Piled raft foundation of a tall building in Frankfurt clay

Fondation pour un gratte-ciel en argile de Francfort

H. SOMMER, Professor, Dr.-Ing., University Kassel, FRG
P. WITTMANN, Consulting Engineer, Darmstadt, FRG
P. RIPPER, Consulting Engineer, Darmstadt, FRG

Synopsis: The construction of a 30-story building required a piled raft foundation due to narrow site with settlement-sensitive neighbouring structures. The tall building rests on floating pilings in Frankfurt Clay. The static design of the foundation is based on the results of finite element analysis. During construction, the bearing behavior of the piled raft foundation is repeatedly checked by exentistive mesurements. The fundamental mechanisms of the load settlement behavior of a piled raft foundation can be explained by the measurement results, and will be compared with the results of FE-computations.

INTRODUCTION

In our overcrowded urban areas, particularly at sites with settlement-sensitive, cohesive soil layers, the degree of structural utilization (number of stories) is mainly dependent on the tolerable settlements of neighboring buildings. In such cases, floating pile foundations, even in cohesive soils, are being increasingly employed as "settlement reducers". Reports on such foundations come primarily from London sites (GREEN/COCKSEDGE, 1964; COOKE et al., 1981).
In the design of pile foundations, the entire load of the structure is to be carried by the piles, while safety factors greater than 2 ensure stability of the structure and low settling. The same procedure is generally used to design foundations with rigid interconnected pile groups (piled raft foundations). Those parts of the load which are directly transmitted by the raft are normally ignored. Theoretical methods for computation of the distribution of loading between piles and raft have not yet been developed. The settling behavior of a pile group can be determined from those of a single pile by means of theoretical (interaction factor, POULOS, 1968) or empirical (settlement ratio, COOKE et al., 1980) procedures. These procedures are only available if the bearing capacity of the piles is not completely utilized.

Reliable measurements on instrumented structures which extend existing experience are extremly rare. In the following, we report on a piled raft foundation where the piles were designed to achieve their ultimate bearing capacity in order to force the supporting function of the raft. The results of computations and measurements are presented.

STRUCTURE AND SUBSOIL

The 130 m-tall structure is built on a narrow site bounded by a triangular intersection of railway bridges within the Frankfurt fair area (Fig.1). The building sits on two separate rafts and is underpassed by a street (Fig. 2).

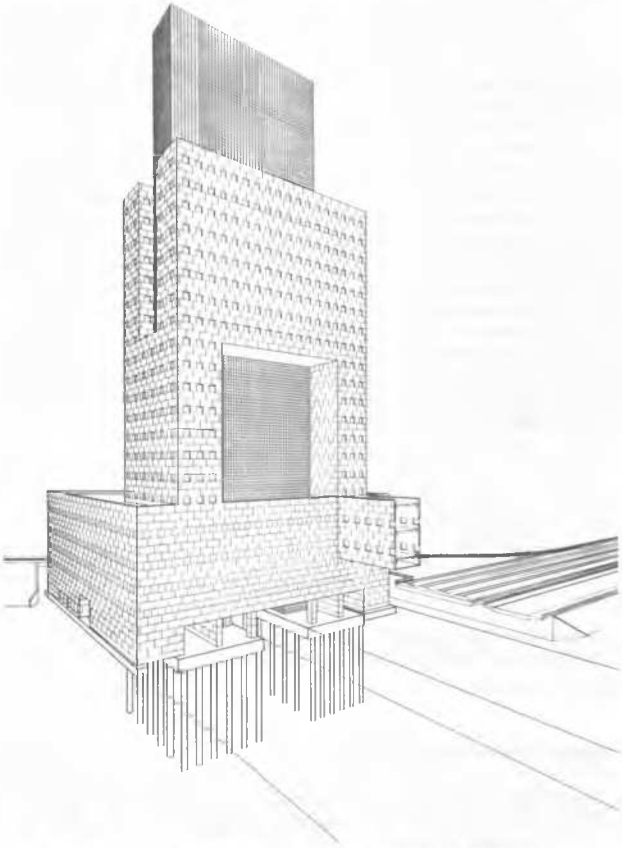

Fig. 1 Isometric view of the building

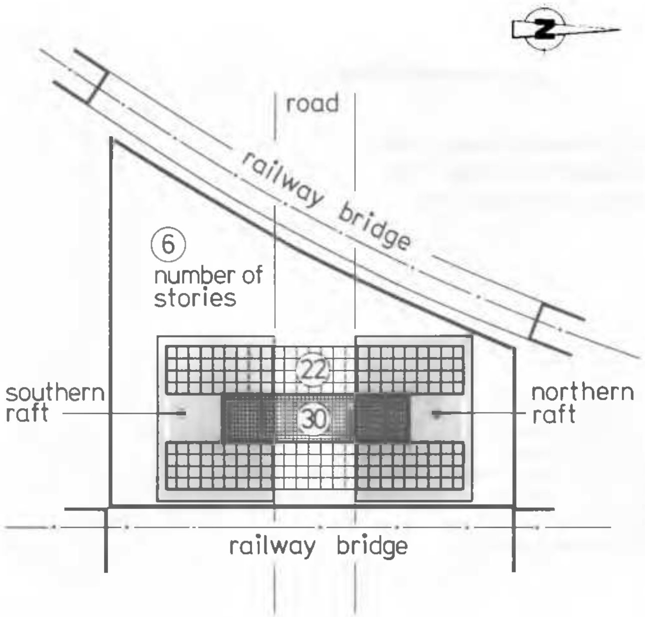

Fig. 2 Site plan with number of stories

Along the periphery of the triangular area, 6-story low-rise buildings are grouped around the high-rise (Fig. 2).
The subsoil consists of quarternary terrace gravel down to 2.5 m below the raft bottom, underlain by layers of Frankfurt clay extending to great depth. Within the clay, thin calciterous sand and silt inclusions, as well as isolated floating limestone layers, are embedded. According to laboratory test results, the undrained shear strength of the fissured, stiff-plastic clay amounts to c_u = 100 - 200 kN/m^2. Its compressibility decreases with depth as a result of the geological preloading (SOMMER, 1977). The increase of the compressibility modulus can be expressed by the formula

$$E_s = E_{s0} \cdot (1 + \alpha \cdot z)$$

E_{s0} = 7 MN/m^2

α = 0,35

z = depth in m below the tertiary-surface

which has been developed from measured settlements at high rise buildings in Frankfurt (BRETH/AMANN, 1975).

FOUNDATION DESIGN

Following favorable experience in pile foundation of heavy buildings in comparable tertiary London clay, a combined piled raft foundation was planned to reduce the settlements. The design of a safe and economic foundation was performed from a finite element study. The FE-mesh employed, consists of 960 elements, with dimensions of 80 m depth and 50 m width. Sections with center-line between the two building rafts, as well as cross-sections with center-lines through the centers of the rafts, were investigated. The deformation behavior of the soil was simulated by a nonlinear elastic constitutive law (DUNCAN/CHANG, 1972). In a total number of 5 computations, both a foundation with monolithic raft, and a piled raft foundation with 15, 20, and 30 m long piles as well as the influence of the superstructure rigidity (20 m long piles), were investigated. The computed settlements are shown on Fig. 3. The greatest settlements of about 26 cm were calculated for the raft foundation. For the piled raft foundation, the settlements become smaller. With increasing pile length, the settlement decreases to approximately 12 cm (30 m-long piles, Fig. 4).

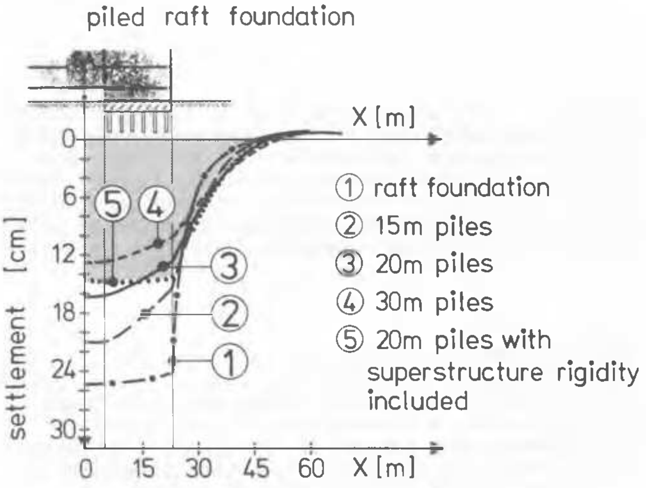

Fig. 3 Computed settlements - north-south section

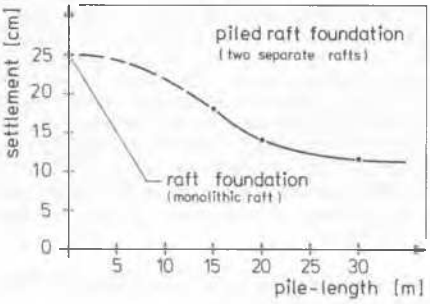

Fig. 4 Influence of pile length on the computed settlements

The settlements of the pile group can be estimated with satisfactory accuracy from simplified methods on the basis of a substitute shallow foundation situated at the pile base level (SOMMER, 1977). Without considering the superstructure rigidity, the rafts tilt toward the center line (1 - 4 Fig. 3). The influence of the superstructure rigidity (5 Fig.3) or the monolithic foundation raft (1 , Fig. 3) considerably reduces this tilting. It can be seen from Fig. 4 that for pile lengths greater than 20 m no significant decrease in the settlements appears. Therefore, the pile length was fixed at 20 m.

The foundation was carried out with 2 separate rafts, each with a total of 42 bored piles of diameter D = 90 cm. The pile spacing varies from 3.5 D to 3.0 D. The surrounding low-rise buildings were shallow-founded on strip and single-base foundations in order to achieve a certain adaption of their settlements to those of the high rise structure.

In the selected design, all piles are utilized at their ultimate bearing capacity. The ultimate values of point pressure and skin friction were obtained by loading tests for large-diameter bored piles in stiff-plastic clay. The remaining structural load must be transmitted directly by the raft.

Approximately 75 % of the total working load is carried by the piles and 25 % by the raft. From measurements on pile-founded buildings in London clay (COOKE et al., 1981), it is known that analogous to the stress distribution under a rigid raft, a piled raft foundation also shows a load redistribution from the center piles to those at the edges. In the present case, an additional load redistribution from internal to external edge piles was expected from the influence of the internal forces by the restraints of the rigid superstructure.
For the static design of the high rise, it was of great importance to determine the pile load and raft pressure distribution in order to compute the restraint moments within the superstructure. This was performed using FE-computations. Fig. 5a presents the simulated arrangement of piles within the finite element mesh. In an earlier stage of planning, which was still current at the time of the FE-computations, the piles were concentrated below the interior core of the high rise. Accordingly, they were asymmetrically arranged in the FE-mesh. Fig. 5b and 5c show the computed pile load distribution at about 70 % of structural load with and without considering the superstructure rigidity. As expected, the influence of the superstructure causes a 15 % greater loading of the external edge piles and a load eccentricity of approximately 0.8 m.

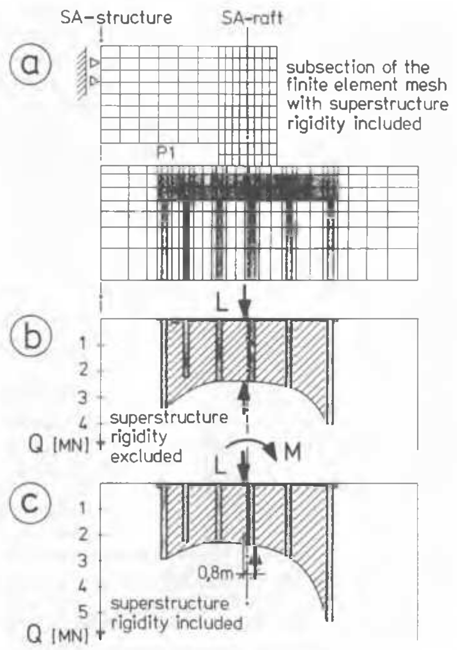

Fig. 5 Subsection of FE-mesh and computed pile-loads (north-south section)

MEASUREMENTS

There is little experience on the bearing behavior of piled raft foundations of completed buildings. For this reason, an extensive measurement program was established for the determination of subsoil deformations, pile loads, and raft pressures during the construction period and the early life of the building.

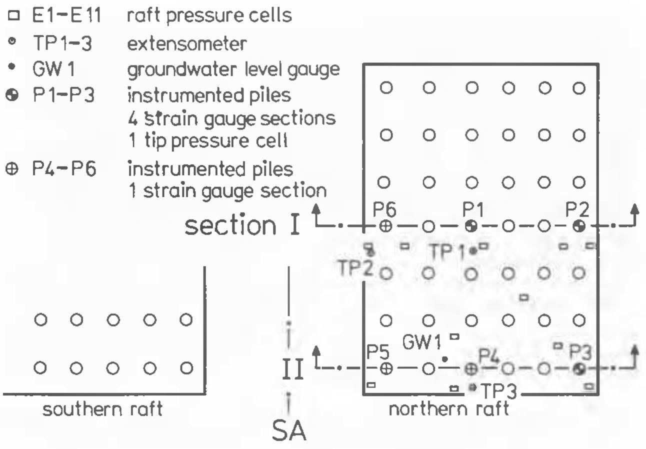

Fig. 6 Foundation plan of southern raft - position of instruments

In order to achieve the highest possible concentration of measurement points at reasonable costs, the instrumentation was concentrated within one section of the southern raft. The positions of the instruments are described and illustrated in the location plan Fig. 6 and in the sectional drawing Fig. 7.
The building is still under construction at present. Approximately 75 % of the structural load had been applied at the time of the last measurement reported herein. The maximal settlements amounted to 4.5 cm. The shallow foundations of the 6-story low-rise buildings had settled by the some amount. Only six months

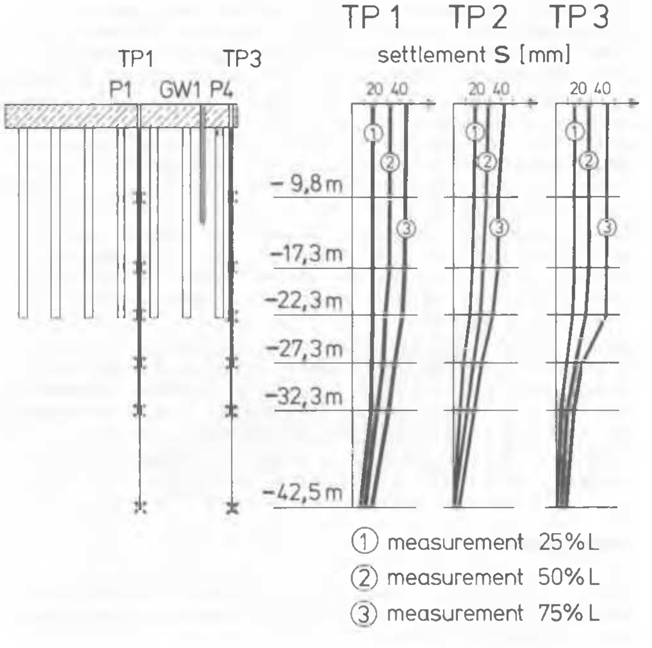

Fig. 7 Position of extensometer anchor points, and measured settlements distribution with depth

have passed between the concreting of the raft and the last measurement. The high construction rate of about 4 stories per month could be obtaind using a slip-formed concrete procedure. Due to the high loading rate, only a small part of the consolidation settlements have occured, so that only 30 % of the computed final settlements were recorded. The settlement distributions with depth measured by three extensometers are shown on Fig. 7. All extensometer rods were installed after the concreting of the raft, so that only those settlements caused by the load of the superstructure could be recorded. The settlements caused by the dead weight of the raft measured geodeticly amount to approximately 1 cm.

The settlements measured by extensometer remain approximately constant down to the pile point level. Lesser values occur at the edges, and especially at the corner areas of the raft at small depths of about 5 to 10 m below the point level. At a depth of about 20 m below this level, only small settlements occur. On the contrary, the extensometer in the center of the raft indicates that approximately 50 % of the settlements occur at levels of 20 m and more below the point level. A qualitatively similar result is found from the FE-computations. The measured soil deformation with seat of settlement below the pile base at low depth (5 - 10 m) in the edge and corner areas, and at great depth (20 m) in the center of the raft, can be compared to those of a flexible shallow foundation positioned at the pile base level.

It is evident that up to the last-measured stage of loading by the superstructure, only negligible compression of the layers embedded among the piles, and therefore no remarkable slippage of piles relative to the soil can have occured. Accordingly, only negligible transfer of superstructure load by the raft to the soil is to be expected. This can be verified from Fig. 8, which describes the measured division of load between piles and raft. The dead weight of the raft was recorded by the raft pressure cells with good accuracy immediately after the concreting of the raft. Following initial setting, the raft pressure decreased slightly with increasing pile loading. Later, after about 25 % of the superstructural load had been applied, a incipiert increase of raft pressure exceeding the dead weight of the raft was recorded (Fig. 8). These measurements agree well with the results of finite element computations. In the design, the raft pressure was calculated to 25 % of the total final load (15 % measured with 75 % L).

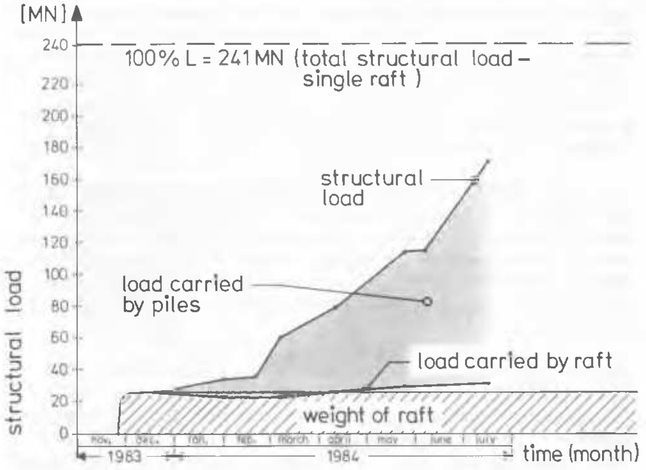

Fig. 8 Measured division of load between piles and raft

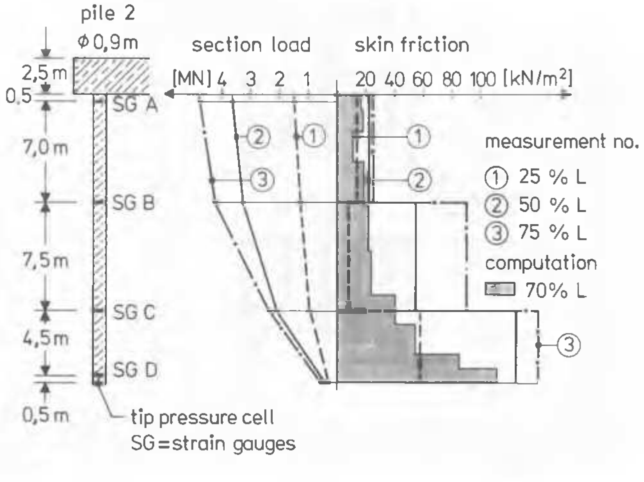

Fig. 9 Measured and computed distribution of skin friction, pile 2

Fig. 9 shows the computed and measured skin friction distribution at the external edge pile P2 (cf. Fig. 6). In qualitative agreement with the computations for the upper portion of the pile shaft, only low skin friction was measured, whereas in the lower part, near the base, rapidly increasing values were recorded.

Within the pile group, a much greater pile loading was measured at the edge, particularly for the corner piles as compared to the center piles. Point pressure and skin friction are affected in the same way (cf. Fig. 5). Considering the bearing load shares of point and skin individually (Fig. 10), a more pronounced load redistribution of skin friction can be seen; this can be explained by the larger pile shaft surface.

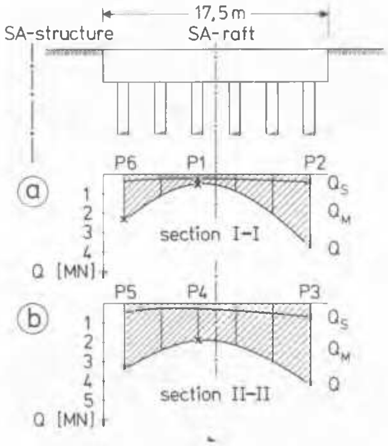

Fig. 10 Measured distribution of pile load in section I-I (center) and II-II (edge)

The eccentricity of the load resultant caused by superstructure restraint can be clearly recognized from the higher loading of the external edge piles.

CONCLUSIONS

The FE-computations performed, permitted a qualitatively acceptable prediction of the bearing behavior of the piled raft foundation. The computed behavior was confirmed by initial measurements, and these agree with measurements on comparable buildings in London clay.

The carcass works of the high rise building will be completed in September 1984. At this writing, about 75 % of the structural load had been applied whereas only 30 % of the computed final settlements have been measured. An increasing cooperation of the raft in directly transmitting the structural load has been observed.
The final valuation will be reported in a subsequent publication.

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