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ANALYSIS OF THE TECHNICAL CONDITION OF THE SEWAGE COLLECTOR WITH THE USE OF NUMERICAL SIMULATION

ANALIZA STANU TECHNICZNEGO KOLEKTORA ŚCIEKOWEGO Z WYKORZYSTANIEM MODELOWANIA NUMERYCZNEGO

Abstract

This article presents a comprehensive analysis of the technical condition of the sewage collector located under Krakowska Avenue in Warsaw. The cross section of the collector is an extended ovoid with the dimensions of 1400×800 mm. Current operational problems as well as the reasons for specific faults and failures were discussed. The numerical models generated according to the collected data and the technical documentation were presented. Boundary and initial conditions taken into account in the analysis process and the assumed calculation scenarios were also described. The results obtained as well as the considered modernization projects, along with selected optimal technical solutions, were discussed.

Keywords: numerical simulation, sewage collectors, geotechnics

Streszczenie

W artykule przedstawiono kompleksową analizę stanu technicznego kolektora ściekowego o przekroju jajowym podwyższonym i wymiarach 1400×800 mm, znajdującego się pod Aleją Krakowską w Warszawie. Omówiono obecne problemy eksploatacyjne, wraz z podaniem przyczyn występowania konkretnych usterek i awarii. Zaprezentowano wygenerowane na podstawie zgromadzonych danych oraz dokumentacji technicznej modele numeryczne obiektu. Przedstawiono uwzględnione podczas analiz warunki brzegowo-początkowe oraz przyjęte scenariusze obliczeń. Omówiono uzyskane wyniki oraz możliwe metody modernizacji kolektora, wraz z doborem optymalnej technologii.

Słowa kluczowe: modelowanie numeryczne, kolektory ściekowe, geotechnika

1. Introduction

All building materials undergo changes and wear. Their parameters are variable in time. The intensity of changes depends on many factors, including project assumptions, appropriate selection, working conditions and detrimental factors that they are exposed to.

The considered collector was raised in the '60s and '70s of the 20th century. It was constructed according to the assumptions of the trenchless tunneling method. The cladding was constructed of reinforced concrete. The construction is elaborated and characterized by the combination of co-working diverse building materials. It should be taken into consideration that the production quality was usually not splendid at the time. Building processes were carried out quickly and efficiently, but obligatory standards were often omitted. What is more, during the forty years of the collector's operation, the construction was constantly exposed to varied detrimental factors.

Factors that are harmful to the collector can be divided into the following three types:

- ▶ mechanical factors
- ▶ physical factors
- ▶ chemical factors

In addition, corrosion processes should be taken into consideration. This process can pose a considerable danger for the cooperation of concrete and steel. In practice, particular factors causing corrosion often occur at the same time. This situation is additionally complicated by the fact that particular parts of the construction are exposed to detrimental factors to varying degrees.

In short, the assessment of technical condition of the construction is a complex assignment, which requires analyzing various processes and phenomena.

2. The object of research

The object of conducted researches and analysis is the bricksewage collector constructed at the end of the 1960s and the beginning of the 1970s, located in Warsaw between Malownicza Street and 1 Sierpnia Street (Fig. 1).

Technical data of the object were obtained from the technical documentation, which had been made available by Warsaw Municipal Water Supply and Sewerage Company (MPWiK). Documentation studying was problematic due to the age of the object and the then methods of technical documentation elaborating and archiving. The difficulties were caused by a diversified level of detail in the documentation, including picture data, which were sometimes significantly inconsistent and different from each other. The situation was additionally complicated by the numerous changes and reconstructions of the collector over the years of operation. For the purposes of this analysis, the most probable technical data of the collector, confirmed in field researches, were assumed.

The considered collector with an extended ovoid cross-section and the dimensions of 1400 × 800 mm was constructed with the use of the trenchless tunneling method. The

cladding was constructed of A-type facing, made of prefabricated reinforce concrete boards with the dimensions of $125 \times 11 \times 6$ cm, 6 cm thick wooden wedges and T-beam shaped steel frames with the dimensions of $11,5 \times 13$ cm. The steel frames were supported on the base constructed of wooden beams with the dimensions of $135 \times 20 \times 24$ cm. The walls of the collector were built of two layers of “150” class sewer brick and “80” mark mortar. According to the project assumptions, the space between the brick layer and the reinforced concrete cladding was filled with concrete of $R_w = 140$ at. Corresponding construction schemes of the collector were presented in Fig. 2.

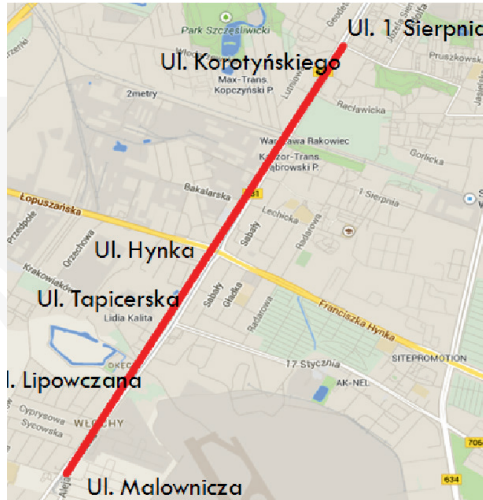


Fig. 1. Construction scheme of the collector (source: own elaboration)

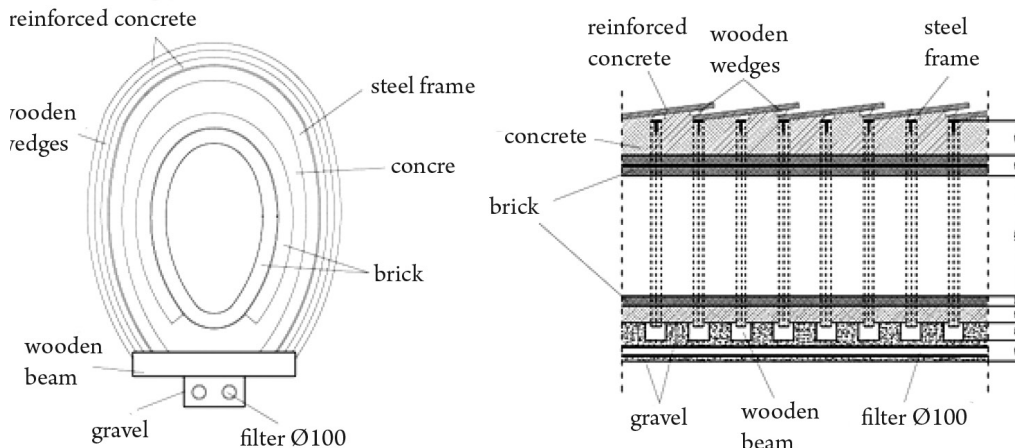


Fig. 2. Construction scheme of the collector (source: own elaboration)

Geological conditions in the subsoil are created mainly by quaternary structures. Occurrence of sandy clay, loamy sand and silt layer was observed. Gravel layers of a small

thickness were formed deeper in the subsoil. The ground water level was localized at the depth of 26.65 m above the level of the Vistula River (Fig. 3). The ground water shows qualities of sulphate and carbonate aggression towards the concrete.

The construction of the very collector as well as the tunnel cladding must carry not only the load resulting from the soil layer above them, but also load of car and tram traffic on the surface.

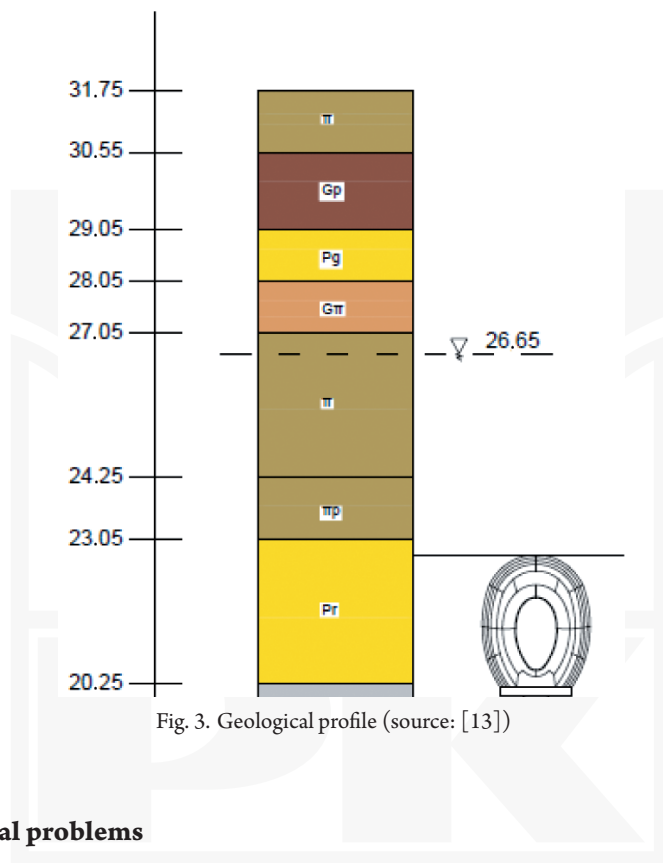


Fig. 3. Geological profile (source: [13])

3. Operational problems

The considered sewage collector causes many operational problems. Its present technical condition can be defined as unsatisfactory. While conducting field research, numerous damages of collector walls, including 3–15 mm wide cracks, were noticed. In addition, a significant loss of bricks and mortar was observed in some places (Fig. 4).

Significant problems with the collector’s tightness were observed. Numerous accretions indicate that water strongly infiltrates inside the object (Fig. 5). A large number of accretions and a tight structure (Fig. 6) limit the possible sewage flow and cause problems with the capacity of the collector.

Accretion forming is caused by mortar and concrete leaching from the construction, which is a result of chemical aggression. Occurrence of empty spaces within the collector cladding, which cause change in static scheme of the cladding work, should be assumed. Significant

cracks and scratches result in the necessity of constant carrying of groundwater flow load by the already weakened construction. Attempts of impact removal of the accretions resulted in strong outflow of highly pressurized water.



Fig. 4. The wall of the collector. No 1, 2, 3 are places of mortar loss (source: [13])



Fig. 5. Leakage into the collector (source: [13])



Fig. 6. Strongly developed accretions on the collector wall (source: [13])

Disturbances in the flow speed in the collector as well as disturbances in longitudinal slopes result in problems with the accumulation of sediments, which cause frequently observed high concentration of hydrogen sulphide. This hampers or periodically precludes conducting works and inspections within the collector.

As a result of occurring leakiness and soil material (brought by infiltrating water) lying on the bottom, there is a significant risk of suffosion processes, which can lead to loosening of the soil structure near the considered object. Processes that can result in soil parameter deterioration can also be caused by sewage, which leaks out of the collector through cracks in its cladding. Taking into account chemical aggression of the sewage and ground water, it must be stated that the probability of damaging the reinforced concrete cladding is high.

The natural consequence of the aforementioned processes and phenomena is soil subsidence. It can lead to damages of the ground surface infrastructure, e.g. tram trackway as well as building disaster and complete destruction of the collector.

In May of 2012, it came to the collapse of the collector near Tapicerska Street [13]. Cave in of the roadway on Krakowska Av. in March of 2010 paralyzed that part of Warsaw for a few hours. Currently, determining the main reasons of the damages and forecasting of the likely course of now occurring processes in the future seems to be the most essential assignment for elaborating optimal renovation plan and modernization of the object.

4. Research of the collector brick lining

For the purpose of determining specific material properties, samples of the bricks and mortar for laboratory researches were taken during the field researches. On the basis of conducted axial compression test, the compressive strength of the sample was determined to be 18 MPa. This results in the range of values required for sewer brick, the strength of which should be at least 15 MPa.

The material obtained from the brick lining of the collector was also subjected to chemical analysis. Samples of water infiltrating into the collector as well as material taken from collector walls, which are samples of accretions, were analyzed [elaboration].

Aggressive carbon dioxide was not detected in the samples in conducted chemical research. The reason is that the carbonate balance is establishing. However, in case of reaction (pH) or temperature change, the possibility of the occurrence of this substance in the water should be assumed. An increase of the alkalinity is probably caused by leaching of concrete hydration products by the flowing water. Solid sample investigation showed a significant amount of calcium compounds, which confirmed the assumption taken before. On the basis of conducted research and analysis, the strength of collector lining bricks was assessed as satisfactory. However, local damages and decreases of material parameters associated to them must be also taken into consideration.

Results of the chemical research indicated problems connected with mortar and concrete. Their strength parameters must be assessed as unsatisfactory. The results obtained were used in further analysis and constructing of numerical model of the object.

5. Numerical simulation

In order to simulate the course of the processes and phenomena occurring within the considered sewage collector, a numerical model of the object was constructed. The simulation was carried out with use of ZSoil 2013v.13.09 [Z_SOIL PC 2013 v.13.09; Zace Services; Lausanne 2014] computer program. Individual sections of the collector were drawn in the AutoCAD software. Then, their geometry was implemented into the Z-Soil program. The calculations were carried out on the assumption of an already raised object, plane strain state and steady filtration. The construction of the collector was reflected in individual parts of the model as accurately as possible.

In the initial stage, the situation was simulated in the 2D model, in regard to different sections of the collector. The following step was 3D simulation in regard to 10 m long section of the collector. The material parameters in the various areas of the model were diversified, while carrying out calculations in order to reflect processes and phenomena occurring within the construction. On this basis, determining the most likely causes of occurring damage and forecast of their further development in time was possible.

5.1. The 2D model

2D simulating was carried out as preliminary calculations in the preparation process of a three-dimensional model of the collector. In the following stages, fields showing individual material areas were created and their parameters were defined (Fig. 7). Material properties of the subsoil were determined on the basis of conducted geological research. In the analysis, typical geotechnical boundary conditions were implemented: horizontal displacements on the outer vertical edges and displacements in both horizontal and vertical direction on the bottom edge of the model were blocked. In addition, the position of the groundwater table was taken into account. In the point of contact of the collector lining and the ground, contact elements of interface type were used (Fig. 7). One elastic-plastic model with Coulomb-Mohr yield criterion was comprehensively used in the calculations.

The specification of material property values used in calculations and presented in the legend of the pictures is shown in Table 1. Due to the lack of the reliable data, the dilatation angle values were omitted.

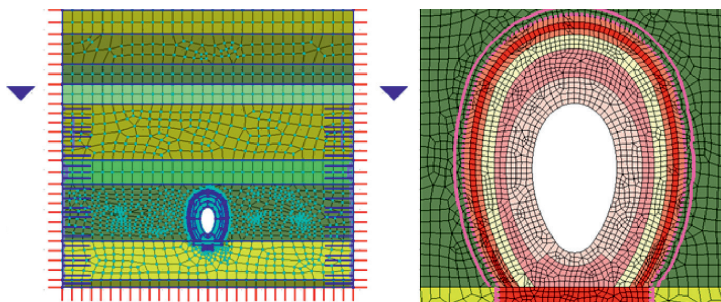


Fig. 7. 2D model generated by Z-Soil (source: own elaboration)

Table 1. The material parameters used in the numerical calculations

| No. | Material | E [MPa] | ν [-] | γ [kN/m ³] | k [m/d] | φ [°] | c [kPa] |
|-----|------------------------------|--------------|--------------|----------------------------------|--------------|------------------|--------------|
| 1 | Sewer brick | 30000 | 0.20 | 20 | 0.00011 | 45 | 2360 |
| 2 | Concrete | 23100 | 0.20 | 23 | 0.05 | 45 | 3350 |
| 3 | Reinforced concrete cladding | 32000 | 0.30 | 25 | 1 | 45 | 5000 |
| 4 | Wood | 200 | 0.25 | 5 | 1 | 45 | 2000 |
| 5 | Steel | 205000 | 0.25 | 25 | 0 | 45 | 5000 |
| 6 | Gravel | 200 | 0.20 | 21.0 | 100 | 40 | 0 |
| 7 | Silt | 50 | 0.30 | 21.0 | 0.5 | 20 | 20 |
| 8 | Sandy clay | 150 | 0.30 | 22.5 | 0.5 | 20 | 20 |
| 9 | Loamy sand | 50 | 0.30 | 22.0 | 1 | 20 | 5 |
| 10 | Silty clay | 50 | 0.30 | 21.0 | 0.5 | 20 | 20 |
| 11 | Sandy loam | 100 | 0.30 | 21.0 | 0.5 | 20 | 20 |
| 12 | Coarse sand | 150 | 0.25 | 20.0 | 25 | 35 | 0 |

Typical symbols were used in the Table:

E – Young's modulus,

ν – Poisson's ratio,

γ_d – soil/soil skeleton volume density,

c – cohesion,

φ – angle of internal friction,

k – coefficient of permeability (Darcy's coefficient).

The calculations were carried out for several different scenarios. In the first one, the process of steady filtration on the assumption of tight collector cladding was analyzed. Afterwards, the influence of local leakages on the course and intensity of the filtration phenomena was simulated. For this purpose, the material parameter values were locally reduced by increasing the value of the hydraulic conductivity coefficient. An elastic-plastic analysis of the construction was carried out in order to determine stress distribution and tensile stresses. To show damages and failures, appropriate material parameters were successively modified with reference to particular areas (E , φ , c). Tensile stresses are particularly dangerous to the collector cladding for they can lead to scratches and leakage in the construction. The results of filtration calculations are presented in Fig. 8 as velocity vectors within the analyzed model. The vectors indicate directions of water flow. Lengths of individual vectors are proportional to flow velocity. On the basis of the calculations, it can be noticed that the largest flow concentration occurs directly under the structure (gravel and drains) and in the soil layer above the collector. These are the places of potential suffusion processes, which can result in local deterioration of the material properties of the subsoil.

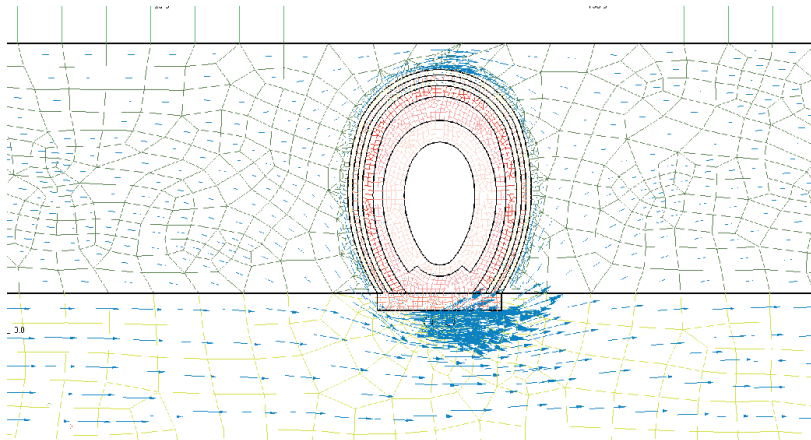


Fig. 8. Vectors of water flow velocity (source: own elaboration)

Stress distribution of the collector lining is presented in Fig. 9. Tensile stresses were marked in red. Occurrence of the tensile stresses in that area may cause chink forming in the mortar or its flaking off the bricks. Both these factors are conducive to forming of preferential leak paths. During field researches, leakages in the upper part of the collector were frequently observed.

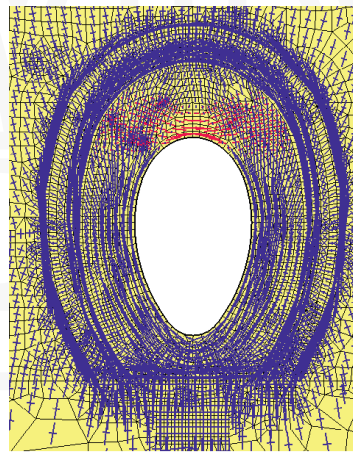


Fig. 9. Tensile stresses in the collector vault (source: own elaboration)

While carrying out further calculations, the material parameter values were being diversified in the individual areas of the model. The course of processes and phenomena within the structure was reflected as accurately as possible. This way, determining the most likely causes of damages was possible. In addition, prognosis of their further development in time and influence on the soil nearby the structure was made. Two variants in which material parameter values were reduced in the upper and lower part of the collector cladding were simulated.

In the first stage, calculations reflecting the potential influence of the tensile stresses in the vault were performed. Then, the possibility of damage in lower parts of the collector cladding was analyzed. This type of damage could have been caused by e.g. incorrect connection of the sewer connectors or subsidences induced by decaying (biological corrosion) of the wooden base made of steel frames. The conducted analysis of the results unambiguously showed the possibility of soil transferring into the collector, which would pose the explanation for locally increased sediment accumulation. Concentration of the flow in the soil occurs directly on the external walls of the collector. The discussed processes were observed and described in the documentation system of WMWSSC (MPWIK) works while repairing the failure near Tapicerska and Instalatorów Streets in Warsaw.

The following step of the calculations was displacement and deformation analysis nearby the structure. For this purpose, the calculations were carried out once more, having taken into account the aforementioned material parameters. The boundary conditions used in this stage were identical as in filtration analysis. Moreover, the load generated by traffic on the ground surface was taken into account. The second stage of the displacement analysis was implementing local decrease of material parameter values of the soil in the immediate vicinity of the collector and above it. Their values are in the range of suffosion danger. The values of deformation module, cohesion and angle of internal friction were modified, mainly in regard to cohesive soil (silts) above the collector. The obtained results confirmed the possibility of ground surface subsidences, which is consistent with field research observations.

5.2. 3D model

The three-dimensional model of the considered collector was generated according to the geometry used before in 2D simulation. It was used to analyze the ground relaxations, which occur locally on the analyzed collector length and to illustrate subsidence of the surface ground in a better way. In that stage, the model of a 10 m long section of the collector, consisting of two 3 m long parts and four 1 m sections between them, was generated. The geometry of points and lines was elaborated using the AutoCAD software. Then, it was imported into the Z-Soil program. Using the program, appropriate three-dimensional solids reflecting the construction of the collector and soil layers nearby were created. The virtual mesh was created by adding new nodes to the already generated elements. It allowed to cover the whole model with mesh coherently.

In the calculations, identical material parameter values as in 2D simulation were implemented. The same type of boundary conditions was used, which is blocking of horizontal displacements on the external vertical edges of the model and blocking of displacements in vertical and horizontal direction on the bottom edge of the model. The elastic-plastic model with Coulomb-Mohr yield criterion was used in the calculations for all material areas, which were taken into account.

The boundary conditions in the calculations were used in the form of variable ground water levels and traffic loads (tram trackway is located directly above the collector). In the zone between the collector and the ground adjacent to it, the elements of interface type were used once more (Fig. 10). Soil loosening was also assumed in the calculations. For this

purpose, geotechnical parameters (E , φ , c) of the sandy loam, silt and silty clay layer were reduced. This way, potentially occurring suffosion processes associated with detrimental filtration phenomena were simulated.

In the area of soil loosening, increased subsidences of the ground surface were noticed (Fig. 10). This confirms previous observations, taken near Tapicerska Street. This situation puts ground infrastructure safety at risk. What is more, it can also generate additional tensile stresses in the construction of the collector. Directly in the area of soil loosening, displacements of the upper surface of the model were noticed. These processes can be additionally intensified by both progressive suffosion and effects of dynamic factors. Consequently, there is a risk of ground surface collapse, which can result in building disaster.

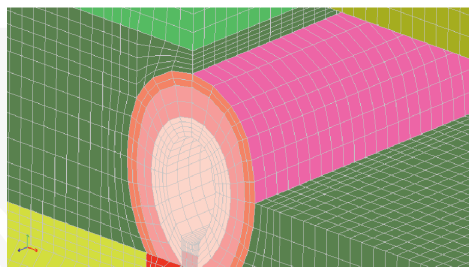


Fig. 10. The contact zone between the collector and the ground (source: own elaboration)

6. Conclusion

The conducted field researches and compression test allowed to determine the condition of the lining bricks as satisfactory. Both infiltrating water and solid samples showed a high content of calcium compounds. This indicates that the collector lining concrete undergoes degradation and leaching out of the hydration products. The mortar is prone to the same processes. Increase of the permeability coefficient (Darcy's coefficient) is followed by strong water flow into the collector. Migration of the soil particles into the object is confirmed by local accumulations of sediments.

Because of detrimental groundwater conditions and flow concentration near the collector cladding, the occurrence of suffosion processes in the subsoil was assumed. These phenomena are recognized by local loosening of the soil, which results in local subsidences.

In each of the analyzed cases, tensile stresses occurred in the upper parts of the collector. The usual indications of their formation are numerous cracks and scratches. These are the places of a particularly intensive groundwater leakage into the object. Results of analysis carried out with the use of the 3D model explain the reasons for ground collapse near Tapicerska Street, which was caused by suffosion processes in silty soils above the collector.

Wooden beams used as a support for steel frames of the reinforced concrete cladding have a negative effect on the current work of the collector. After years of work, they have undergone serious damages due to wood decay process. The idea of using these construction elements proved to be a project mistake.

Currently, the main purpose of the collector modernization should be reducing the inflow of infiltrating water as well as tightening of the collector along with sealing its lining.

Examples of solutions that are possible to implement include:

- ▶ constructing of a new collector,
- ▶ use of GRP modules,
- ▶ use of sleeve,
- ▶ compaction grouting technology and chemical technologies.

Construction of a new collector is not possible due to legal reasons (obtaining a construction permit is a long-lasting process) as well as technical causes: a new object would have to be connected to sewer connector pipes.

The whole situation is additionally complicated because of the social costs of potential maintenance works, which would result from the fact that the collector is located under one of the most important roads of Warsaw.

The use of GRP modules seems to be a problematic solution, as they must be input inside the collector. The implementation of this method would require building shafts and chambers. Intensively conducted works on the ground surface could lead to a significant increase of the investment costs. The elaborate shape of the cross section of the collector (extended ovoid) constitutes an obstacle to use the so-called sleeve. In addition, providing constant contact of the lining with the wall of the collector, particularly in the upper part of its cross section, poses some difficulty. This solution cannot be implemented due to risk of potentially creating preferential leakage paths. In addition, it must be noticed that the latter two solutions would result in the reduction of the cross sectional area of the collector and its capacity.

In these conditions, the optimal solution is using local compaction grouting technology in sites, which are most endangered by groundwater infiltration, along with applying thermosetting lining on the walls of the collector. Instead of thermosetting lining, mortar rich with highly penetrating compounds may be used. The introduction of this solution would provide construction tightness as well as an increase of the strength parameter values of the whole lining and soil surrounding of the collector.

Using this technology, renovation costs are proportional to the quantity of used material (injection substance). Determining the quantity and effectiveness of the method is not possible at this stage of research. Another essential issue is the number of necessary holes. The method of performing injections should also be considered. It can be realized vertically, from the inside of the collector or horizontally from sewer manholes.

In this case, construction of modernization test sections is indispensable. Conducting an accurate assessment is also necessary.

7. Findings

- ▶ While performing technical condition assessment of a collector, taking into account soil conditions of its foundation place is indispensable.

- ▶ Carrying out a geotechnical research, including investigation of groundwater conditions in the place of foundation, especially in the surroundings of changes inside the collector, is indispensable in order to perform the technical condition assessment.
- ▶ Changes of groundwater conditions have a significant influence on the condition of the collector as well as infrastructure nearby.
- ▶ Inappropriate choice of construction materials (wooden beams) combined with adverse groundwater conditions is the main reason for failures and operational problems in case of the considered object.
- ▶ Periodical technical condition assessments of collectors' built with use of similar technology are essential for further operation of these objects.
- ▶ The suffosion process can result in severe damages of hydrotechnical constructions. It should be taken into account while analyzing technical condition assessments of underground structures.
- ▶ Numerical modelling provides broad opportunities for technical condition assessing of constructions. However, the accuracy of calculations depends on the assumed material parameter values and calculation variants.
- ▶ Technologies of modernization depend on execution and economic factors.

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