MODERN SOLUTION FOR THE FOUNDATION OF POLAND'S LARGEST ARCH BRIDGE

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SUMMARY

The paper discusses the basic issues regarding the design, execution and execution supervising of the pile foundation of the arch bridge, the largest structure of that kind in Poland and one of the largest in the world. The slender arch without ties, with two spans of 270 m, has been founded on relatively short precast reinforced concrete piles with diameter of 400 x 400 mm, which is a unique solution for that class of structures. Tests and measurements carried out during the construction of the bridge proved the correctness of the design assumptions and possibility to apply precast piles in the foundations of large arch bridges loaded with significant vertical and horizontal loads.

Keywords: *Arch bridge, design, pile foundation, prefabricated reinforcement piles, sheet piles, driven piles, pile tests, piling works.*

1. INTRODUCTION

Experience is a great virtue of engineers. Yet, it is surpassed by their knowledge, which is based on the tradition dating from hundreds of years ago. While designing and supervising the execution of technically complicated foundations of two large road bridges over the Odra and the Regalica rivers in Szczecin, the designers from PONT-PROJEKT, the company from Gdańsk, made the first steps to design the foundations of one of the largest city bridges in Poland and in Europe (Fig. 1) [1]. Owing to the experience they had gained before, the unique design to found a large arch bridge on driven precast reinforced concrete piles was created, applying the solutions which had been tested in smaller structures.

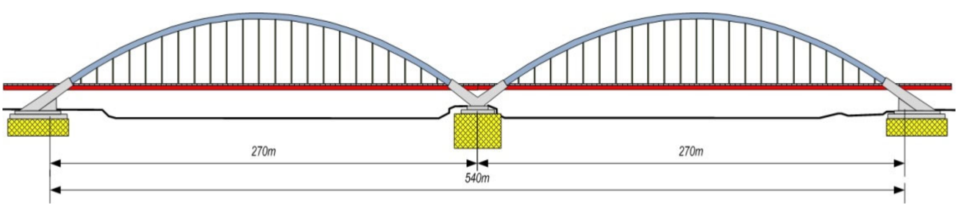

Fig. 1. Bridge scheme with the range of piling works.

The arches of the bridge in Toruń span the banks of the Vistula river using the natural sand dune which was transformed into an artificial island where the composite foundation of the central pier was performed. On the river banks there are the foundations combined of piles and piling sheets, transferring simultaneously huge vertical loads as well as even bigger horizontal loads. Foundation works with the use of steel sheet piles and driven precast reinforced concrete piles, as well as accompanying technological designs, were performed by AARSLEFF [2].

The effective application of driven precast reinforced concrete piles in the foundation of a large arch bridge without ties is undoubtedly a technological achievement. Moreover, it proves what has already been documented: that "small" piles have huge potential.

2. DESIGN ASSUMPTIONS

The Vistula river is a difficult obstacle to bridge. It is the largest Polish river, whose bed in Toruń is approximately 500 m wide and is featured by difficult sailing conditions due to numerous shoals caused by sands floating from the dam in Włocławek, located about 30 km away. The frequent changes in the condition of the river bottom modify the main current and the navigation route. Thus the administrative body (Regional Directorate of Water Management in Gdańsk) recommended that the number of bridge piers located in the river bed should be limited to minimum. Eventually the decision was made to bridge the river with two spans, with one pier located in the river bed. The final decision where to locate the river pier was preceded by the detailed analyses of navigability. A 30-year period of consecutive records was analysed to collect the information on the changes in the river current before the optimal location of the river pier was chosen. Another problem to solve was to minimize the impact of the river pier on the river bottom. The solution to be applied was an artificial spindle-shaped island with the length of 130 m. The longitudinal axis of the island goes along the river current, which is skewed by 12° from the axis of the central pier (the road crosses the river at the angle of 78°). The accepted location of the island fits the natural sandy shoal, which was proved by the simulations and the research into the changeable river bottom.

The decision about the shape of the bridge was taken much earlier. Toruń is a historical city, one of the UNESCO's World Heritage Sites, dating back to 1230. Its skyline, including numerous Gothic buildings and the Vistula river, strongly affects newly erected structures, also bridges. The existing bridges in Toruń are truss structures with characteristic parabolic upper chords. That was the reason why an arch structure was chosen as the most suitable so that it could perfectly match the skyline of the historical city of Toruń and its Gothic arches. The final choice was two continuous steel arch spans of 270 m each, supported with massive reinforced concrete abutments. The static diagram of a single span is a parabolic fixed arch without ties, mounted in piers. The deck is suspended from the arches. The crowns of both arches make the bridge a continuous structure. The final decision to adopt this solution was preceded by the analyses of other static diagrams, e.g. two- or three-hinged arches with ties, which, however, turned out to be less effective.

A significant issue in the architectural analyses was various shapes of central and end piers. (Fig. 2) [3].

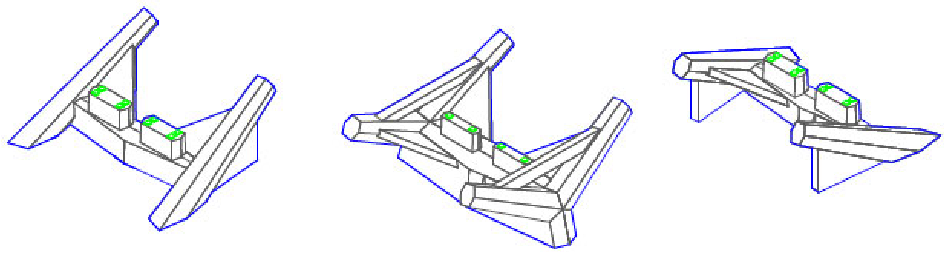

Fig. 2. Architectural forms of piers.

The adopted solution, i.e. fixed arch, had a positive impact on the development of the arch girders and enabled their optimal slenderness. The lack of joints and ties made it also possible to avoid the installation of huge bearings, to simplify the assembly while in the future it will significantly reduce the management costs. And last but not least, the effectiveness of a frail tie is limited in the assumed two-span structure and it provides transfer of only some of lateral thrust from the arches. Eventually it was decided that the abutments will transfer all the thrust stress, simultaneously blocking the possibility of girder rotation. Such a construction system needed the cooperation with the foundation and the structural integrity of work done by foundation, piers and arches. The design assumptions needed specific solutions for the foundation which was supposed to restrain gigantic lateral stress, nearly twice as big as the vertical stress from the span of 270 m.

3. SOIL AND BRIDGE FOUNDATION

Soil condition on the site is characteristic for the Vistula bed in the area of Toruń. The upper layer is made up of loose and medium-density sands. Below, at the depth of 5-8 m, there are silty sands, while at the depth of 20-25 m there is a thick layer of lignite silts. The latter was the cause of serious technological problems during piling works when the motorway bridge over the Vistula near Toruń was being constructed several years before. Thus it was a favorable solution to limit the depth of piling works and to locate pile foundation in the sands above the layer of silts. Driven precast piles seemed to be a perfect choice. The advantage was the possibility to incline piles which lets transfer the horizontal transverse reaction to the ground.

It was incredibly difficult to design the foundation in accordance with the design assumptions for the aforementioned soil conditions. The biggest problem was to transfer huge horizontal loads from the resultant reaction of the arch inclined at a 30° angle to the abutments. The inclination of the reaction from the arch is about 1:2, which technologically exceeds the possibility to incline driven piles (3:1). The characteristic horizontal reaction at the abutment is about 81 MN while the vertical component is 46 MN. The solution was to change the inclination of the reaction from the arch by adding the weight of massive abutments and crowns and their advantageous eccentricity location towards the system of piles. The interesting architectural forms of the piers analysed before were combined with their massive bodies. The changeable character of some loads (working load, temperature) and the resulting change in bending moments at the arch skewbacks cause the continuous change in the resultant reaction which had to be considered as an envelope. With the dominating permanent load the values of the envelope of the inclination angle were a few degrees. The similar rule was used while developing the central pier, where the piles are responsible for the transfer of the reaction resulting from uneven loads on both spans.

The bridge was numerically modelled as an integral structure made up of arches, massive blocks of skewbacks and precast piles. Piles were modelled in the elastic ground. The numerical model (Fig. 3) made it possible to assess the internal forces in individual piles at each state of load under analyses.

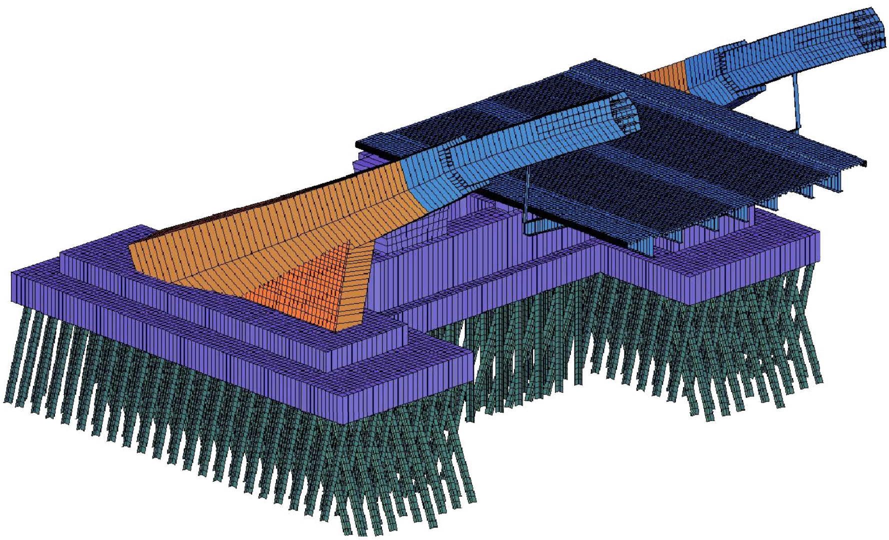

Fig. 3. *Numerical model of the end pier.*

4. CENTRAL PIER - ASSEMBLY OF THE BRIDGE

The method to assemble the spans of the bridge adopted by the contractor was different from the one adopted in the design assumptions. The design assumed the symmetrical assembly of the arches with temporary staying masts. The method was supposed not to evoke significant horizontal loads on the central pier, ill-suited to transfer such. The method adopted by the contractor provided for the sequential assembly of arch girders in individual spans in 2 months' time. The arches of both spans, with the weight of approx. 2,800 tonnes each, were assembled on the installation yard, and later on floated to the site on pontoons. That method evoked large, asymmetrical horizontal loads having impact on the central pier. The numerical analyses confirmed that the new assembly method was possible due to the significant total weight of the integrated central pier. Yet, the operation was still threatened with the high Vistula's level which could increase the buoyant forces affecting the piers and decrease the effectiveness of the ballast, limited at that construction stage, with the weight of the span. The acceptable water levels were calculated and they were monitored during the installation operation. Picture 4 shows the stage of arch installation which caused the most unfavourable load diagram for the central pier.

Fig. 4. Central pier - installation load.

5. CONSTRUCTION OF ARTIFICIAL ISLAND AND CENTRAL PIER

One of the design assumptions was to make active use of the Vistula bed natural features to erect a central pier. An artificial island (Fig. 5, Tab. 1) was constructed by surrounding a natural sandy shoal, located in the middle of the river bed, with sheet pile walls. Due to the changeable water level in the Vistula, sheet pile had to be constructed from a special floating rig which was stabilized with stilt supports (Fig. 5). The buoyancy of the rig enabled the progress of piling work with the use of vibrator hammer mounted at the mast of a heavy pile driver. With the use of such equipment the vibration of sheet piles provided the accuracy of sheet pile driving, which is of vital importance when work is carried out off-shore.

Fig. 5. "Closing" the perimeter of the island. Island steel perimeter. Floating rig with stilt supports, tugboat and vibratory pile driver.

Sheet pile vibration was accompanied by dredging and silting works, keeping the waterway navigable (the minimum depth necessary to carry out work is about 1.2 m) as well as the works protecting the island perimeter against undercutting. The latter also included performing an additional sheet pile wall making up a temporary starling (Fig. 6) and filling local undercuts with bags which formed a part of the target bottom protection in the vicinity of the artificial island. All these actions were a necessary reaction to the dynamic changes in the river bottom, so characteristic for the Vistula bed. The river bottom position often changed by several meters in a few hours' time.

Closing the steel perimeter enabled the progress of silting works which aimed at filling the chamber up to the first technological level, on which steel tie rods were mounted. Their positions had to be coordinated with the complicated geometry of the pile foundation made up of driven precast reinforced concrete piles, mostly inclined in various directions (Fig. 7 and Fig. 8). After a working rig was erected above mounted tie rods, the actual piling works could be commenced. The size of the island enabled carrying out work by a number of pile drivers at a time.

Table 1. *Technological parameters of the island hosting a central pier.*

Element	**Characteristics/value**		
Dimensions in plan	129.5 × 30.0 [m]		
Island area	2 636.8 [m^2]		
Section	Island perimeter	Starling core	Starling perimeter
Length of protection in plan	266 [m]	11,2 [m]	20,4 [m]
Sheet pile type	AZ18-700	AZ18	GU6N
Sheet pile length	17,0 [m]	14,0 [m]	13,0 [m]
Perimeter area	4522 [m^2]	156.8 [m^2]	265.2 [m^2]
Steel for sheet pile	S355GP		
Tie type	Rods		
Maximum stress in tie	805 [kN]		
Number of tie rods	51		
Total length of tie rods	1292 [m]		

A vital engineering task was to solve logistics problems, e.g. to provide the access for pile drivers, cranes and other construction machines to the island from floating vessels at changing water level. To this end, a special access pier was designed which later on served all the technological flow between the island and the land.

Piling works started with a research phase during which the design assumptions regarding pile capacity were verified and piles driveability was checked. The analyses of driveability took into consideration the need to drive a big number of piles in the limited area of the island without excessive deformations of the perimeter and overloading temporary tie rods. It was inevitable in such a situation, yet, assumed in the design that basic piling works were accompanied by soil compaction, unification of foundation conditions around the central pier as well as widening and shaping the steel perimeter which was technologically limited due to the system of tie rods. It was only during the basic piling works when the island was given its final shape which was within the tolerances set by the designer. When the piling works were completed, reinforced concrete caps of the pile foundation, the caps of the steel sheet pile walls making up the island perimeter and permanent tie rods were installed. Simultaneously, a range of hydrotechnical works were carried out in the vicinity of the island which are supposed, along with the precise location of the island in the river bed and its well-suited shape, to protect the central pier of the bridge against undercutting and provide it with predictable lifespan under unpredictable conditions of the Vistula bed.

The artificial island is a working rig, a hydrotechnical structure (waterfront) and a large composite structural element made up of the sheet pile perimeter with the cap, the system of sustainable reinforced concrete ties, natural and backfilled soil and the system of piles with caps. All the constituent elements of the central pier cooperate with each other making up some kind of supporting superelement. For the pile works, individual requirements were defined for every single component of that structure and every individual installation stage. However, the main aim of meeting those requirements was to provide structural integrity of the whole foundation used in the global analyses of the engineering structure.

Table 2. *Technological parameters of pile foundation.*

Pile foundation	**End pier No 14 (towards Toruń)**	**Central pier No 15**	**End pier No 17 (towards Łódź)**
Foundation dimensions	34.8m x 48.2m	20.4m x 52.4m	34.8m x 47.7m
Number of piles:	538	395	538
Cross-section of piles:	400 × 400 mm	400 × 400 mm	400 × 400 mm
Length of piles:	12m (10m+2m) 13m (11m+2m)	20m i 21m	12m (10m+2m) 13m (11m+2m)
Inclination of piles (range):	1:1 ÷ 3:1	1:1 ÷ 3:1	1:1 ÷ 3:1
Total length of driven piles:	6686 m	8068 m	6682 m
Pile concrete		C40/50	
Pile reinforcement	12ϕ12mm or 12ϕ12mm+8ϕ 16mm	12 ϕ12mm or 12ϕ12mm+8ϕ16mm	12ϕ12mm or 12ϕ 12mm+8ϕ16mm
Q_r [kN]	1015	1100(C) / 590(T)	1037
$R_{d,calc}$ [kN]	1390	1240(C) / 605(T)	1340
Number of load tests			
SLT	(C) 6	(C) 4 + (T) 1 = 5	(C) 6
DLT (A)	21	14	20
DLT (B)	70	60	74
Results of load tests - R_d w [kN]			
SLT	1700÷2129	2067÷2207(C)/667(T)	1770÷2605
DLT (A)	1496÷2717	1528÷2776(C)/ 756÷1244(T)	1187÷2495
DLT (B)	1801÷3407	1570÷2637(C)/ 612÷1454(T)	1620÷2538

Key: SLT – static load testing of pile capacity, DLT – dynamic load testing of pile capacity at large displacements, (A) – before pile, (B) – after pile, (C) – press test, (T) – pull-out test, Qr – pile load, $R_{d,calc}$ – calculated capacity, R_d –tested capacity

Fig. 6. *The island after the completion of piling works.*

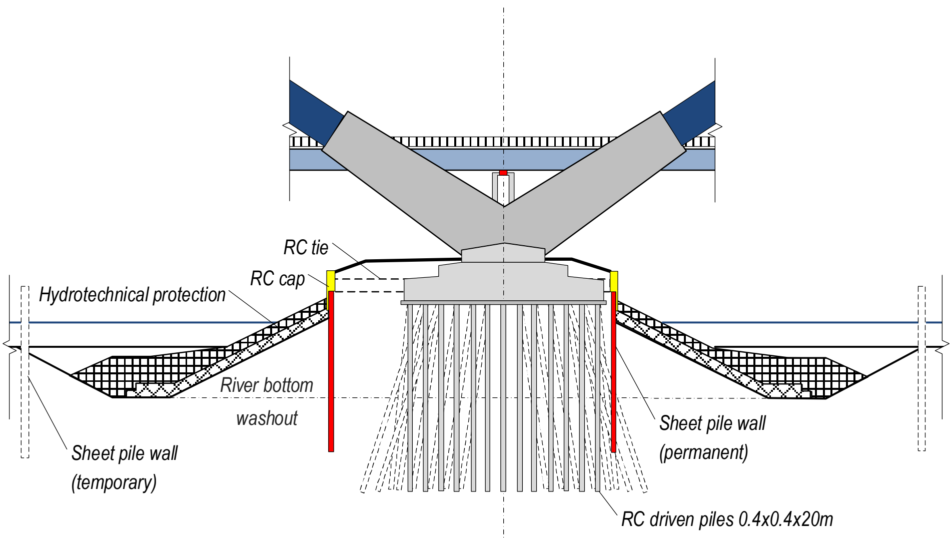

Fig. 7. *Schematic diagram of pile foundation of central pier.*

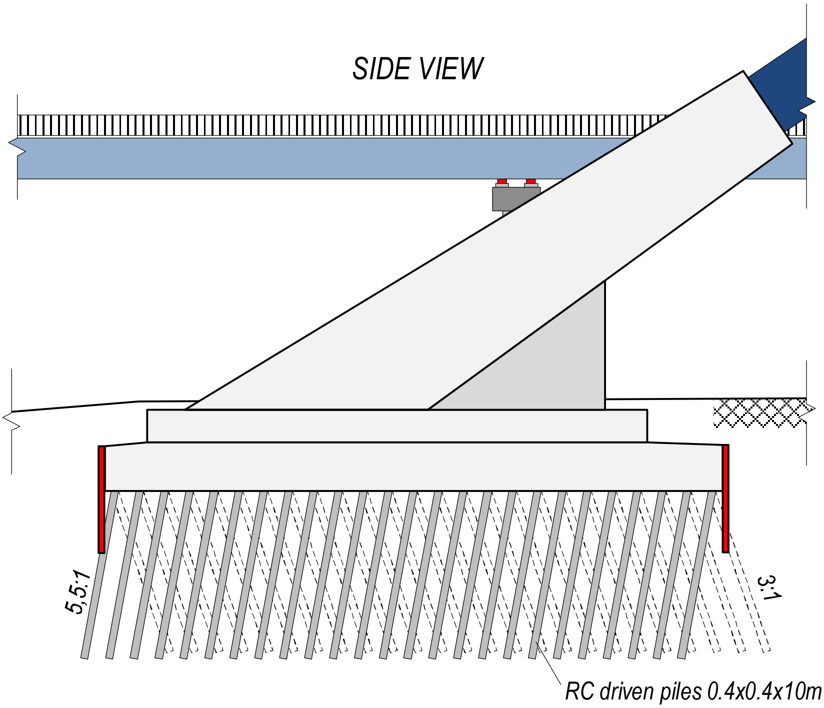

Fig. 8. *Schematic diagram of pile foundation of end pier.*

6. CONCLUSIONS

Performed foundation works become valuable only after they go through verification process, i.e. engineering tests and measurements. During installation a series of pile capacity tests were carried out (pile capacity tests preceding basic pile works), technological tests were performed (test piles for driveability analyses) as well as as-built tests (tests of pile capacity carried out at random or on piles pointed by the supervisory body). Static and dynamic capacity tests were performed for approx. 25% of piles. Moreover, the evaluation of total capacity of all piles was obtained from the analyses of driveability parameters. Horizontal capacity of the foundation was verified on the construction site by means of displacement measurements which were updated in the course of the installation. In case of such a large engineering structure technological phases and the evoked reactions have a vital impact on the solutions applied in foundations, thus the displacement measurements for piers taken in the course of works are practically the result of horizontal test load for the foundation. Measured vertical and horizontal displacements of piers are insignificant and they fall into the tolerances assumed in the design. The most unfavourable horizontal load during the installation of the first arch span resulted in an average horizontal pier displacement of 6 mm against 13 mm set in the design. Owing to the applied structural and technological solutions for the pile foundation, the obtained values of horizontal displacement are over 10 times safer than the acceptable values calculated analytically.

In case of the bridge in Toruń driven precast reinforced concrete piles which make up the pier foundation are only a part of a greater whole. The adopted piling technology actively facilitated the foundation conditions for each foundation. The soil under the piers was mainly sands o varied density. The use of driven precast piles enabled the unification of soil in the vicinity of the piers and improved the conditions for foundation. The system of inclined piles applied on a large scale enabled the transfer of significant forces to the ground.

The analyses of the foundations presented above was carried out in two stages. At the first stage all the foundation body was analyzed (aforementioned superelement), and then its internal structural system including precast piles was shaped in such a way so that it could work properly in the whole system. Thus, in case of the discussed engineering structure it is difficult to call the pile foundation a classical example. Piles rather make up a component of larger structural systems which are the foundations of that huge bridge. The innovativeness of the solution discussed in this paper consists in:

- an unconventional and total use of individual features of driven precast reinforced concrete piles and
- intelligent matching of structural (along with controlled transfer of loads from the arches to the ground) and architectural development of piers.

Atypical pile foundations along with the other applied structural and technological solutions resulted in the construction of an expressive slender bridge which is characterized by its clear and correct structural form.

So far many more interesting pile works for large bridges have been executed in Poland using precast reinforced concrete piles. Yet, all the applied solutions are not as complicated and innovative as the solution presented in this paper and applied in the construction of the bridge in Toruń. However, they confirm that small piles have immense possibilities.

REFERENCES

[1] PONT-PROJEKT. Projekt budowlany, projekt wykonawczy, projekt montażu mostu łukowego przez Wisłę w Toruniu, Gdańsk, 2008-2012.

[2] SOBALA D. and others, Żelbetowe pale prefabrykowane wbijane w fundamentach mostu łukowego przez Wisłę w Toruniu, *Wrocławskie Dni Mostowe*, Wrocław, 2015.

[3] WĄCHALSKI K. CYWIŃSKI Z., Die neue Straßenbrüke in Toruń, Poland, Teil 1: Planung und Bau. *Stahlbau* (84) 4/2015, pp. 267-274, Ernest & Sohn.