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Full-scale static load test of CFA piles

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ABSTRACT: A wastewater treatment plant was built on the Danube riverbank, downstream from city of Vukovar. Structures and technological facilities within the plant are supported by CFA piles with a diameter of 600 mm, passing through a sand embankment constructed for the plant and existing sand and clay in subsoil at greater depths. A total of 640 piles was performed with length varying from 12 m to 20 m. Full-scale static load tests on two instrumented piles length of 18 m and 20 m were performed up to a maximum axial load of 2000 kN. The testing was carried out according to the ASTM D1143/D1143M-07(R2013) standard, with measurements of force, pile displacement and relative deformations along the piles. The test results were used to verify axial pile resistance calculated from soil parameters obtained from geotechnical investigation borings and pile resistance according to CPT testing.

KEYWORDS: Piles, static load tests, full-scale.

1 INTRODUCTION

The Wastewater Treatment Plant (WWTP) of the city of Vukovar is located east of the city, at the "Petri skela" site, next to the Danube River. The project area lies within the riverbed and had to be filled and protected from high water levels with a city-type riverbank embankment. Sand from Danube was used to construct the sand plateau for the plant. Through a dredging process the sand was deposited and leveled to the planned elevation of 85.10 meters above sea level. The height of the sand embankment reaches up to 11 meters, while at the position of piled foundation embankment height is up to 6 m.

Geostatic analyses for the shallow foundation variant revealed total settlements of the structures that significantly exceed permissible values, including excessive differential settlements that do not meet technological requirements for the pipelines and plant. Deep foundations with reinforced concrete piles were selected as the optimal solution, ensuring structural stability against vertical forces as well as stability against buoyancy (Tomljanović, 2016).

2 PROJECT DESCRIPTION

2.1 *Pile foundation data*

Structures within the plant are founded on precast concrete piles length 12-20 m. All piles are 60 cm in diameter and constructed with CFA technology. A total of 640 piles were constructed, amounting to 11 985 m' of piles. Depending on the position and foundation depth of each structure, the pile length within the newly constructed sand embankment ranges from 3 to 6 meters.

The technological unit within the WWTP that is the largest and most heavily loaded, and beneath which the test piles were installed, is the biological treatment structure with floor plan dimensions of 149,7 x 27,6 m. The structure contains three chambers: the left and right chambers, each measuring 56 x 27,6 m, supported by 190 piles (each 18 m long, arranged in a 3,0/2,9 m grid) and the central chamber, measuring 37,6 x 27,6 m, supported by 140 piles (each 20 m long, arranged in a 2,7/2,9 m grid).

2.2 *Ground conditions*

For the design purpose and construction of the facility, extensive geotechnical investigation works were carried out. The field investigation works included:

- three boreholes with SPT testing and four CPTu tests during the preliminary design phase, at depths ranging from 12,7 to 35 meters.
- ten boreholes with SPT testing during the main design phase, at depths from 10 to 20 meters.
- five CPTu tests and five DMT tests during project execution, for quality control of the reclaimed sand embankment, at depths of 7,4 to 12 meters.

The project layout with positions of investigation works and test piles is shown in Figure 1. Investigation works positions are marked with black, blue and green circles, while test piles are marked with red circles.

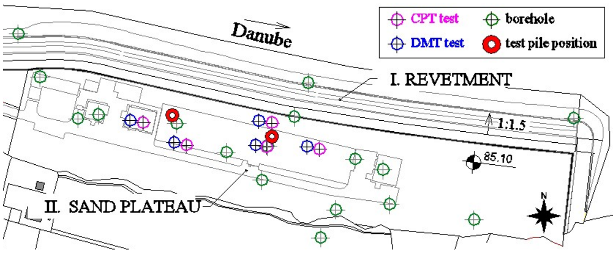

Figure 1. Project layout, investigation works and test pile position.

Subsurface conditions prior to sand embankment placement, with original ground level at 75–79 m a.s.l., can generally be described as:

1. from 0,5 to 1,6 meters below ground level: alluvial sandy-clayey mixtures.
2. down to 72–77 m a.s.l.: silty sand, loose, fine to medium grain size, classified as SM, SW/SM, SP/SM, with SPT N-value= 4–30.
3. down to 65–71 m a.s.l.: clay of medium to high plasticity CI/CH, with strength parameters c = 16–31 kPa, φ = 18–34°, q_u = 121–550 kPa.
4. down to 60 m a.s.l. or lower: silty sand, partially clayey, fine to medium grain size, medium dense to dense, classified as SP/SM, SC, SW, with SPT N-value= 25-50.
5. in some boreholes below 60 m a.s.l.: clay of medium plasticity, stiff to hard consistency, q_u = 420 kPa

The sand plateau was constructed from original ground level up to planned elevation with fine to medium grain size sand, with uniformity coefficient $U=d_{60}/d_{10}$ ranging from 1,86 to 2,18 and containing about 2% of particles smaller than 0,063 mm (Institut IGH, 2017).

Tables 1 and 2 show the stratification of the foundation soil at test pile locations, along with the range of individual parameters obtained through the analysis of laboratory test results, CPT and DMT probing and correlations with the results of in-situ SPT testing. The characteristic values of soil layer parameters were adopted based on the results from boreholes and tests located closest to the test piles.

The relative elevation 0.0 in the tables is the pile head level at the plant structure “biological treatment”, i.e., which corresponds to elevation of 81.6 m above sea level.

Table 1. Soil properties at test pile position 1 (L=18 m)

Soil layer	depth (m)	γ (kN/m^3)	c (kPa)	Φ (°)	c_u (kPa)
Sand-fill	0,0*-4,9	17,5-18,5	0	40	-
SM	4,9-7,1	20,0	0	30	-
CI/CH	7,1-16,0	20,7	21-24	27-31	145
SP/SM	16,0-18,0	20,0	0	34-35	-

Table 2. Soil properties at test pile position 2 (L=20 m)

Soil layer	depth (m)	γ (kN/m^3)	c (kPa)	Φ (°)	c_u (kPa)
Sand-fill	0,0*-4,5	17,5-18,5	0	38	-
SM	4,5-7,0	20,0	0	28-35	-
CI/CH	7,0-15,3	18,8-20,9	16-26	18-33	80-155
SP/SM	15,3-20,0	20,0	0	32-35	-

3 FULL-SCALE PILE TESTING

The foundation project prescribed static load test of two test piles of 18 and 20 m length, each 60 cm in diameter, up to a maximum test load of 2000 kN. The pile testing was conducted in accordance with ASTM D1143/D1143M-07(R2013) – section 8.1.3 (Geotest, 2017). The ASTM standard implicitly includes a pile load-bearing criterion: a pile is considered satisfactory if the deformation rate at the highest load stage falls below 0.25 mm/h.

3.1 *Test setup and procedure*

The test piles were constructed at the center of a group of four tension piles that transfer the reaction load into the ground. Figure 2 shows the positions of the test piles beneath the plant structure “biological treatment”.

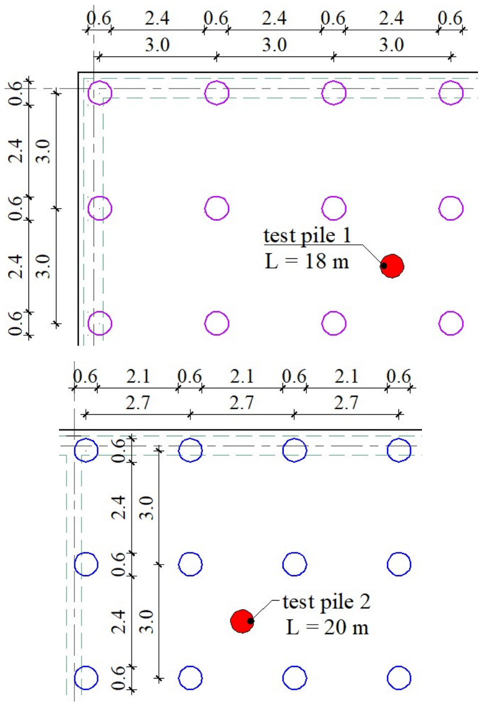

Figure 2. Pile layout and test piles positions

The load transfer system consisted of a steel frame made of HEB260 and HEB320 beams, centrally positioned above the test pile and anchored to the tension piles via 3-meter-long steel anchors. Figures 3 and 4 illustrate the load application system with the piles. A hydraulic press with a capacity of 3000 kN and a stroke of 90 mm, along with a high-pressure pump rated at 1000 bar, was used to apply the load.

A measurement of relative deformations along the test piles was performed by six vibrating wire extensometers with resolution of 1 μm/m and range ±2500 μm/m attached to the pile’s longitudinal reinforcement at 3 m intervals. In addition to relative deformations, the following values were measured during the test:

- load applied to the pile via a load cell,
- hydraulic pressure using a pump-mounted manometer,
- piston extension of the press using electrical transducers,
- deflection of the main load beam using an electronic displacement transducer,
- vertical displacement of pile head using two electronic displacement transducers, control analog gauge and optically by geodetic level,
- vertical displacement of tension piles using a geodetic level,
- pile temperature via sensors embedded in the reinforcement cage.

Figure 3. Pile test frame and reaction piles.

Figure 4. Pile loading setup

3.2 *Test results*

Total static load test time on each pile was 13,5 hours. Vertical displacement of tension piles were recorded with 1 mm only at 2000 kN load increment, except for tension pile 2 which is located next to test pile 2, where measured displacement was

3 mm. Figures 5 and 6 show the force-time-displacement diagrams for the test piles 1 and 2.

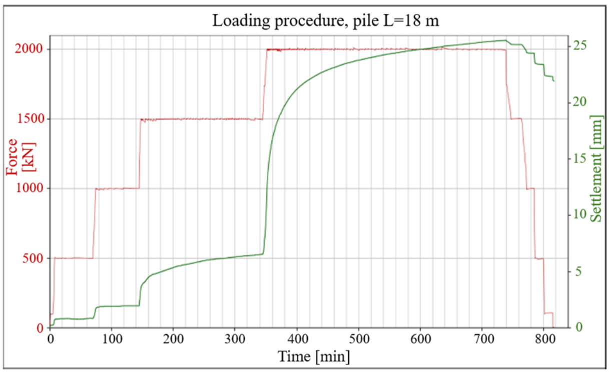

Figure 5. Loading procedure, test pile 1, L = 18 m.

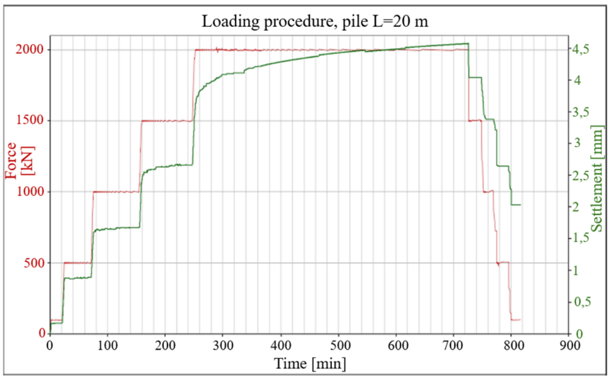

Figure 6. Loading procedure, test pile 2, L = 20 m.

Permanent deformation in test pile 1 was 5,5 mm, while in test pile 2 was recorded only 1 mm.

Based on the measured relative deformations, the distribution of axial force along the pile was calculated, as shown in Figures 7 and 8. Solid lines (labeled "b" in the legend) represent the force in the pile at the beginning of each load level, while dashed lines (labeled "e") represent the force at the end of each load hold period.

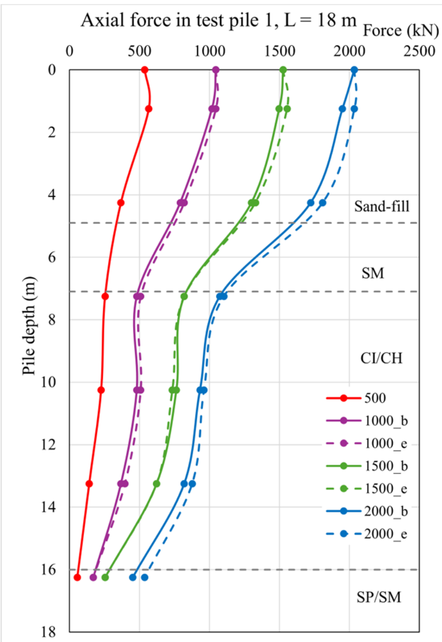

Figure 7. Distribution of axial force along the test pile 1

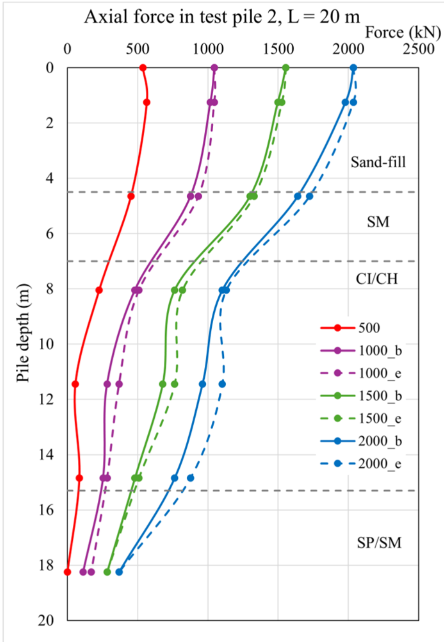

Figure 8. Distribution of axial force along the test pile 2

Load distribution at test pile 1 shows that for 2000 kN test force contribution of pile tip is 27% of total capacity, while at test pile 2 only 19% of applied load transfers to pile tip. It is clearly visible that maximum sleeve friction is measured in a silty sand layer within interval 4-8 m (distance observed from the pile head) and in pile tip zone where sandy soil layer was also recorded.

4 CALCULATION OF PILE RESISTANCE

4.1 *Calculation of pile resistance*

The resistance and settlement of the test piles were calculated according to DIN 4014. Soil bearing capacity parameters were determined based on the measured deformations and displacements during the pile tests. These values of shaft and base resistance served as input parameters for back-analysis using the GEO Tools v.13.1 software by GEOTEC Software Inc. Table 3 shows the soil layer properties used for the back-analysis.

Table 3. Soil properties used for back analysis

Soil layer	Depth (m)	q_c (kN/m^2)	c_u (kPa)	τ (kPa)
Sand-fill	0,0-4,5	4000	-	40
SW/SM	4,5-7,0	2000	-	115
CI/CH	7,0-15,3	-	180	22
SP/SM	15,3-20,0	15000	-	65

The load-settlement curve from this back-analysis is shown alongside resistance curves based on exploratory investigation results (Figures 9 and 10).

The compressive resistance of each individual pile was also calculated analytically, using correlations with static cone penetration resistance (according to DIN 1054). All calculated values, including those from the main foundation design (based on Reese and EC7 method), are shown in Table 4. Shaft resistance Q_s, base resistance Q_b, and total resistance Q are presented separately.

Table 4. Calculated pile resistance

Approach	Pile length (m)	Q_s (kN)	Q_b (kN)	Q (kN)
Reese	18	1575	545	2120
	20	1780	600	2380
EN 1997	18	1285	1040	2325
	20	1495	1200	2695
DIN 1054	18	1830	990	2820
	20	2280	990	3270

4.2 *Comparation of test results with calculations*

Figures 9 and 10 show a comparison of the measured load-settlement values during the test pile loading with the calculated results and back-analysis based on DIN 1054.

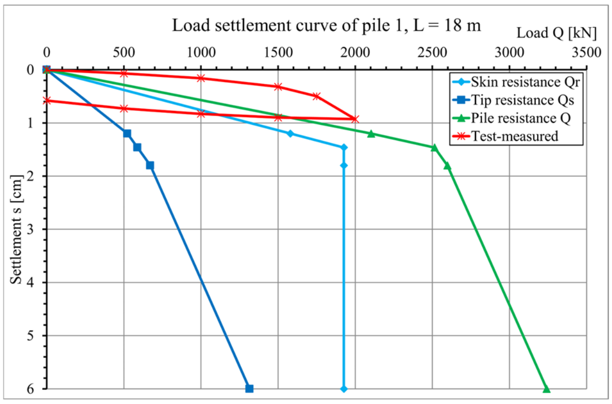

Figure 9. Load settlement curve – test pile 1 (L = 18 m)

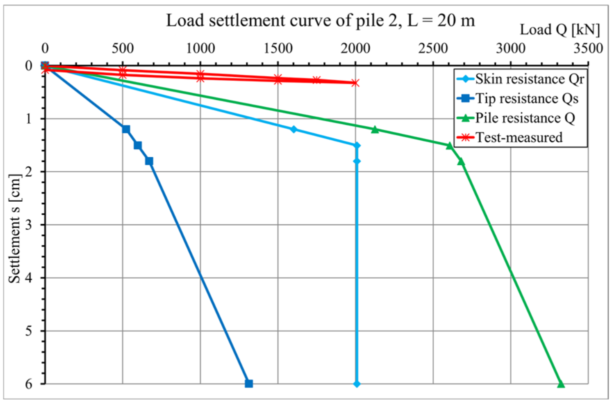

Figure 10. Load settlement curve – test pile 2 (L = 20 m)

For the test pile 1 measured settlement correlates very well with values obtained by back analysis – 0,95 cm according to testing in relation to 1,2 cm according to calculations. For the test pile 2 measured settlement is 0,35 cm and comparison is not so accurate as in the case of test pile 1.

5 CONCLUSIONS

The static load tests on the two test piles were carried out correctly and the required resistance defined in the project was confirmed. The bearing capacity obtained through static testing was greater than the values calculated based on soil parameter data from site investigations.

The measured settlement values of the 18 m pile closely matched those calculated using DIN 4014. However, the settlement of the 20 m pile obtained during static testing was significantly lower than the calculated settlement.

The authors believe this discrepancy may be due to different soil characteristics at the pile tip. The stratification data at the test pile location was assumed based on the nearest exploratory borehole. Due to the relatively steep slope of the underlying clay (which correlates with a nearly vertical loess ridge approximately 19 m above the site), it is possible the pile tip ended in a stiff clay layer rather than medium-dense sand as previously assumed. Because of the technology of pile installation there was no possibility for confirmation of the soil characteristics at pile tip. Since the load test has considerably confirmed requested pile resistance this unknown detail was marked as noncrucial for continuation of pile installation and object construction.

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