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TECHNICAL CONDITIONS OF THE UNIQUE STRUCTURE OF INVERTED SIPHON – HISTORY & PRESENT

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Abstract

An inverted siphon is sometimes used to enable a watercourse to pass under an obstacle. Such solution is usually applied for irrigation and sewage canals, but it is rarely observed in the case of rivers. There are two such passages in Poland the bigger one is the Klodnica River siphon under the Gliwice Canal, commissioned in 1936. The first part of the paper presents the history of the Gliwice Canal and, simultaneously, of the Klodnica River siphon. The further part describes the structure of the siphon and its usage assumptions as well as the technical condition of the construction after nearly 80 years of operation, including inspection results concerning the underwater parts. The description is supplemented with results of chemical examinations. Basic repair recommendations are also provided.

Keywords: **Inverted siphon; Watercourse crossing; Structural damage; Concrete; Corrosion; Long-term utilization.**

1. INTRODUCTION

If two surface watercourses meet in natural conditions, they merge into one because they run on the same level. Thus, there are no watercourse crossings in nature which would allow one to study the natural solutions and reproduce them in the technical solutions. A certain exception here is a crossing of an aboveground watercourse and an underground one or a crossing of two underground watercourses (in karst lands), but such cases are extremely rare. The crossing of the Nielba River and the Welna River near Wagrowiec (Poland) is one of two such phenomenon in the world. Both rivers were created artificially during the melioration works in 1930. A concrete weir was built here, which makes the water set in a whirling motion and causes that the water does not mix with each other. This solution was designed by Adalbert Schulemann to protect the city against flooding.

The necessity for a crossing of two independent aboveground watercourses arises when at least one of them is an artificially created structure, further referred to as a canal. The specificity of the solution for such crossing depends on the size of the watercourses and their level difference (this concerns both the water table levels and the bottom levels).

One applied solution is a two-level crossing, with the higher watercourse running along an aqueduct, which structure is located above the upper water table level of the lower watercourse. An impressive example of this solution is the Magdeburg Water Bridge leading the Mittelland Canal (German: Mittellandkanal) over the Elba River near Magdeburg. It is the largest structure of this type in Europe: it is 918.2 m long and its greatest span length equals 106.2 m [1]. Its construction lasted from 1998 to 2003 and cost approx. 500 million EUR. A similar structure (the Minden Aqueduct), with a length of approx. 370 m, had

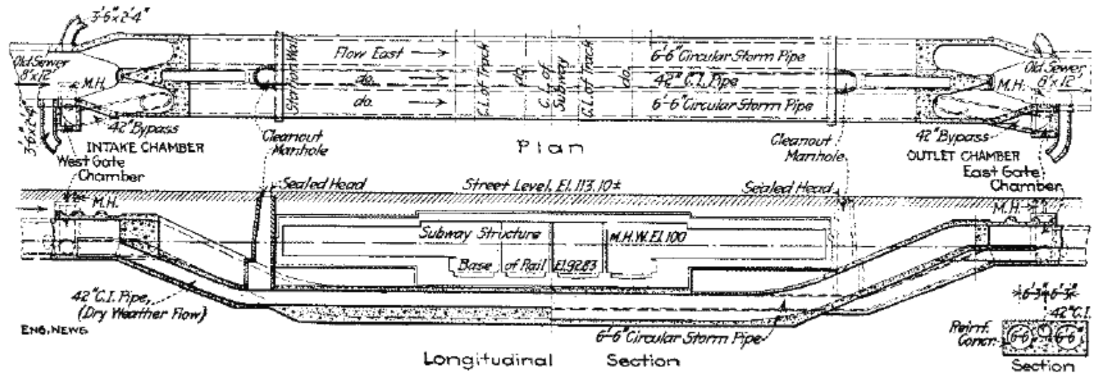

Figure 1.
The view of the inverted siphon under the subway at 110th Street in NY [3]

already been built in the years 1911–1914 to lead the Mittelland Canal over the Weser River near Minden [2]. It was destroyed during World War II, then rebuilt in 1949 and finally modernized.

However, if the water surface level difference between the canal and the river is too small (i.e. when the river does not have enough space under the canal bed), the abovementioned solution is impossible to implement. The only possibility in such situation is an inverted siphon, which allows for leading one watercourse under the bottom of the other.

A similar solution is sometimes applied if the watercourse (natural or artificially created) passes under a different obstacle, such as deep foundations or important communication object – as in case of the large sewers, which have been passed under the subway by means of siphon at 110th Street in New York (Fig. 1 – reprinted from the [3]).

The inverted siphon is also built to lead an irrigation channel (e.g. Yuma Siphon under the Colorado River [4]) or a sewer system under a river bed (e.g. Middlesex Canal under the Mystic Lake in Winchester [5]), or to provide protection against flooding (San Antonio River Flood Tunnel and San Pedro Creek Tunnel [6]). However, such solutions are rare due to their construction cost and operation problems, especially those concerning accumulation of deposits which reduce the flowing capacity of the canal. Further usage problems are related to weather conditions. They concern the frazil ice and ice jamming during ice period. The ice accumulation process at the inlet of the inverted siphon is problematic and required special analysis to prevent the ice jamming and to ensure the safety both of the structure and the water conveyance-system, especially in mountains [7, 8].

The siphon consists of an inlet and outlet structures, and a closed conduit pipe which is able to withstand all loads from outside (depending of the object located above) and the hydrostatic pressure from inside. Additionally, at the inlet and outlet of a siphon the transitions for changing cross sections are demanded. This allows to reduce head losses and to prevent erosion in unlined canals [9].

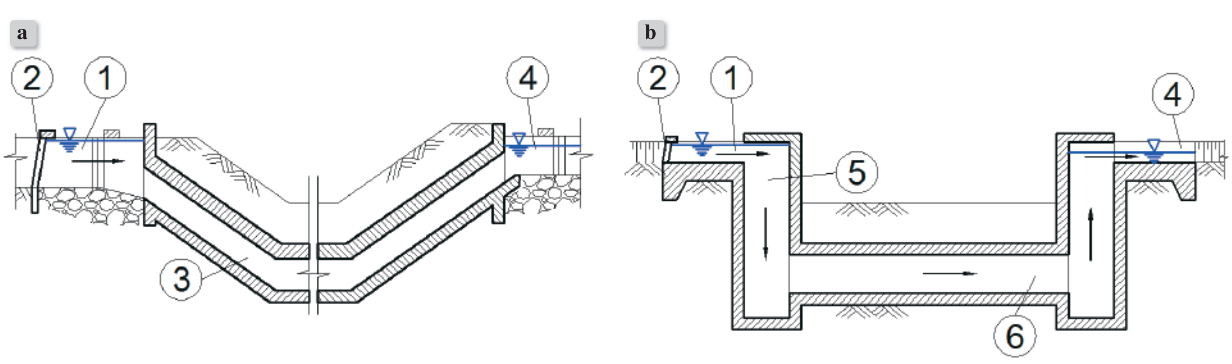

Figure 2.
Layout of inverted siphon [9]: a) inclined, b) shaft. 1 – inlet, 2 – operating bridge, 3 – conduit pipe, 4 – outlet, 5 – shaft, 6 – horizontal conduit pipe

According to the topography and flow discharge two types of conduit pipe – inclined or shaft (Figs. 2a and b) – are adopted. The first solution is used when the main watercourse intersects with road or other canal and their elevation difference is small. The inclined conduit pipe is widely employed in small and short inverted siphon, where the pipe slope should not be steeper than 2:1. The shaft conduit pipe is applicable for small flow discharge and low head at 3–5 m; it is simple in construction but worse in flow pattern. Generally, inlet and outlet should be so layout to meet the requirements for hydraulic conditions, reliable operation, sufficient resistance against sliding and scouring, etc [9].

Inlet and outlet construction availability, allowable siphon velocities and also the economy determine the size of the siphon [10]. Thus, it is necessary to assume internal dimensions for the siphon and compute all head losses such as entrance, friction, bend, and exit. The sum of all the computed losses should approximate the difference in energy grade elevation between the upstream and downstream ends of the siphon (available head structures). In general, siphon velocities should range from 1.07 m/s to 3.05 m/s, depending on available head and economic considerations. To avoid sedimentations, the minimum velocity that is considered is 0.6 m/s [10, 11].

There are two inverted siphons in Poland as well: the crossing of the Klodnica River with the Gliwice Canal (described in this paper) and the crossing of the Flis Stream with the Bydgoszcz Canal. The third Polish watercourse crossing is the aqueduct in Fojutowo, where the Czerska Struga River flows under the Brda Great Canal.

One should be aware that the use of siphons in water transport solutions has a long history because they were first applied in antiquity [12].

2. HISTORY OF THE KLODNICA CANAL

The water route connecting the Upper Silesia with the Odra River was created due to increasing coal extraction in the Luiza mine in Zabrze and in the Krol mine in Krolewska Huta (today: Chorzow) as well as the plans of transporting it westwards. Since Gliwice lies on the Klodnica River (the biggest river in the region), it was considered as the best location for the final port.

The first plans concerning the construction of a canal connecting Gliwice with the navigable part of the Odra River were developed in the final years of the 18th century. That initial project anticipated the Klodnica River regulation (1788), but a project of an actual canal connecting Gliwice with Kozle (so-called Klodnica Canal, or Klodnitzkanal) was developed just a year later. Canal construction began in 1792 and ended in 1812, but the individual sections had already been used before the completion date. The Klodnica Canal was 46 km long, 12 m wide and approx. 0.6 m deep. In 1822, it was dredged and its depth reached 1.6 m, allowing for the use of barges with a load capacity of 140 tons. 18 locks were built along the canal. They were wooden at first, but then they were gradually replaced with brick ones. The locks allowed for overcoming the level difference reaching 49 m. The canal was extended to reach Zabrze as early as during its construction.

The glorious period for this water route was the middle of the 19th century, when the total weight of transported goods reached 73,500 tons downstream and 14,600 tons upstream (the volume anticipated during the construction was 22,000 tons). However, the significance of the Klodnica Canal started to decline as early as in the second half of the 19th century. The reason was the increasing popularity of railway transport. Moreover, technical parameters of the canal proved insufficient with time, causing excessive costs of transportation on relatively small barges. The next peak fell on the years 1915–1923; in 1920, a record volume of 130,000 tons of goods (mainly coal) was transported downstream.

As the railway transport was becoming increasingly competitive, it forced the use of barges with greater load capacities for inland navigation. In 1917, the Odra River section downstream of Kozle was adjusted to barges with a load capacity of 500 tons and it was planned to introduce barges with a load capacity of up to 1,000 tons. In such situation, the Klodnica Canal parameters proved insufficient. The Gliwice – Zabrze section was liquidated first (in 1916), while the Gliwice section of the canal was liquidated in 1936 together with the port. Two bridges remained in the Gliwice city centre till 2014, when they were liquidated during the construction of the Silesian Central Highway.

The above-mentioned standards of the barges flowing along the Odra River downstream of Kozle forced the design and construction of a new canal the parameters of which would allow those big vessels to navigate it. The Gliwice Canal (German: Gleiwitzer Kanal, Oberschlesischer Kanal, Adolf-Hitler-Kanal) was designed partially in the location of the Klodnica Canal, but it reached a new port situated north-west of the city centre, beyond the area of the city itself.

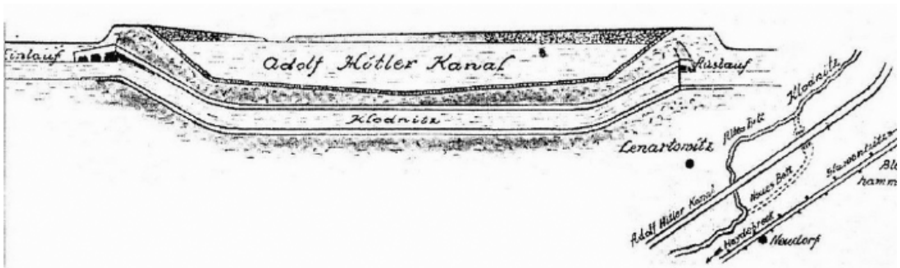

Figure 3.
The cross-section of the crossing and the location of the Klodnica River [16]

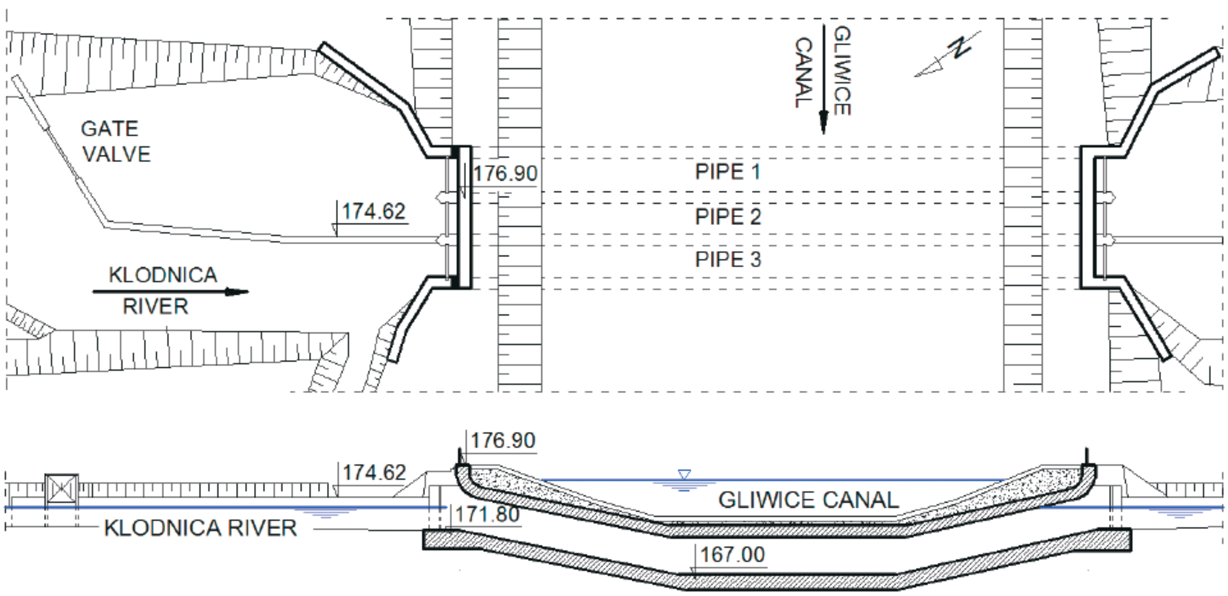

Figure 4.
The view and cross-section of the Klodnica siphon

The first preparatory works began near the end of 1933, while the construction officially commenced on May 14th, 1934. The Gliwice Canal was commissioned on December 8th, 1939 and became fully navigable in 1941 after the removal of results of two serious breakdowns. It is 40.6 km long, its width ranges from 38 m (on the excavation level) to 41 m (on the embankment level) and its depth equals 3.5 m. Those parameters made it possible to use identical barges as those flowing along the Odra River. Six locks were built along the canal; they allow for overcoming the level difference reaching 43.6 m. The canal is classified as one of the most important water routes in Poland [13, 14, 15].

One of the unique solutions along the Gliwice Canal is its crossing with the Klodnica River, built as an inverted siphon and known as the Klodnica siphon.

3. DESCRIPTION OF THE KLODNICA SIPHON

The canal runs along an embankment in the place where it crosses the Klodnica River and the water level difference between the two watercourses reaches approx. 2.5 m, which made it impossible to build an aqueduct because the rated depth of the Gliwice Canal is 3.5 m. Thus, the designers decided to build an inverted siphon under the Gliwice Canal bed. The anticipated cross-section of the siphon was supposed to pass the entire water flow, also during floods. The crossing was built beyond the original bed of the Klodnica River and then the river course was changed (Fig. 3). A service road runs over the siphon in addition to the canal bed. The rated flowing capacity of the siphon was established at 120 m^3/s – a significantly higher value than the normal flowing capacity (estimated during structure designing at

30 m^3/s) plus the flood state value (50 m^3/s). This means that the designers assumed a 50% flowing capacity reserve and transferring the possible surplus to the canal via a permanent spillway [13].

In structural terms, the siphon was built as a monolithic reinforced concrete structure ending with heads both on the inlet and outlet side. Its length measured along the axes of the gates is approx. 56 m (an approx. 20 m long horizontal middle part as well as the inlet section and the outlet section with an inclination of 1:5). The transverse section of the siphon consists of three square pipes (each with a 3.0 × 3.0 m cross-section) with cut corners. The structural elements are approx. 0.8 m thick. The head elevations reach +176.9 m, the siphon bottom elevation at the water inlet is +171.8 m and the siphon bottom elevation in the lowest spot equals +167.0 m. The parameters are presented in Fig. 4.

The structure was built in an excavation performed inside Larssen sheet pile walls. The same piles were used to frame the structure inlet and outlet as well as the embankment sections at the siphon inlet and outlet. Figures 5 and 6 present the general view of the construction of the siphon, from the east and south side, respectively.

The concrete works concerning siphon construction were completed in May 1936, while in August 1936, the Klodnica River waters were directed to the siphon via a new bed and old river bed liquidation commenced [13].

During normal operation, the entire water flow is directed to pipe No. 3. The two remaining pipes are filled with water, but do not work. This is ensured by a Larssen sheet pile wall which prevents water from flowing into pipes No. 1 and 2. It is possible to let water into those pipes purposefully by lifting the gate valve in the wall. During a flood, excess water flows into them over the wall coping. The last time the latter happened was during the 1997 flood. The described solution was anticipated to prevent the siphon from becoming silted up during low water levels by forcing a relatively fast flow through the lower pipe. The inlets and outlets of the three pipes were equipped with baffles installed in previously performed cuts. They were aimed not only at providing access to the individual pipes (after pumping the water out), but also at washing out the silt (by making the dammed-up water flow through after their sudden opening).

An interesting historical fact is the cost of the siphon (together with the local change of the Klodnica River bed) estimated at 625,000 marks, it was relatively high in comparison with the cost of the entire investment, estimated at approx. 44,000,000 marks [13].

4. TECHNICAL STATE OF THE STRUCTURE

The siphon structure has not virtually been improved since its commissioning, i.e. since 1939. Therefore, its present technical state reflects nearly 80 years of its use in very unfavourable conditions and exemplifies the durability of concrete and steel structures.

4.1. Reinforced concrete structure

The concrete grade was assessed using sclerometric method [17–19], which was calibrated on destructive laboratory tests [20]. The performed material tests classified the concrete in the structure as C16/20 or C20/25 with a good homogeneity. These values identified a concrete type of rather low strength, but, in each case, the quality and concrete texture (visually assessed) are suitable to perform any repair work. However, the key issue concerning the described structure was its operation conditions: permanent flooding of the siphon part with water and exposure of the part above the water level to variable humidity and negative temperatures.

The technical state of the structural elements permanently underwater was very good and showed virtually no damage. The only exception was slight damage at the inlets to the individual pipes, caused by flowing tree trunks hitting them during floods. The uncovered rebars underwent corrosion in this spots (Fig. 7). Interestingly, the transverse expansion joints of the individual pipes showed no leaks from above (Fig. 8), which proves that the Gliwice Canal bed insulation was perfectly performed and is still effective (according to [13], the canal bottom section above the siphon was sealed with a loam layer, while the structure itself was insulated with bituminous materials; according to [15], full watertight facing of the bottom was applied only on a 200 m long section of the canal beyond the siphon zone and had the form of a basalt breakstone skeleton filled with a liquid mixture of mastic asphalt and covered with a layer of sand asphalt concrete with a thickness of approx. 30 mm).

Pipe No. 3 (the one used on a daily basis) was not silted up, but there was a layer of stones carried by flood waters on its bottom. Pipes No. 1 and 2 (the unused ones) were heavily silted up, which hindered access to certain concrete surfaces. The described observations

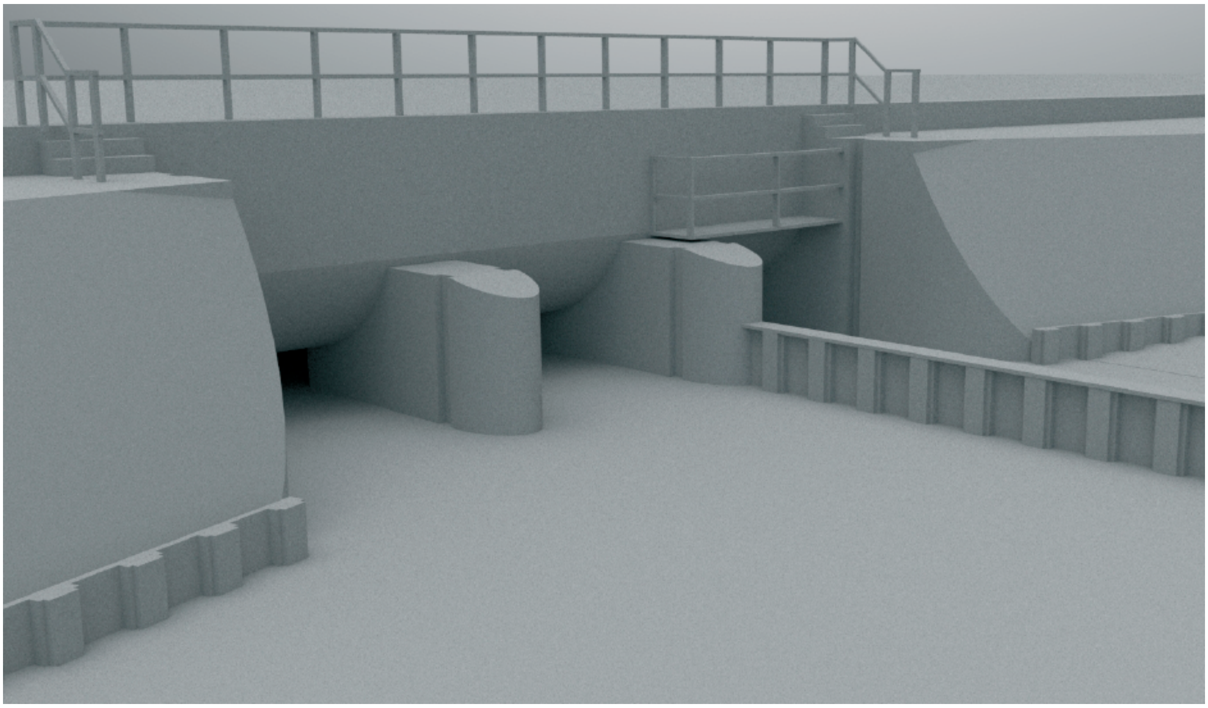

Figure 5.
Visualisation of the siphon from the east side (inlet)

Figure 6.
The general view of the siphon from the south side (outlet)

Figure 7.
Damaged inlet of the duct with corroded reinforcement

Figure 8.
The expansion joint with no leak of water above

Figure 9.
Destroyed surface of the concrete

Figure 10.
Destroyed surface of the concrete with the streaks of acid calcium carbonate

are fairly typical of concrete elements remaining permanently underwater. This may be caused by lowered permeability of the concrete cover after a certain time spent underwater [21] as well as by limited underwater contact with oxygen, carbon dioxide and other harmful elements or chemical compounds.

The technical state of all the reinforced concrete elements of the part above the water was much worse: the surface layer of their concrete was destroyed to a large extent; in certain spots, deeper concrete layers were destroyed as well (Figs. 9, 10). The deeper damage was accompanied by reinforcement corrosion. The structure part above the water has been exposed to a constant impact of its surroundings for nearly 80 years. That impact has shown great variability, especially in the scope of temperature and humidity. Such conditions are highly unfavourable to concrete structures, so the majority of the observed damage is corrosive and perfectly natural in those circumstances. However, the effects of the corrosion affecting the surface layer of concrete are strengthened by the damage caused by a volume increase of corroding reinforcement inserts. This results in negative synergy of the destructive effects of concrete and steel corrosion. It must be highlighted that the Klodnica River was heavily polluted with industrial wastewater for many years, which intensified the aggressive action of water on the structural materials.

Certain parts of the concrete surface were densely overgrown with moss and lichens, which also contributed to the material surface destruction due to biological corrosion. Moreover, the edges of the heads and walls showed many traces of mechanical destruction caused by flowing objects hitting them during floods and by the roots of trees growing along the canal which gradually made them burst.

The basic properties of concrete in the cover layer were determined by performing tests of collected samples in the scope of pH reaction as well as the content of sulphate and chloride ions. The samples were collected from two spots on the structure – on the outlet and inlet side. They were ground and dried until they became a solid mass (at a temperature of +105°C) and then appropriate weighed samples were boiled in water (to measure the pH reaction and the chloride ion concentration) and in a hydrochloric acid solution (to measure the sulphate ion concentration). Three samples were tested each time and the results were averaged out.

The pH reaction was measured in the solution using an Elmetron CP411 pH-meter. The obtained result for the outlet cover is pH = 9.77 and that for the inlet cover is pH = 12.09. The former value is much below the borderline pH value (11.8), which means that the passive layer protecting the reinforcing steel against corrosion was destroyed and that the carbonatization degree constitutes a real corrosion hazard even for correctly covered reinforcement. The latter value shows that the concrete meets the condition of reinforcement protection against corrosion (only in the places where the concrete structure is correct and its continuity has not been broken).

The sulphate (SO_4^{2-}) and chloride (Cl^-) ion content was measured in the solution using a Dionex ICS-5000 ion chromatograph. Sulphate corrosion is caused by sulphate anions present in water coming from industrial processes, wastewater, sea water and groundwater. Sulphate anions penetrate concrete and react with hydrated calcium aluminates coming from cement hydration. This creates ettringite or gypsum, which are characterized by poor solubility and a significant volume increase. Salt crystallization in concrete pores may completely destroy the concrete structure. The permissible borderline value of sulphate SO_4^{2-} ion content in cement is 3%. The samples collected from the structural elements of the siphon contained 0.223% of sulphate ions on the outlet side and 0.591% on the inlet side (percentage by weight in relation to concrete mass). This gives approx. 1.8% and approx. 4.7% respectively after conversion to percentage by weight in relation to cement mass. In the latter case (the inlet side), the borderline value is significantly exceeded, which means a significant hazard of sulphate corrosion.

Chloride ions contribute to corrosion of reinforcing steel in concrete. The standard [22] imposes 0.20% or 0.40% as the borderline value of chloride content in reinforced concrete structures in relation to cement mass. The chloride ion content measured on the outlet and inlet side reached 0.002% and 0.02% respectively in relation to concrete mass. This gives approx. 0.016% and 0.16% respectively after conversion to cement mass. Those values do not exceed the lower of the two values permitted by the standard. This observation is interesting taken into account the fact that the Klodnica River, which feeds the Gliwice Canal, used to carry heavily saline groundwater from mines because it was discharged to that river for years.

Figure 11.
Strong corrosion of the steel sheet piles (inlet side)

Figure 12.
Bad condition of the steel sheet piles (outlet side)

4.2. Steel elements

The described structure features Larssen steel sheet piles as stay-in-place bottom formwork of the heads. They were used to make a wall separating pipes No. 1 and 2 from flowing water during normal operation and a short wall reducing water whirling next to the outflow of pipe No. 3.

The technical state of the steel sheet piles in all those elements was very bad; some of them were completely destroyed (Figs. 11, 12). The walls were later reinforced with sheet metal in many spots, but it also underwent complete corrosion. The most significant damage was observed close to the water surface, i.e. in the zone of variable exposure of the elements to contact with water.

When analysing the results of chemical tests of concrete, one can observe a significant concentration of sulphate (SO_4^{2-}) ions, which probably partially come from the heavily polluted waters of the Klodnica River. These are undoubtedly not the only aggressive factors in the water because the Klodnica River collected industrial wastewater from numerous Upper Silesian plants for years, which explains the observed corrosion of the steel elements.

5. ASSESSMENT OF THE STRUCTURE STATE AND RECOMMENDED ACTIONS

Given the technical state of the structure and the excellent quality of concrete in the underwater (siphon) part, the latter may be operated virtually without repairs. The local damage from the inlet side of pipes No. 1 and 2 caused by hitting objects is an exception here. Those spots require local repairs using any PCC (Polymer Cement Concrete) system.

The state of the external parts of the structure (those above the water level), especially the heads and the endings of the partitions between the pipes, is much worse because they show highly advanced corrosion of concrete and rebars. That damage does not constitute a breakdown hazard for the entire structure due to its location, but its scope must be treated as serious. Therefore, those elements require comprehensive repair and protection. Special attention should be paid to the necessity of removing the weakened or degraded cover fragments, removing the corrosion products from the reinforcement, filling in the excessive reinforcement losses and correct reprofiling of the elements. It is extremely important to adjust the repair system to the substrate parameters (due to the relatively low concrete durability) and to the structure operation conditions. It is recommended to perform hydrophobization of all the concrete structures after repairing them.

The sheet pile walls are damaged to a varying extent; some of them are completely destroyed. They require a comprehensive improvement or, preferably, replacement (if they are necessary from the operation point of view).

A project concerning a comprehensive improvement of the siphon structure was implemented in the first half of 2017; it included replacement of all the sheet pile walls as well as clearing and reinforcing the river banks downstream and upstream of the siphon. Project implementation is anticipated for 2018 or 2019.

6. SUMMARY

The inverted river siphon structure presented in the paper is neither big nor complicated. Despite that fact, it is a unique solution not only in Poland, but also in Europe and even worldwide. Although significantly damaged, the siphon structure also proves the durability of reinforced concrete used for several decades in extremely unfavourable conditions. All this makes that structure worthy of improvement works which will ensure its appropriate technical state and durability and at the same time retain its similarity to the original structure to the extent possible. The Klodnica siphon, just like the entire Gliwice Canal, is a proof of the excellent technical thought from the beginning of the 20th century. Thus, it should be treated as a monument and the evidence of the technical mastery demonstrated by the previous generations. That structure simultaneously has undiminished practical significance as it constitutes one of the elements which allow for breakdown-free use of the ever important water route – the Gliwice Canal.

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