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New Exhibition Hall 3 in Frankfurt – Case History of a Combined Pile-Raft Foundation Subjected to Horizontal Load

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NEW EXHIBITION HALL 3 IN FRANKFURT – CASE HISTORY OF A COMBINED PILE-RAFT FOUNDATION SUBJECTED TO HORIZONTAL LOAD

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ABSTRACT

Concerning the load bearing behaviour of vertical loaded Combined Pile-Raft Foundations (CPRFs) many studies and publications are available whereas for CPRFs subjected to horizontal or inclined loads scientific results or case histories are very rare. But also for horizontal loading it is possible to obtain a very economic foundation design and to reduce the movements by using a CPRF. Following a theoretical illustration of the load bearing behaviour of a CPRF subjected to horizontal loads the paper is focused on the new exhibition hall 3 in Frankfurt am Main. With a length of 210 m, a width of 130 m and a height of 45 m it is one of the biggest exhibition halls in Europe. The high horizontal loads resulting from the arch thrust of the roof with a free span of 165 m are transferred to the subsoil by two CPRFs. The structure of the hall, the design concept of the foundation, the subsoil conditions and some aspects of construction are described. During the construction process of the hall and afterwards the foundation was observed with an extensive geotechnical measurement program. The measurement program and the results of the measurements are described and valuated.

INTRODUCTION

Compared to traditional pile foundations where building loads are assumed to be transferred to the soil only by piles, the Combined Pile-Raft Foundation (CPRF) is a rather new approach. A CPRF is consisting of the three bearing elements piles, raft and subsoil. The load share between piles and raft is taken into consideration and the piles can be used up to a load level equal or greater than the bearing capacity of a comparable single pile. This design concept can lead to a considerable cost reduction for foundations of more than 50 % compared to the traditional pile foundations. Concerning the load bearing behaviour of vertical loaded CPRFs many studies and publications are available (e.g. Poulos, 2001) whereas for CPRFs subjected to horizontal or inclined loads scientific results or case histories are very rare (Kulhawy & Prakoso, 1997). But also for horizontal loading it is possible to obtain a very economic foundation design and to reduce the movements by using a CPRF. Comparable to vertical loaded CPRFs, where piles are used to reduce settlements and differential settlements in order to guarantee the serviceability of the construction, horizontal loads are transferred to the piles and a reduction of horizontal displacements occurs. Especially for buildings which are very sensitive concerning horizontal displacements, stability and serviceability could be insured by using a CPRF.

BEARING BEHAVIOUR OF HORIZONTAL/INCLINED LOADED CPRFs

The total vertical resistance of a CPRF R_{tot}, which is depending on the settlement s, is given by the sum of the vertical raft resistance R_{raft} and the sum of the vertical pile resistances $\Sigma R_{pile,i}$ (Katzenbach & Moormann, 2001).

$$R_{tot} = \sum R_{pile,i} + R_{raft} \tag{1}$$

The vertical pile resistance $R_{pile,,i}$ is derived by integration of skin friction $q_{s,j}$ and pressure at pile toe $q_{b,j}$, the vertical raft resistance R_{raft} by integration of the contact pressure σ_r (Fig. 1). The total horizontal resistance of a CPRF H_{tot} is given by

$$H_{tot} = \sum H_{pile,i} + H_{raft} \tag{2}$$

where H_{raft} is the horizontal shear resistance of the raft which is derived by integration of the shear stresses τ_r acting between raft and soil and $H_{pile,i}$ is the horizontal resistance of pile i. H_{raft} and $H_{pile,i}$ are depending on the horizontal displacement u.

The normal and shear stresses acting beneath the raft (σ_r and τ_r) and the pile toe ($q_{b,j}$ and $\tau_{b,j}$) are changing with coordinates of the horizontal plane x and y. In contrast to the vertical loaded CPRF, where the normal and shear stresses acting on the pile shaft ($\sigma_{s,j}$ and $q_{s,j}$) are only depending on the depth z, these stresses are changing for constant z along the circumference of the pile when applying horizontal loads to the CPRF.

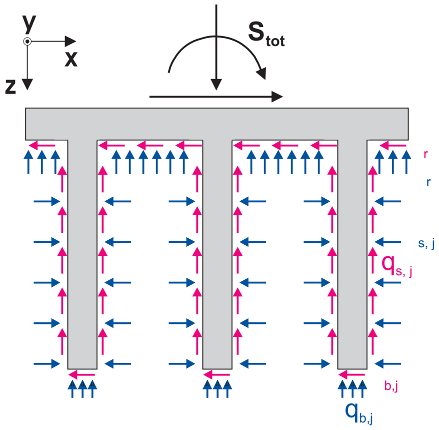

Fig. 1. Stresses acting between CPRF and subsoil

As reported by Kulhawy & Prakoso [1997] research activities concerning the bearing behaviour of horizontal/inclined loaded CPRFs are needed. Mokwa & Duncan [2001] and also Kim et al. [1979] have shown by conducting field tests, that a large portion of the horizontal load acting on a CPRF is transferred to the subsoil by the raft. Thus neglecting the horizontal resistance of the raft leads to an underestimation of the total resistance of the foundation and to an overestimation of the horizontal displacements and of the axial and shear forces of the piles.

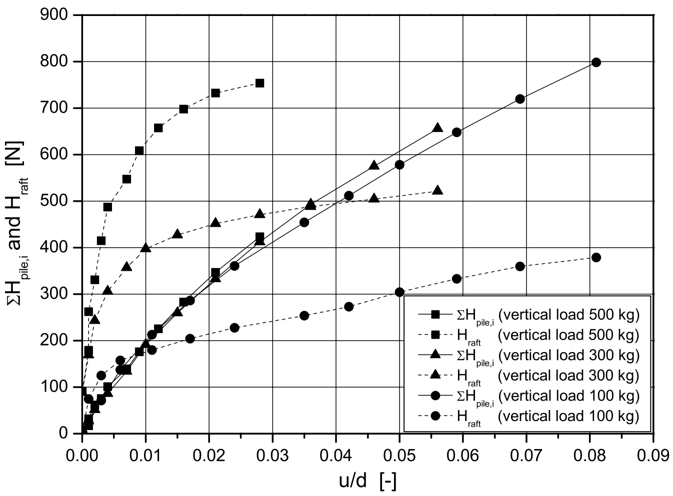

Fig. 2. Results from model tests with CPRF: Horizontal raft and pile resistance for vertical load of 100 kg, 300 kg and 500 kg (u = horizontal displacement, d = diameter of piles)

Due to the interaction between the load bearing elements of a CPRF a strong dependency between the horizontal and the vertical load displacement behaviour of a CPRF exists. The results of small scale model tests performed at Darmstadt University show that e.g. an increase of vertical load transferred by the CPRF leads to a strong increase of horizontal raft resistance H_{raft} and just a slight increase of horizontal pile resistance $\Sigma H_{pile,i}$ (Fig. 2). Increasing horizontal loading leads to increasing settlement and to a redistribution of vertical load from the piles to the raft. Quite similar results were obtained by Watanabe et al. [2001] by performing centrifuge model tests.

Fig. 3. New exhibition hall 3 in Frankfurt am Main

Up to now guidelines or recommendations for the design of CPRFs subjected to horizontal loads are not available and the existing scientific results are not sufficient for the creation of such guidelines. Thus a suitable tool, which includes the effects of interaction between the different load bearing elements has to be used for the design. The finite element method is an appropriate tool that meets this requirements and it was used to design the foundation of the new exhibition hall 3 in Frankfurt am Main (Fig. 3).

THE NEW EXHIBITION HALL 3

The new exhibition hall 3 was designed by the architects Nicholas Grimshaw & Partners, London (Fischer, 2002) and the construction was finished in 2001. With a length of 210 m, a width of 130 m and a height of 45 m the new exhibition hall is one of the biggest exhibition halls in Europe. The roof with a free span of 165 m was designed as a double curved three-dimensional load bearing structure consisting of 5 arched compression trusses and 6 arched tension trusses.

12 A-frames, 6 each at each side, serve as support for the roof (Fig. 4). These A-frames with a height of 24 m are constructed of two vertical steel tubes carrying vertical tension forces and two inclined steel tubes carrying compression forces. The vertical loads of the roof are transferred completely to the A-frames. The horizontal loads resulting from arch thrust of the compression trusses are split between the A-frames and the tension trusses depending on the stiffness of these load bearing elements. For the reason that the roof is very sensitive concerning movements of the A-frames an asymmetric CPRF was designed as foundation of the A-frames and both, vertical and horizontal loads are transferred to the subsoil by the CPRF. The roof was constructed in 5 segments, each segment includes one compression truss. During the construction

process these segments were supported by temporary support columns located in the interior of the hall. After a segment was finished it was connected to the A-frames, the temporary supports were removed and the loads were transferred to the A-frames and the foundation. Detailed information concerning the construction of the new exhibition hall 3 was published e.g. by Altner & Roth [2002] and Meese & Ziesler [2002].

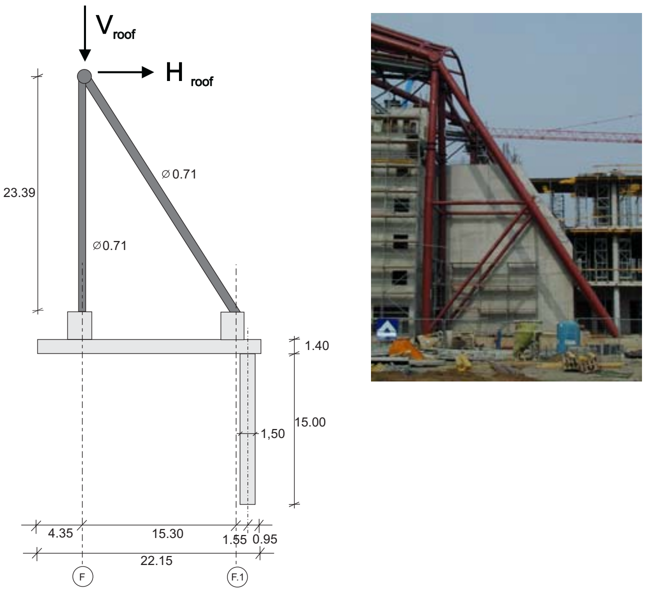

Fig. 4. A-frames – support of the roof

FOUNDATION OF NEW EXHIBITION HALL 3

Before the foundation of the new exhibition hall 3 was designed, the subsoil of the site was investigated and characterized as described in the following (Fig. 5). Beneath a layer of fill and loam with a thickness varying between 0.5 m and 4.0 m a layer of quaternary sand and gravel (thickness 1.5 m to 5.0 m) exists. These quaternary layer is followed by tertiary sediments. During soil investigation a graben (width up to 180 m, depth up to 16 m) lying at the surface of the tertiary sediments was discovered. This graben is filled with tertiary sand and gravel and it crosses the site in diagonal direction. Next to the graben and beneath the graben there is settlement active Frankfurt clay (Katzenbach et al., 1999).

Due to the strong interaction between settlements, differential settlements and horizontal displacements and the internal forces acting in the trusses of the roof and in the A-frames a strong limitation of the displacements of the foundation was necessary. Horizontal displacement or tilting of the A-frames to the inside of the hall leads to an increase of forces acting on the A-frames and decreasing internal forces of the tension trusses of the roof. In contrast displacement and tilting of the A-frames to the outside causes increasing tension forces in the tension trusses. After analyzing several proposals for the foundation design of the A-frames it was finally decided to design an asymmetric CPRF. The dimensions of the CPRF were determined based on the results of three-dimensional finite element calculations performed by Reul (see e.g. Reul, 2002). Beneath the outer edge of each of the two base slabs with a thickness of 1.4 m, a length of 127.5 m and a width of 22.15 m (Fig. 6 and Fig. 7) 14 bored piles with a diameter of 1.5 m and a length of 15.0 m are located (Fig. 4).

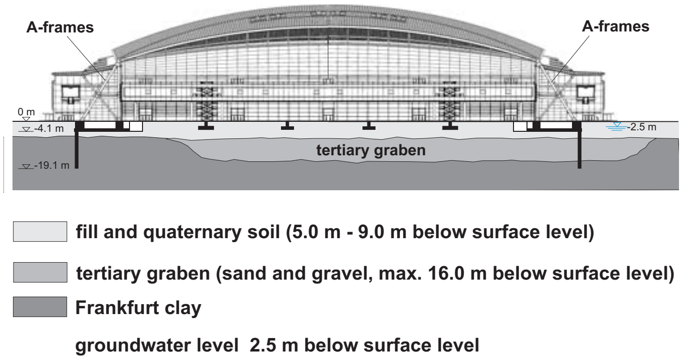

Fig. 5. Subsoil conditions

Concerning the design of the roof and the A-frames the limiting case of no foundation displacement was investigated. This limiting case led to an increase of construction steel mass of about 50 % compared to a case of foundation displacements within certain limits. Thus it was necessary to obtain a foundation design which allows displacements within these limits. The limit values were defined during final design of the roof. Based on the results of the three-dimensional finite element simulations horizontal displacements of the CPRF in a range of 0 – 3 cm were estimated. The settlements of the CPRF were estimated in a range of 1.5 – 3.5 cm.

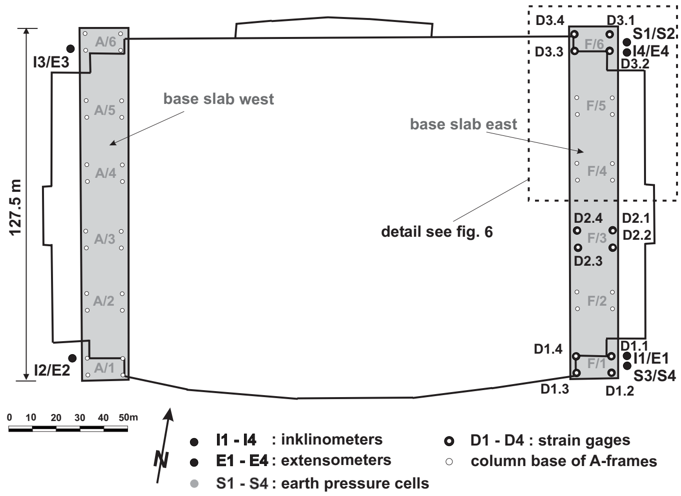

Fig. 6. Ground plan with measurement devices

Due to the aforementioned inhomogeneities of the subsoil the estimation of displacements of the foundation, which have strong influence on the internal forces of roof and A-frames, was only possible within a certain tolerance. Thus a design of the joints between the column base of the vertical tension trusses of the A-frames and the foundation was chosen that allows for a displacement correction in vertical direction with the help of hydraulic jacks. After the construction of the roof was finished and the increase of settlements and horizontal displacements due to consolidation was small, a correction of vertical displacements, as described before, was carried out. This displacement correction of about 2 – 3 cm led to a condition of internal forces similar to the design values. A displacement correction would not have been possible if the displacements would have exceeded the range defined during design.

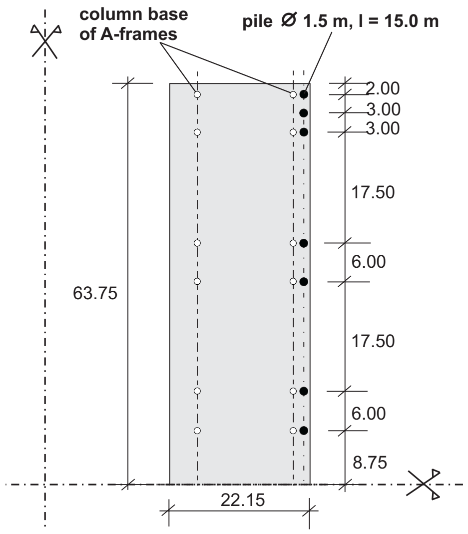

Fig. 7. Detail of ground plan of CPRF

GEOTECHNICAL AND GEODETICAL MEASUREMENTS

The observational method for large civil engineering projects like the new exhibition hall 3 is in the actual state of knowledge an important part of the safety concept. In terms of the Eurocode (EC) 7 CPRFs are classified as structures of the highest geotechnical category, i.e. the geotechnical category GC 3 and the foundation behavior has to be monitored. In particular for the new exhibition hall 3 with its horizontal loaded CPRF and strong limitations concerning foundation displacements, a consequent application of the observational method was indispensable. Therefore geotechnical measurement devices were installed and geodetic surveying has been carried out during construction stage and further on.

The horizontal displacements of the foundation and the subsoil were observed with 4 inclinometers reaching 50 m below surface level, which means about 30 m below the pile toes. The inclinometers are located at the corners of the building (I1 – I4 in Fig. 6). In combination with these inclinometers 4-fold rod extensometers with anchoring points 10 m, 20 m, 35 m and 50 m below surface level were installed (E1 – E4 in Fig. 6). The displacements of the foundation were also observed by geodetic measurements. The change of stresses in the subsoil due to the construction of the hall was monitored with bore hole cells. These bore hole cells are located in a boring at the northeastern corner of the building and a boring at the southeastern corner. In both borings three bore hole cells were installed in a depth of 5 m and three in a depth of 10 m (S1 – S4 in Fig.6). The hydraulic cells were installed vertical in order to observe the changes in horizontal stresses. The internal forces of the A-frames were observed with strain gages applied on the steel trusses of three A-frames located on the eastern foundation (D1.1 – D3.4 in Fig. 6).

Before the roof was set on the A-frames small horizontal displacements, up to 3 mm, in the direction of the interior of the hall were observed with the inclinometers. After the roof was set on the A-frames horizontal displacements of about 7 mm in the opposite direction occurred (Fig. 8).

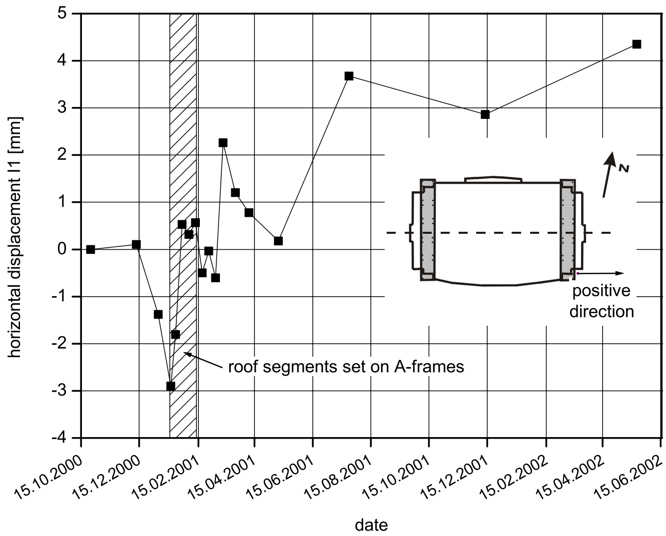

Fig. 8. Horizontal displacement of inclinometer I1 in a depth of 1 m below surface level

The settlements measured with the extensometers are shown in Fig. 9. The maximum value was measured with extensometer E2 located in the southwestern corner of the building. About 70 % of the total settlement occurred in the upper 20 m of the subsoil. The settlements measured between 30 m and 50 m of depth are negligible. The differences of settlements between the 4 extensometers E1 – E4 are caused by the inhomogeneities of the subsoil due to the tertiary graben.

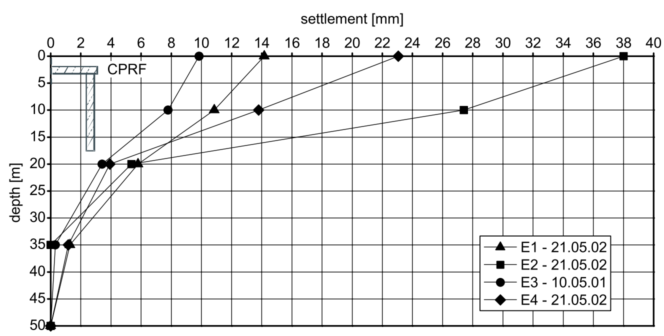

Fig. 9. Settlements measured with extensometers

The results obtained from the measurement of stresses with the bore hole cells S1 – S4 show an increase of the horizontal stress level in the subsoil due to the construction of the hall of about 20 – 50 kN/m². The increase of the internal forces of the trusses of the A-frames due to the connection of the roof segments with the A-frames was calculated from the measurements of the strain gages D1.1 – D3.4. These measurement results are in good agreement with the internal forces calculated during design.

SUMMARY AND CONCLUSIONS

The strong co-operation between structural and geotechnical engineers during the development of the foundation of the new exhibition hall 3 in Frankfurt, which is subjected to high horizontal loads, led to an innovative design of a Combined Pile-Raft Foundation (CPRF). The foundation and the steel structure were observed by geodetic and geotechnical measurements in terms of the observational method. The differences between displacements observed during construction and the estimations used for design are small and it was possible to minimize these differences by performing a displacement correction which was already planed during design.

Even though the construction of the horizontal loaded CPRF of the new exhibition hall was successful, there is still a lack of scientific results or case histories concerning the load bearing behaviour of horizontal loaded CPRFs. To study the load bearing behaviour of horizontal loaded CPRFs small scale physical model test and numerical analyses are currently carried out at Darmstadt University. For these studies experiences and results from geotechnical measurements obtained during the construction of the new exhibition hall 3 in Frankfurt are taken into account.

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