Pile load tests at the deepest foundation piles in Germany

R Katzenbach\textsuperscript{1,2}, A Werner\textsuperscript{1} and S Fischer\textsuperscript{1}

\textsuperscript{1} Ingenieursozialtät Professor Dr.-Ing. Katzenbach GmbH, Pfaffenwiese 14A, 65931 Frankfurt am Main, Germany

\textsuperscript{2} katzenbach@katzenbach-ingenieure.de

Abstract. Since 2001 the so called Hafencity arises in Hamburg, Germany. Currently it is europe's biggest urban development project. So far the most famous building of this area is the well known Elbphilharmonie. Now another impressive building is in planning – a huge skyscraper. The new skyscraper will get an overall height of 245 m. Due to the little bearing capacity of the ground a deep foundation is needed. To found the building Germany's deepest foundation piles, with lengths up to 75 m, will be executed. In advance, to determine the bearing capacity of the surrounding soil, four test piles, with lengths up to more than 110 m, have been executed.

1. Subscription of the building
The area “Hafencity” is located in the middle of Hamburg directly on the river Elbe (figure 1). Figure 2 shows the famous building “Elbphilharmonie” in the front and the planned new skyscraper in the rear.

![Figure 1. Location of the construction site in Hamburg.](image-url)

The skyscraper with an over all height of 245 m (figure 2) will be erected on a foundation plate with an area of about 17,000 m\(^2\). The triangular foundation plate owns dimensions of nearly 200 m in north-south-direction and nearly 130 m in the east-west-direction.
Figure 2. Area “Hafencity” in Hamburg with the Elbphilharmonie and the new skyscraper.

The structural load of the 60 floors of the high-rise building results in approx. 2,200 MN which corresponds to a mass of 220,000 tons. Due to the very high loads and the different height of the base building and the high-rise-building, which are built on a monolithic foundation-plate, large caliber foundation piles are needed.

2. Soil conditions
Extensive soil investigations were carried out to explore the subsoil to a depth of approx. 200 m. These geotechnical site investigations consisted of:

- Exploration drillings;
- Crosshole measurements;
- Cone pressuremeter testing;
- Laboratory testing.

Based on these extensive soil investigations the following soil model (figure 3) has been elaborated:

- **Layer 1**: sandy filling, partly rubble.
Layer 2: clay and mud, cohesive filling, partly rubble.
Layer 3: sand with silty deposits.
Layer 4: sand middle dense to dense.
Layer 5: sand dense to very dense.
Layer 6a/b: clay/silt with thin sandy layers.
Layer 7: sand partly silty with silty layers.

3. Pile load tests

3.1. General
To determine the bearing capacity 4 pile load tests have been carried out (figure 4). To be able to make a prediction for all affected soil layers, piles with different lengths have been executed. The most important layer for the load transfer is layer 7. For this reason 2 piles reaches into this layer. The following piles have been executed:

- Testpile 1: length = 110 m, ultimate load = 22,500 kN
- Testpile 2: length = 110 m, ultimate load = 27,500 kN
- Testpile 3: length = 75 m, ultimate load = 15,700 kN
- Testpile 1: length = 35 m, ultimate load = 10,750 kN

![Figure 4. Location of the testpiles P1 to P4.](image)

All testpiles have a nominal diameter of 1.85 m. The load was applied by two so called Osterbergcells (O-cells) ([1] and [2]). The O-cells (fig. 5) are located approx. 6 m above the base of the piles. The testpiles were equipped by the following instruments:

- Extensometers;
- displacement transducers;
- strain gauges.
Figure 5. O-cells within the reinforcement case.

Figure 6 shows the production time of the testpiles P1 to P4.

![Figure 6](image)

**Figure 6.** Production time of the testpiles P1 to P4.

3.2. Results and recalculation of the pile load tests

One of the main results of a pile load test is the load-displacement curve. On the basis of the measured distribution, soil characteristics can be recalculated e.g. by using the finite-element method ([3], [4], [5] and [6]). Our simulations of the pile load tests are based on the numerical software Plaxis by using the constitutive model Hardening soil ([7]).
As input values the geometry of the test piles, characteristics of the concrete, the location of the soil layers, the specific weight of the soils and also the load regime of the O-cells are well known. By fitting the calculated and the measured curves of the load-displacement the unknown characteristics

- stiffness modulus ($E_{50}$, $E_{oed}$, $E_{ur}$ and $E$),
- power $m$,
- friction angle $\varphi$,
- cohesion $c$,
- dilitancy angle $\psi$

can be found.

The calculations were performed using axisymmetric models with depth of 150 m and wide of 15 m (figure 7). Due to the unknown glacial preloading of the soils calculations with and without preloading have been carried out.

Figure 7. Dimensions and discretization of the numerical models.

Figure 8 to figure 11 show the measured and the recalculated load-displacement curves of the test piles P1 to P4 without any preloading. Figure 12 to figure 15 show the measured and the recalculated load-displacement curves of the test piles P1 to P4 with preloading due to ice age. The value of the preloading, 600 kN/m², was recalculated using the over consolidation ratio (OCR) determined by pressuremeter tests.
Figure 8. Load-displacement of testpile P1 without preloading.

Figure 9. Load-displacement of testpile P2 without preloading.
Figure 10. Load-displacement of testpile P3 without preloading.

Figure 11. Load-displacement of testpile P4 without preloading.
Figure 12. Load-displacement of testpile P1 with preloading.

Figure 13. Load-displacement of testpile P2 with preloading.
Figure 14. Load-displacement of testpile P3 with preloading.

Figure 15. Load-displacement of testpile P4 with preloading.

Figure 16 shows the different models for recalculating the characteristics of the soils without using a preloading, (left), with using a preloading applied in an extra calculation phase, (middle) and by using the modeling technique pre-overburden pressure (pop) of the software Plaxis, (right).
In addition to the “curve-fitting” we compared the measured and the calculated axial forces in the lower pile segments as a plausibility check (figure 17).

4. Foundation
An overview on the design of piled rafts and its behavior is given in [8] to [15]. For the prediction of the settlements and especially to proof the acceptable inclination of the skyscraper, various three
dimensional numerical calculations were executed taking into consideration scientific works like [16], [17], [18] etc. Figure 18 shows the dimensions of the numerical model.

![Figure 18](image1.png)

**Figure 18.** Dimension of the numerical model for the settlement prediction.

Figure 19 shows the final layout for the large caliber foundation piles as well as the “small” foundation piles with a length of 15 m for the base building.

![Figure 19](image2.png)

**Figure 19.** Pile layout.

In the result of the calculations, including several sensitivity studies, the layout shown in fig. 19 with 66 large caliber piles with diameter \( d = 2.0 \) m and length \( l = 75 \) m is, in accordance to [19], a safe and economical design of the foundation for the third highest high-rise-building in Germany.
References

[1] England M 2009 Review of methods of analysis of test results from bi-directional static load tests Deep Foundations on Bored and Auger piles (Taylor & Francis Group, England) 235–9
[2] Zhussupbekov A and Omarov A 2019 Complex of static loading tests of bored piles International Journal of GEOMATE 16 8–13
[3] Wehnert M and Vermeer P 2004 Numerical analyses of load tests on bored piles Numerical methods in geomechanics-NUMOG IX pp 505–11
[4] Wehnert M 2006 Ein Beitrag zur drainierten und undrainierten Analyse in der Geotechnik Mitteilung 53 des Instituts für Geotechnik University Stuttgart
[5] Kania J K, Sorensen K K and Fellenius B H 2020 Analysis of a static loading test on an instrumented CCFA pile in silt and sand Int. J. of Geoengineering Case Histories 5(3) 170–81
[6] Fellenius B H, Edvardsson F, Pettersson J, Sabattini M and Wallgren J 2019 Prediction, testing, and analysis of a 50 m long pile in soft marine clay Journal of the Deep Foundation Institute 13(2) 1–7
[7] Schanz T, Vermeer P A and Bonnier P G 1999 The hardening soil model: Formulation and verification Proc. Int. Symp. Beyond 2000 in computational geotechnics pp 281–96
[8] Reul O 2000 In-situ-Messungen und numerische Studien zum Tragverhalten der Komminierten Pfahl-Plattengründung Mitteilungen des Institutes und der Versuchsanstalt für Geotechnik der Technischen Universität Darmstadt 53
[9] Sew I, Chin I and Shong I 2003 A brief guide to design of bored piles under axial compression – a Malaysian approach Seminar and Exhibition on Bridge Engineering (Kuala Lumpur, Malaysia) pp 8–22
[10] Van Impe W F Deformation of deep foundations 1991 Proc. 10th ECSMFE, Florence (Rotterdam: Balkema) vol 3 pp 1031–62
[11] Poulos H G 1968 The settlement behaviour of single axially loaded incompressible piles and piers Géotechnique 18 (3) 351–71
[12] Poulos H G 1980 Pile Foundation Analysis and Design (New York: John Wiley & Sons)
[13] Poulos H G Settlement prediction for bored pile groups 1993 Proc. Conf. Deep Foundations on Bored and Auger piles Ghent (Rotterdam: Balkema) pp 103–17
[14] Poulos H G Comparison of some methods for analysis of piled rafts 1997 Proc. 14th ICSMFE (Hamburg) (Rotterdam: Balkema) vol 2 pp 1119–24
[15] Randolph M F and Wroth C P 1979 An analysis of the vertical deformation of pile groups Géotechnique 29 (4) 423–39
[16] Katzenbach R, Arslan U and Gutwald J 7-9 September 1994 A numerical study on pile foundation of the 300 m high Commerzbank Tower in Frankfurt am Main Proc. 5th Europ. Conf. on Num. Methods in Geomech. (Manchester, UK 7-9 September 1994) pp 271–7
[17] Katzenbach R, Arslan U, Moormann C and Reul O 1998 Piled raft foundation – Interaction between piles an raft Proc. Int. Conf. on Soil-Structure Interaction in Urban Civil Eng. Darmstadt Geotechnics 4(2) pp 279–96
[18] Randolph M F 1994 Design methods for pile groups and piles rafts Proc. 13th ICSNFE (New Delhi) (Rotterdam: Balkema) vol 5 pp 61–82
[19] ISSMGE 2013 Combined Pile-Raft Foundation Guideline ed R Katzenbach and D Choudhury