IOP Conf. Series: Materials Science and Engineering 456 (2018) 012083 doi:10.1088/1757-899X/456/1/012083

Simulation of strain-stress behavior of a tunnel collector in the combined anthropogenic effects conditions

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Abstract. In the intensive development conditions of urban engineering and transport infrastructure long-operating sewage tunnel collectors face the action of unfavorable anthropogenic effects combination. The external anthropogenic effects include additional static and vibro-dynamic loads caused by ground and underground transport, changes in urban planning and geotechnical situation, as a rule, during joint underground and high-rise construction. The internal effects include sign-alternating (headed and non-headed) influence of aggressive sewage waters and, consequently, structural corrosion and beyond-limit decrease of its bearing capacity during long-term exploitation. The paper gives real practical examples and shows that pre-limit strain-stress behavior simulation of tunnel collectors under the conditions of combined anthropogenic effects and calculative substantiation of protective measures provide bearing capacity and service reliability during their lifecycle at the stages of reconstruction and use.

1. The analysis of exploitation features and results of tunnel collectors monitoring during anthropogenic effects

Long-term operation and intensive engineering infrastructure development of megalopolises increase the requirements to ecology and efficient use of land resources. During engineering development of such a megalopolis underground space the design of integrated measures for town-planning environment protection against negative anthropogenic impact is very relevant. Therefore, there must be introduced special safety requirements for sewage and water treatment facilities [1].

So far around 88% of all sewage collectors are made of reinforced concrete, about 7% - of metal (steel, cast iron), about 3% - of bricks, plastic, ceramics. Tunnel sewage collector diameters ranges from 1.2 to 5.6 m, they are embedded at the depth from 3 to 60 m underground.

At St. Petersburg State Transport University the authors of the paper conducted monitoring observations analysis of defects changes dynamics and strain-stress behavior of tunnel collectors in St. Peterburg during the recants 30 years. The volume of observations was more than 25 km of tunnels with the diameters from 1.85 m to 3.4 and the depth from 16 m to m to 37 m [2]. The analysis results showed that difficult conditions of tunnel embedment and a combination of static and dynamic effects lead to displacements and deformations of tunnels, which cause force cracks and violation of lining structures integrity. The analysis identified such defects almost at all areas of dynamic impact and amount to 83% of the total observations amount with the dynamic of development up to 1.5-2.0% per year.

Figure 1 shows the dynamics of growing the tunnel settlement in unstable soils in the area of dynamic transport load influence in the period of 1975-2010.

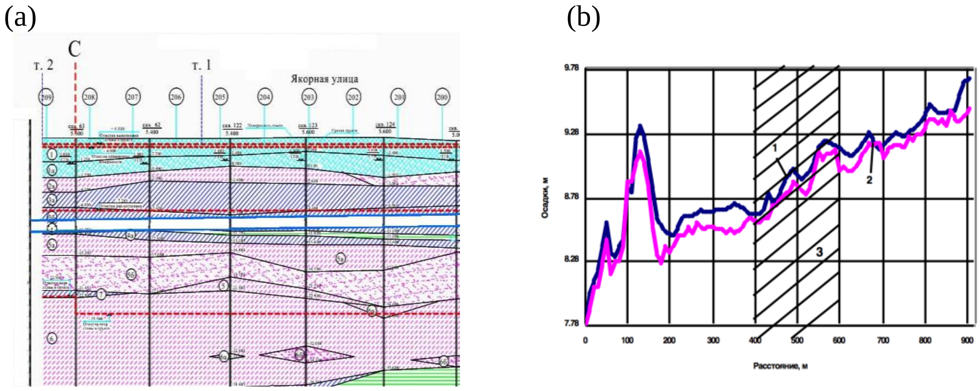

Figure 1. The diagram of compressions comparison along the arch axis of the collector: (a) the geotechnical profile, typical for laying sewage tunnels in St. Petersburg, (b) the diagram of compressions: 1 – 2010 survey results, 2 – executive survey data of 1975, 3 – the area of the collector protected from the influence of the construction with a screen of low modular material.

Geotechnical analysis of the sewage tunnel was carried out for the most typical section located in a zone of transport intense dynamic impact and the new construction impact.

Figure 1 shows the diagram of the tunnel compressions during more than 35 years of service.

Uneven tunnel compressions, modified along the arch axis, range from 5 to 276 mm. The comparative analysis of geotechnical profiles along the tunnel route and its placement on the plan relative to the traffic junction showed that the greatest compressions up to 276 mm are located in the area of the tunnel under intense dynamic traffic effects; they pass the layer of thyrotrophic quaternary deposits.

Evaluation of the transport dynamic impact was carried out by studying the oscillatory process with a set of manifold gauges CM TSP installed in the arch and blocks of recording equipment [3].

The frequency of the collector oscillations during various traffic loads ranged from 15 to 35 Hz, and the vibration amplitude of 35-70 microns was recorded. According to the research [4, 5], as for the soil deposits type and the appropriate level of decrease dynamic effects of strength characteristics C and φ comprises up to 35% and 17%, respectively. In order to provide operational reliability vibration protection measures for tunnels such as the technical conditions geotechnical analysis of long-operating sewage tunnels under intensive anthropogenic impact and the use of spiral-wound technology for internal lining of the tunnel were suggested.

In the framework of this research there was set a task of geotechnical support simulation for flawless level of external effects on the tunnel taking into account its residual bearing capacity and strain-stress behavior [5- 8].

2. Simulation of external effects on a tunnel collector and calculative substantiation of protective measures

As for the site of buildings “ODC” monitoring and geotechnical substantiation of protective measures for the tunnel collector of 2250 mm in diameter located at the depth of 14-15 m in a very soft thyrotrophic 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 is located close to the designed complex “ODC”, within the area of its influence at the stage of construction and operation. In order to provide geotechnical safety and monitoring of the collector, the influence of “ODC” complex was evaluated and methods of its geotechnical protection were developed. While this task solving, finite element method, geotechnical packages “Plaxis 3D Foundation”, “Plaxis 3D” Tunnel and design package “Robot 3D” have been used [9, 10].

Construction activities and arrangement of protective measures were simulated in the form of calculation steps which are given in Table 1.

Table 1. Numerical modeling steps.

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

The following steps were simulated as protective measures (see Figure. 2): complete soil substitution – a; partial soil substitution – b; geotechnical barrier application in the form of protective trench made of thyrotrophic paste with a weighting agent (E=2÷3 MPa; γ=2.15÷2.20 t/m3; φ=50; c=0.003 MPa; ν=0.48) – c.

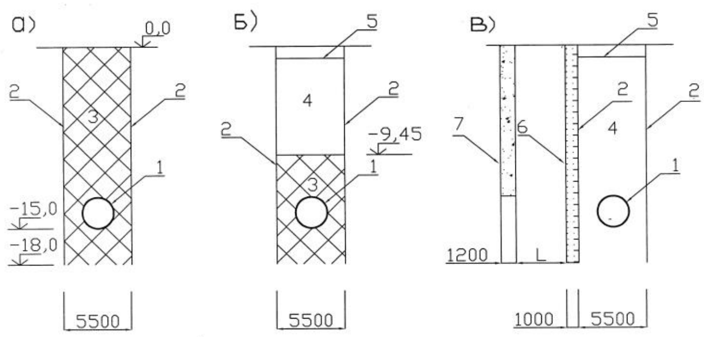

Figure 2. The protective measures to decrease influence on the collector: 1 – reinforcement of the tunnel structure using the spiral-wound technology; 2 – brace sheet walls L – 5 to the length of the protected section; 3 – stabilized soil E=200 MPa; 4 – existing soils; 5 – the metal binding belt; 6 – the geotechnical barrier (thyrotrophic paste with a weighting agent - barium); 7 – the wall in soil.

The task of numerical modeling in the objective allocation by Plaxis3D Foundation means evaluation of polydimensional deformations and a strain level in longitudinal cross-sections of the collector liner. Selection of this model was conditioned by the fact that the collector has curved alignment in the plan view and the high-rise complex of buildings is represented in the uneven form (see Figure 3).

The 3D model is represented as a block with the plan view dimensions 800x800 m. The lower boundary of the model is located at an actual elevation – 170 m, which is conditioned by the depth of mass contractibility, according to the geology and loads (see Figure 4).

Figure 3. 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.

(a)

Number	Name	ν [10⁻³]	E_{ref} [10^3 kN/m^2]	c_{ref} [kN/m^2]	φ [°]	γ_{unsat} [kN/m^3]	γ_{sat} [kN/m^3]
1	ИГЭ 01 насыпные	300,000	25,000	25,000	25,000	18,000	19,000
2	ИГЭ 01а техногенный	300,000	10,000	1,000	23,000	18,000	19,000
3	ИГЭ 02	340,000	8,000	17,000	18,000	19,900	19,900
4	ИГЭ 03А суглинки	360,000	7,000	8,000	12,000	19,600	19,600
5	ИГЭ 03Б суглинки	360,000	6,000	7,000	9,000	18,600	18,600
6	ИГЭ 04/4а водоупор	360,000	6,000	10,000	11,000	18,600	18,600
7	ИГЭ 02...04	340,000	8,000	10,000	10,000	19,000	19,000
8	ИГЭ 05Б пески	300,000	30,000	6,000	34,000	21,100	21,100
9	ИГЭ 05 супеси	340,000	8,000	12,000	16,000	20,100	20,100
10	ИГЭ 06* супеси	320,000	31,000	33,000	25,000	21,700	21,700
11	ИГЭ 11* глины дислоцир	340,000	40,000	150,000	17,000	21,300	21,300
13	ИГЭ 12* глины твердые	340,000	180,000	340,000	26,000	22,200	22,200
14	ИГЭ 13* глины твердые	340,000	250,000	610,000	32,000	22,300	22,300

(b)

ID	Name	ν [-]	E_{ref} [kN/m^2]	γ_{unsat} [kN/m^3]	γ_{sat} [kN/m^3]	R_{inter} [-]
12	В35 стены	0,20	3,45E7	25,0	25,0	0,10
13	барретты	0,35	2E7	24,0	24,0	1,00
15	сваи	0,35	1,5E7	22,5	22,5	1,00
17	бентонит	0,48	1,0	12,0	12,0	1,00
18	maquette	0,35	5E6	2,0	2,0	0,10
19	perm16	0,45	3000,0	16,0	16,0	0,10
20	perm18	0,45	3000,0	18,0	18,0	0,10
21	perm20	0,45	3000,0	20,0	20,0	0,10
22	perm22	0,48	800,0	22,0	22,0	0,10
23	perm14	0,48	800,0	14,0	14,0	0,10
24	жидкий бетон	0,40	1000,0	25,0	25,0	1,00

Figure 4. The geological profile – a, and the material parameters – b.

At the stage of operating loads application from the high-rise building complex the collector deformations in the area of the maximum proximity were 62 mm and the settlements – 134 mm; the axial forces ranged from +0.2 MN (tension) to – 0.5 MN (compression), the bending moments – up to 2 NMm.

A flat model (2D) served for analysis of the protective measures against the influence on the collector, and it 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 (see Figure 5).

Figure 5. Simulation of the protective measures.

The modeling results are given in Table 2 and show that the trench protection provides a decrease of both vertical and horizontal deformations. The total decrease of deformations is more than 3 times.

A structure preservation criterion implies maximum deformation and maximum oscillation of the collector, which ensure chatter stability of the soil bulk the collector contains. Maximum deformations and values of allowable displacements depending on the deformed section length of the tunnel collector were calculated using Robot Structural Analysis Professional program for different sections of the collector (see Figure 6).

(a) (b)

Figure 6. A fragment of the design diagram (a), and modeling of maximum deformations of the collector (b): 1 – the collector tubing; 2 – the reinforced concrete jacket; 3 – a reinforcement layer of the tunnel.

Table 2. Displacement of the collector at the construction stages.

Stage of development	Protective measure*	Displacements, mm		
		X	Y	total
Development of the first layer with the flooring slab concrete casting	Trench – GTB no	-3.99 -5.38	+2.10 +1.39	4.46 5.45
Development of the second layer with concrete casting of the flooring slab and with piers account	Trench– GTB no	-2.89 -12.97	+7.04 +15.34	7.43 20.07
Development of a ditch with simultaneous concrete casting of the bottom	Trench – GTB no	-7.59 -11.17	+23.87 +35.95	24.77 37.57
Loading of the building model	Trench– GTB no	-6.66 -30	-20.08 -60.26	23.39 67.22

*GTB – Geotechnical barrier

Monitoring was aimed at values provision of the collector lining displacements not to exceed the design values shown in the diagram (see Figure. 7).

Reinforcement of the collector lining using the spiral-wound technology (SATURN) makes it possible to increase the maximum allowable tunnel displacement up to 3-5 times depending on the length of a deformed section [3, 11, 12].

The results of the numerical modeling and monitoring of the geotechnical system "tunnel collector - city planning object - protective measures" used in the area of geotechnical influence of "ODC" construction can be recommended for other large-scale unique objects under construction in the area of location of tunnel collectors [13, 14].

3. Conclusions

The simulation concept and strain-stress behavior monitoring of tunnel collectors during anthropogenic effects provides sustainable service of underground line structures.

The results of strain-stress behavior simulation of a tunnel structure with its displacement in the soil bulk due to anthropogenic effects show that the geotechnical barrier use made of low-modulus material and reinforcement of the tunnel internal surface with carbon-plastic lining material results in more than threefold increase of an area of limit admissible deformations. It also enhances resistance of the reinforced structure against vibro-dynamic effects.

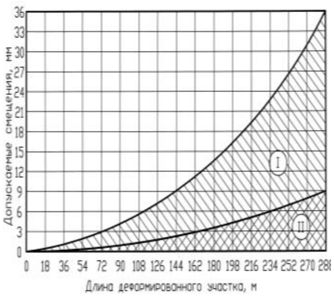

Figure 7. The values of the collector lining allowable displacements depending on the length of a deformed section: I - monitoring of a “safety corridor” of the collector displacements with lining reinforcement; II – the initial state of the collector without reinforcement.

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