Modelling and monitoring of security unique underground structures of the sewerage system of major towns in difficult ground conditions

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Abstract. On the basis of many years of experience in the construction, reconstruction and operation of underground engineering infrastructure of the metropolis developed the concept and philosophy of the creation and operation of Geomonitoring security system of the tunnel collector. The philosophy of construction of space-time structure of Geomonitoring is described. The article presents the experience of modeling, monitoring and taking protective measures aimed at ensuring the safety of tunnel reservoirs located in the area exposed to the geotechnical effects of underground and high-rise construction. The analysis of calculation and experimental data and the results of long-term monitoring aimed at ensuring the safety of underground drainage and treatment facilities of megepolis. 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.

1. System of geomonitoring ensuring of construction and maintenance of engineering subsurface structures

Geomonitoring system is intended to ensure resistance of engineering structures of town-planning environment to the exposure, on one hand, and development of preventive measures in order to eliminate negative influence on town-planning environment as a result of breaking of regular operating modes of engineering systems functioning.

Civil engineering infrastructure of Saint-Petersburg develops under increasing requirements to ecology and rational use of land resources. At engineering development of underground space of such a megalopolis, elaboration of complex measures on protection of town-planning environment against negative anthropogenic impact is of special actuality. This elaboration includes geomonitoring insurance of technosphere safety.

Experience of designing, construction and maintenance of a unique treatment facilities complex in Saint-Petersburg pointed to the necessity of creation of such systems. It is known that Saint-Petersburg
complex of sewage drainage and disposal consists of more than 110 underground pumping stations. Sewage collectors with diameter from 1.5 to 4.5 m have a developed network of more than 300 km long and 15 to 80 m deep. They are 35-45 years old, mainly laid in one line, and are heavily worn out. Base pumping stations (BPS) together with other engineering structures (at 70 m embedding into the ground and with cross-section up to 2000-3000 thous. sq.m.) have side surface contact area of up to 150-200 thous. sq.m, intersect several (up to five and more) waterbearing formations and have a considerable effect on town-planning environment. As per analysis data [1], almost in 60 per cent of cases deformations of urban development are conditioned by the adjacent construction and influence of engineering systems.

On the instructions of SUE "Vodokanal of St. Petersburg" the institute “Lengiproinzhproekt” together with PGUPS developed system of geomonitoring ensuring of technosphere safety. Currently it is implemented step-by-step at the construction and maintenance of subsurface engineering structures of the city (see Figure 1).

The scientific and production company “Transspetsstroy”, being a constant and reliable partner, is a scientific and production base for aprobation and implementation of solutions developed in the institute.

The basis for formation of space-time structure of geomonitoring and conditions of its functioning is as follows: 1 – programs of complex calculations and predictions of change in engineering and geologic conditions and stress-strain state of the geomassif at different modes of structure erection; 2 - technical equipment system of instrumental observation and control over change in the individual elements of "structure-geomassif" system; 3 - information-measuring system of collection, processing, storage and identification of parameters (data) of observation and control; 4 – complex of geotechnological methods of purposeful impact on the ground massif and structure.

![Figure 1. System of geomonitoring ensuring of technosphere safety of construction and maintenance of underground engineering structures](image)

2. **Experience of geomonitoring use in construction of large-size structures**

Elaborated and tested on the basis of results of full-scale and experiment-calculated works was the complex system of geotechnical ensuring of immersion of open caissons with diameter of 50 and 66 m at construction of treatment facilities in Saint-Petersburg. The slotted soil column for monitoring objects is characterized as follows: top part is presented by Quaternary beddings to the depth of 14.0-25.0 meters (middle-density water-saturated dust sand E=11 MPa, C=0 MPa, ϕ=30°; laminar silt
sandy loam $E=4\text{ MPa}, C=0.01\text{ MPa}, \psi=15^\circ$; laminar silt loam, very soft $E=9\text{ MPa}, C=0.025\text{ MPa}, \psi=16$; semisolid silt loam with gravel, pebbles $E=14\text{ MPa}, C=0.028\text{ MPa}, \psi=28^\circ$), lower part is represented by top of positioned Proterozoic bluestone ($E=19\text{ MPa}, C=0.04+0.06\text{ MPa}, \psi=18-21^\circ$).

This system includes three complexes: control and measurement complex; complex of signal estimate and transmission for control over engineering procedures; complex of operational influence on engineering procedures.

**Figure 2.** Scheme of estimated network of geomonitoring: K-caisson contour; A, B – trigonometric points; 1р, 2р – origins of trigonometric networking; 3-7 – permanent points of trigonometric network; 8вр, 9вр, 10вр – temporary points at the inner wall of the caisson

**Figure 3.** Monitoring at construction of large-scale open caisson KNS in Saint-Petersburg

Measuring complex (see Figure 2-4) provided control over attitude position, displacement of contour of the caisson cover and ground massif. It included the dimensional orientation devices (optical range finders, reflector marks, roll measuring gauges).

**Figure 4.** Change of radius $R$ and displacement of center of caisson circle $O$ at its immersion to the depth $H$: a,b – 6-th and 7-th layers of concrete casting correspondingly, distance from banquette to the top of layer is 34.5 and 40.5 m; I - for $H=17\text{ m} R=32.93\text{ m}, Mx,y=0.067\text{ m (September)}$; II - for $H=29\text{ m} R=32.85\text{ m}, Mx,y=0.05\text{ m (December)}$; III - for $H=25\text{ m} R=32.75\text{ m}, Mx,y=0.048\text{ m (November)}$; IV - for $H=29\text{ m} R=32.76\text{ m}, Mx,y=0.067\text{ m (December)}$; O(I-II)=0.108 m; O(III-IV)=0.234

NDS control subsystem ensured monitoring of parameters characterizing behaviour of the “structure-geomassif” system (see Figure 5), particularly: mode of deformation of ground, which is estimated as per results of measurement of contact pressures, pore pressure and earth handling (sets); mode of deformation of the structure material, including concrete and reinforcement; inclination of
structure and sets of ground in the impact area. Sensing devices were installed in design sections along the contour and layers.

Complexes of discrete-continuous registration of sensor readings included digital period meter PTsP-1; stand-alone interface device – K1-20; PTsP controller, controller switch, controller computer, PTsP switch, controller-PDU, switch-sensors).

Figure 5. Three-dimensional diagram of “n”-coefficient of horizontal stresses irregularity at immersion of caisson: “n” = \( \frac{P_n}{P_r} \), where \( P_n \) – experimental “peak” values of soil pressure, \( P_r \) – design values of soil pressure \[2\]

At the stages of erection, which were predicted to be most difficult (with “inclinations”, “strippings”, etc.) by way of numeric calculations the technologically feasible geotechnological methods have been chosen: changes in geomassif stress-strain state in the basement of structure or along the side surface, arrangement of leading pores, decrease of friction by means of electroosmosis.

As a result of monitoring the following fact of great importance is determined: peak values of horizontal pressure exceed design values in the moment of “inclination” by 2.3-2.5 times \[2\]. It may cause microcracks in the structure concrete, which will inevitably entail damage of the structure waterproofing. This fact was noticed after 10-15 years of maintenance of BPS in Saint-Petersburg treatment facilities complex.

3. Experience of geomonitoring ensurance of technosphere safety of tunnel collectors in the area of geotechnical impact of overground construction

In order to evaluate the state of line underground structures – collectors in the course of construction works in the area of geotechnical impact the system of structure deformation and displacement monitoring is developed. The system of monitoring of objects state includes: 1 – subsystem of computerized geodetic testing, by means of GPS connected to the base station; 2 – subsystem of continuous control of mode of deformation (NDS) of tunnel collector structures; 3 – subsystem of assessment of the collector vibrodynamical resistance; 4 – subsystem of control over line structure offsetting at the selected base and crack opening dynamics.

This system was successfully tested on the number of objects of civil engineering infrastructure, such as “Monitoring of sewage collector state at arrangement of pile field and loading of piles in the area of construction of complex “Shkipersky Rynok”, “Monitoring of sewage collector state at construction and reconstruction of buildings complex “Birzhevoy Complex”, “Monitoring of state of structures of the collector brick vault in Konnogvardeysky boulevard at performance of anti-wreck measures”, “Monitoring of sewage collector in the area of geotechnical impact of construction of high-rise buildings of “Okhta-Center”.

Collector oscillating process was examined by means of sets of sensors SM-3KV installed in the collector vault. Use of this kind of sensors allows registering oscillations with the amplitude from 0.5 \( \mu m \) to 2000 \( \mu m \), frequency from 2 to 200 Hz, error of not more than 10%. Sensors are protected from the external field viewing, have a temperature compensation device, waterproofing (for recording
Oscillations in water. They are characterized by minimum mutual impact (up to 5% of orthogonal oscillations). Diagram of oscillations registering is shown in Figure 6.

The set includes three sensors, which allow recording vertical and two horizontal (orthogonal) components of oscillation amplitudes.

Oscillations monitoring has been performed continuously in the period of construction works related, for example, to pile driving in immediate proximity to the collector or to erection of underground part of the object under construction.

Results were processed as per each component of oscillation amplitude. As a result, average and maximum possible values of oscillation amplitudes were obtained. In all cases probability level was 0.995.

At monitoring of sewage collector state at arrangement of pile field and loading of piles in the area of construction of complex “Shkipersky Rynok” the analysis of obtained results showed that maximum amplitudes of displacements and ground displacement speed at change of distance from the oscillation source are described as per power dependence. Thus, for example, at pile arrangement at a distance of $6 \div 8$ m from the testing point maximum amplitudes of displacement $A_{\text{max}}$ and displacement speed $V_{\text{max}}$ were, correspondingly, as follows: $30 \div 70 \, \mu\text{m}$ and $0.11 \div 0.15 \, \text{cm/s}$, in case of moving away to a distance of $20 \div 25$ m they decreased to the level of $1 \div 2 \, \mu\text{m}$ and $0.012 \div 0.045 \, \text{sm/s}$, i.e. decreased by $25 \div 30$ times.

Data obtained at monitoring indicated that in case of pile arrangement as per low impact technology with arrangement of pilot hole, critical distance of its immersion is considered to be the moving-away from the nearest point of collector in the range $L = 6 \div 10$ m.

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It was established, that works performed at the construction site related to the arrangement of pile field in the area of collector road caused definite active background of external dynamic loads, which value is higher than that of the background ones, but lower than it is prescribed by instructions and standards. These loads caused no considerable inertial processes in structures, which could result in oscillations of the “collector structure – ground massif” system as a whole, old cracks opening and generation of new ones.

In order to ensure resistance of emergency collector located at crossing of Konnogvardeysky boulevard and Dekabristov proezd, relieving archy screen structure was developed and collector brick vault was enhanced by structural reinforcing with carbon fiber. As a result of analysis of the obtained monitoring results the following conclusion on the collector vault rigidity increase was made: after arrangement of anti-wreck measures periods of the collector own oscillations along the orthogonal axes changed correspondingly from 0.12 s and 0.54 s to 0.07 s and 0.19 s, i.e. by 35 ÷ 58 %.

Control of the line structure offsetting at the selected base and crack opening dynamics was performed by means of linear displacement transducers of magnetic and striction type BTL5-T110-V0050-P-103 with sensitivity of 1 micron. Subsystem included base controller unit, interface, sensors with IP level of protection, special-purpose software. Structure of the whole subsystem allowed easy enhancing of its facilities, both as per interval of measured displacements and as per number of measuring lines. Information received from sensors with the preset interrogation interval accumulated in the memory block.

4. 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 [3].

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).

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 10).

5. The geotechnical analysis of the influence of anthropogenic factors on reliability of the long-operated sewage tunnels

5.1. 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 53-71 m.

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.

Figure 10. The scheme of location of the tunnel sewage collectors in St. Petersburg.

Figure 11. 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.
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 2019). 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) 2000-2019. 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 12 shows the dynamics and structure of defect manifestation during the operation period of the tunnel sewage collectors from the late 1970s to 2019.

Figure 12. The dynamics and structure of defect manifestation in a long-term operation period of tunnel sewage collectors: a) 1970-80s; b) 1980-2000s; c) 2000-2019. 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 2000-2019 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.

5.2. 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 [4,5].

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 [6,7].

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.

6. 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 1998-2019.

| 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 soil bulk during the construction of the deep transport tunnel above the tunnel sewage collector | Construction of a protective screen of reinforced soil to prevent the uplift of the pit bottom, monitoring. | The transport 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 sanation 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 sanation 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 Tovarischesky prospect |

Table 1. Geotechnical measures of protection of the tunnel sewage collectors.
7. Numerical modeling and monitoring of geotechnical system "tunnel collector - city planning object - protective measures".

Earlier [6,7,8] the large-sized subsurface object of monitoring was represented from the point of view of system approach and methods of optimum control in the form of the integrated geotechnical system (IGTS) – “subsurface structure and its elements – geological object (the geomassif area containing the structure and interacting with it) – city planning object (the fragment of urban development limited by the area of active influence of subsurface construction). On the basis of numerical modeling and monitoring means a system and methods of protective measures geotechnology optimization were created.

As for the object of buildings of “Cultural and Business Center Okhta”, the monitoring and geotechnical substantiation of protective measures in tunnel collector 2,250 mm in diameter located at a depth of 14-15 m in very soft thixotrop loam was carried out. The collector has been in operation for more than 30 years and its condition, as per the technical inspection materials, was considered as restrictedly serviceable.

The collector being in close proximity to the projected complex “Cultural and Business Center Okhta” falls within the area of its influence at the stage of construction and operation. To provide geotechnical safety and monitoring of the collector the influence of “Cultural and Business Center Okhta” complex was evaluated and methods of its geotechnical protection were developed. In the course of solving such a task, use has been made of the finite element method, geotechnical packages “Plaxis 3D Foundation”, “Plaxis 3D” Tunnel and design package “Robot 3D”.

Construction activities and arrangement of protective measures were simulated in the form of calculation steps which are given in Table 2

| № | Description of calculation steps |
|---|---------------------------------|
| 1 | Original stress and strain state of the system |
| 2 | Arrangement of protective measures |
| 3 | Construction of walls in the ground |
| 4 | Construction of piers and barrettes |
| 5 | Tier-wise development of ground with concrete casting of flooring and bottom |
| 6 | Application of load from building and foundation loading (700 kPa for tower and 200 kPa for stylobate) |

The following was simulated as protective measures (Figure 13): complete ground substitution – a; partial ground substitution – b; application of geotechnical barrier in the form of protective trench made of thixotropic paste with weighting agent (E=2÷3 MPa; γ=2.15÷2.20 t/m³; φ=5°; с=0.003 MPa; ν=0.48) – c.

![Figure 13](image.png) Protective measures for decrease of influence on collector: 1 – reinforcement of tunnel structure as per spiral-wound technology; 2 - brace sheet walls L-5 to the length of the protected section; 3 - stabilized soil E=200 MPa; 4 – existing soils; 5 - metal binding belt; 6 – geotechnical barrier (thixotropic paste with weighting agent - barium); 7 – wall in ground
The task of numerical modeling in the objective allocation by Plaxis3D Foundation means includes evaluation of polydimensional deformations and strain level in longitudinal cross-sections of the collector liner. Selection of this model was conditioned by that the collector has curved alignment in plan view and the high-rise complex of buildings is represented in the wrong form (figure 14).

![Figure 14. Geometry of a 3D model of the complex (the plan and general view): 1 – the protected collector; 2 – the wall in soil; 3 – the stylobate part of the building; 4 – the high-rise part of the building.](image)

The 3D model is represented as a block with plan view dimensions 800x800 m. The lower boundary of the model is located at an actual elevation of minus 170 m which is conditioned by the depth of mass contractibility according to the geology and loads (see Figure 15).

![Figure 15. Geological column – a, and materials parameters – b](image)

At the stage of operating loads application from the high-rise building complex the collector deformations in the area of the maximum approach were 62 mm and settlements – 134 mm; at that, axial forces had variation range from +0.2 MN (elongation) to – 0.5 MN (compression), bending moments – up to 2 NMm[9,10,11].

Flat model (2D) served for analysis of protective measures influence on the collector and represented the schematic cross-sections of the high-rise buildings complex and the adjacent collector. The calculation model is represented as a block with dimensions 160x125 m (figure 16).
Figure 16. Simulation of the protective measures.

The modeling results are represented in Table 3 and show that the trench protection provides for a decrease in not only the vertical but also the horizontal deformations. General decrease in deformations is observed as more than in 3 times.

Table 3. Displacement of collector at construction stages.

| Stage of development                                      | Protective measure * | Displacements, mm |
|-----------------------------------------------------------|----------------------|-------------------|
|                                                           |                      | X     | y     | total |
| Development of the first layer with concrete casting of flooring slab | Trench –GTB         | -3,99 | +2,10 | 4,46  |
|                                                           | no                   | -5,38 | +1,39 | 5,45  |
| Development of the second layer with concrete casting of flooring slab and with account of piers | Trench –GTB         | -2,89 | +7,04 | 7,43  |
|                                                           | no                   | -12,97| +15,34| 20,07 |
| Development of a ditch with simultaneous concrete casting of the bottom | Trench –GTB         | -7,59 | +23,87| 2477  |
|                                                           | no                   | -11,17| +35,95| 37,57 |
| Loading of building model                                 | Trench –GTB         | -6,66 | -20,08| 23,93 |
|                                                           | no                   | -30   | -60,26| 67,22 |

*GTB – Geotechnical barrier

Structure preservation criterion is maximum deformation and maximum oscillation of the collector, which ensure chatter stability of the ground massif, which contains collector. Maximum deformations and values of allowable displacements depending on the length of deformed section of tunnel collector were calculated as per Robot Structural Analysis Professional 2009 program for different sections of collector (see Figure 17).

Monitoring was aimed at provision of that the values of the collector lining displacements do not exceed design values shown at the diagram (see Figure 18).

Reinforcement of collector lining as per the spiral-wound technology (SPR) makes it possible to increase the maximum allowable tunnel displacement up to 3-5 times, depending on the length of the section being deformed.

The results of numerical modeling and monitoring of the geotechnical system “tunnel collector - city planning object - protective measures” used in the area of geotechnical influence of “Okhta-Center” construction can be recommended for other large-scale unique objects under construction in the area of tunnel collectors location[12,13,14].
Concept of the geomonitoring ensuring of technosphere safety of construction and maintenance of tunnel collectors, principles of its formation and functioning should provide reliability, safety and efficiency of underground structures construction. In some cases they can be successfully used at engineering development of underground space of a megalopolis, when it is necessary to provide protection of town-planning environment against negative technical impact. In other cases, vice versa, they can be used to provide preservation of underground spot or line structure being erected against change in condition of exposure of town-planning environment or other polyanthropogenic factors, which disturb conditions of technosphere safety.
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