Special aspects related to the behavior of piled raft foundation

Aspects particulaires concernant le comportement du radier empilés

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ABSTRACT

The quick growth of main cities in the last two decades all over the world led to a rapid increase in the number and height of high rise buildings even in unfavourable subground conditions. Since the 80's, a new foundation technique, the so-called piled rafts, has been developed and used extensively in order to reduce the maximum as well as the differential settlements and the associated tilting of the buildings. The analysis of piled raft is a very interesting example of the soil-structure interaction that requires the co-operation between the geotechnical and structural engineers to reach the most economic foundation system. Some aspects of behavior of piled rafts will be discussed.

RÉSUMÉ

La croissance rapide des grandes villes pendant les deux dernières décades dans le monde entier a conduit à une augmentation rapide du nombre et de la hauteur « des immeubles de grandes hauteurs », même dans des conditions souterraines défavorables. Depuis les années 80, une nouvelle technique de fondation, radiers empilés, a été développée et largement utilisé au but de réduire les tassements maximaux et différentiels et l'inclinaison de ces bâtiments. L'analyse de ces radiers est un exemple très intéressant de l'interaction sol-structure, qui nécessite une coopération entre les ingénieurs géotechniques et structuraux pour atteindre le système de fondation le plus économique. Certains aspects du comportement des radiers empilés seront discutés

Keywords : High rise building, conventional raft foundation, piled foundation, piled raft, soil-structure interaction, numerical analyses, constitutive laws.

1 INTRODUCTION

The foundation of high rise buildings on compressible subground presents a challenge for both geotechnical and structural engineers. Despite that the cost of the foundation of a high rise building is only a small fraction of the total cost (less than 10 to 15%), the foundation is one of the main design elements, which affects the whole behaviour of the building. On the other hand, the construction time of the foundation and basement floors takes about 30 to 50 % of the total construction time. These conditions make the foundation of high rise building one of the most critical construction items regarding the risk assessment analyses and optimization of construction schedule. Therefore, investigating the subsoil conditions and determining the related design parameters play an important role to achieve the most effective and economic foundation design of complex high rise buildings.

2 CONCEPT OF PILED RAFT

The piled raft is a composite geotechnical foundation system consisting of piles, raft and soil. Figure 1 demonstrates the principles of piled raft foundation and the different interactions (e.g. pile/pile and pile/raft) that govern its behavior. In the conventional design of pile foundations, it is assumed that the total applied load has to be carried only by the piles with a certain factor of safety against bearing failure. Considering the contribution of the raft, this can lead to a more economic foundation in comparison with a pure pile foundation. The piles can be designed in such cases to carry loads close to their ultimate capacity (Burland et al. 1977, Hanisch et al. 2002). The main criterion that governs the design of piled rafts concerns the relative proportion of load carried by raft and piles "α_L" and the effect of the additional pile support on foundation settlements "α_s" (Fig. 1).

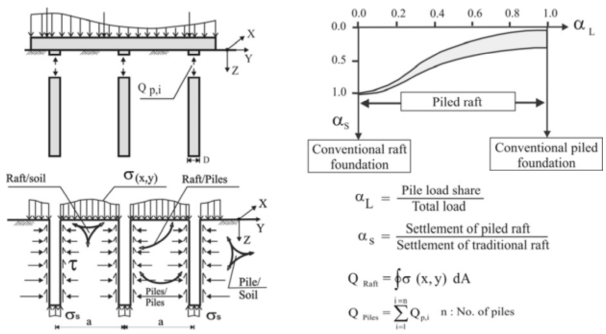

Fig. 1: Principles of piled raft.

3 LOAD SETTLEMNT BEHAVOR OF PILED RAFT

The need for more office space in the centers of large towns (e.g. Frankfurt) leads to an increase in the demand for high rise buildings due to the lack of available building sites. Frankfurt is, however at a disadvantage due to its overconsolidated highly plastic clay subsoil (Breth 1970) resulting in relatively large settlements. The piled raft foundation was then developed and extensively applied to achieve economic solutions that fulfill the stability as well as the serviceability requirements. Figure 2 shows the succsess of piled raft to reduce the settlement compared with traditional raft foundation.

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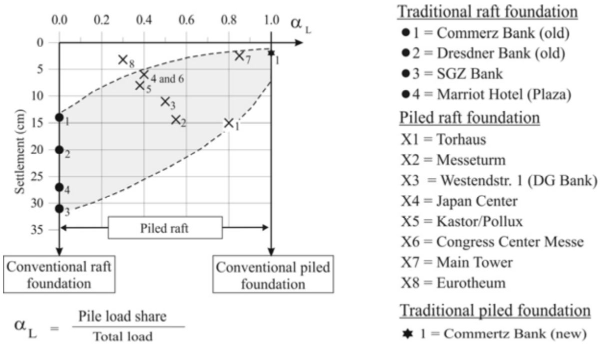

Fig. 2: Settlement behavior of high rise buildings in Frankfurt, Germany.

The Messeturm (Sommer and Hoffmann 1991, Fig. 3) is a good example of piled rafts. Only 64 piles with pile length of 29 to 35 m and a pile diameter of 1.3 m were enough to reduce the settlement to 14.4 cm and the tilting to 1:2400. One of the very interesting features of the behavior of piled raft is the development of skin friction along pile shafts (Fig. 3 e). Skin friction increases with load from tip to top in contrast to single piles. Near the underside of the raft the soil is forced to settle by rather the same amount as the piles do and no skin friction can develop just beneath the raft.

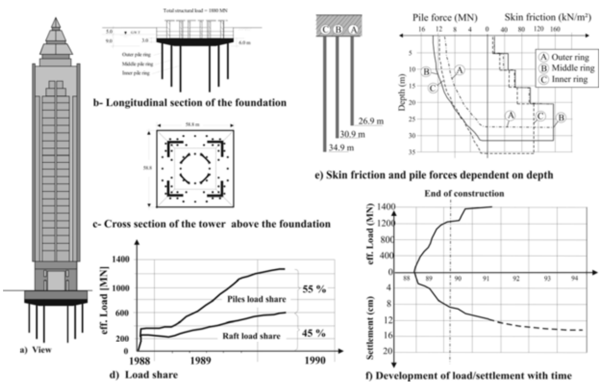

Fig. 3: Behaviour of piled raft foundation of Messeturm High rise building.

In the same time, the raft/soil contact pressures are causing an increase of the soil stress level round the piles like a corresponding overburden layer. Therefore the load settlement behaviour and the ultimate limit state of piled raft piles are changed compared with a single pile and pile group. Fig. 4 shows calculated load settlement relationships of the same pile under different cases of boundary conditions. The measured loads of the piled raft piles lay between 10 to 18 MN. Comparing this behavior with that of single pile (case (1) in figure 4), this load level is not attainable at all by the single pile. But at the same time the modulus of pile reaction, i.e. the load/settlement ratio, decreases in case (2) and even more in case (3) in comparison with case (1). Therefore, the interaction of the pile group piles of case (2) as well as the pile/pile and the pile/raft interactions of case (3) decrease the modulus of pile reaction on the one hand, but on the other hand they increase the pile bearing capacity. These effects depend on the load level, on the raft and pile group dimensions and on the pile location within the pile group.

The increase of the ultimate capacity of an individual pile in a pile group under drained conditions (effective stresses) is due to the increase of the horizontal stresses due to the confinement by the neighboring piles. The increase in its settlement is due to the integration of the deformations of other piles, i.e. group action. These two effects were

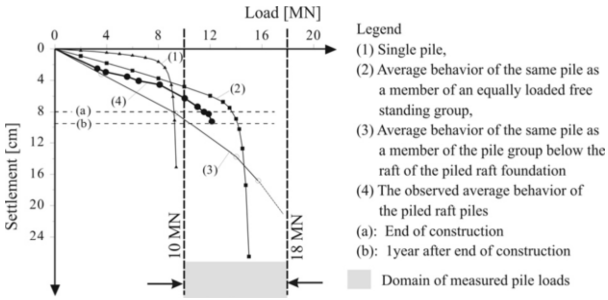

Fig. 4: Load settlement behavior of single pile, pile groups and piled raft (DG-Bank Frankfurt, El-Mossallamy xxx).

discussed in different literature (O´Neill 1983). The raft/soil contact pressures increase strongly the above mentioned two effects. Thus, the piled raft piles exhibit a larger ultimate capacity and a larger settlement than does the single pile and even the individual piles of a pile group. This effect depends also on the pile spacing within the pile group. By very small pile spacing (less than 3 pile diameter), the block behavior may govern the bearing capacity of the whole piles. This is an extra argument for the application of piled raft with fewer piles to avoid the block behavior so that the bearing capacity of the individual piles can be better mobilized.

4 DESIGN CONCEPT OF PILED RAFT

Figure 5 shows schematically the proposed design sequence of piled raft foundations considering the required co-operation between both the geotechnical and the structural engineers. The pile/soil stiffness and the subgrade reaction distribution beneath the raft were found to be a very convenient interface between the geotechnical and the structural engineers.

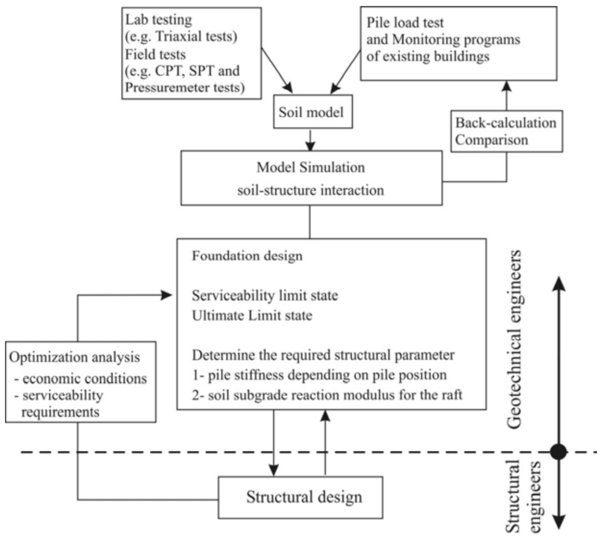

Fig. 5: Flow chart for the design of piled raft

A realistic numerical model is a central part of the design of the piled raft foundation. The numerical model includes the applied numerical method and the constitutive laws to model the soil stress-strain behaviour. According to the gathered experience, the three dimensional nature of the complex piled raft plays a very important role and should be considered by the applied numerical model to obtain realistic results which can be used for the design of the structural elements. The nonlinear behaviour at pile shaft and pile base should be modelled in a realistic manner.

Different numerical procedures in conjunction with different constitutive laws are applied to analyse the behaviour of single piles, pile groups and piled raft foundations. Special diligence may be necessary to determine realistic design parameters of subground needed for the applied constitutive law or for helpful simplifications.

5 SIMPLE DESIGN METHOD

Simple design methods are always applied in the feasibility studies of most geotechnical projects to help the planer to find the most economic solution that fulfils the specific project conditions. The number and length of piles, the pile load share, the total bearing capacity of the piled raft and its settlement are the main design criteria that should be investigated during a feasibility study to check the validity of a piled raft. Therefore, a simple method that can help to give a quick answer on these design criteria is highly recommended from the practical point of view.

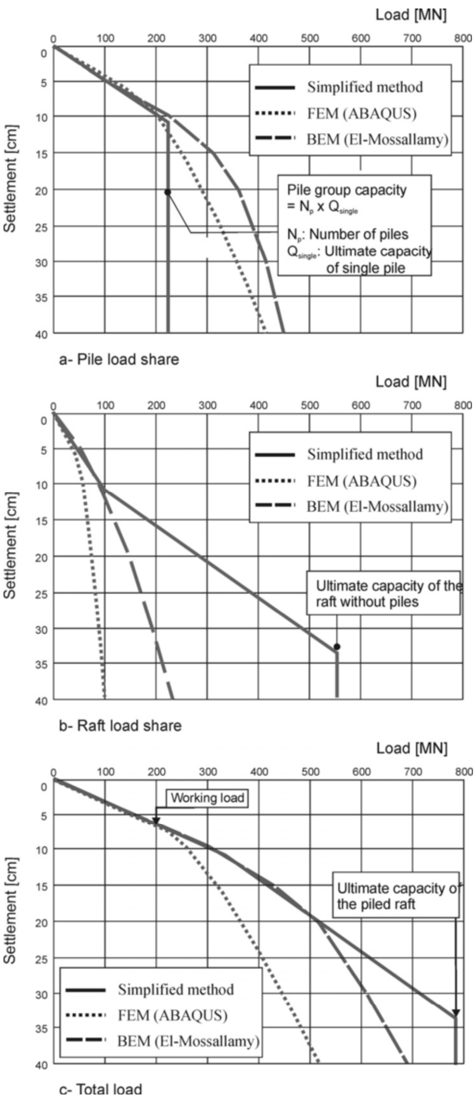

Fig. 6: Load-settlement relationship of the piled raft

Several assumptions regarding the stress-strain behaviour of the piles, the subsoil and the superstructure should be made to create such a simple design method. The piles and the superstructure are assumed to be rigid. The soil as well as the pile-soil response under working conditions is assumed linearly elastic. Considering these assumptions, a simple method based on the work of Randolph (1983) and Randolph/ Clancy (1993) was developed by Lutz 2002 (El-Mossallamy et. al. 2009) and Lutz et. al. 2006 based on the work of Poulos (1980) and Randolph (1983). Hanisch et al. 2002 have studied the load settlement relationship of a piled raft with 25 piles applying a three dimensional finite element analyses (Program ABAQUS). This example was further calculated using the boundary element method applying program GAPR (El-Mossallamy 1996) and the above-mentioned simplified method (Lutz 2002).

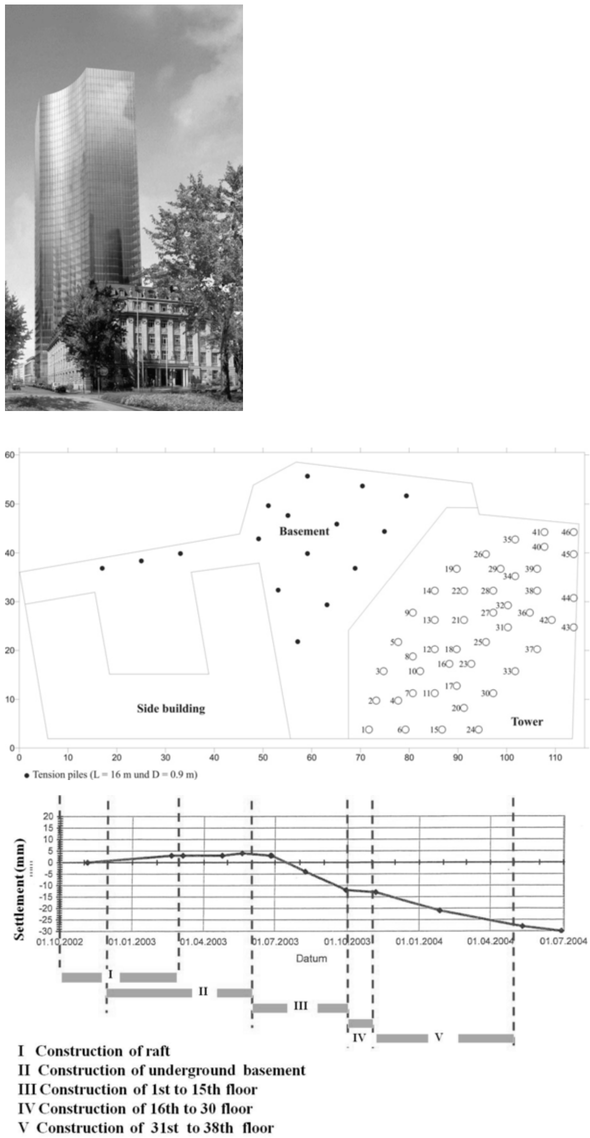

Fig. 7: High rise building "Skyper", Frankfurt, Germany

For the high rise building "Skyper", located in Frankfurt (see Fig. 7) the german DIN committee for piled rafts and pile groups made a study comparing several calculation methods during the building was constructed. In this study the BEM (El-Mossallamy 1996) and FE-Method (Katzenbach 2006) as well as various simplified methods were applied. All calculations resulted in a predicted settlement of 5 up to 7 cm for the tower, while the pile load share α_L was computed in a range of 0.6 to 0.85. The observed settlement was (until now) 5.5 cm.

It was found that the different values of α_L do not affect the needed reinforcement very much, so that the use of simplified methods are useful connected with increased factors of safety or comparable approaches.

6 THE ULTIMATE CAPACITY OF PILED RAFT

The pile/raft load share and the settlement of piled raft can be determined as mentioned above to check the serviceability limit state of the foundation. Another design criterion is the ultimate limit state. The problem of bearing capacity of a piled raft is rather complicated and there is no unique mechanism that governs the failure of such complex combined system of piles, soil and raft (Fig. 8). Even numerical studies with sophisticated constitutive laws did not lead to trustworthy results. Although this design criterion seems somewhat exaggerated because in most cases of piled rafts the serviceability limit state of the superstructure should be decisive (Franke et al. 2000), a rational simplified method to estimate the bearing capacity of piled raft should be helpful to fulfil the design requirements.

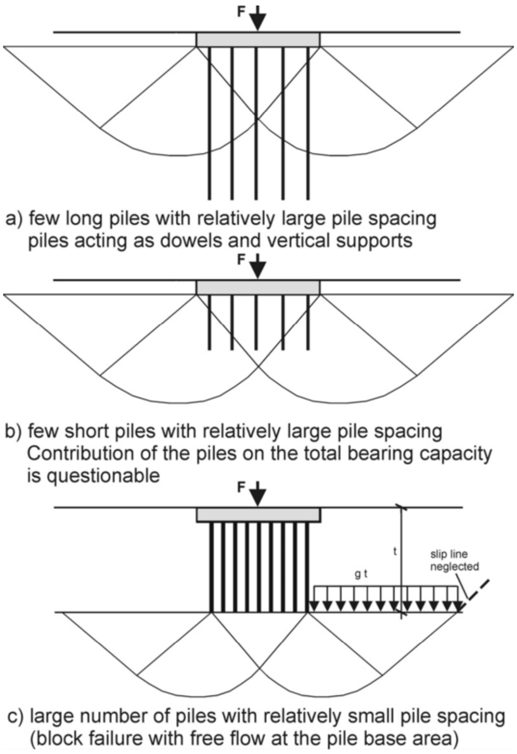

Fig. 8: Different possible failure mechanisms for piled rafts.

7 CONCLUSIONS AND RECOMMENDATIONS

The geotechnical engineer's objective is to guarantee stability of foundations and to ensure the serviceability requirements of the building taking the profitability of project implementation into consideration. The piled raft foundation is an excellent example to show the interactive process between the observational method, the numerical analyses and the development of new geotechnical systems to achieve an economic solution that fulfils all stability and serviceability requirements. The piled raft foundation provides a skillful geotechnical concept for the design of foundations not only for high rise buildings but also for residential buildings and bridges which allows an outstanding level of both technical and economical optimization of the construction. The fact, nearly any kind of eccentric construction can be safely founded on soft to stiff clay as well as on medium to dense sand and even on highly weathered rock formations by appropriate distribution of piles, staggering the pile length and suitable pile diameters means almost unlimited possibilities for the construction of foundations.

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