VOL. 13, NO. 23, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

NUMERICAL EXPERIMENTS ON THE MODELING OF COMPENSATORY INJECTION FOR THE PROTECTION OF BUILDINGS DURING TUNNELING

P. A. Demenkov, O. V. Trushko and I. V. Potseshkovskaya
Saint-Petersburg Mining University 21-st Line V.O., Saint Petersburg, Russia
E-Mail: ov_trushko@mail.ru

ABSTRACT

The paper presents the results of numerical experiments on the simulation of compensatory injection for the protection of the buildings while tunneling performed in the Plaxis software. A comparison is made of the change in the maximum surface subsidence and upheaving during compensation measures during and after tunneling. The regularities of the change in the maximum subsidence and upheaving of the earth's surface are obtained depending on the change in the injection volume for different widths of the injection zone, different locations of the injection zones relative to the tunnel arch, different depths of tunnels.

Keywords: compensatory injection, surface subsidence, building underworking, solution injection, injection zone, protection, buildings, structures.

INTRODUCTION

The development of the transport infrastructure of megacities requires the active development of the underground space in order to expand the metro lines. The construction of tunnels and metro stations in a closed way causes subsidence of the ground surface in close proximity to the construction site (Demenkov, Karasev, Petrov, 2017), which in turn can damage the buildings, utilities, road surfaces, etc. (Makovskiy, 1985).

There are various reasons for subsidence of the ground surface, the main are the deformations of the face crown and poor-quality plug-pack of the anchored space. This is typical for both shield and rock driving. In addition, when the driving shield is moving, deformations of the tunnel lining are possible. When rock tunneling, overcutting is possible, a significant lag of the temporary support from the crown of the face, insufficient rigidity, and the untimely construction of a permanent lining.

To minimize the subsidence of the ground surface, various planning, structural, technological and protective measures are used in order to ensure the safety of the building and structures in the undermining territories. For this purpose, the constructions of lining, pressed into the ground, mechanized shields with face counterweight (Protosenya, Demenkov, Belyakov, 2017), construction clearance compactor, anchor and abrasive-concrete temporary fasteners, hardening of the face crown with fiberglass anchors, reinforcement of the constructions of buildings and their foundations, arrangement of protective shields, physical and chemical soil consolidation, etc. (Makovskiy, Chebotarev, Sula, 2005). These lead to substantial terms lengthening and an increase in the construction cost (Demenkov, Karasev, Petrov, 2017). In this regard, there is a need to improve the effectiveness of protective measures.

To reduce the subsidence of the ground surface and its leveling, compensatory solution injection into the soil mass between the foundations of the undermining buildings and the tunnel is often used (Pankina, Chebotaev, Ilichev, 1998).

Successful application of compensatory injection is available in various countries' experience - Great Britain, Austria, Germany, Portugal, the USA, Canada, etc. (Demenkov, Karasev, Petrov, 2017; Makovskiy, Chebotarev, Sula, 2005; Pankina, Chebotaev, Ilichev, 1998; World Tunnelling and Subsurface Excavation, 1994; Mayer, Chait, 1995; Tunnels et ouvrages souterrains, 1998; Ground Engineer, 1992; Tunnels and Metropolises, 1998). Compensatory injection works were carried out during the construction of two underground metro lines in Lisbon (Portugal) (Mayer, Chait, 1995). The compensatory injection was also used in the construction of the Waterloo station in the UK (Tunnels and Tunnelling International, 1998). This technology was used in the construction of two parallel single-track running tunnels of the metro in Baltimore (USA) (Makovskiy, Chebotarev, Sula, 2005; Pankina, Chebotaev, Ilichev, 1998).

The compensatory injection can be performed both in the close proximity of the ground surface (foundations of buildings) and near the underground structure. This depends on the engineering-geological conditions, the depth of the tunnel, the parameters of the injection area, the nature of the distribution and intensity of external loads, stresses in the base of the foundations and a number of technological factors (the presence of a counterweight in the shield face, the drilling rate, the injection system for lining, etc.).

The results of the efficiency evaluation of the considered technology on the basis of the technical and economic comparison of compensatory injection with other special methods of soil mass stabilization (chemical grouting, freezing, cementation) are given in (Kravchenko, 2010). The use of compensatory injection requires fewer expenditures in comparison with chemical grouting - by 25-30%, with freezing - by 35-40%, with cementation - by 30-35%.

VOL. 13, NO. 23, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

METHODS

There are two options for compensatory injection - from the ground surface or from existing or newly constructed underground workings (mine shafts, chambers, foundation pits), drilling vertical, horizontal or down-hole wells, or immersing special injectors into the ground (Figure-1). This does not require the opening of the soil surface does not violate the urban traffic and minimizes the soil deformation.

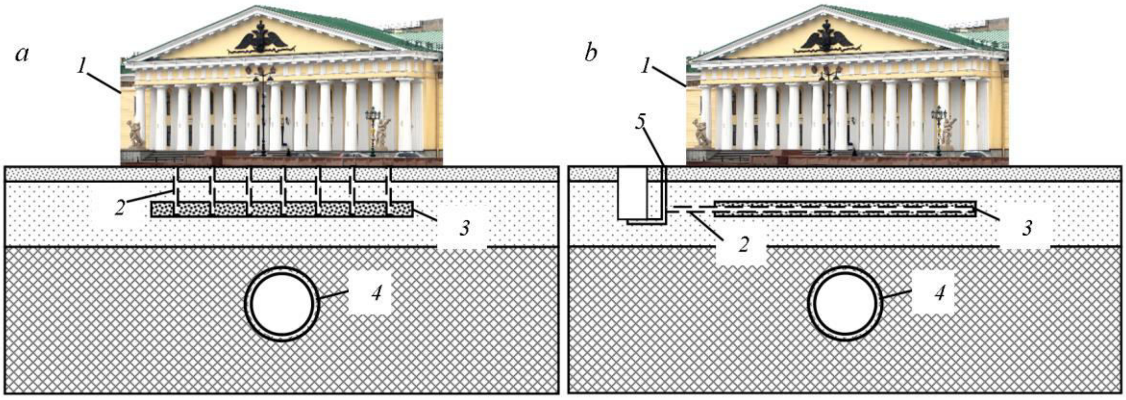

Figure-1. Scheme of compensatory injection from the ground surface (a) and from the mine shaft (b): 1 - protected building; 2 - wells for injection; 3 - injection area; 4 - tunnel; 5 - mine shaft
The main criterion for choosing the option is the convenience (possibility) of its implementation in each specific case. Therefore, in this paper, they were not compared.

The efficiency of compensatory injection depends very much on the moment of its performance. The graph of the maximum ground subsidence and upheaving, depending on the change in the injection volume during (Model 1) and after (Model 2) tunnel excavation is shown in the figure Figure-2. Usually, in practice, the second option is used (Model 2). Compensatory injection is made only after the building or structure has subsided. However, as can be seen from the curve lines built, the compensatory injection is most effective at the tunnel cutting (Model 1), before the deformation of the enclosing rock mass. Thus, it is necessary to coordinate the tunnel cutting with the compensatory injection.

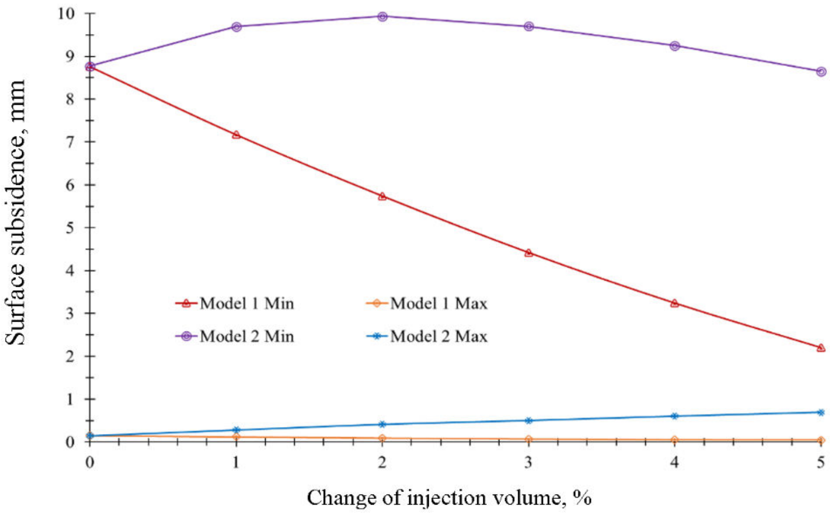

Figure-2. The graph of the maximum ground subsidence and upheaving depending on the change in the injection volume during (Model 1) and after (Model 2) tunneling: Model up - ground surface upheaving; Model down - ground surface subsidence.

To carry out the injection simultaneously with the tunnel face advance, it is not enough to provide the geodetic observations of surface subsidence only, it is also necessary to control the deformations of the enclosing rock mass near the tunnel (Bogdanov, 2009). This will allow timely injection, limiting the surface subsidence and deformation of buildings and structures, thereby achieving maximum efficiency. For this purpose, the automated

ARPN Journal of Engineering and Applied Sciences

tracking systems are used, comprising electronic instrumentation and modern computer equipment (Tunnels et ouvrages souterrains, 1998).

Nowadays, in order to determine parameters of compensatory injection, field experiments are used. The numerical calculation methods, mainly the finite element method, are also widely used (Protosenya, Ochkurov, Karasev, 2017; Protosenya, Verbilo, 2017).

Model description

The simulation was carried out in a two-dimensional formulation using the Plaxis 2D software. Numerical experiments were aimed at revealing the patterns of ground surface subsidence with varying conditions: the depth of the tunnel, a different volume of the injected solution, the distance between the injection zone and the tunnel arch, and the width of the injection zone.

The following geometric dimensions of the model were adopted: width 500 m, height 60 m (Figure-3). It is forbidden to move the bottom along the Y-axis and the sides of the model along the X-axis.

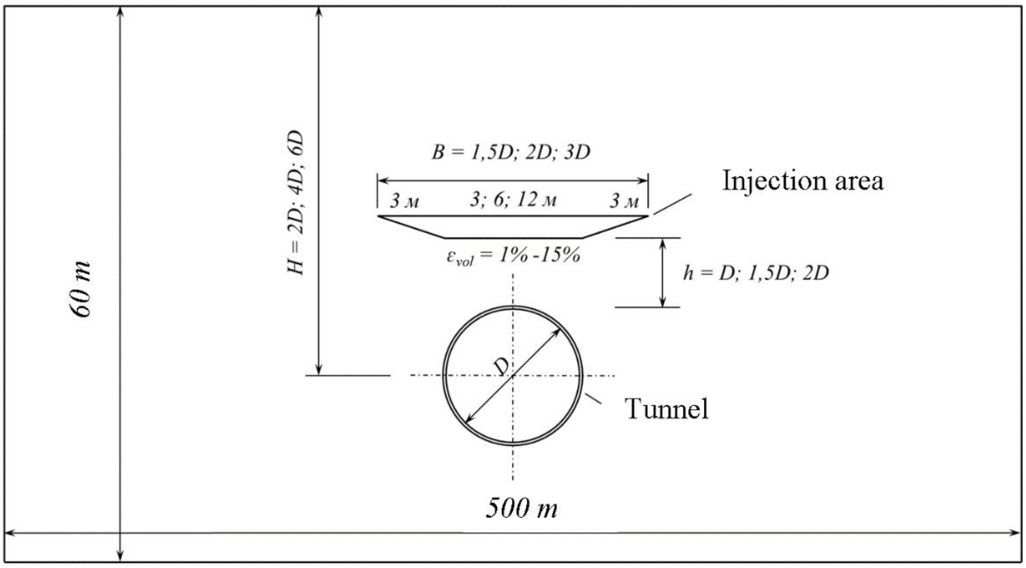

Figure-3. Model for numerical experiments.

The name of the models encrypts their main distinctive parameters. The first letter H and the digit indicate the depth of the deposit, the second letter *h* and the digit - the distance between the injection zone and the tunnel arch, the third letter *b* and the digit - the width of the injection zone. All parameters are given in the diameters of the tunnel *D*, which is assumed equal to 6 m. The last letter *V* and the digit indicate the magnitude of change in the volume of the injection in% (range from 1 to 15%). The distinctive parameters of numerical models are given in Table-1.

Table-1. Distinctive parameters of numerical models.

H	m	*h*	m	*b*	m
6*D*	36	1*D*	6	1,5*D*	9
4*D*	24	1,5*D*	9	2*D*	12
2*D*	12	2*D*	12	3*D*	18
V = 1, 3, 5, 7, 10, 15 % (intermediate values are used in some cases)					

Clay was used as the enclosing soil. Its physicomechanical characteristics, most typical for St. Petersburg (Dashko, Karpova, 2016), are presented in Table-2.

Table-2. Physical and mechanical characteristics of the model with clay soils.

γ_{unsat}, mN/m^3	γ_{sat}, mN/m^3	e_0	E_{50}, MPa	E_{oed}, MPa	E_{ur}, MPa	m	c, kPa	φ, ^{0}	ψ, ^{0}	$\gamma_{0,7}$	G_0, MPa
18.5	21	0,65	15	15	60	0.9	20	15	0	$0{,}15\cdot10^{-3}$	120

Note: γ_{unsat} - soil bulk density at natural humidity; γ_{sat} - specific fully water-saturated soil density; e_0 - initial value of the porosity coefficient; E_{50} - the module of the ground deformation; E_{oed} - odometric module of soil deformation; E_{ur} - the module of soil elasticity; m - an indicator considering the influence of medium stresses on the deformation properties of the ground; c - effective adhesion; φ - the effective angle of internal friction; ψ - the dilatancy angle.
In numerical experiments, the injection was modeled simultaneously with tunneling.

DISCUSSION AND RESULTS

The following figures show the changes in the subsidence and upheaving of the ground surface depending on the change in the injection volume for the three variants of the injection zone width and the three variants of its location above the tunnel arch located at a depth of 24 m (Figure-4, Figure-9).

With an increase in the volume of the solution injection, in addition to the positive effect of reducing the subsidence of the ground surface above the tunnel, a negative effect was also observed - an upheaving of the ground surface at a distance of 15-20 m from the axis of the tunnel. The built graphs made it possible to find the optimum injection volume at the intersection of the subsidence and upheaving curve lines of the corresponding models.

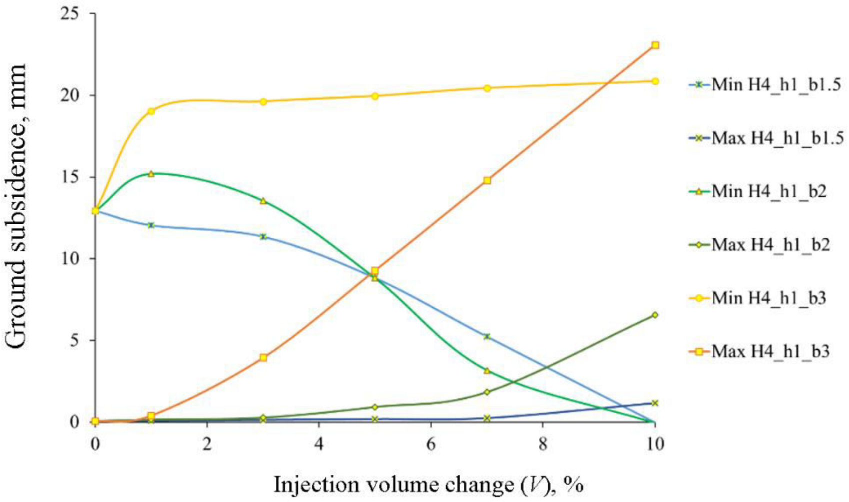

Figure-4. Graphs of the maximum value of the ground surface subsidence and upheaving depending on the change in the injection volume for the three variants of the injection zone width (the injection zone is located at a distance of 6 m (1D) from the tunnel arch, the depth of the tunnel is 24 m (4D)):Min - ground surface subsidence; Max - ground surface upheaving

The large width of the solution injection zone (3D), regardless of its location relative to the tunnel arch, gives the opposite effect of compensatory injection and leads to a significant increase in the ground subsidence (Figure-4, Figure-5, Figure-6, subsidence curve H4_h1-2_b3). It can be explained by a significant increase in the weight of the grout when injecting the solution since its density is higher than the density of the surrounding soil. At the same time, an increase in the injection pressure has a negative effect on the deformation of the tunnel lining, which also increases in the ground subsidence. Thus, it can be concluded that using a too wide compensation zone (3D) is inefficient.

The curves for zones of width 1.5D and 2D (b1.5 and b2) show approximately the same decrease in surface subsidence (at a volume of 5 and 10% they even intersect). However, a small injection volume (1-2%) leads to an additional ground subsidence, which can be explained by an increase in the weight of the compensation zone due to the higher density of the grout mix. In addition, the curve (b2) demonstrates a significant ground upheaving to 7 mm.

Analysis of the curves of the graph (Figure-4) shows that for injection zone placement at a distance of 6 m (1D) from the tunnel arch, the discharge volume for the zone width of 1.5D - 9.5% will be the most effective, while the surface subsidence level will decrease by 10 times to about 1 mm, for the width of the 2D zone - 7.5%, while the level of surface subsidence will decrease by 5 times to about 2.5 mm. It can also be noted that the volume of the injection solution in the second case is 1.5 times more than in the first case.

ARPN Journal of Engineering and Applied Sciences

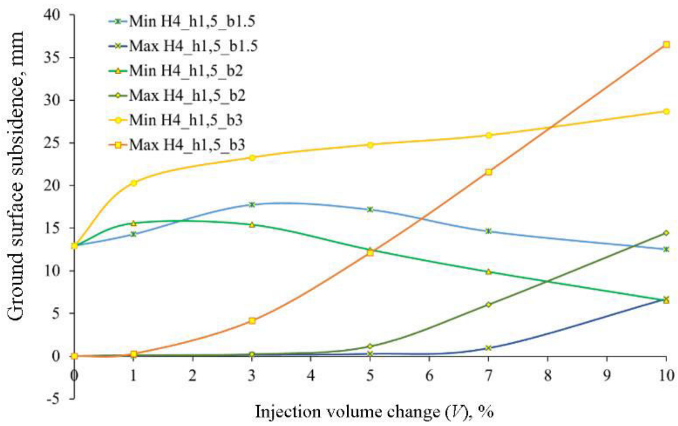

Figure-5. Graphs of the change in the maximum value of the ground surface subsidence and upheaving depending on the change in the injection volume for the three variants of the width of the injection zone (the injection zone is located at a distance of 9 m (1.5D) from the tunnel arch, the depth of the tunnel is 24 m (4D)) : Min - ground surface subsidence; Max - ground surface upheaving

Analysis of the curves of the graph (Figure-5) shows that when the injection zone is located at a distance of 9 m (1.5 D) from the tunnel arch for the width of the zone 1.5D (b1.5), the injection volume will be the most effective - 12%, while the subsidence level will decrease not essentially. Thus, it can be stated that the zone width of 1.5D is not efficient. For the _b2 model, the 8% injection volume is the most effective. It allows reducing the ground surface subsidence by only 30% - to about 8.5 mm.

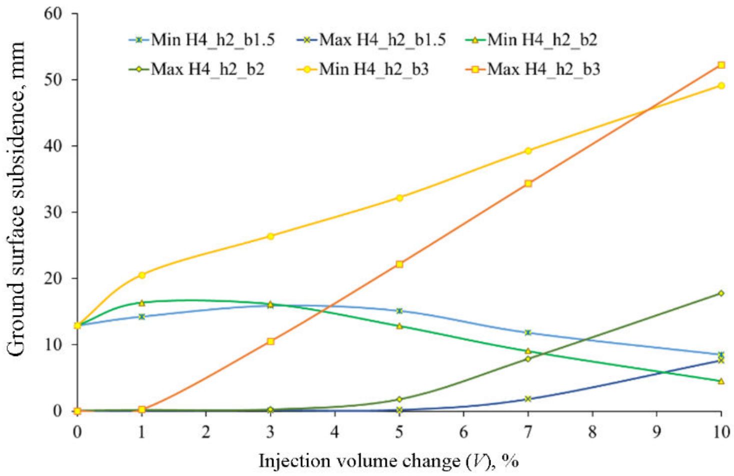

Figure-6. Graphs of the change in the maximum value of the ground surface subsidence and upheaving depending on the change in the injection volume for the threevariants of the injection zone width (the injection zone is located at adistance of 12 m (2D) from the tunnel arch, the depth of the tunnel is24 m (4D)):Min - ground surface subsidence;Max - ground surface upheaving

The analysis of the curves of the graph (Figure-6) shows that if the injection zone is located at a distance of 12 m (2D) from the tunnel arch for the width of the zone 1.5D, the most effective the injection volume will be 10%, while the surface subsidence level will decrease by 30% - 8.8 mm, for injection zone width of 2D - 7%, while the level of surface subsidence will also decrease by 30% to a value of 8.8 mm. Both variants show approximately the same result, however, the volume of the injection solution in the second case is 1.5 times more than in the first one.

The figures below show the changes in the maximum ground surface subsidence and upheavingdepending on the change in the injection volume for the three variants of the location of the injection zone from the roof of the tunnel at a distance of 6, 9, 12 m (h1, h1.5, h2) (Figure 7 - Figure 9).

The analysis of the curves of the graph (Figure-7) shows that with a width of the compensation zone of 9 m (1.5 D), the most effective option includes the location of the injection zone at a distance of 6 m (h1) from the tunnel arch. The surface subsidence will decrease 10 times - to 1 mm. At a distance of 12 m (h2), a lower efficiency of compensation measures is shown. The surface subsidence

ARPN Journal of Engineering and Applied Sciences

will decrease by only 30%. At a distance of 9 m (h1.5), it practically does not affect the surface subsidence.

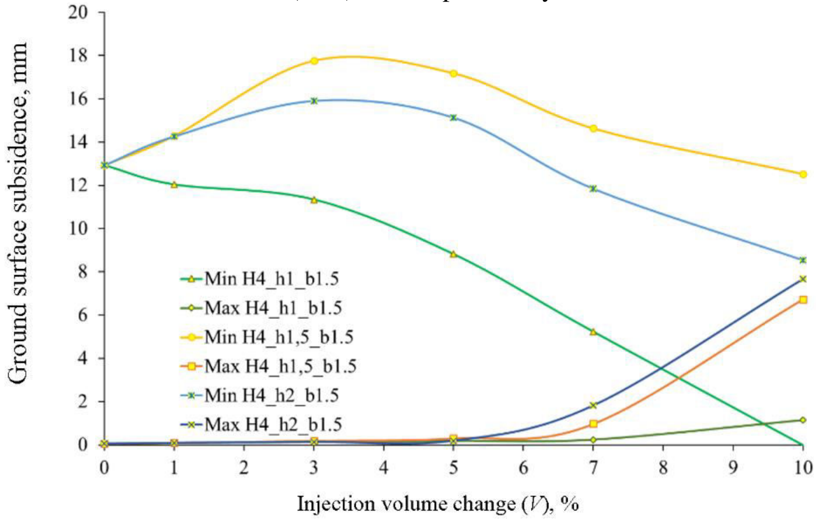

Figure-7. Graphs of the injection in the maximum value of the ground surfacesubsidence and upheaving depending on the change in the discharge volume for thelocation three variants of the injection zone relative to the tunnel arch (at a distance of 6, 9, 12 m) (injection zone width 9 m (1.5D), the depth of the tunnel - 24 m (4D)): Min - ground surface subsidence; Max - ground surface upheaving

The curves of the graph (Figure-8) show that with the width of the compensation zone of 12 m (2D), the location of the injection zone from the tunnel arch at a distance of 6 m (h1) will be the most effective. Options (h1.5 and h2) show approximately the same results - ground surface subsidence is reduced by 30% - to 8.8 mm. While the injection volume for the option (h1.5) will be greater. This can be explained by the fact that, in case of option (h2), the compensation zone is located closer to the surface and will require less pressure of the grout mix.

The graph (Figure-9) shows that a too large width of the compensatory injection zone will make all the compensation measures not effective, due to the increase in the weight of the ground, regardless of the location of the injection zone relative to the tunnel arch.

An analysis of the results shows that when carrying out compensation measures, the distance at which the injection zone is located relative to the tunnel arch is of great importance. The most effective is its close location to the tunnel.

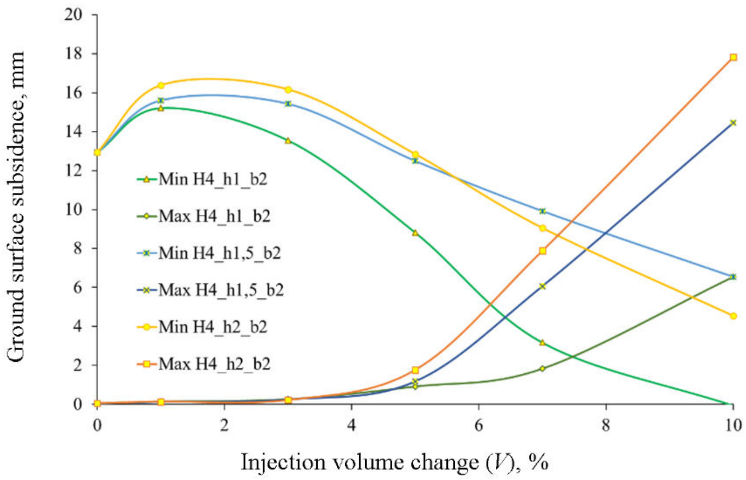

Figure-8. Graphs of the change in the maximum value of the ground surface subsidence and upheaving depending on the change in the injection volume for the three location variants of the injection zone relative to the tunnel arch (at a distance of 6, 9, 12 m) (the width of the injection zone is 12 m (2D), the depth of the tunnel - 24 m (4D)): Min - ground surface subsidence; Max - ground surface upheaving

ARPN Journal of Engineering and Applied Sciences

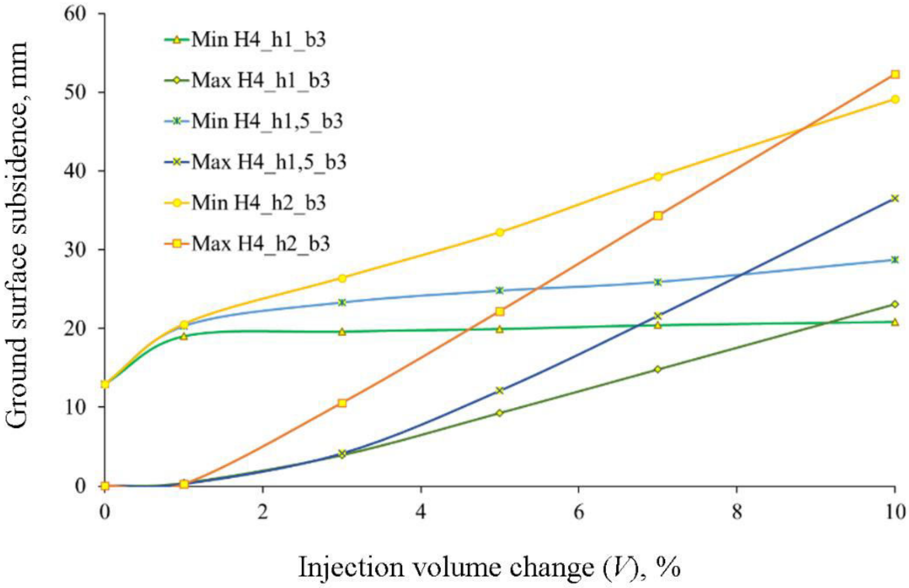

Figure-9. Graphs of the change in the maximum value of the ground surface subsidence and upheaving depending on the change in the injection volume for the three location variants of the injection zone relative to the tunnel arch (at a distance of 6, 9, 12 m) (the width of the injection zone is 18 m (3D), the depth of the tunnel - 24 m (4D)): Min - ground surface subsidence; Max - ground surface upheaving

Based on the simulation results, the ground surface deformation curves are built for different model parameters, which are shown in the figures below (Figure-10).

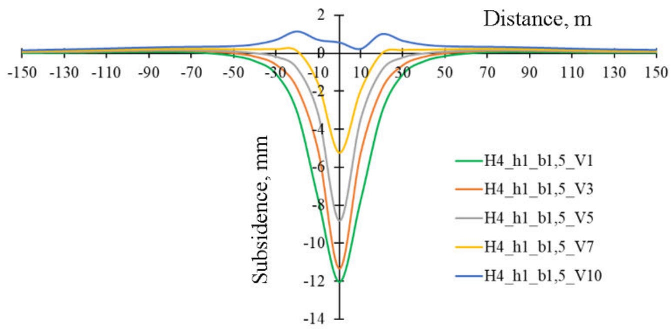

Figure-10. Curves of the ground surface displacement depending on the changein injection volume (V,%) for the injection zone located at a distance of 6 m (2D) from the tunnel arch and the injection zone width of 9 m (1.5D) (tunnel depth - 24 m (4D))

The graphs of the ground surface subsidence, depending on the change in the injection volume (V,%) for the depth of the tunnel 36 m (6D) are shown in Figure-11.

ARPN Journal of Engineering and Applied Sciences

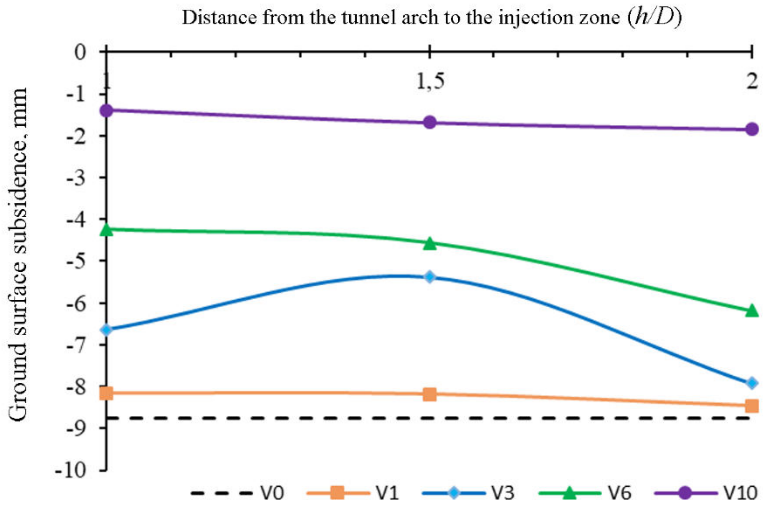

Figure-11. Graphs of ground surface subsidence, depending on the change in the discharge volume (V,%) for different locations of the injection zone at a distance from the tunnel arch (injection zone width 9 m (1.5D), tunnel depth - 36 m (6D))

CONCLUSIONS

Summing up the research it is possible to note that compensation injection is necessary to be provided during a tunneling before the ground deformations are on the surface. After the tunneling, when the surface subsidence is observed, the injection efficiency is much lower.

The change in the width of the injection zone has a significant effect on efficiency. With a very large injection zone equal to 3D (18 m), instead of reducing the subsidence, a reverse picture is observed. A significant increase in the volume of injection to 15% does not change the situation. The change in the location of the injection zone relative to the tunnel arch in this case also does not show a positive effect. It can be explained by increasing the volumetric weight of the injection zone, which loads the enclosing soil. Thus, it can be concluded that it is necessary to select the proper size of the injection zone.

The same results are observed when the injection zone is located at a distance of 6 m for its width of 9 and 12 m with respect to the tunnel arch. With an increase in the distance between the injection zone and the tunnel from 6 to 12 m, the efficiency of reducing the subsidence of the ground surface for a zone width of 1.5 D (9 m) falls to 30%. Moreover, the worst results are observed at a distance of 9 m. This can be explained by a sufficiently large distance from both the tunnel and the ground surface. The volume of the injection zone is not sufficient to prevent the surface subsidence. However, at this distance, a zone with a width of 2D (12 m) has good indicators. Thus, the relations between the width of the zone and its location relative to the tunnel arch is visible.

With a deeper location of the tunnel, a larger volume of the injected solution is required, all other conditions being equal.

ACKNOWLEDGEMENTS

The research has been funded by the grant of the Russian Scientific Fund (project No. 16-17-00117).

REFERENCES

Bogdanov V.V. 2009. Kompleksnyygeotekhnicheskiy monitoring priustroystvekotlovana v inzhenerno-geologicheskikhusloviyakh Sankt-Peterburga [Integrated geotechnical monitoring in the construction of a pit in the engineering and geological conditions of St. Petersburg] IzvestiyaPeterburgskogouniversitetaputeysoobshcheniya. St. Petersburg, Peterburgskiygos. un-t puteysoobshcheniya. 2(19): 110-119.

Dashko R. E., Karpova Y. A. 2016. Engineering geology and geotechnics of fractured clays as building base and surrounding medium (by the example as clayey bedrocks in Saint-Petersburg). Bulgaria: SGEM. 3: 85-92.

Demenkov P.A., Karasev M.A., Petrov D.N. 2017. Predicting land-surface deformations during the construction of underground facilities of complex spatial configuration. International Journal of Civil Engineering and Technology. 8(11): 1161-1171.

1992. Ground Engineer. 25(9): 30-31.

Kravchenko V.V. 2010. Effektivnyetekhnologicheskieparametrykompensatsionnogonagnetaniya v tonnelestroenii [Effective technological parameters of compensatory injection in tunnel construction]. Candidate's thesis: 05.23.11, St. Petersburg. 143.

Makovskiy L.V. 1985. Gorodskiepodzemnyetransportnyesooruzheniya [Urban underground transportation facilities]. Moscow, Stroyizdat. 439.

Makovskiy L.V., Chebotarev S.V., Sula N.A. 2005. Innovatsionnyekonstruktivno-tekhnologicheskieresheniya v transportnomtonnelestroenii. Obzornayainformatsiya [Innovative design and technological solutions in transport tunnel construction. Overview information]. Federal'noedorozhnoeagentstvo. Moscow, FGUP "Informavtodor. 1: 97.

Mayer R., Chait D. 1995. Tekhnologiyakompensiruyushchego in"etsirovaniyarastvorov v grunt [Technology of compensating injection of solutions into the soil] Dzhedzhestzarubezhnoyinformatsii. Moscow, Inform.-izdat. tsentr «TIMR». 2: 43-45.

Pankina S.F., Chebotaev V.V., Ilichev V.L., *et al*. 1998. Obshchayageotekhnicheskayakontseptsiyastroitel'stvatonnelya v Lefortovo (Moskva) imeropriyatiyapozashchiteistoricheskikhzdaniyotdeformatsiy [General geotechnical concept of tunnel construction in Lefortovo (Moscow) and measures to protect historical buildings from deformations]. Osnovaniya, fundamentyimekhanikagruntov. 2: 17-21.

Protosenya A. G. Ochkurov V. I., Karasev M. A. 2017. Introduction of the method of finite-discrete elements into the Abaqus/Explicit software complex for modeling deformation and fracture of rocks. Eastern European Journal of Enterprise Technologies. 6(7): 11-18.

Protosenya A.G., Demenkov P.A., Belyakov N.A. 2017. The method of determining the rational tunnel face pressure based on a prediction of the stress-strain state of "soil-lining" system in the bottomhole zone of the tunnel during the tunneling operation using TBMC. International Journal of Civil Engineering and Technology (IJCIET). 11(8): 1181-1191.

Protosenya A.G., Verbilo P.E. 2017. Izuchenieprochnostinaszhatietreshchinovatogogornogomassiva [Investigation of compressive strength of a fractured mountain mass]. Zapiskigornogoinstituta. 223: 51 - 57.

Tunnels and Metropolises. 1998. Rotterdam: Balkema. 1047-1052.

1998. Tunnels and Tunnelling International. 30(3): 35-38.

1998. Tunnels et ouvrages souterrains. 149: 423-426.

1994. World Tunnelling and Subsurface Excavation. 7(8): 65-68.