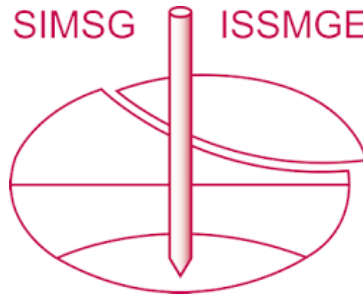


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Geotechnical aspects of security for long-operated underground collectors in conditions of soft soils and increasing technogenic influences

Aspects géotechniques de la sécurité pour les collecteurs souterrains à fonctionnement durable dans des conditions de sols mous et de l'influence technogène croissante

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ABSTRACT: The special protection against technogenic influence is required for long-operated tunnel sewage collectors. This paper, based on the extensive data of studying the work of the tunnel collectors in conditions of soft soils and intense technogenic influences, describes new methods of diagnosing, the features of defects, and the results of modeling joint interaction of the "tunnel – soil bulk" as well as experimental data on experimental objects. The geotechnical methods for protecting the long-operated tunnel collectors have been developed, and there has been given the unique experience of their application in the objects of St. Petersburg together with their monitoring support.

RÉSUMÉ: La protection spéciale contre l'influence technogénique est requise pour les égouts collecteurs des eaux usées qui soient durables. Cet article, s'appuyant sur les données détaillées des études des travaux des collecteurs tunnels dans des conditions de sol mou et de l'influence dynamiques et technologique, décrit de nouvelles méthodes de diagnostic de leur état technique, des caractéristiques de classification des défauts de la construction des tunnels, ainsi que les résultats de la modélisation du fonctionnement du «tunnel - sol en vrac» et des données des objets expérimentaux. Des méthodes géotechniques de protection des collecteurs tunnels de longue durée d'exploitation ont été élaborées. On parle d'une expérience unique de l'application des méthodes développées pour les installations situées à Saint-Petersbourg et de la surveillance monitorée.

KEYWORDS: tunnel collectors, protective measures, geotechnical monitoring

1 THE GENERAL CHARACTERISTIC AND DEGREE OF WEAR OF THE SEWAGE TUNNELING SYSTEMS IN THE LARGEST RUSSIAN CITIES

In cities with an expanded historical center, long-operated tunnel sewage collectors need special protection from anthropogenic influence. As objects referred to the structures of enhanced level of responsibility tunnel collectors should have the required bearing capacity and exploitation reliability in order to meet normative standards of safe use excluding the risk of occurring hazardous technogenic accidents (FL # 384, 2009).

The authors have collected and analyzed data on the current technical state of sewage collectors of 15 largest cities in Russia including Moscow, St. Petersburg, Ekaterinburg, Samara, Novosibirsk etc. of total length of more than 2300 km. For general sampling there have been used such properties as the length of the tunnel network (from 100 km to 500 km and more); the period of exploitation (from 30 to 70 years); complex geotechnical conditions of tunneling (presence of unstable soils, intersecting aquifers including the heading ones).



Figure 1. The scheme of location of the tunnel sewage collectors in St. Petersburg

Practically for the majority of the cities under consideration the network of the tunnel collectors has an average level of physical wear in the range of 55-66% with the dynamics of development of 0.5-1.0% per year. It is registered that in the cities with an expanded historical center and developed transport infrastructure, first and foremost, Moscow and St. Petersburg, but the degree of

tunnels wear has higher values of 71% and 83% with the faster dynamics of development up to 1.5-2% per year.

As the system of tunnel sewage in Moscow had been established by the end of the 1930s and in St. Petersburg it had happened by the end of 1950s, the degree of the tunnel wear and the dynamics of development is faster in St. Petersburg. The tasks of protection of tunnel collectors and identifying the reasons of their high degree of wear are extremely urgent for substantial development of this unique historical city (see Figure 1).

2 THE PARTICULARITIES OF OPERATION OF THE TUNNEL SEWAGE COLLECTORS IN ST. PETERSBURG AND THE ANALYSIS OF FACTORS INFLUENCING THEIR TECHNICAL STATE

Nowadays the total network of the tunnel sewage collectors in St. Petersburg is about 270 km. The system of sewage tunnel collectors represents pipelines of the diameter of 1.5 – 4.7 m excavated by the mining excavation method using tunneling machines at the depth of 6 - 90 m. The bearing structure is made of reinforced concrete tubing of B15 concrete with a reinforced concrete "liner" of a shotcrete coating inside. The space between the bulk of bearing strata and the tubing frame is filled with slurry through injection holes.

The major part (up to 75%) of the tunnel sewage collectors is located in the central historical part of the city in very difficult geotechnical and hydrogeological conditions in terms of construction and it does not have any doublers.

Within the central part of the city the strong crystal deposits are encountered at the depth of 120-220 m. They are overlain by a thick sedimentary cover. The main part of the area is covered by a bulk of quaternary deposits Q. Saturated clayey soils associated with lacustrine-marine, lacustrine-glacial and moraine deposits are noteworthy. Down to the depth of 30-120

m soil strata are represented by silty saturated sands of medium density - $E=7-11$ MPa, $C=0$ MPa, $\varphi=27-30^\circ$; plastic silty clayey sands $E=3-5$ MPa, $C=0,01-0,02$ MPa, $\varphi=12-17^\circ$; stratified liquid-plastic silty sandy clays - $E=5-8$ MPa, $C=0,015-0,025$ MPa, $\varphi=10-16^\circ$; silty sandy clays with semi-solid gravel, pebbles - $E=12-15$ MPa, $C=0,016-0,028$ MPa, $\varphi=24-28^\circ$. The whole soil bulk is unstable to technogenic influences. Only in the southern part of the city there is a roof of dislocated Cambridge deposits at the depth of more than 30 m - $E=19-34$ MPa, $C=0,04-0,06$ MPa, $\varphi=17-21^\circ$. Aquifers are represented by a super-moraine aquifer (superficial ground waters); an upper super-moraine aquifer located at the depths of 7 - 30 m with the heading value of 5-28 m and a lower inter-moraine aquifer – at the depths of 25-120 m. The Venda aquifer system (Gdov aquifer) is located in Pre-Quaternary Upper Proterozoic deposits at the depths of 70 m and more, where the heading value reaches 80-160 m.

Due to the scouring of pre-quaternary deposits by paleo-rivers, the bulk of quaternary deposits is characterized by a large weir of absolute elevations (Dashko, 2011). Non-symmetric strata of soils of different strengths are characterized by sharp slopes reaching 50 % and more. This factor is especially detrimental for long-operated tunnel sewage collectors in the light of increasing anthropogenic impacts, firstly the vibro-dynamic ones (Perminov, 2014).

3 THE GEOTECHNICAL ANALYSIS OF THE INFLUENCE OF ANTHROPOGENIC FACTORS ON RELIABILITY OF THE LONG-OPERATED SEWAGE TUNNELS

3.1 The analysis of the defects of the sewage tunnel collectors, their structure and the dynamics of their development.

There have been analyzed the archive data of technical inspections of the tunnel collectors belonging to the “Vodokanal-SPb” by the maintenance service. In the period from the late 1970s to nowadays the authors have conducted the tool inspections of the technical state of the tunnels (the total length of about 15 km) located in the historical city center (the depth of 12-15 m) and beyond it, within the approaches to three main sewage pumping stations collecting all sewage outflows of the city, embedded at the depths of 53-71m.

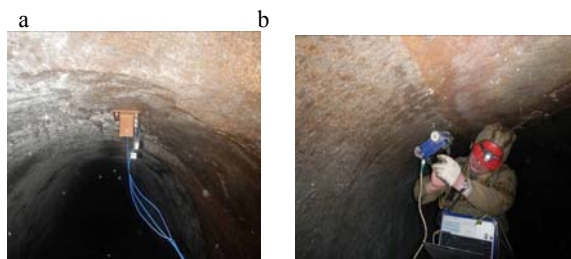


Figure 2. Tests of the structures in the operating tunnel sewage collector: a) oscillation measurements using the ICP accelerometers; b) scanning integrity of the structures of the tunnel using a georadar OKO-2.

The technical tool inspections included: in-situ tachometric survey of the spatial location of a tunnel in between the shafts; georadar scanning of the state of the tunnel internal surface evaluating its integrity; core sampling and conducting tests using a tear-off method with scanning to assess strength properties of concrete; sampling for chemical and biochemical analyses; evaluation of a corrosion degree and reinforcement using non-invasive methods; vibro-dynamic tests on oscillations of internal tunnel structures caused by external and construction vibration impacts.

Uniqueness of the data on observations of the state of the tunnels is that the technical inspection of the structures has been conducted during the long period since the late 1970s to nowadays (the end of 2016). During this period the same parts of collectors have been inspected several times. As a rule, each inspection was followed up by the tunnel state monitoring performed for several years. Therefore, there has appeared a possibility to track the dynamics of defects development.

The observation period was divided into three sub-periods:

a) the 1970-80s; b) the 1980-2000s; c) 2000-2016. The identified defects which are more typical and influencing the exploitation reliability and bearing capacity of the tunnel were divided into 7 groups: d1- shrinkage cracks in the concrete liner; d2- gas corrosion features; d3- dripping leakages; d4- force cracks in the arch and along the lateral surface of the tunnel; d5- concrete biological corrosion features; d6- reinforcement corrosion, conduit dusting; d7- the presence of heading leakages.

The Figure 3 shows the dynamics and structure of defect manifestation during the operation period of the tunnel sewage collectors from the late 1970s to 2016.

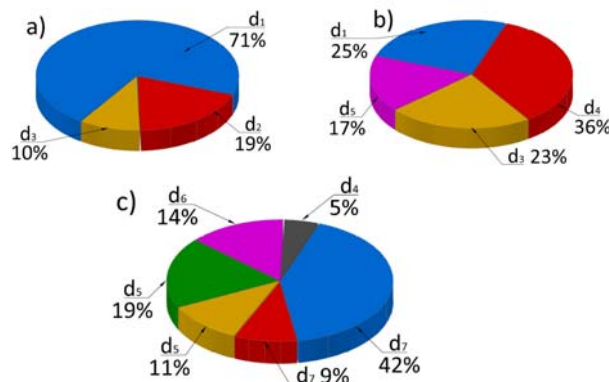


Figure 3. The dynamics and structure of defect manifestation in a long-term operation period of tunnel sewage collectors: a) 1970-80s; b) 1980-2000s; c) 2000-2016. Classification of defects: d1-d7 – primary defects caused by shrinkage cracks and manifestation of gas corrosion features before development of force cracks and occurring heading leakages (see description in the text).

The analysis of the dynamics and structure of defects manifestation shows that during the initial period of operation of the tunnel collectors there have been observed defects in the form of shrinkage cracks in the concrete liner with dripping leakages and gas corrosion features. The nature of the defects prevailing in the first 15-20 years of the tunnel exploitation and their influence on the bearing capacity and exploitation reliability can be considered as negligible; their technical state can be regarded as serviceable according to the existing Russian State Standards and Construction Codes.

The subsequent 20 years of the tunnel operation are characterized by manifestation of force cracks and considerable increase of the defects in concrete due to its gas and biological corrosion. However, their technical state was described as partially serviceable.

The analysis of the defects appeared in the period of 2000-2016 is of particular interest. It is noteworthy that in this period the amount of the defects influencing the tunnel bearing capacity has increased: almost 40% growth in the number of force cracks in the arch and along the lateral surface of the tunnel; the features of reinforcement corrosion and dusting of the conduit; the presence of heading leakages in the tunnel body; the increase in the proportion of the defects associated with biological and gas corrosion. The technical state of the tunnel structure is characterized as partially capable. The tunnel sewage collectors require monitoring of their technical state,

taking actions on reconstruction of the bearing capacity and exploitation reliability of the structure.

3.2 The factors conditioning intensive development of the defects of the tunnel sewage collectors

The comprehensive long-term technical inspections of the tunnel sewage collectors allow conducting a retrospective analysis and identifying factors, which condition manifestation and development of the defects. The factors can be divided into internal and external ones according to the nature of their influence.

The nature of the internal factors is explained by the processes linked to transportation of sewage outflows. The main factors are the corrosion of the internal structures (gas-biological), the conduit dusting, sewage pumps etc. These factors lead to rather static development of the defects. The definition of the ultimate acceptable values of their influence on the tunnel sewage collectors pertains to the area of research and activity of the sanitary-technical services. (Pankova, 2015, Vasiliev, 2013).

The external factors are characterized by the complex interaction of the tunnel structure and the embedding soil bulk, which form a natural-technical system under the influence of the anthropogenic factors.

The evaluation of this interaction and definition of the area of the ultimate acceptable values of mutual influence of the natural-technical system elements is a task of geotechnical predictions. Other papers of the author is dedicated to the issues of optimum management of the natural-technical system elements (Perminov, 2004, Perminov, 2014).

In the framework of the given inspection we have a task of geotechnical support of the safe level of external anthropogenic impacts on the tunnel structure with account of its residual bearing capacity.

4 PREVENTIVE GEOTECHNICAL MEASURES OF PROTECTION OF THE TUNNEL SEWAGE COLLECTORS

Geotechnical and structural measures to ensure reliability and safety of the long-operated tunnel sewage collectors should be selected basing on comparison of competing options, but the main requirement they should meet is a possibility of preventive use substantiated by geotechnical and structural calculations.

The Table 1 presents examples of some geotechnical measures successfully taken in the projects of protection of the tunnel sewage collectors in St. Petersburg in 1998-2016.

Table 1. Geotechnical measures of protection of the tunnel sewage collectors

The nature of technogenic impacts	Geotechnical and structural measures	The object for protection
Supernormative static and dynamic influences on the brickwork arch of the collector	Construction of an unloading screen and reinforcement of the structures; monitoring.	The brickwork sewage collector XVIII century under Konnogvardeysky boulevard
The increase in static load applied to the tunnel sewage collector due to the weight of the building being constructed above it	Construction of an unloading bridge with load transfer to the soils below the tunnel bottom, monitoring.	The sewage collector in Nalichnaya street
Unloading of a	Construction of a	The transport

soil bulk during the construction of the deep transport tunnel above the tunnel sewage collector	protective screen of reinforced soil to prevent the uplift of the pit bottom, monitoring.	tunnel above the tunnel sewage collector along the Obvodny Canal and the bridge of Alexander Nevsky
Prevention of horizontal displacement of the tunnel sewage collector at unilateral unloading of a soil bulk during reconstruction of the embankment.	Construction of a geotechnical barrier, monitoring.	The tunnel sewage collector along the highway in the embankment of the Fontanka River
Expansion of an area of ultimate acceptable displacements of the tunnel sewage collector at unilateral unloading of a soil bulk during reconstruction of the embankment.	Structural reinforcement and sanitation of the tunnel sewage collector using the spiral-coiling method in order to increase the ultimate acceptable tunnel displacements, monitoring.	The tunnel sewage collector along the embankment of the Kryukov Canal and the Moyka River
The increase in static load applied to the tunnel sewage collector due to the impact of heavy road transport and trams.	Structural reinforcement and sanitation of the tunnel sewage collector using the coiling method in order to restore the bearing capacity of the tunnel up to the design level, monitoring.	The 840-m-long tunnel sewage collector in Tovarishesky prospect

The calculation substantiation of the geotechnical protection measures was made according to the algorithm: collection of loads and impacts, definition of the physical-mechanical properties of soil and tunnel materials; creation of a geo-mechanical calculation model and calculation of displacements using the software Plaxis3DTunnel; creation of a calculation model using the software Robol; selection of the parameters of tunnel reinforcement. The calculation example is shown in the figure 4.

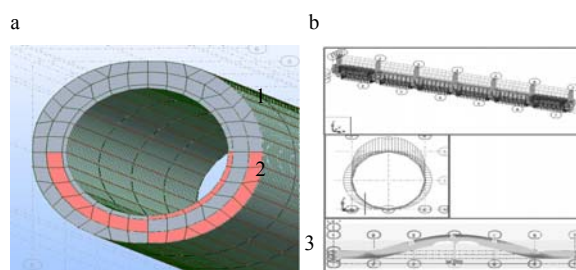


Figure 4. The fragments of the calculation scheme – (a) simulation of the ultimate acceptable displacement of the collector – (b): 1- the collector tubings; 2- the concrete liner; 3-the layer of reinforcement and sanitation using the coiling method

5 THE EFFECTIVE EXPERIENCE OF APPLYING GEOTECHNICAL MEASURES DURING REPAIRING OF THE TUNNEL SEWAGE COLLECTORS IN CONDITIONS OF SEWAGE OUTFLOWS TRANSPORTATION

5.1 The object description

The tunnel collector in Tovarischecky prospect with the intervals 359m and 485m diameters $D=2.5$ m and $D=1.5$ m at the depth of 1274 m has been operating for more than 40 years. According to the inspection results the wear degree was more than 79%, the subsidence at the crossroads reached 25 mm. It was necessary to ensure protection of the tunnel sewage collector against the enhanced external static and dynamic transport loads and impacts. According to the georadar scanning there was identified overall peeling of the concrete liner from the tubing lining with occurrence of heading leakages (Figure 5).

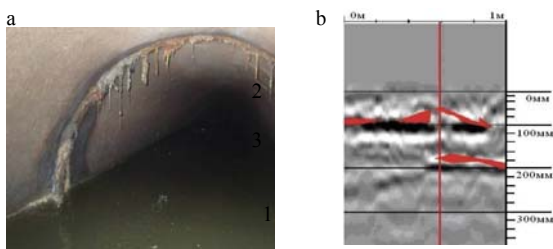


Figure 5. The defect of peeling the structures: a) heading leakage features; b) a fragment of the radargram with the features of peeling the tunnel structures – 1-tubing lining; 2 – RC liner; 3- a heading water layer.

5.2 Calculation substantiation of the protection measures for the tunnel sewage collector.

The calculation sequence followed the algorithm above mentioned in section 4 of the paper, the calculation fragments are shown in (Figure 3), the ultimate acceptable displacements before the protection measures and after them are shown in the graph (Figure 6): 1- $D=1.5$ m, 3- $D=2.5$ m - tubing lining with defects of the concrete liner; 2- $D=1.5$ m, 4- $D=2.5$ m – tubing lining with reconstruction of the concrete liner and refractory lining reinforcement of the structure.

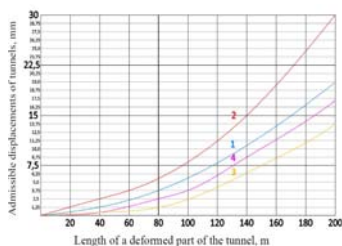


Figure 6. The ultimate acceptable displacements of the sewage tunnels $D=1.5$ and $D=2.5$ before (1.3) and after (2.4) reinforcement of the structure using coiling technology

5.3 The description of the method and results of the protection measures for the tunnel sewage collector.

A special requirement for the protection measures was the use of such a method which allowed repairing in conditions of constant transportation of sewage outflows.

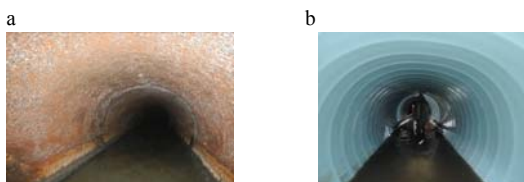


Figure 7. The state of the tunnel sewage collector: - a) before the repair and b) after the reinforcement of the structure and its sanitation using the coiling method.

The sanitation technology by coiling was applied for repairing and restoring bearing capacity of the tunnel. The scope of working operations included: cleaning the tunnel and preparing the surface; structural gluing of the concrete liner and the tubing lining by injection of SikaDur; reinforcing the arch surface by

structural reinforcement with SikaWrap carbon fiber; coating the tunnel surface with PVC coiling profile; injecting polymer-cement mortar ($P_{comp}=65\text{MPa}$) into the intertubular space for structural gluing of the PVC lining with the tunnel structure. The operation fragments are shown in (Figure 7).

According to the conducted monitoring it was found out that vibro-dynamic tests of the tunnel before and after the repair demonstrated changes of the period of the collector's own oscillations from 0.54 sec. to 0.19 sec. i.e. by 58%, the amplitude of its own oscillations decreased from $A=300$ micron to $A=15$ micron, i.e. almost by 2 degrees of order. It shows provision of the integrity of the structure and joint operation of its layers (Figure 8). After repairing the guaranteed period of reliable work of the tunnel sewage collector is minimum 50 years.

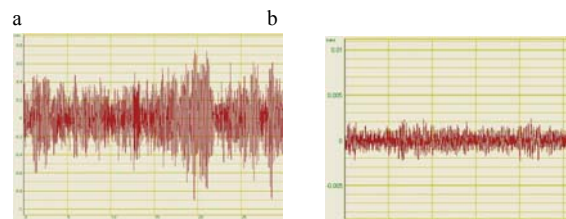


Figure 8. The results of the measurement of the oscillations of the tunnel structures at applying the exterior vibro-dynamic transport load: a) the oscillogram of the fluctuation process of the tunnel structures with the peeling defects $A=300-800$ micron and b) the same after reinforcement with "the structural gluing" and sanitation using the coiling method $A=15-20$ micron.

6 CONCLUSIONS

Due to long operation, the tunnel sewage collectors in Russia have a wear of $55 \div 66$ %. Complicated soil conditions in St. Petersburg have led to the wear of the tunnel sewage collectors up to 83% with the fast dynamic of development $1.5 \div 2\%$ because of the action of different technogenic factors.

The proposed geotechnical methods of protection of the tunnel sewage collectors including the methods of structural reinforcement and sanitation in conditions of transporting sewage outflows accompanied by the monitoring system provide enhancement of the bearing capacity of the structure of the tunnel sewage collectors and their exploitation reliability.

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