Geomonitoring of structural safety of unique underground sewage facilities operating for a long term in difficult soil and anthropogenic conditions of the megacity

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Abstract. Anthropogenic and dynamic impacts on facilities of underground urban infrastructure increase at intensive development of megacities. The unique long-operating underground structures of sewage system require special protection against anthropogenic influence as their wear degree in difficult soil conditions reaches 70\% and more. Therefore, providing structural (mechanical) safety of underground structures of excessive level of danger and responsibility defines sustainable operation and future development of geotechnical infrastructure of the megacity in general. Long-term studying dynamics of changes of technical state of underground sewage structures of the megacity, long operating (for more than 70 years) in soft soils, allowed establishing regularities of influence of intensive anthropogenic and dynamic impacts on this process. For the first time, based on developed continuous models of defective structures potentially dangerous sections have been identified, they are subjected to manifestation of critical failures; ways of their correction are presented. Numerical simulation has defined borders of defectless joint operation of the system “target area – geobulk – underground structure”. Scientific substantiation of boundaries of areas with potentially dangerous sections of underground sewage facilities with account of external anthropogenic and dynamic impacts constitutes the basis for elaborating regulations on safe development of geotechnical infrastructure of the historical area of St. Petersburg. The proposed methods of monitoring and protection of geotechnical infrastructure have been successfully used for many years by St. Petersburg Vodokanal in areas of influence of anthropogenic factors and objects under construction on underground structures, they ensure an optimal combination of sustainable operation and development of geotechnical infrastructures of megacities.

1. Introduction

Sustainable development of urban geotechnical infrastructure is a condition of sustainable development of megacities. This condition increases the role of sustainable operation of long-operating underground structures of the sewage system. With urban development there is a need to solve tasks of increasing power and capacity of networks of sewage tunnels. These elements of the sewage system draw more attention during their whole lifecycle. It is especially evident at the stage of their long-term operation in difficult geological and hydrogeological conditions at increasing anthropogenic impacts.
Manifestation of these unfavorable conditions is the most characteristic for St. Petersburg. During the last 25 years State Unitary Enterprise “St. Petersburg Vodokanal” together with Emperor Alexander I St. Petersburg Transport University and State Unitary Enterprise “Lengiproinzhproyekt” have been conducting regular examinations of the current state of tunnels; monitoring factors, which influence development of structural defects, and developing technical solutions for repair and sanitation of sewage structures.

The conducted analysis of scientific research [1, 2, 3, 4] allowed identifying the features of interaction of long-operating sewage tunnels in difficult soil conditions at increasing dynamic and anthropogenic loads as a result of actively developing engineering-transport and city planning infrastructure of the city. Application of the obtained results defined directions in the field of provision of structural safety of tunnels, monitoring of their current technical state, development of repair technologies of sewage tunnels to ensure their operational reliability and sustainable operation at anthropogenic and dynamic impacts.

In the cities with vast historical downtowns long-operating sewage tunnels require special protection against the anthropogenic impacts. As the facilities pertaining to structures of an increased level of responsibility sewage tunnels should meet the normative regulations of safe operation, which exclude the risk of emerging dangerous anthropogenic accidents [4].

The authors have collected and analyzed materials of the current technical conditions of sewage tunnels of the largest Russian cities, including Moscow, St. Petersburg, Ekaterinburg, Samara, Novosibirsk etc., of total length more than 2300. For general sampling there have been sorted out such features as development of a tunnel network (from 100 km to 500 km and more); duration of operation (from 30 to 70 years and more); difficult geotechnical conditions of lining routes of sewage tunnels (presence of soft unstable soils, crossing aquifer horizons, including the headed ones).

![Figure 1. The scheme of location of sewage tunnels in St. Petersburg. The areas of active anthropogenic influence.](image-url)

Almost for the majority of cities under consideration a network of sewage tunnels has a medium value of physical wear within 55-66% with development dynamics 0.5-1.0% per year. It was noted
that in the cities with vast historical development and developed transport infrastructure, first and foremost, it refers to Moscow and St. Petersburg, a degree of wear of tunnels has significantly larger values, reaching 71% and 83%, respectively, at higher dynamics of development up to 1.5-2% per year. The system of sewage tunnels in Moscow was constructed by the 1930s, in St. Petersburg it happened at the end of the 1950s, but the degree of wear and its dynamics in it are higher, therefore, here are the most relevant tasks of protection of sewage tunnels and finding out causes of the high degree of their wear for sustainable development of this unique historical city (figure 1).

2. Analytical studies of the interaction of sewer tunnels with the soil environment and analysis of factors affecting their technical condition

Nowadays the total network of sewage tunnels of St. Petersburg is about 270 km. The system of sewage tunnels represents pipelines of 1.2-5.6 m diameter laid using a drilling method with a help of tunnel boring shields, they are located at the depths ranging from 3 m to 90 m. Bearing structures consist of RC tubings of concrete of B25 grade with reinforced concrete lining of B15 grade or coating of tormix. Usually tubing thickness is 200 mm, their waterproofness is provided with a lock joint on its planes of 10 mm width and 30 mm depth. A space between the bulk of embedding soil and tubing support is filled with slurry through jet openings. The major part (up to 75%) of sewage tunnels is located in the central historical downtown, it does not have dubbing and it is laid in extremely difficult geotechnical and hydrogeological conditions in terms of construction practice. In the central part of the city strong crystal deposits lie at the depths 120-220 m. A thick sheath of sedimentary deposits lies above. The main part of the territory is covered with a bulk of Quaternary deposits Q. Among the latter one should specially mention soils belonging to lacustrine-marine, lacustrine-glacial and moraine deposits. Down to the depths 30-120 m soil strata are represented by saturated silty 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, $\varphi=12-17^\circ$; liquid-plastic stratified silty loams $E=5-8$ MPa, $C=0.015-0.025$ MPa, $\varphi=10-16^\circ$; semi-solid silty loams with gravel, pebbles $E=12-15$ MPa, $C=0.016-0.028$ MPa, $\varphi=24-28^\circ$. All this soil bulk is unstable to anthropogenic impacts. Only in the southern part of the city at the depth more than 30 m there is a roof of dislocated Cambrian deposits $E=19-34$ MPa, $C=0.04-0.06$ MPa, $\varphi=17-21^\circ$. Aquifers are represented by the above-moraine aquifer (surface ground waters); upper above-moraine aquifer, located at the depths from 7 to 30 m with the head values 5-28 m and lower inter-moraine aquifer – at the depths 25-120. Venda aquifer suite (Gdov aquifer) is located in Pre-Quaternary Upper-Proterozoic deposits at the depths from 70 and more where the head value reach 80-160 m.

Due to scouring deposits of Pre-Quaternary age by paleo-rivers the bulk of Quaternary deposits is characterized by a big drop of absolute elevations [5]. Asymmetric strata of soils of different strength are characterized by abrupt slopes reaching the value of 50 % and more. This factor exerts a particularly negative influence on long-operating sewage tunnels in terms of increasing anthropogenic impacts, first and foremost, the vibro-dynamic one [6, 7, 8].

2.1. The geotechnical analysis of influence of anthropogenic factors on reliability of long-operating sewage tunnels

There was carried out the analysis of the archive data of technical examinations implemented by the department of operation of sewage tunnels of the State Unitary Enterprise “St. Petersburg Vodokanal”, as well as tool evaluations of a technical condition of tunnel structures of total length about 15000 m both in the central historical part of the city, the depths - 12-15 m, and beyond, at approaches to three main sewage pump stations accumulating all the city sewage - sewage pump station Olgino, sewage pump station - Yug, sewage pump station – Bely Ostrov, put at the depths 71.0 m, 58 m and 53 m, respectively, and connected with tunnels at the same elevations, which have been conducted by the author in the period from the late 1970s till now.
Figure 2. Testing structures of an active sewage tunnel: (a) measuring vibrations with an accelerometer ICP; (b) scanning integrity of tunnel structures with a georadar OKO-2.

Technological tool examinations include: in situ tacheometric survey of spatial location of a tunnel in intervals between shafts, georadar scanning of states of the internal surface of a tunnel with assessment of its integrity; taking core samples and making breakoff test with scanning to define strength properties of concrete, taking specimens for chemical and biochemical analysis, assessment of a degree of corrosion of reinforcement by non-destructive methods, vibro-dynamic test on vibration of internal structures of a tunnel due to external and construction vibration impacts.

The uniqueness of data of observation of tunnels implies that the technical examination has been implemented for a long term – since the late 1970s to nowadays (the end of 2020). Within this period the same intervals of tunnels were examined several times. As a rule, during several years after an examination monitoring of a tunnel state was conducted. Therefore, there appeared an opportunity to trace dynamics of development of defects.

The time range of observations was divided in 3 periods:
a) the 1970s-80s; b) the 1980s-2000s; c) 2000-2016. The identified, most characteristic defects, which influence operational reliability and bearing capacity of a tunnel were classified in 7 groups: d1-shrinkage cracks in concrete lining; d2- features of gas corrosion; d3- drop leakages; d4- force cracks in the crown and lateral surface of a tunnel; d5- features of biological corrosion of concrete; d6-corrosion of reinforcement, abrasion of a tray; d7- presence of headed leakages;

Figure 3 represents the structure of manifestation and dynamics of development of defects during operation of sewage tunnels from the 1970s to 2020.

Figure 3. The example of the dynamics and structure of defect manifestation during a long period of operation of sewage tunnels: (a) the 1970s-80s; (b) the 1980s-2000s; (c) the 2000s-2020s. Defect classification: d1-d7 – the primary – from shrinkage cracks and manifestation of features of gas corrosion to development of force cracks and manifestation of headed leakages (see description in the text).

The analysis of the structure of manifestation and dynamics of development of defects show that in the initial period of operation of sewage tunnels there were observed such defects as shrinkage cracks in concrete lining with occurring drop spillages and features of gas corrosion. The nature of the defects, which prevail during the first 15-20 years of operation of tunnels, and their influence on
bearing capacity and operation reliability of structures can be considered as negligible, their technical state can be recognized as serviceable according to the existing Russian GOSTs and Construction Codes.

The next 20 years of operation of tunnels are characterized by the features of emerging force cracks and considerable increase of concrete defects due to its gas and biological corrosion. However, their technical state is regarded as limitedly serviceable.

The results of the analysis of defects occurred in the period 2000-2016 is of special interest. It is noteworthy that in that very period there increased an amount of defects, which influence on bearing capacity of tunnel structures: almost 40% growth of an amount of force cracks in the crown and lateral surface of a tunnel; the features of corrosion of reinforcement and abrasion of the tray; presence of headed leakages in the tunnel body; an increase of a share of defects associated with biological and gas corrosion. In terms of the categories of technical state of a tunnel it refers to the “limitedly capable”. Operation of sewage tunnels requires monitoring of their technical condition, taking measures on recovery of structural bearing capacity and operation reliability.

2.2. The factors causing intensive development of defects in sewage tunnels

Comprehensive surveys, which have been conducted at increasing anthropogenic and dynamic impacts during a long-term period of examination of sewage tunnels, allowed implementing back analysis and defining factors causing manifestation and development of defects. The factors can be grouped according to the nature of influence as the internal and external ones.

The nature of internal factors implies processes connected with transportation of sewage discharge. The main factors include corrosion of internal structures (gas, biological), tray abrasion, discharge accumulation etc. These factors lead to rather static development of defects. Definition of limit admissible values of their influence on sewage tunnels is a field of research and activity of sanitary-technical special services. They tackle these tasks successfully [6].

External factors are characterized by difficult interaction of the above-ground urban environment, tunnel structure, embedding geobulk, forming natural-technical environment, which operates under influence of anthropogenic factors.

Evaluation of this interaction and definition of an area of limit admissible mutual influences of elements of the system of natural-technical environment is a subject of geotechnical predictions. Separate works of the author are devoted to optimum management of elements of natural-technical environment [7, 9, 10, 11].

In the framework of this paper we set the task of geotechnical provision of safe level of external impacts on a tunnel structure with account of residual life of its bearing capacity [12 to 17].

The results of examination of long-operating tunnels under difficult soil conditions show that tunnel deviations in the vertical plane from the horizontal design axis are caused by the influence of factors of natural, natural-anthropogenic and anthropogenic nature.

As a rule, the natural factor manifests itself in the period of construction at shield tunneling. Moving in soils of inclined stratification of different strength, a TBM loses its horizontal stability, thus subsiding, at the moment of occurrence in a lens of quick soils with thixotropic properties. In this case following the TBM tunnel lining also settles.

The anthropogenic factor acts in conditions of increasing development of anthropogenic impacts, mainly the vibro-dynamic ones, on a sewage tunnel through an embedding soil bulk. At this impacts the effect of softening of vibro-sensitive soil and decreasing its strength properties poses a danger. More frequently it leads to accumulation of vibro-settlements of tunnels, which have been making intensive vibro-dynamic impact for a long term and lie in soft thixotropic soils.

The factors of natural-anthropogenic nature manifest themselves in those geotechnical situation when there is implemented an effect of joint superposition of tunnel settlements in the period of tunneling in a bulk of unstable soils with simultaneous location of a tunnel in an area of intensive growing vibro-dynamic impacts and, consequently, “accumulation of the effect of stability loss of soils of an embedding bulk.”
In all cases displacement of the tunnel axis in vertical direction due to anthropogenic impacts causes the necessity of considering this factor to provide structural reliability of a structure and development of protective measures.

To evaluate the conditions of interaction of slurry (density 1.8 t/m$^3$) with a tunnel having parts with geometrical irregularity of operational (live) section at a different thickness of the layer of tray concreting ($d_{outer}$/hc.t. from 10% to 50%) there have been made calculations, which results are given in figure 4.

The analysis of the graphs shows that geometrical irregularity of the section, which in our case is caused by different thickness of tray concreting, has a considerable influence on a reduced density of the tunnel. The reduced density of a tunnel is calculated based on different conditions of geometrical irregularity of the tunnel cross-section with account of varying external geometrical characteristics ($d_{outer}$; density of structural elements – tubings, reinforced concrete of lining, reinforced concrete of the tray and density of sewage liquid at different degrees of tunnel filling (h/D from 0 to 1).

The examples of parts of sewage tunnels with irregular sections of tunnels: (a) the sewage tunnel Vyborgsky from shaft 137a to shaft 136; (b) the sewage tunnel Tovarischesky; (c) the sewage tunnel “Okhta”, where: K- a coefficient of section narrowing; -Δ and +Δ- settlement and uplift, respectively.
Analyzing the nature of curves for reduced densities of the tunnel and soil, one can mention that existence of parts of curves with a smaller reduced density of the tunnel relating to the density of embedding soil demonstrates an unstable state of the system “embedding geobulk – tunnel structure”. At the empty tunnel (without filling with the sewage liquid) the effect of instability increases. In real conditions the system stability is reliably provided by forces of interaction of mineral particles and structural links between them. However, one should consider that in structurally unstable soils, which are sensitive to vibro-dynamic loads and prone to vibro-creeping, reliability of this geomechanical provision of the tunnel stability can be violated (figure 5).

According to the results of examination [7] the nature of geometrical irregularity of a tunnel results in settlements and uplifts of the tunnel at anthropogenic and dynamic impacts.

2.3. The analysis of the conditions of interaction of a sewage tunnel with embedding soil milieu, which is unstable to vibro-dynamic impacts

Combined application of static and dynamic loads leads to a change of the state of tunnel subsoil. The soil goes through phases from hardening and forming initial shears to the failure [5,18]. Vibrational consolidation occurs due to release of physically bound ground water, unleashing structural links, changing strength properties $(C, \varphi)$ and reducing its porosity [9, 18].

Soil vibrations can lead to deformation of the protective layers of primary and control grouting between tubing lining and soil and, as a consequence, to leakages in a tunnel with possible wash-out of soil, that can cause tunnel settlement.

In order to evaluate vibration impact there were conducted in situ tests. As due to structural features of sewage tunnels transversal force vibro-dynamic impacts are the most critical, locations of crossing routes of sewage tunnels and transport ways were selected as the sites of observation (figure 6).

![Figure 6. The test ground of crossing the crossroad with an intensive traffic and the route of sewage tunnel #24 in St. Petersburg.](image-url)
The tunnel has been operating since 1970. The depth of tunnel is 16.1 m - 14.2 m, to the whole depth of the tunnel the embedding soil environment is represented by strata of soft Quaternary deposits, which have a low vibro-stability and thixotropic properties.

The part of the sewage tunnel under investigation is located in a congested area of a network of ways with intensive traffic. Moving trams, trolleybuses and cars create a high level of vibrations.

In situ measurements of vibro-dynamic impact from transport were made on the ground surface in the area of location of the route of sewage tunnel and at the same time inside the sewage tunnel on the surface of its structures.

Investigation of the sewage tunnel vibration process was carried out with a help of measurement and calculation set of MIG type and accelerometers МС-201, and sets of gauges SM-3KV, which were installed inside the tunnel on the lateral surface and in the crown. Applying sensors of this type allows recording vibration with the amplitude from 0.5 micron to 2000 micron, the frequency from 2 to 200 Hz with an error not exceeding 10%. The gauges are protected from inducing an external field, they have a temperature compensator, waterproofing (to log vibrations in water), and are characterized by minimum mutual influence (up to 5% of orthogonal oscillations).

The set includes gauges allowing recording vertical and two horizontal (orthogonal) components of vibration amplitudes.

The characteristic results of vibro-dynamic changes are shown in accelerograms (figure7 (a) and 7 (b)). The changed level of vibrations on the structure of the sewage tunnel ranged from 15 micron to 35 micron.

![Figure 7. Accelerograms of vibro-dynamic changes: (a) on the surface; (b) on the crown of the tunnel structure.](image)

Laboratory tests of soils characteristic for the soil bulk embedding the sewage tunnel were made to evaluate vibro-dynamic properties of soils embedding the tunnel. The tests were conducted in a vibro-stabilimeter built by PGUPS according to the standard methods. The main results of the tests showed that at the level of soil vibration in vibro-stabilimeter in the characteristic range of vibro-dynamic impact corresponding to in situ measurements (from 15 micron and more) strength properties of clayey soil decrease for silty loam – up to 31% (unit resistance «ε») and for silty sand – up to 25%.

The conducted works on technical examination of sewage tunnels, field and laboratory tests provide a quantitative evidence of the fact of influence of the vibro-dynamic impact of transport loads on reducing strength properties of soft clayey soils of Quaternary deposits at the depth of tunnel embedment from 25% to 31%, and consequently, decreasing its vibro-stability in the embedding soil bulk.

3. Geotechnical research to protect sewer tunnels from dynamic and anthropogenic impacts

The geotechnical and structural measures to provide safety and reliability of long-operating sewage tunnels should be selected on the basis of comparison of competitive options, but the main requirement, they must meet, is an opportunity of preventive use substantiated by geotechnical and structural calculations.
The table gives examples of some geotechnical measures, which were successfully taken for protection of sewage tunnels in St. Petersburg in 1998-2020.

**Table 1. The experience of geotechnical support of structural safety of sewage tunnels.**

| Nature of anthropogenic effects                                         | Geotechnical and structural measures                                      | An object of protection                                                                 |
|------------------------------------------------------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Excessive static and dynamic impacts on the tunnel brick crown         | Construction of an unloading screen and strengthening of structures with composite materials, and monitoring | The brickwork sewage tunnel was built in the XVIII century under Konnogvardeisky boulevard |
| Increase of static load on the sewage tunnel due to the weight of building under construction above it | Construction of an unloading bridge with load transfer to soils underlying the tunnel base, monitoring | The sewage tunnel in Nalichnaya street                                                  |
| Unloading of soil bulk at construction of deep transport tunnel above the sewage tunnel | Construction of an unloading screen made of reinforced soil to prevent uplift of the pit bottom, monitoring. | Transport tunnels above the sewage tunnel along the Obvodny canal and A. Nevsky bridge.  |
| Prevention of horizontal displacement of the sewage tunnel at unilateral unloading of soil bulk at reconstruction of the embankment. | Construction of a geotechnical barrier, monitoring.                        | The sewage tunnel routes along the embankment of the Fontanka River.                    |
| Increase of an area of ultimate admissible displacements of the sewage tunnel at unilateral unloading of soil bulk at reconstruction of the embankment. | Structural reinforcement and sanitation of the sewage tunnel applying the method of spiral coiling technology to increase ultimate admissible displacements of the sewage tunnel. | 840-m-long sewage tunnel in Tovarischesky avenue.                                      |
| Increase of static and dynamic loads on the sewage tunnel due to the impact of heavy transport and trams. | Structural reinforcement and sanitation of the sewage tunnel applying the method of coiling to recover bearing capacity of the tunnel up to the design level, monitoring. | 840-m-long sewage tunnel in Tovarischesky avenue.                                      |

The calculation substantiation of the geotechnical protective measures was implemented according to the algorithm: collecting loads and impacts, defining physical-mechanical properties of soils and tunnel materials; building a geomechanical calculation model in the software Plaxis3DTunnel; building a calculation model for structural calculations in the software Robot; selecting parameters of tunnel reinforcement. The calculation example is shown in figure 8.

**Figure 8.** (a) fragments of the calculation scheme; (b) modeling ultimate admissible displacements of the sewage tunnel: 1 is tunnel tubings; 2 is concrete lining; 3 is a layer of strengthening and sanitation via coiling method.
4. Experience in the use of geotechnical measures in the repair of sewer tunnels to ensure their structural safety

4.1. The site description
The sewage tunnel in Tovarischesky avenue with the intervals diameters D= 2.5 m and D= 1.5 m at the depths 12-74 m was in operation for more than 40 years, according to examination results it had the degree of wear more than 79%, settlements at street crossroads up to 25 mm. It was necessary to provide protection of the sewage tunnel against increased static and dynamic transport impacts. According to georadar scanning there was identified overall peeling of concrete lining from tubing lining with occurring headed leakages (figure 9).

![Figure 9](image)

**Figure 9.** The defect in form of peeling structures: (a) features of headed leakages; (b) a fragment of radargram with features of peeling of the tunnel structures – 1 is tubing lining; 2 is RC lining; 3 is a layer of headed water.

4.2. The calculation substantiation of protective measures for the sewage tunnel
The sequence of calculations was made according to the algorithms given above in section 4 of the paper; fragments of the calculation are given in figure 8. The ultimate admissible displacements before and after taking protective measures are shown in the graph (figure 10): 1 - D=1.5m, 2 - D=2.5 – tubing lining with defects of concrete lining; 3 - D=1.5 m, 4 - D=2.5 - tubing lining with defects of concrete lining.

![Figure 10](image)

**Figure 10.** The ultimate admissible displacements of sewage tunnels D=1.5 and D=2.5 before (1.3) and after (2.4) reinforcement of the structure using coiling technology.
4.3. Description of the method and results of taking protective measures for the sewage tunnel

The main requirement to taking protective measures was to use such a technology which would allow carrying out repair works in conditions of continuous transportation of sewage discharge.

The technology of sanitation using the method of coiling was used for repair and recovery of bearing capacity of the tunnel. The scope of workflow included: cleaning the tunnel and preparing its surface; structural gluing of concrete lining and tubing lining through jetting SikaDur material; strengthening the crown surface by structural reinforcement carbon plastic SikaWrap; facing the tunnel surface with PVC coiling profile; jetting polymer-cement slurry (Pcomp.= 65MPa) in inter-pipe space for structural gluing PVC envelope with the tunnel structure. The fragments of operation are shown in figure 11.

![Figure 11. The state of the sewage tunnel: (a) before repair and (b) after reinforcement of the structure and sanitation by the coiling method.](image)

According to the conducted monitoring it was found out: vibro-dynamic tests of the tunnel before and after repair showed changes of the period of self-oscillations of the sewage tunnel from 0.54 s to 0.19 s, i.e. by 58%, the amplitude of self-oscillations dropped from A= 300 micron to A= 15 micron, i.e. almost two times. It witnesses the provision of integrity of the structure and joint operation of its layers (figure 12). The guaranteed period of reliable operation after repair of the sewage tunnel is minimum 50 years.

![Figure 12. The results of oscillation measurements of tunnel structures at applying external vibro-dynamic transport load: (a) oscillogram of the vibration process of tunnel structures with peeling defects A=300-800 micron; (b) the same, after reinforcement with “structural gluing” and sanitation using the coiling method A=15-20 micron.](image)

5. Conclusions

As a result of long-term operation, tunnel sewers (TC) in Russia have wear up to 55 = 66 %. Difficult ground conditions in Saint Petersburg as a result of various man-made and dynamic impacts led to even greater wear of the TCC up to 83% with high dynamics of development up to 1.5 = 2% per year.

The proposed geotechnical methods of TCC protection, including structural reinforcement and sanitation technologies in the conditions of wastewater transportation, accompanied by a
Geomonitoring system, provide an increase in the load-bearing capacity of the TCC structure and its operational reliability.

It is recommended to use these methods for the sustainable functioning of geotechnical infrastructure in the development of large cities with an extensive historical center in the face of increasing man-made impacts.

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