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Load test of large diameter piles for the bridge across Danube river in Belgrade

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Abstract. The bridge over the Danube will be part of the so-called north main tangent - NMT as one of the most important elements of the future road and street network base in Belgrade. It will be the second bridge over the Danube in Belgrade. In this paper the results of the pile load tests for the central bridge structure foundation will be analysed, using the EC 7 standard. The length of the test pile was 46 m and its diameter was 2.0 m. Load test was carried out with the contra load of 2100 tons in the form of pre-stressed reinforced concrete beam, which is founded on piles, each about 60 m. For the realization of a vertical pressing force to the pile head, five hydraulic presses were used, that were securing the force from 3000 to 6000 kN.

Keywords: Pile; Static pile load test; EC 7 standards; Geotechnical conditions;

1 INTRODUCTION

The bridge under construction across the Danube in Belgrade (the Zemun-Borca Bridge) is part of the so-called North main tangent (NMT). In just three years, after its construction, Belgrade will get its second capital bridge (the first is the Ada Bridge across the Sava built in 2012). The Zemun-Borca Bridge is being built a few kilometres upstream from the so-called Pancevo Bridge. It will be only the second bridge across the Danube in Belgrade (Figure 1).

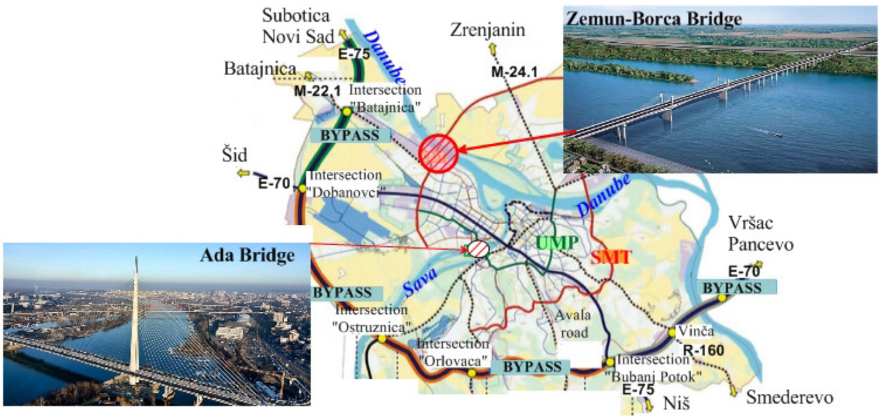

Figure 1. Location and layout of new bridges across the Danube and Sava Rivers in Belgrade

The bridge length is 1482 m and the length of all access roads is around 21600 m. The bridge consists of: south approach structure that has a length of 97 m which is supported by the first two piers (foundation is performed on piles 1.2 m in diameter), the main bridge structure above the waterway is 362 m in length and supported by the piers from no. 3 to no. 6 (piers are founded on piles 2.0 m in diameter), the inundation (waterside) structure 726 m in length is being built from pier no. 6 to pier no. 21 (piers are founded on piles 1.5 m in diameter) and north approach structure of the bridge to pier no.

30, which is 297 m in length (foundation is performed on piles 1.2 m in diameter). All 30 piers of the bridge structure are founded on 336 piles which are arranged in groups from 8 to 26. Pile length is ranged from min 25 m to max 40 m. The bridge is 29.1 m wide and 22.8 m high, and it will have six traffic lanes and pedestrian-bicycle tracks on both sides. The main bridge structure consists of two larger cable-stayed spans, due to the necessity of ship sailing. The bridge construction started in April of 2011, and it is planned to be completed in late October of 2014.

2 BASIC GEOTECHNICAL CHARACTERISTICS OF TERRAIN AT THE LOCATION OF THE BRIDGE

Geotechnical investigations for the bridge construction were carried out in two phases. The first phase was carried out for the Preliminary design. On this occasion, 550 m of exploration drilling was carried out with a depth of exploration boreholes between 10 m and 100 m. Also, 34 static penetration tests (CPT) and seismic refraction tests were carried out on two profiles 224 and 219 m in length. The second phase was made for the Main project and on this occasion additional researches were carried out in the Danube riverbed and in the inundation structure area. In the riverbed, 7 exploration boreholes 46.6-70.7 m deep were carried out, while on the left bank of the inundation structure route (flooding zone of the terrain) 3 boreholes 30.5 - 40.0 m deep were carried out. Also, 84 standard penetration tests (SPT) were carried out in the exploration boreholes. The research results yielded a division of the bridge route into three basic geological units: the Zemun loess plateau which consists of 5 loess horizons separated by layers of ''interglacial soils'' (right bank of the Danube), alluvial deposit in the Danube riverbed (made of sands, gravelly sands, silts and low plasticity clays) and alluvial sediments on the left bank of the Danube represented by facies: flood plain facie (surface silty-sandy clays), oxbow lake (alevritic and muddy sands) and riverbeds (fine to medium grained sands with lenses of gravelly sand and gravel). The obtained data enabled a formation of a geotechnical model of the terrain on which the bearing capacity analysis of vertically loaded pile was carried out in accordance with recommendations from EC 7 standards. In the test pile area, geotechnical model is formed based on the results of SPT tests and geomechanical laboratory tests of samples from the exploration borehole IB-1 (51.7 m) (Figure 2).

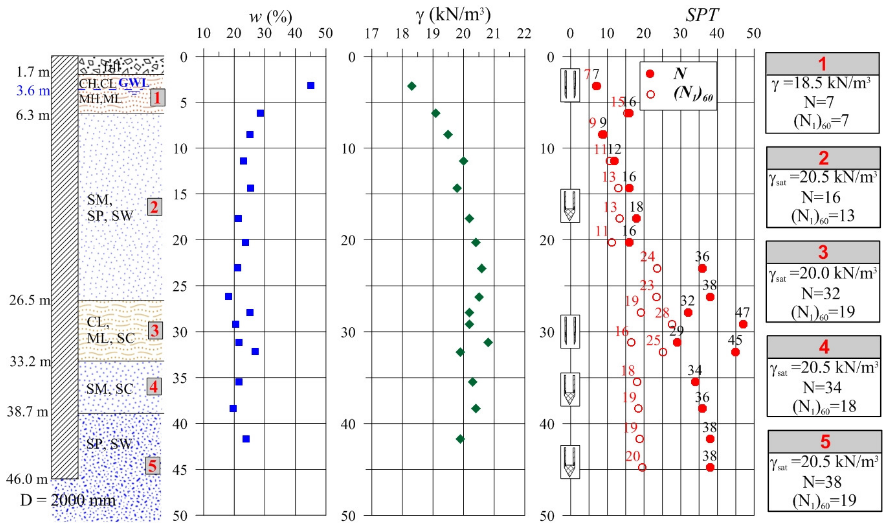

Figure 2. Physical-mechanical characteristics and accepted geotechnical terrain model

3 PILE LOAD TEST PERFORMANCE

The test load was carried out on a reinforced concrete bored pile 2.0 m in diameter (D) and 46.0 m in length (L), on the left bank of the Danube. In order to achieve the contra load of 20000 kN, a special pre-stressed beam, 2.8 m wide and 4.0 m high, was built. The pre-stressed beam is founded on two anchor piles 1.5 m in diameter (D) and 60.0 m in length ($L_1 = L_2$). Anchor piles were carried out with 6.0 m axial distance from the test pile. On the part above the test pile, the pre-stressed beam height was 3.0 m. Pads of steel plates (1.5x1.5 m) were placed between hydraulic presses and the beam which connected anchor piles, as well as between presses and the pile head. The pads had adequate strength to uniformly transfer force to the superstructure, i. e. to the pile (Figure 3).

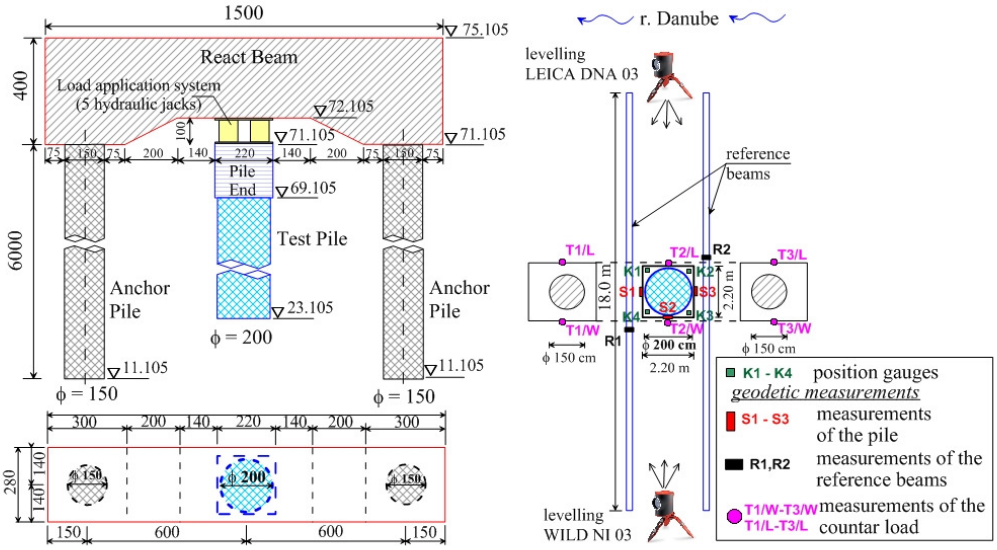

Figure 3. Static load test structure with location of gauges and points of geodetic observation

For the achievement of the vertical pressure force on the pile and measurement of the applied force on the pile head, five hydraulic presses were used. They were placed on the pile head with dimensions of 2.2 x 2.2 x 2.0 m (Figure 4). This ensures a force of 21500 kN, which was also the declared force in the presses (two presses of 7000 kN and the remaining three of 2500 kN). These presses are connected to the two hydraulic pumps over the high-pressure hoses. During the operation, one pump was connected to the larger presses of 7000 kN, while the smaller presses of 2500 kN were connected to the other pump.

Figure 4. Display of the system for pile test load with locations of hydraulic presses

Digital gauges were tied to the reference beams at an angle of 90° and they were used for the measurement of the pile head vertical displacement. This system of reference beams presents rigidly connected frame of steel I profiles 18.0 m in length, which are supported by four supports on the ground. Parallel by the measuring of the pile vertical displacement using gauges, surveying measurement of pile settlement was performed with two levelling instruments ”Leica“ and ”Wild“ which were rigidly attached to the pile. With the levelling instrument ”Leica“, readings were done by levelling rods (T1/L, T2/L i T3/L – measurement locations on the contra load), while readings made by levelling instrument ”Wild“ were done by levelling rods (T1/W, T2/W i T3/W – measurement locations on the contra load). Measurement locations on the test pile are marked S1, S2 and S3. In addition to those observations, reading was done at the division which was attached to the reference beam (gauge carrier), with marks R1 and R2. Observations were made at the end of each load, and the condition for consolidation achievement was 0.24mm/60min. The positions and marks of measuring points are presented in Figure 3.

4 BEARING CAPACITY ANALYSIS OF THE PILE USING THE EC 7 STANDARD

Piles transfer the load to soil over the pile base surface and the pile shaft surface. Therefore, the load bearing capacity of the pile is calculated by the following equation:

$$R_d = R_k / \gamma_t \quad ; \quad R_d = R_{b,k} / \gamma_b + R_{s,k} / \gamma_s \tag{1}$$

where: $R_{b,k}$ - is limiting bearing capacity of pile base, $R_{s,k}$ – limiting bearing capacity of pile shaft, and γ_t, γ_b, γ_s, - partial factors for total bearing capacity or individual bearing capacity of base and shaft. Limiting bearing capacity of a base and limiting bearing capacity of a shaft are calculated as follows:

$$\begin{aligned} R_{b,cal} &= A_b \cdot q_{b,k} \\ R_{s,cal} &= \sum_i A_{s,i} \cdot q_{s,k,i} \end{aligned} \tag{2}$$

where: $q_{b,k}$ – is limiting soil pressure beneath the pile base level, $q_{s,k}$ - limiting shear resistance along pile shaft, A_b - area of pile base, A_s - area of pile shaft. In accordance with EC 7 (EN 1997-1–Part 1, 2004; EN 1997-1–Part 2, 2007), obtained values are reduced by the correlation factors (ξ) and partial resistance factors (γ). If the effects of loading, which can be favourable or unfavourable, are taken into consideration, partial factors on actions (γ_F) can also be used. The recommended values of correlation factors depend firstly on the method used in calculations (results of pile load test and soil investigations) as well as on the number of performed pile load tests or the number of geotechnical models. They are given in table format and are dependent on the accepted design approach (DA-1, DA-2 and DA-3). In a case when the bearing capacity analysis is based on the soil investigation results, then the adopted value of R_k is the minimal value in accordance with the following relation

$$R_k = Min\left\{ \frac{(R_{cal})mean}{\xi_3}; \frac{(R_{cal})min}{\xi_4} \right\} \tag{3}$$

Dependent on the number of analysed models, the values of correlation factors are between min. $\xi_4 = 1.08$ to max. $\xi_3 = \xi_4 = 1.4$ (EN 1997-1:2004, Table A.10.). If the analysis is based on the results of pile load test, obtained values are reduced depending on the number of pile load tests performed, by correlation factors ξ_1 and ξ_2. These values are between min. $\xi_1 = \xi_2 = 1.0$ to max. $\xi_1 = \xi_2 = 1.4$ (EN 1997 -1:2004 Table A.9.) and according to the following equation

$$R_{c;k} = Min\left\{ \frac{(R_{c;m})mean}{\xi_1}; \frac{(R_{c;m})min}{\xi_2} \right\} \tag{4}$$

where: *($R_{c;m}$)mean* – is mean value of limiting bearing capacity of pile in relation to the number of pile load tests and *($R_{c;m}$)min* – obtained minimal value of limiting bearing capacity of the pile from the carried out pile load tests. Load-bearing capacity analysis has also been performed on the basis of the pile test results and standard penetration test (SPT) results for the accepted geotechnical model (Figure 2). From SPT results, limiting bearing capacity of the base is calculated as follows (Shioi and Fukui, 1982)

$$q_{b,k} = C \cdot N(MPa)$$
$$R_{b,cal} = q_{b,k} \cdot A_b = C \cdot N \cdot A_b = 0.1 \cdot 38 \cdot 3.14m^2 = 11938\,kN \tag{5}$$

The limiting bearing capacity of pile shaft has not been calculated for the first 1.7 m, considering that in this part the pile is carried out in embankment. The limiting bearing capacity of pile shaft is calculated as follows (Shioi and Fukui, 1982; Decourt, 1982)

$$q_{s,k} = A + BN(kPa); \quad fine-grained: A = 10; B = 3.3 \quad coarse-grained: A = 0; B = 1.0$$
$$R_{s,cal} = q_{s,k} \cdot A_s = \sum_i (A + BN) \cdot A_s \tag{6}$$
$$R_{s,cal}1 = 394\,kN; \quad R_{s,cal}2 = 2078\,kN; \quad R_{s,cal}3 = 4841\,kN; \quad R_{s,cal}4 = 1176kN; \quad R_{s,cal}5 = 1744\,kN$$
$$R_{s,cal} = \sum_1^5 R_{s,cal} = 10234\,kN$$

In accordance with (SPT) results, the obtained limiting bearing capacity of the pile is

$$R_{c,k} = \frac{R_{b,cal} + R_{s,cal}}{\xi_{3,4}}; \quad R_{c;k} = Min\left\{\frac{11938kN + 10234kN}{1.4}\right\} = 15837\,kN \tag{7}$$

Results of the pile load test are presented in Figure 5. The suggestion in EC 7 is that the limiting bearing capacity of the pile is the value of the load that causes settlement of the pile which is 1 % of its diameter. In this particular case, where pile diameter is D = 2000 mm, load that corresponds to 20 mm settlement is approximately 17800 kN.

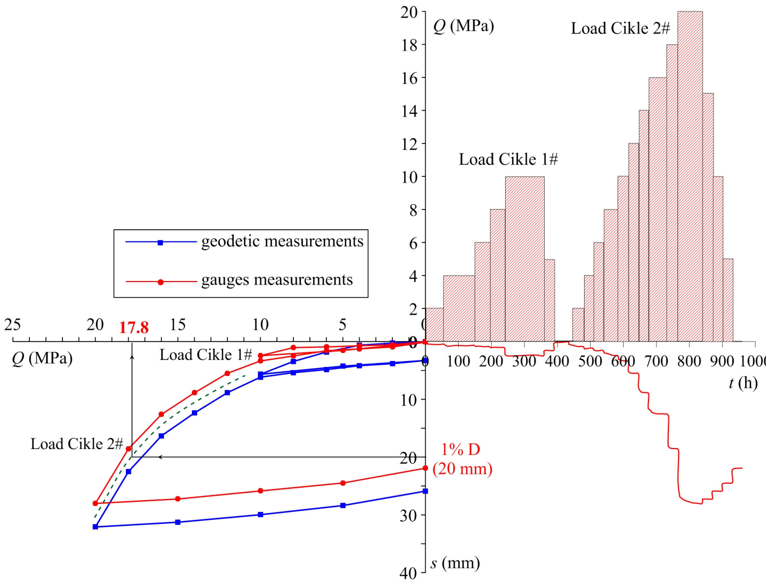

Figure 5. Results of a pile load test

Considering that only one pile load test has been carried out, the correlation factors are $\xi_1 = \xi_2 = 1.4$ and limiting bearing capacity is

$$R_{c;k} = Min\left\{\frac{17800\,kN}{1.4}\right\} = 12715\,kN \tag{8}$$

In accordance with the suggested design approaches, the obtained bearing capacity values have to be corrected with partial resistance factors (γ). In this paper, two approaches have been analysed (DA-1 and DA-2). However, within the DA-1 approach, two combinations of partial factors are possible. Values of allowable bearing capacity of the pile based on the analysed data are shown in Table 1.

Table 1. Allowable bearing pressure in pile dependant on calculation methods (kN)

Partial factors of resistance dependent on the applied approaches		Standard penetration test (SPT)		Pile load test
		R_d (γ_t)	$R_d = R_{b,d} + R_{s,d}$ (γ_b, γ_s)	R_d (γ_t)
DA-1	γ_t=1.15; γ_b=1.25; γ_s=1.0	13771	14132	11055
	γ_t=1.5; γ_b=1.6; γ_s=1.3	10558	10952	8475
DA-2	γ_t=1.1; γ_b=1.1; γ_s=1.1	14397	14397	11560

From Table 1 it can be seen that the obtained values vary in dependence of the applied approach. However, previous analysis did not show the effects of load, which are introduced into the calculations through partial factors on actions (γ_F). Ultimate limit state is checked for two possible combinations of partial factors on actions (factors A1 and A2, EC 7 1997-1, table A.3)–for the case of permanent action – partial factor γ_G and for variable action – partial factor γ_Q. Values of these factors, dependent on the applied approach, are shown in Table 2 with the remark that factors of unfavourable actions have been adopted. The analysis has been performed for permanent load G_k=7200 kN and for variable load Q_k=600 kN. Based on this, realistic safety factors have been calculated and the obtained results are shown in Table 2.

Table 2. Factors of safety depending on the method of calculation

Partial resistance factors dependent on applied approaches		F_c kN	Standard penetration test (SPT)		Pile load test
			FS (1)	FS (2)	FS (1)
DA-1	γ_G=1.35; γ_Q=1.5	10620	1.297	1.330	1.041
	γ_G=1.0; γ_Q=1.3	7980	1.323	1.372	1.062
DA-2	γ_G=1.35; γ_Q=1.5	10620	1.356	1.356	1.089

5 CONCLUSION

In accordance with EC 7 guidelines, the obtained results based on a pile load test results and standard penetration test (SPT) results have shown certain discrepancies. One of the possible reasons for such discrepancies is probably due to identical values of correlation factors ξ_1=ξ_2=1.4, which are used when only one pile load test is carried out and when correlation factors are ξ_3=ξ_4=1.4, which are used when terrain and laboratory tests define only one geotechnical model (Rakić, D. et al., 2010). However, the pile load test encompasses many factors influencing pile bearing capacity and eliminates unreliability of certain theoretical and empirical solutions. Therefore, in these cases, it would be justified to make corrections of these factors through the national annexes, either by reducing the factors ξ_1i ξ_2 or by increasing the factors ξ_3 i ξ_4.

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