = 14$ MN/9 = 1,56 MN the settlement of the comparable single pile in Fig. 7 is $s_E = 2{,}1$ cm. Hence the average settlement of the group is estimated to be:

$$s_G = s_E \cdot S_1 \cdot S_2 = 2{,}1 \cdot 2{,}2 \cdot 0{,}8 = 3{,}7\,cm \tag{5}$$

The normalised group settlement is:

$$s_G/D = 3{,}7/130 = 0{,}028 \approx 0{,}03 \tag{6}$$

This value is close to 0.03, so the design chart in Fig. 3a can be used to predict the pile resistances. With the input parameter a/d = 0,359 the values of the factor F_1 from this chart are F_1 =0,76 (corner pile), F_1 = 0,59 (edge pile) and F_1 = 0,35 (centre pile).

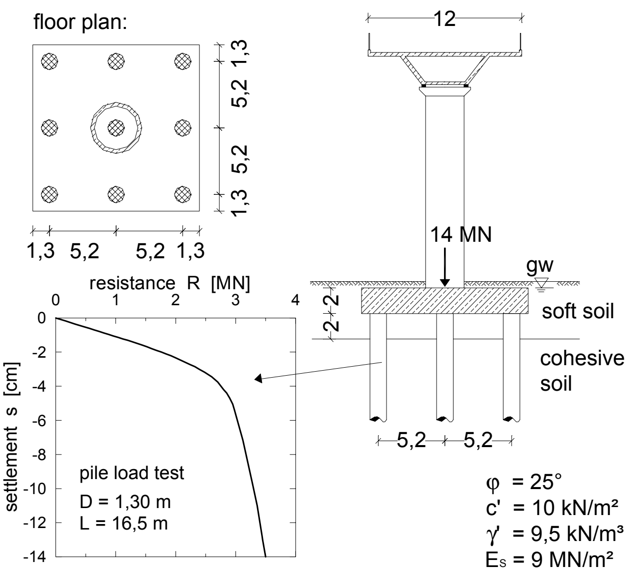

Figure 7. Layout of the pile-foundation of a pier and resistance-settlement-graph of a pile load test.

From Fig. 3b the second factor F_2 for the centre piles is $F_2 = 1.02$, for the corner and edge pile this factor is 1,0. As already mentioned above the factors F_3 and F_4 from Eq. 1 are set to 1,0. The value of factor F_5 is also 1.0, because the given bored pile group belong to the standard group.

Hence, the predicted pile resistences are:

$$R_{corner}(s = 0{,}028 \cdot D) = 2{,}56 \cdot 0{,}76 = \quad 1{,}95 \text{ MN} \tag{7}$$

$$R_{edge}(s = 0{,}028 \cdot D) = 2{,}56 \cdot 0{,}59 = \quad 1{,}51 \text{ MN} \tag{8}$$

$$R_{centre}(s = 0{,}028 \cdot D) = 2{,}56 \cdot 0{,}35 \cdot 1{,}02 = 0{,}91 \text{ MN} \tag{9}$$

At a settlement of s = 0,028·D the predicted total resistance of the group is:

$$R_G(s = 0{,}028 \cdot D) = 4 \cdot 1{,}95 + 4 \cdot 1{,}51 + 0{,}91 = 14{,}75 \text{ MN} \tag{10}$$

This value is of little account superior then the value of the total force of $F_G = 14{,}0$ MN, because the design charts for a settlement of s = 0,03·D are used, whereas the predicted settlement s = 0,028·D is maginally lower.

4.1.2 *Limit state design*

The design of the given pile foundation have to satisfy both the serviceability limit state and the ultimate limit state design criteria. Assuming that the allowable settlement of the pile group is taken as $s_2 = 0{,}03 \cdot D$, the above calculated value of the total group resistance can be taken to demonstrate that the pile foundation will support the serviceability limit state design criterion:

$$E_{2,d} = E_{1,k} \leq R_{2,d} = R_{2,k} \quad \rightarrow \quad 14{,}0 \text{ MN} \leq 14{,}75 \text{ MN} \tag{11}$$

For the ultimate limit state design, the total resistance should to be calculated using Eqs. (6) to (10) for a settleement of $s_1 = 0{,}1 \cdot D$. Hence, the values of the pile resistances are:

$$R_{corner}(s = 0{,}1 \cdot D) = 3{,}45 \cdot 1{,}0 = \quad 3{,}45 \text{ MN} \tag{12}$$

$$R_{edge}(s = 0{,}1 \cdot D) = 3{,}45 \cdot 0{,}99 = \quad 3{,}42 \text{ MN} \tag{13}$$

$$R_{centre}(s = 0{,}1 \cdot D) = 3{,}45 \cdot 0{,}97 \cdot 1{,}02 = \quad 3{,}41 \text{ MN} \tag{14}$$

Thus, the total resistance of the group at ultimate limit state is:

$$R_G(s = 0{,}1 \cdot D) = 4 \cdot 3{,}45 + 4 \cdot 3{,}42 + 3{,}41 = 30{,}89 \text{ MN} \tag{15}$$

To ensure safety against failure at ultimate limit state design the following criterion have to be demonstrated:

$$E_{1,d} = E_{G,k} \cdot \gamma_G + E_{Q,k} \cdot \gamma_Q \leq R_{1,d} = R_{1,k} / \gamma_{Pc} \tag{16}$$

Thereby the characteristic values of the effects of actions and resistances are converted to design values by safety factors of DIN 1054:

$$10 \cdot 1{,}35 + 4 \cdot 1{,}50 = 19{,}5 \text{ MN} \leq 30{,}89/1{,}20 = 25{,}74 \text{ MN} \tag{17}$$

Therefore the safety of the foundation for serviceability as well as ultimate limit state is verified.

5 EFFECTS OF ACTIONS DUE TO GROUP EFFECT ON THE SUPERSTRUCTURE

In the previous section the pile resistances and the avarage settlement of the pile group is calculated. From this values it is possible to derive springs with a stiffness for the relevant section of the resistance-settlement-graph to determine section forces. In this case the piles are replaced by springs.

The value of the spring-stiffnesses taking the group effect at a settlement of s = 0,028·D = 0,0364 m into account are:

$$R_{corner}/s = 1{,}95/0{,}0364 = 53{,}6 \text{ MN/m} \tag{18}$$

$$R_{edge}/s = 1{,}51/0{,}0364 = \quad 41{,}5 \text{ MN/m} \tag{19}$$

$$R_{centre}/s = 0{,}91/0{,}0364 = 25{,}0 \text{ MN/m} \tag{20}$$

Without the group effect and a given settlement of s = 0,021 m all piles are represented by a spring of

$$R_{single}/s = 1{,}56/0{,}021 = \quad 74{,}3 \text{ MN/m} \tag{21}$$

To assess the influence of the group effect on the loadings of the pile group, the bending moments M_{xy} in the pile cap are pictured in Fig. 8 for the case of calculations with and without the group effect. In the presented example the effects of actions are not significantly affected due to the group effect. But this observation is not generally admitted for other cases. However, it is obvious that the settlement clearly increases due to the group effect.

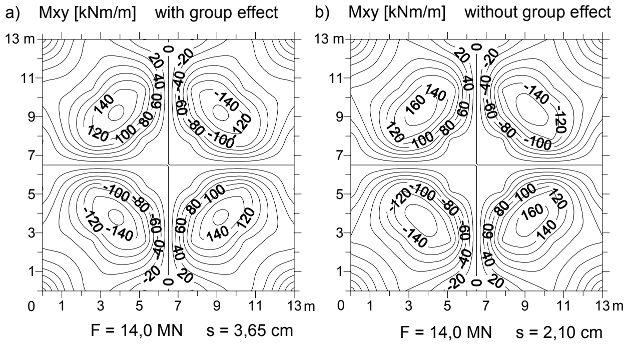

Figure 8. Moments M_{xy} in the pile cap a) with and b) without considering the group effect.

6 CONCLUSIONS

A parametric study was performed using the FE-method to study the group effect of pile groups. The results are used to derive a simple approach for the design of pile groups considering the group effect without using computer programs.

An example is also given for the application of the proposed approach. In the example, it was possible to show the procedures of calculating the average group settlement, the pile resistances and how to design the pile group. In a further step static calculations are carried out replacing the piles with springs to investigate the influence of the group effect on the effects of actions to the pile cap.

Generally, it can be concluded that the presented approach is an adequate method of designing standard situations of pile groups. This paper presents only extracts from Rudolf (2005). Further investigations has been carried out for vertical loaded pile groups subjected to bending moments. The presented approach should also be extended for driven piles and non quadratic pile groups.

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