Justification of the method of soil densification of the interstation tunnel by jet injection based on computer modeling

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Abstract. The article is devoted to a topical issue - the development of a method of densification of the base of the underground interstation tunnel to prevent further intensive subsidence of tunnel structures. Based on computer-mathematical modeling, the work establishes experimental dependence between the angle of inclination of jet grouting piles and the amount of subsidence of the distribution plate on which the tunnel structures rest upon. Inspection of the technical condition and analysis of defects in a comprehensive comparison with subsidence graphs allowed us to identify the main typical deformations during subsidence of a shallow tunnel built from blocks of a solid-section frame, namely their characteristic features, geometric parameters and placement points.

1. Introduction
The importance of underground lines cannot be overestimated. Traffic flows throughout the city depend on their reliable technical condition. The closure of only one of the central lines can lead to a transport collapse throughout Kyiv. When designing shallow underground structures in weak, unstable soils, it is often necessary to fix the surrounding area, both for the safety of work and to prevent subsidence of surrounding objects near construction. There are dozens of methods of fixing soils, each of which has its own disadvantages and advantages, but depending on technological, economic and hydrogeological conditions, each of them is more or less appropriate.

During the operation of interstation tunnels of underground constructed from solid-section frames in difficult hydrogeological conditions, deformations may occur due to uneven subsidence caused by vibrodynamic loads from the movement of underground trains. Significant funds are being spent on the repair and maintenance of such tunnels, which could be used to build new underground stations. Foreign experience and the introduction of the latest geotechnologies allows us to state that the issue of subsidence and deformation of tunnels can be solved using modern technology, design methods and work.

The study [1] describes a series of tests of centrifuge models aimed at studying the effect of sequential construction of two-level tunnels on an existing pile group under load in dry sand. Laying a tunnel of two levels was modeled in two stages: the first tunnel was laid at half the...
depth of the pile, and the second - at the depth of the pile or below the depth of the pile. There were also two tests of different sequence and construction of two-level tunnels. The first tunnel was laid at or below the pile-laying depth, and the second tunnel was laid at the middle of the pile-laying depth. The tests were performed by the method of finite element analysis, which takes into account the strength of the soil from deformation. The results of measurements and calculations showed that changing the sequence of construction of two-level tunnels significantly affects the subsidence, slope and displacement in the cross-section of the pile group. No significant effect on bending moment and load transfer mechanism in piles was found.

The authors in their work [2], created a model of a test system that simulates horizontal freezing of the soil and shows the temperature distribution and displacement of frost heaving based on a real project of freezing of the Shanghai underground double tunnel. The results of model tests showed that soil displacement during frost heaving is closely related to time. In this test, a successive freezing mode was adopted, the displacement during frost heaving during the freezing period of the downlink tunnel was less than during the freezing period of the uplink tunnel under the action of water displacement. The authors conducted numerical simulations of horizontal soil freezing of double tunnels with successive freezing and simultaneous freezing of tunnels on the ascending and descending lines. successive freezing of the soil reduces the displacement of frost heaving to a greater extent than simultaneous freezing. It can be used as a reference material in the design and construction of double tunnels by artificial freezing of the soil.

The article [3] substantiates the influence of the initial tunnel design on the level of soil vibration during the operation of the underground line in the future. This is important because the construction of the tunnel leads to soil disturbance, which indicates a high level of soil deformation near the tunnel. As a result, soil stiffness worsens, which affects ground vibrations and their propagation to foundations near buildings, and this requires research. To solve this problem, a new hybrid modeling approach was developed, consisting of a model construction and an elastodynamic model.

Underground transport infrastructure has an impact on increasing urban population [4]. These tunnels are built next to a tall building that rests on a fuel yard, which reduces differential saggings in structures.

In this study, three-dimensional numerical simulations were performed using an improved hypoplastic soil model to study the response of an existing pile yard to the passage of two-level tunnels at different depths. In the simulation, the first tunnel was laid at a depth of mid-depth of the piles, the second tunnel was built either at the depth of the piles, or below. In addition, three more analyses were performed to study the impact of changes in the sequence of construction of two-level tunnels in the pile yard. The greatest subsidence, but at the same time the smallest bending moment of the pile yard caused a variant below the depth of the passage of a two-level tunnel. The greatest slope of the pile yard occurred in the case below the depth of the pile yard. The first tunnel in each case caused the load to be transferred from the base to the piles. However, the second tunneling caused an increase in the load on the base due to its penetration into the soil. The diverse sequence of construction of two-level tunnels significantly affected the subsidence and formation of the slope of the pile yard.

Very often in urban conditions there are difficult geological conditions for tunneling, insufficient rock pressure to ensure the safety of tunnel work, which can lead to damage to neighboring buildings. The publication [5] obtained the maximum reference pressure at the tunnel boundaries, also analyzed the effect of internal friction angle, adhesion to the ground, the angle of friction at the interface, the thickness of the coating layer and the structure of the tunnel. The soil is presented as a hard plastic material. In addition, a mathematical model of static equilibrium with an extended boundary equilibrium limit has been developed. The distribution
of pressure and mechanisms of destruction of the beginning of the tunnel is obtained by the finite element method. It was found that the pressure decreases with increasing angle of internal friction. When comparing the results obtained with the results found from the relevant links, it should be noted that the sliding line method for calculating the reference pressure at the beginning of the tunnel is reliable. In addition, it is extremely convenient when it is necessary to take into account the angle of internal friction and the slope line of the structure.

In weathered rocks in the first section of the arc tunnel, cracking and crushing were observed [6]. This happened during the construction of the second tunnel. Therefore, for almost one year, distributed monitoring was performed using opto-fiber to study the deformation and stress of the damaged lining of the first tunnel. Optical fibers were attached on opposite sides of the temporary support of the arch. The development of cracks was detected on the concrete lining and vertical ovality. Over time, compression deformation began to develop. With the help of opto-fiber, the radial displacement of the concrete cladding, which was caused by the bending moment, was calculated.

Comparing the results obtained with the help of total stations revealed obvious errors. A more precise method for determining the deformation regime of arched structures based on fiber-optic deformation data was proposed.

In concrete tunnels, segmental joints are the most vulnerable parts of the cladding. In most existing models of segmented joints, it is not possible to assess the damage and destruction due to elastic deformation. Segmental damage to tunnels may occur in the field. The study [7] presents full-scale tests of the segment connection of the gas tunnel. The segment hinge is constantly loaded to the maximum value of effort. The internal forces, deflection and fracture characteristics of the segmental joint during loading were calculated, and a comparison was made with previous studies on flat segments.

Prefabricated reinforced concrete segments in most cases are loaded with traction jacks at the stage of installation [8]. Then it is necessary at this stage to prevent the formation of cracks and damage to the segments to ensure their integrity. Using fiber admixtures in the form of fibers can reduce the number of cracks, in addition, the fibers help prevent local damage, such as chipping edges and corners of segments.

In a segmented underground tunnel, cracks, water leaks and other structural defects usually occur at the segmental joint, which has less rigidity than the section of the main segment of the tunnel. In this study [9], a model of a typical concrete segment joint was modeled using 3D-continuous elements. The simulation was performed using shear springs: the stiffness of conventional springs is mainly determined by the bolt itself, and shear springs take into account the friction of the bolt segment, the interaction and shear resistance of the bolt. Meanwhile, the interaction between two adjacent tunnel segments is modeled using elements in contact with each other.

The study [10] presents the results of laboratory tests, which allows to characterize the two-component filler during the curing period. A detailed study of the effect of the presence of filler material on the behavior of the support system of the tunnel was conducted. The filler in concrete increases the modulus of elasticity of the segmental lining of the tunnel. Using the method of Einstein and Schwartz, you can determine the bending moments and normal forces acting on the supporting structure of the tunnel, having the parameters of stiffness only overlays of the tunnel segment.

The mechanical behavior of sealing gaskets for district connections in the Z2 tunnel of the Tianjin Metro Line was investigated using an experiment [11]. To do this, a new device was developed to measure the mechanical properties of the gaskets of the joints. Four types of EPDM profiles and composite cross-section profiles with different hole combinations were tested. Water pressure and joint opening coefficient were used to study the mechanical characteristics of the gaskets.
The test results of the two gasket profiles were compared and the effect of the gasket hole area was discussed. To correlate the mechanical behavior of the gasket and the sealant, it was proposed to adopt the ratio of water resistance to average contact pressure. The results showed that the opening and shear of the gasket seam had a great influence on the water resistance. A relatively small change in the area of the gasket hole can lead to a significant change in mechanical and waterproof characteristics. Leak analysis has shown that bolt holes, wheel joints and concrete cracks are common leaks during tunnel construction and operation.

In loess soils, the subsidence of the tunnel depends on the angle of installation of the reinforcement bolt.

In [12] a mechanical calculation model was developed, which coordinates the deformation and displacement of the arch leg between the steel frame and the FRB. The influence of the anchor tube angle on the subsidence of the tunnel arc was investigated using finite element modeling. It was found that the maximum anti-slip force is at an angle of FRB 47 degrees.

In [13] it is argued that the pile-beam-arch method is suitable for the construction of shallow urban metro stations with heavy ground traffic. The main construction process consists of four stages: construction of pilot tunnels, installation of piles and beams, installation of arches and excavation of rocks inside the metro station. This study uses numerical calculations to study the patterns of loads during the development of the earth’s surface. Empirically identified key steps to control subsidence of the surface.

The results show a linear relationship between the distance between the columns and the subsidence of the surface, with a smaller interval between the columns decreases the subsidence. The nonlinear dependence of the cross-sectional area of the column on the surface deposition is obtained. Surface deposition is stable at cross-sectional dimensions of $1.5 \times 1.5$ m. The results of this study make it possible to predict the subsidence of the surface during the construction of tunnels.

To improve the corrosion resistance of underground arches in the embankment structure, steel rods have been replaced by rods with basalt fibers and hybrid steel rods [14]. The study was conducted on eight arches. Quasi-static compression was performed to assess the structural characteristics of the arches. Concrete arches reinforced with composite rods have elastic-plastic deformation.

Arches have a typical bending mode, where the destruction is determined by the crushing of compressed concrete. Arches reinforced with composite rods have ductility and higher load capacity than arches reinforced with steel bars.

The publication proposed a method of analytical design for predicting load-bearing capacity. This method has tolerable errors.

This article [15] proposed a method for recognizing cracks in paved tunnels. The technique consists of three stages: pre-processing and image improvement, selection of signs and characteristics of cracks. To highlight the cracks, the images are improved using special algorithms. This paper proposes differential noise filtering and an improved segmentation method that detects crack boundaries. A self-regulating calibration method is used to characterize cracks. Experiments confirm the stability and reliability of the technique.

The main attention in solving the problem of reducing the intensity of subsidence is paid to strengthening the base, which takes loads through structural elements, and therefore the primary step to prevent further deformations is to perform work on strengthening the soil of the tunnel base.

2. Aim/tasks
Evaluate different options for fixing soils depending on the angle and depth of fixing the elements of underground tunnels. The use of computer simulation will make it possible to predict the positive effect of fixation.
3. Research methods
The aim of the work is to study and substantiate an alternative method of fixing the soils of the base of the underground interstation tunnel at a high intensity of subsidence during operation.

When designing foundations and principles, it is necessary to exclude the possibility of deformations that can cause the destruction of the foundation or structure, and when calculating deformations of the foundation with complex engineering and geological conditions, or if the load-bearing capacity of the foundation is insufficient, it is necessary to provide measures to reduce the negative impact of these deformations. To improve the properties of soils, compaction (mechanical or physical) and fixing (mechanical or chemical) are used at the site of their occurrence.

When using jet injection technology, jet grouting piles with a diameter of up to 1000 mm are arranged, the parameters of the jet, the speed of its rotation and sliding movement up, the type, brand and amount of cement introduced into the soil are determined in the project based on research work performed at the design site.

In tunnels and substructures of the underground, it is necessary to provide for the installation of control and measuring equipment for uninterrupted observations (monitoring) of the condition of frames, structures of underground structures, engineering networks and the surrounding ground environment.

When comparing the methods of fixing the base, the most appropriate ones at the stage of design and operation of the interstation tunnel of the underground are chemical fixing of soils and the method of jet injection. Studying the experience of using these methods close to the specified conditions, we can conclude that chemical soil consolidation requires improvement or replacement as the main method for fixing the soils of interstation tunnels of the underground in water-saturated sands.

Analyzing the previous experience in reducing the intensity of subsidence, by fixing soils by two soluble silicatization, in areas from station “Vydubychi” to station “Kharkivska” failed to achieve significant results. As a result, the necessity appears to reduce the speed of trains to prevent further development of deformations.

The research area is the stage between stations “Pozniyaki” (SC232 + 92) - “Kharkivska” (SC245+50) belongs to the Syretsko–Pecherska line of the Kyiv Metro. The interstation tunnels were built by PJSC “Kyivmetrobud” cut-and-cover with the opening of the pit to a full profile, in sandy water-saturated soils with artificial lowering of the ground water level by deep wells. The stage length is 1258 m. The customer was PUC “Kyiv Metro”. Commissioning was carried out on December 28, 1994.

The geological structure to the explored depth is composed of a series of alluvial quaternary deposits of different ages in the Dnieper river valley, lying on the eroded surface of the Buchak layer of the Paleogene, covered from the surface by a soil-vegetation layer, partially bulk soil and alluvial sand. The thickness of the alluvial layer is about 5 meters. The thickness of alluvial quaternary deposits is represented by small, medium and large sands, sometimes with the inclusion of gravel and pebbles of crystalline rocks.

The interstation tunnels are constructed from blocks of solid-section frames (see figure 1), on a separate monolithic reinforced concrete slab, 300 mm thick, which is laid on a layer of crushed stone rammed into the ground.

To reduce the ground water level to 1-2 meters below the level of pit excavation, the project provided for the simultaneous operation of 10 water-lowering wells for each section with a length of 100 m. Water reduction was performed with needle filters. To absorb deformations of building structures, the device of compensatory expansion joints was provided, which are located in places where the type of structure or soil layers in the base change.

The survey of the technical condition of the tunnel frame made it possible to assess the damage and defects that occurred during the period of operation due to natural factors, design
errors and construction technology violations. The complex of examinations included visual and instrumental inspections. The technical condition of separate structures was determined as a result of a general analysis of defects and damages identified by the results of the survey. According to the load-bearing capacity and operational properties, the technical condition of the structure is classified as one of the categories.

Most of the observations are made up of instrumental measurements of subsidence or deformation values, which are performed mainly by geodetic methods.

Geodetic observations of subsidence or deformations of artificial structures of the underground are carried out in order to determine the degree of deformation and assess the stability of the structure, take timely measures, study the causes of deformations of the underground structures, check calculated data and develop a methodology for predicting them [16].

Inspection of the technical condition of the tunnel frame was carried out along the I and II tracks on the section within SC235+80 ÷ SC243+80 of the stage between stations “Pozniyaki” - “Kharkivska” of the Syretsco–Pecherska line. Additionally, the surface above the tunnels was inspected for sinkholes and subsidence.

So the main detected defects and damages are:

- transverse and longitudinal cracks with an opening of up to 5 mm in track concrete;
- cracks with an opening of up to 5 mm in the locations of embedded parts in the WCA blocks;
- slots up to 10 mm at the junction of WCA blocks;
- chips of the protective layer of concrete with exposure of corroding reinforcement in the WCA blocks;
- filtration of ground water with sand removal through the joints of WCA blocks.
The active zone of propagation of power vibration loads in watered sands is located within a radius of 4.0-4.5 m [17].

The presence of filtration of ground water indicates a violation of the tightness and integrity of waterproofing [18].

4. Results and discussion

According to the results of periodic instrumental geodetic and survey observations of the high-altitude position of tunnels on the surveyed stretch, the maximum values of subsidence, counting from the time of commissioning, reached (as of September 2018):

- on I track on SC242+29 – -345 mm (see figure 2);
- on II track on SC236+00 – -321 mm.

![Figure 2. Subsidence of tunnel structures on SC242+29 along 1 track.](image-url)
As can be seen from the subsidence graph, its propagation along the length occurs unevenly. During the visual inspection of the tunnel frame sections, cracks with an opening of up to 5 mm in the WCA blocks and track concrete were found in the area of individual upper peak points, as well as cracks of up to 10 mm in the joints between the blocks. The greatest opening width of the slits was observed in the arch of the tunnel frame.

Insufficient thickness of the protective layer of concrete in reinforced concrete blocks of a solid-section frame leads to corrosion of the reinforcement. Corrosion products, increasing in volume, lead to the creation of excessive internal pressure, which in turn causes cracking, peeling and chipping of the protective layer of concrete.

The presence of filtration of ground water indicates a violation of the tightness and integrity of waterproofing.

Based on the results of survey data for March 2019 (table 1) it was found that the maximum subsidence rates of interstation tunnels on individual pickets during the last half-year and for the year reached the following values:

| I - track | II - track |
|-----------|-----------|
| SC | maximum amount of subsidence within six months | maximum amount of subsidence within year | SC | maximum amount of subsidence within six months | maximum amount of subsidence within year |
| 240+00 | -301 | -18 | -30 | 239+51 | -237 | -7 | -15 |
| 240+77 | -319 | -10 | -18 | 240+00 | -270 | -11 | -23 |
| 240+97 | -331 | -13 | -20 | 240+39 | -220 | -12 | -27 |
| 241+67 | -214 | -14 | -22 | 241+80 | -237 | -11 | -25 |
| 242+29 | -353 | -8 | -19 | 242+74 | -125 | -13 | -26 |
| 243+45 | -204 | -13 | -22 | 243+19 | -192 | -23 | -37 |

Over the past five years, there has been a tendency to continue increasing the intensity of subsidence. So in the following years, the amount of subsidence on 1 track SC242+29 (table 2) was as follows:

| Date | Subsidence |
|------|------------|
| 02.2015 | -303 mm |
| 02.2016 | -306 mm |
| 03.2017 | -319 mm |
| 03.2018 | -334 mm |
| 03.2019 | -353 mm |

Analyzing the results obtained, it should be noted that on this stage there is a continuation and increase in the intensity of subsidence of the tunnel frame with the appearance of characteristic deformations (cracks, chips, expansion of joints).
Based on the above and taking into account the presence of damage in reinforced concrete structures, it is necessary to perform work on fixing the ground of the base to prevent further deformations of the tunnels.

Let’s consider the simulated options for fixing the ground base of the underground intersatation tunnel using jet injection technology.

In the process of modeling, the properties of the soil cement material and the geometric dimensions of soil cement piles were selected as the most optimal for the specified conditions.

Ground-cement piles built using jet-grouting technology with a diameter of 0.8 m in increments of 1.8 m from the center of the axis and a calculated deformation modulus of 3000 MPa are used as fixing elements of the array [17–19].

The essence of the calculation is to determine the values of subsidence before and after fixing the soil by jet injection. For the modeling process, 3 variants of fasteners with angles of inclination of 30 (see figure 3), 35 and 40 degrees relative to the surface were selected. The expected result is a reduction in the subsidence of the tunnel structures (distribution plate) after the device is fixed with jet grouting piles.

![Figure 3. Calculated model for 30 degrees $E_{cp}=41.42$ MPa.](image)

The total load of rolling stock and vibrodynamic impact from train traffic is assumed to be 200 kN/m in the left and right tunnels.

The calculation of subsidence is performed according to the method, the essence of which is that jet grouting piles and soil are considered as a soil array with a cellular deformation modulus $E_{cp}$.

Based on the calculation results, the following is established:

1. The amount of subsidence of tunnel structures, namely the distribution plate on which the WCA blocks are supported, without the use of fixing elements is – 25.55 mm (see figure 4);
2. When fixed at an angle of 30 degrees, the subsidence - 7.8 mm (see figure 5), at 35 degrees – 8.19 mm, and at 40 – 8.82 mm.

In order to save material and the total cost of construction work, the option of fixing soils with jet grouting piles of reduced length (10 m) at an angle of inclination of 30 degrees was additionally developed and calculated (see figure 6).
5. Conclusions

Analyzing the results of mathematical modeling, the most effective was the option of fixing at an angle of 30 degrees, which allowed to reduce the subsidence by 70%. Computer-mathematical modeling has shown that as the angle of the soil-cement piles increases, the amount of subsidence of the tunnel increases. When installing soil-cement piles at an angle of 30 degrees, it is possible to reduce the length of the pile by half, reducing material consumption by 40-45%, which will lead to a slight increase in tunnel subsidence by 2.6% compared to 20.5 m and angle 30 degrees.
Figure 6. The subsidence of the slab after fixing the soil with jet grouting piles at an angle of 30 degrees.

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