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DETERMINATION OF BOUNDARIES PARAMETERS OF THE COMPUTATIONAL MODEL FOR ASSESSING THE IMPACT ON THE SURROUNDING FACILITIES FROM TUNNELING

Armen Z. Ter-Martirosyan [1], Rustam H. Cherkesov [2], Ilya O. Isaev [2], Viktoriya V. Rud [1], Mariya I. Ambrushkevich [1]

[1] National Research Moscow State University of Civil Engineering, Moscow, RUSSIA
[2] Institute Mosinzhproekt Limited Liability Company, Moscow, RUSSIA

Abstract. As a result of active development of Moscow underground space, as well as due to the increased density of urban development, it is necessary to forecast additional displacements of surrounding buildings from new construction in order to prevent emergency situations. For this reason, one of the important directions is mathematical modeling of the additional displacements of the surrounding building after erection. Establishing the parameters of design boundaries of a geotechnical model is one of the factors that greatly influence the results of the simulation. This study deals with the assignment of the lower boundary of the scheme when estimating the impact from tunneling works in a two-dimensional formulation. A review of international experience in simulating the design scheme depth for various geotechnical problems and its comparison with Russian experience in modeling schemes has been made. The deformation marks located on the ground surface in the zone of influence of the Rublevo-Arkhangelskaya and Troitskaya (Kommunarskaya) lines of the Moscow Metro under construction were selected for the analysis. The authors carried out the selection of the lower boundary of the scheme by changing it in proportion to the outer diameter of the tunnels in dispersed and rocky soils. The obtained data were compared with geodetic monitoring one. Calculations were made for three different soil models such as Mohr-Coulomb, Mohr-Coulomb with increasing deformation modulus of the prism under the excavation and Hardening soil. In addition, calculations were made for two cases of assignment of the overburden coefficient - according to normative documentation and available research on the subject. As a result of this work, more than 600 calculated cases were obtained. Based on these cases, recommendations were developed for adjusting the scheme depth for the considered soil models.

Keywords: Impact zone, the finite element method, vertical deformations, Mohr-Coulomb, Hardening Soil, forecast settlements, tunneling, Plaxis 2D

ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ГРАНИЦ РАСЧЕТНОЙ МОДЕЛИ ПРИ ОЦЕНКЕ ВЛИЯНИЯ НА ОКРУЖАЮЩУЮ ЗАСТРОЙКУ ОТ ТОННЕЛЕПРОХОДЧЕСКИХ РАБОТ

А.З. Тер-Мартиросян [1], Р.Х. Черкесов [2], И.О. Исаев [2], В.В. Рудь [1], М.И. Амбрушкевич [1]

[1] Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ
[2] Институт Мосинжпроект, г. Москва, РОССИЯ

Аннотация. В результате активного освоения подземного пространства города Москвы, а также вследствие повышенной плотности застройки города необходимо осуществлять прогноз дополнительных перемещений окружающей застройки от нового строительства с целью предотвращения аварийных ситуаций. По этой причине одним из важных направлений является математическое моделирование прогноза дополнительных перемещений окружающей застройки после строительства. Установление параметров расчетных границ геотехнической модели - один из факторов, в значительной степени влияющих на результаты расчета. В данном исследовании рассматривается назначение нижней границы схемы при оценке влияния от тоннелепроходческих работ в двумерной постановке. Произведен обзор международного опыта моделирования глубины расчетной схемы для различных геотехнических задач и его сравнение с российским опытом моделирования схем. Для анализа были подобраны деформационные марки, располагающиеся на грунтовой поверхности в зоне влияния строящихся перегонных тоннелей Рублево-Архангельской и Троицкой (Коммунарской) линий Московского метрополитена. Авторы осуществили подбор нижней границы схемы, путем ее изменения пропорционально внешнему диаметру тоннелей в дисперсных и скальных грунтах. Полученные расчетные данные сравнивались с данными геодезического мониторинга. Расчеты производились для трех различных моделей грунта Mohr-Coulomb, Mohr-Coulomb с увеличением модуля деформации грунта призмы под выработкой и Hardening soil. Дополнительно расчеты производились для двух случаев назначения коэффициента перебора грунта - согласно нормативной документации и имеющимся исследованиям по данной теме. В результате проделанной работы было получено более 600 расчетных случаев, на основании которых были разработаны рекомендации по корректированию глубины схемы для рассмотренных моделей грунта.

Ключевые слова: зона влияния, метод конечных элементов, вертикальные деформации, Mohr-Coulomb, Hardening Soil; прогнозируемые осадки, тоннелирование, Plaxis 2D

INTRODUCTION

The subway plays a significant role in the transport unloading of megacities. Over the past decades, the shield tunneling method has gained enormous popularity all over the world, since this method is the most efficient and has a minimal impact on the environment [1].

Currently, in Moscow an active construction of the subway is being carried out. As a result of development of underground space in one way or another there is a need for mathematical simulation of surrounding buildings in order to determine the impact of construction of new tunnels on existing facilities. Based on the results of the impact assessment, a monitoring program is developed. It is necessary to trace the ground massif movements and, in case of necessity, to work out anti-damage actions [2]. Thus, it seems important to correctly simulate the calculation scheme, which is one of the main tasks of engineers.

In one of the previous papers [3], several most important factors of mathematical modeling, which affect the accuracy of calculation results in the software Plaxis 2D, were considered. Namely: soil model; computational modeling scheme; discretization of finite element mesh; modeling of work stages; construction dewatering by needle filters and open dewatering system; consideration of strength and rigidity of contact elements. According to the research, the factors that have the greatest influence on the accuracy of calculations are the choice of a soil model, type of a calculation model (2D or 3D) and compliance with the technology when specifying the construction phases.

In this paper, one of the factors affecting the results of construction impact assessment calculations is the area occupied by a computational model. On this basis, the authors perform the selection of the lower bound of the computational model for the tasks of impact assessment from tunneling works.

Researchers around the world have raised the issue of the applicability boundaries of the mathematical modeling scheme. One of the first who studied this issue were the authors of the article [4], which was published back in 1996. The mentioned paper argued that it is necessary to reduce the physical domain, thus introducing one or more artificial boundaries in the numerical simulation of displacement processes. This action leads to the fact that the calculation may not be justified and its results will not be correct.

Indeed, setting boundaries in mathematical models is one of the most important conditions. For example, the influence of scheme boundaries on the correctness of calculations is investigated in geophysics as well. Researchers in the article [5] consider simulation of circuit boundaries in electric tomography. It is argued that the most correct calculation can be done when the computational domain is expanded, but at the same time, this leads to an intractable problem and a large amount of time spent on the simulation. These problems are solved by setting simulation bounds, which in turn lead to calculation errors. Therefore, the authors in their study propose solutions to correct the errors associated with truncation of the computational domain in order to optimize prediction.

Lidija Zdravkovic and Stavroula Kontoe [6] considered the reduction of soil domain boundaries in geotechnical earthquake analysis. Simulation of correct boundaries for such a problem is problematic, since the earthquake source may be located at a considerable distance from the structure, and its inclusion in the geotechnical prediction would lead to simulation of a very large-sized model. The authors studied the behavior of three types of boundary conditions during an earthquake. As a result, the researchers identified the most acceptable scheme boundary setting in terms of calculation correctness as well as in terms of time consumption.

Table 1 shows the international experience of modeling the boundaries of calculation schemes depending on the tunnel diameter for various geotechnical problems.

Table 1. Analysis of international experience in mathematical modeling

No	Problem formulation	Ссылка на исследование	Модель грунта	Расстояние от низа тоннеля до низа схемы в зависимости от диаметра тоннеля, м	Диаметр тоннеля D, м
1	Assessment of the impact of tunneling on the surrounding area	[7]	HS	3.3D	8.5
		[8]	MC	2.5D	6.15 9.15 10.65 12.15
		[9]	MC	3.5D	4.35
		[10]	MC	3.5D	10
		[11]	HSS	1,8D	6.7
2	Simulation of soil-foundation interaction	[12]	MC	1D	6
		[13]	MC	2D 6.3D	11 4.9
3	Determination of surface settlement as a function of loading pressure	[14]	MC	1.5D	6
4	Creation of universal 3D models during TBM tunneling	[15]	MC	3D	6.9
		[16]	MC, Modified Cam-Clay, Linear-Elastic	3.5D	9.3

However, one should note that the definition of the boundaries of the modelling schemes currently being modeled in Russia differs significantly from the international experience. Recommendations on the choice of the size of the calculation area and geomechanical soil model for our country are set out in Table E.2 of SP 249.1325800.2016 "Underground utilities. Design and construction by closed and cut-and-cover methods". The recommended value of the model design domain depth (b) is determined by the formula (1), when modeling closed excavations according to the normative document.

$$b=0,5D_s \tag{1}$$

where D_s id the diameter or cross-sectional dimension of the closed excavation [17].

In this regard, it is important to note that according to international experience, the lower limits of schemes in geotechnical modeling take values from 1D to 6.3D. In comparison with the Russian documentation, this distance is 2-12 times greater.

One of the studies on this issue [18] examined the influence of the boundaries of the soil model on the calculation results. According to the results of that experiment, limiting the size of the computational domain has the greatest effect on the ideal elastic-plastic Mohr-Coulomb (MC) soil model [19], while for the Hardening soil (HS) [20], an elastic-plastic model with soil strengthening, and the Hardening soil model with small-strain stiffness (HSS) [21], a model of strengthening soil at small strains, limiting the computational domain has much less effect.

The purpose of this work is to analyze the international experience in the selection of the lower boundaries and to choose appropriate model sizes for calculating the impact assessment of construction on the surrounding structure in PC Plaxis 2D from tunnel drilling, increasing the lower bound of the scheme and comparing the obtained results of the calculations with the results of geotechnical monitoring.

METHODS

In this paper, deformation marks located on the ground surface in the zone of influence of the construction of the Rublevo-Arkhangelskaya and Troitskaya (Kommunarskaya) line of the Moscow Metro were selected to correct the scheme boundary. All projected tunnels are reinforced concrete with external diameter D=6.0 m and thickness 0.3 m. Geotechnical monitoring of engineering communications are performed from the surface of the ground, therefore for this task the marks were selected according to the following advantages:

- perpendicular to the sinking in order to have several geodetic marks in the section at once with the possibility of fixing the movements of these marks by the width of the trough;
- in different engineering-geological and hydrogeological conditions with different layering of soils.

Marks on communications that showed heaving instead of settlement based on the results of geotechnical monitoring were not included in the calculation.

Figure 1 shows a typical plan of the location of the deformation marks of the communications.

The following input data are available for each of the selected communications:

-engineering and geological conditions of the site where the communication is located, well columns and engineering and geological cross sections;

-soil characteristics, including the verified geotechnical indicators required for calculation in the HS model;

-project for the organization of construction of the main line tunnels;

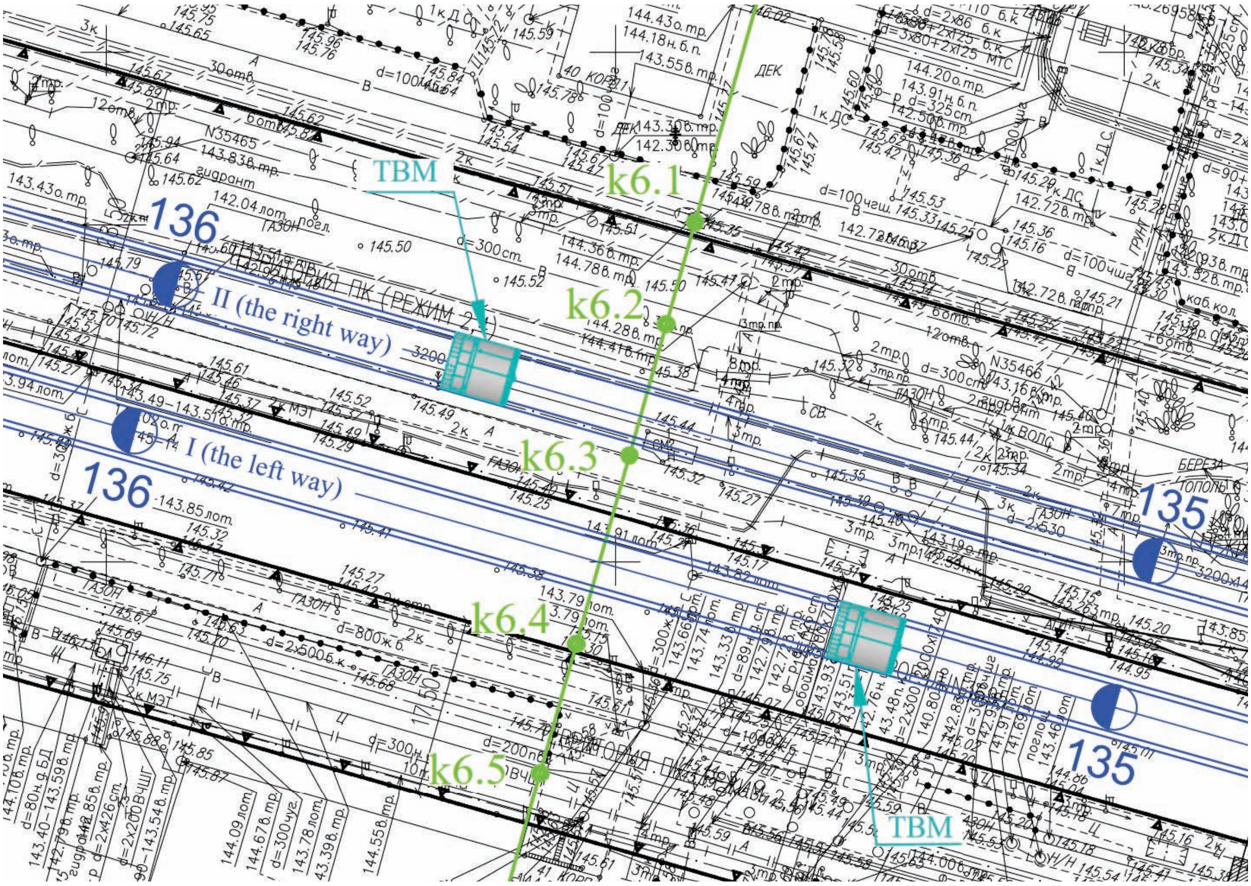
-data of communications monitoring with indication of absolute settlement of marks.

The width of a separate calculation scheme is constant and accepted in accordance with the current normative documentation [17].

In addition, during the calculations in the PC Plaxis 2D the contact elements - interfaces necessary for simulation of the interaction between the structure and the soil were used. The discretization of the finite element mesh was adopted with the standard element distribution "Very fine".

The excess excavation value was set using the tool "Line contractions" with the set value C_{ref} value in accordance with previous studies of the authors [22-25], in order to test the value of the calculated parameter. Then, the excess excavation value was set in a similar way, but its value was set according to Table Z1 of SP 249.1325800.2016 [17]. The results obtained using the excess excavation value according to the regulatory documentation and the same coefficient obtained from the research were analyzed.

Rocky soils, represented by fractured limestone, were simulated using the Linear Elastic soil model.



<u>Figure1.</u> Typical plan of the selected communication with the indication of geodetic marks on the example of communication k6

The computational model in Plaxis 2D considers all the stages of the tunneling work. Accordingly, the calculation is performed in the following steps:

- simulation of the initial natural stresses preceding the construction. The engineering-geological and hydrogeological structure of the site corresponds to the layering of soils on the longitudinal profile;
- activation of the objects of the surrounding buildings, nullification of displacements;
- driving of the left main tunnel;
- driving of the right main tunnel.

A representative calculation of the scheme was performed using the MC model at a distance of

0.5D from the bottom of the tunnel to the end of the scheme, and the calculated displacements of the marks were recorded in tabular form. Then, the distance to the bottom of the scheme was increased again by 0.5D and a new calculation of the scheme was made with fixing the obtained displacements at this distance to the bottom of the scheme. The action was repeated until the additional surface deformations had completed the change depending on the geometry of the scheme or had become equal to the settlements obtained by geotechnical monitoring.

In addition, after completing the calculation using the MC model, the prism with increased deformation moduli was modeled using the MC model with increased deformation modulus of the prism soil under the excavation (Fig. 2) according to the recommendations [26]. And all schemes were recalculated similarly to the previous ones.

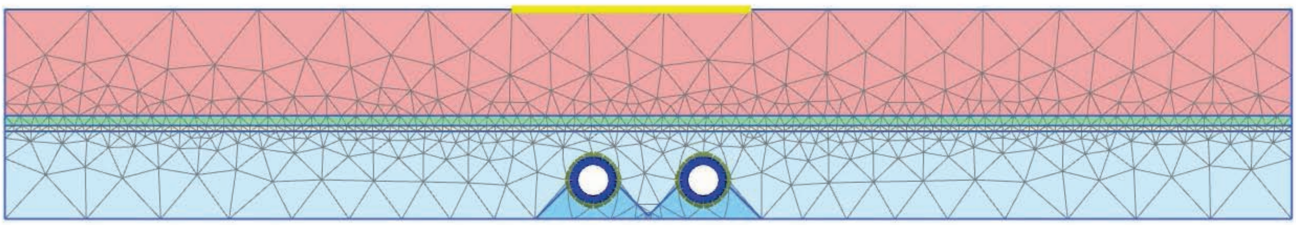


Figure 2. Calculation scheme for evaluating the effect of tunneling with increased soil deformation modulus (areas with darker color) under the tunnels

Separately, the scheme with soils specified by the HS model was also calculated using a sectional calculation pattern using the MC soil model with a tabular fixation of displacements at each increase in the distance to the bottom of the scheme.

Thus, more than 600 design cases were simulated and 6 comparison plots were obtained. Subsequently, the calculation results were analyzed by comparing the obtained displacements with geotechnical monitoring data.

RESULTS AND DISCUSSION

The results of geometry optimization of schemes with different depths of the tunnels are presented below. The average depth in 5 sections was from 20.0 to 26.6 m. However, in section 1-1 the depth of tunneling was 16.5 m.

The number of iterations in the schemes was limited to "soil heaving" the ground surface in the scheme to the opposite side.

Table 2 summarizes the results of the calculations.

Plots of additional vertical displacements vs. distance from tunnel's bottom to the bottom of the computational scheme as a function of tunnel diameter D according to the results of schemes calibration are shown in Fig. 3-4. The graphs are demonstrated for the schemes with the C_{ref} excess excavation value set according to the studies [22-25]. The red dot on the graph indicates the iteration in which the calculated vertical displacement reached the closest value to the results of geodetic monitoring.

The results of scheme calibration with MC model showed that a reliable settlement is obtained when the distance from the tunnel flume to the bottom of the scheme is 0.5-1.5D during the first-third iteration. As the distance increases, the settlement decreases rather quickly (as compared to calculations in other ground models) already at 7-9 iterations the surface bulges out.

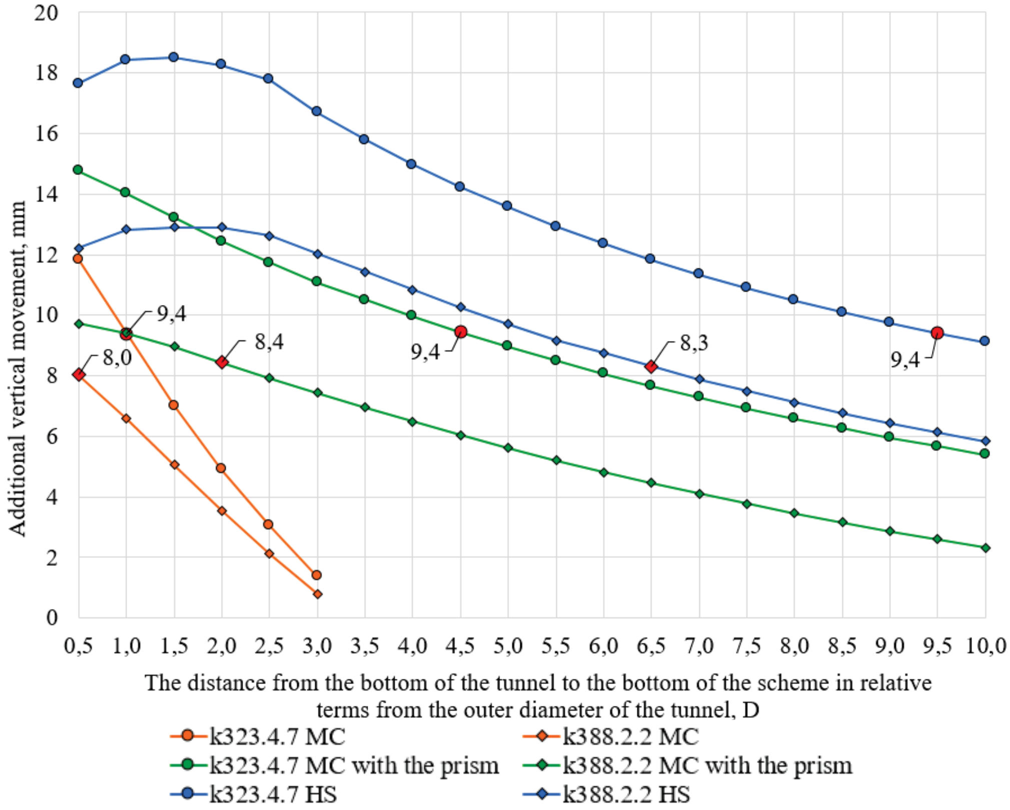


Figure 3. Displacements at H=16.5m in dispersed soils (section 1-1)

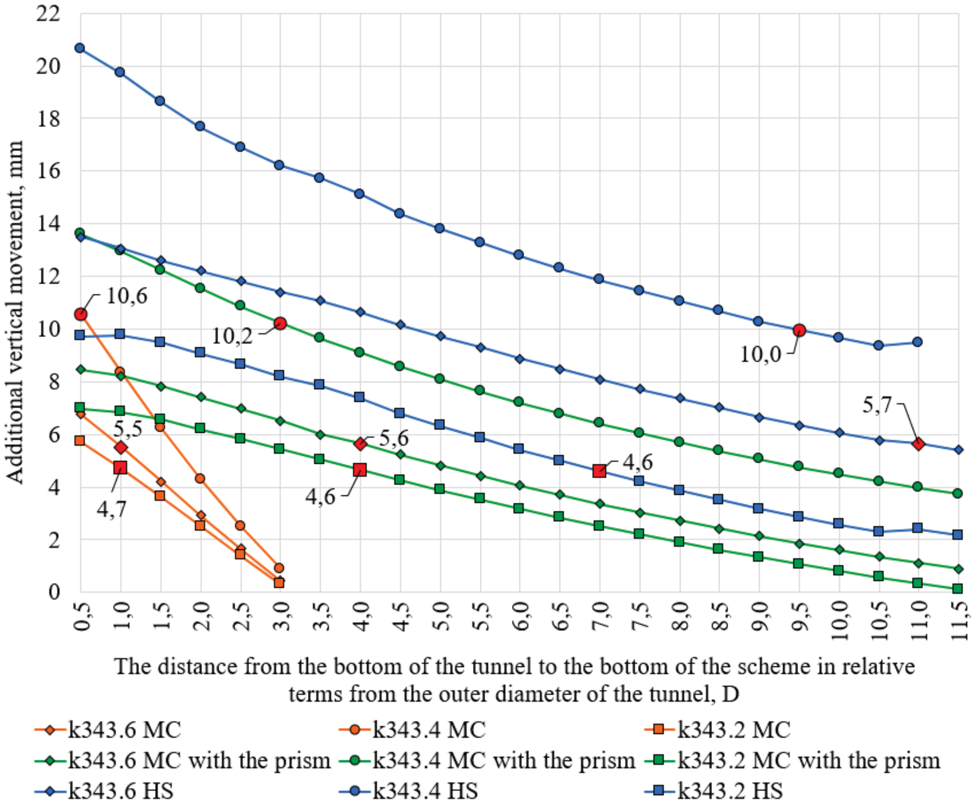


Figure 4. Displacements at H=25m in dispersed soils (section 2-2)

At the same time, the results obtained using the MC model with increased strain modulus in prism and HS are different from MC. The settlement decreases smoothly with increasing distance to the bottom of the scheme, especially in the schemes with the HS ground model. Meanwhile, in the MC model with prism, the displacement reaches the approximate value of actual settlement according to geotechnical monitoring at 2-7D, but in the HS model only at 6-16D.

Besides, there is an increase in settlement with increasing distance to the bottom in the first iterations, and only then the settlement starts to decrease in the HS ground model schemes with shallow tunneling depths.

The results of calibration of the scheme with the MC soil model and using a prism show similarity with HS at shallow depths, at greater depths this method of modeling gives a difference in the results up to 2 times.

In addition, the authors investigated the influence of the lower boundary in the schemes with rocky soils represented by fractured limestone. It was found that changing the boundary from the distance from the tunnel flume to the bottom of the scheme equal to 2.5D does not affect the calculation results.

The calculation of the model using the excess excavation value according to Table Z1 of SP 249.1325800.2016 showed insufficient similarity with the results of field monitoring in that the settlement reached extremely high values during the calculation with these coefficients. This was especially noticeable when calculating using MC model with increasing deformation modulus of the prism soil under the excavation and HS model. It was not possible to reach a suitable lower boundary of the scheme when calculating using these ground models due to a huge distance to the end of the scheme at which the displacement obtained by monitoring would be achieved. As a consequence, the results of calculations with excess excavation value given by the regulatory documentation are presented in Table 1 only for calculations using the classical elastic-plastic MC model. The results of scheme calibration using the MC model and the excess excavation value set according to the regulatory documentation showed that the settlement reaches the value obtained from the monitoring results at the distance from the tunnel flume to the bottom of the scheme equal to 7-12D.

For convenience of the analysis, the graphs constructed by the results of calibration of schemes with characteristic excess excavation value were excluded from the figures, because in their nature they repeat the graphs presented above, differing by a huge number of iterations.

As a result of the study, the authors have developed recommendations for the choice of the lower boundary of the scheme according to the following principle: it is proposed to use the minimum value of the obtained distance, depending on the soil model used. As a result, the authors recommend using the algorithm for selecting the lower bound of the computational scheme shown in Fig. 9 (depending on the given C_{ref} excess excavation value) when solving the problems of influence estimation.

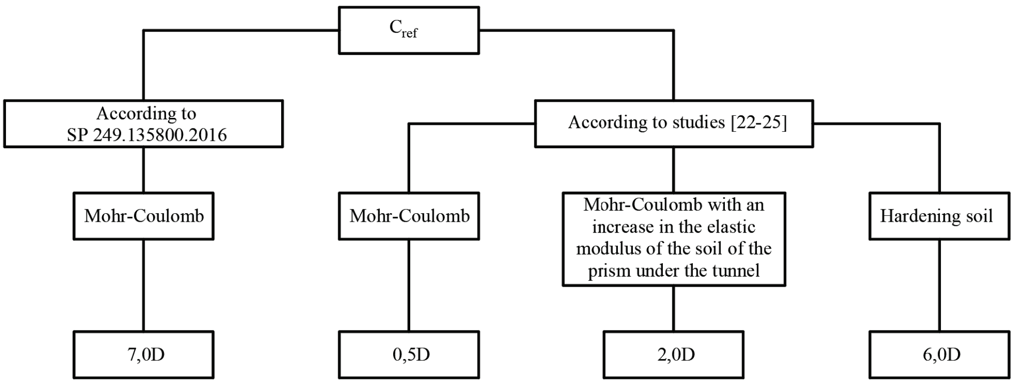


Figure 5. Block diagram for determining the lower boundary of the calculation scheme in a two-dimensional setting in dispersed soils

CONCLUSION

Analysis of international experience shows that the lower boundary of the design scheme regardless of the soil model is set from 1.0D to 6.3D in the cases considered by the authors. Moreover, there is no possibility to determine the regularity of the decision regarding the lower boundary, since the depth of the scheme is set arbitrarily, unlike the Russian designers, who refer to the regulatory document and set the lower boundary at 0.5D for the construction of closed excavations.

The studies presented in this article show the importance of determining a suitable scheme geometry for impact assessment calculations. It is recommended to choose the depth of the scheme depending on the way of assigning the excess excavation value (according to the regulatory documentation or existing studies) and the adopted soil model:

1. In the schemes for estimating the effect from tunneling works in dispersed soils using different soil models, the assignment of the lower limit of the scheme when taking into account the excess excavation value on the basis of SP 249.1325800.2016 and studies [22-25] is recommended to take according to the flowchart in Fig. 5, based on the results of the analysis of Table 2
2. Due to the large scatter of data, in order to ensure the safety of structures, it is proposed to use the minimum values of the obtained distances from the tunnel flume to the bottom of the calculation scheme when creating the calculation schemes:
   - MC (according with SP 249. 1325800.2016) – 7.0D;
   - MC – 0.5D;
   - MC with prism – 2.0D;
   - HS – 6.0D.
3. Using Linear Elastic as the soil model for the rock, at a certain depth (2.5D) the displacements stop changing, which is clearly shown in Figure 4. A similar development of additional deformations occurs when specifying Cref according to the regulatory documents. Thus, there is no need to set the boundary more than 2.5D in the problems of impact assessment in the presence of rocky soils.
4. The C_{ref} value significantly affects the final surface settlement. Depending on the purpose of the excess excavation value, a different lower boundary should be set in the calculated section. In turn, increasing the boundary also affects the reduction of additional surface displacements.
5. The use of the MC soil model with an increased strain modulus under the excavation is permitted to be used in the calculation schemes when considering the lower boundary according to the flowchart in Fig. 5. However, it should be considered that the results of prediction in this way of modeling the soil mass differ from the results of prediction with the HS soil model.
6. It is recommended to recalculate the model at each stage of construction on the basis of monitoring data to optimize its input parameters in order to improve the accuracy of geotechnical prediction.

Since the results of the scheme calibration were not sufficiently pronounced, especially for the MC soil models with increased strain modulus under the excavation and HS, this issue requires further investigations.

Table 2. Optimization results for the calculation scheme

Section number	Section 1-1 H=16.5 m, dispersed soils		Section 2-2, H=24.8 m, dispersed soils			Section 3-3, H=26.6 m, dispersed soils				Section 4-4, H=25.5 m, dispersed soils				Section 5-5, H=20.0 m, dispersed soils			Section 6-6, H=20.1 m, rock soil		
Название точки	k388.2.2	k323.4.7	k343.6	k343.4	k343.2	k10	k307.2	k307.1	k304.3	k376.1	k376.2	k376.3	k323.2.1	k316.7.1	k392.1.1	k392.2.6	K6.3	K6.2	K6.1
Settlement according to the results of monitoring S, mm	8.20	9.20	5.50	9.7	4.5	4.30	9.40	9.00	4.30	5.60	6.60	5.90	3.90	8.00	9.80	6.60	5.9	19.2	11.9
At which boundary the displacement is reached / C_{ref} according to [22-25] / MC	0.5 D	1D	1D	0.5 D	1D	1.5 D	0.5 D	0.5 D	0.5 D	1D	1.5 D	1.5 D	1.5 D	0.5 D	1D	1D	-	-	-
At which boundary the displacement is reached / C_{ref} according to [22-25] / MC with prism	2D	4.5D	4D	3D	4D	6D	3D	3D	3D	3.5D	6.5D	7D	6.5D	2.5D	5D	4.5D	-	-	-
At which boundary the displacement is reached / C_{ref} according to [22-25] / HS	6.5D	9.5D	11D	9.5D	7D	13.5D	8D	7.5D	6D	10D	16D	15D	11.5D	7D	15D	9D	-	-	8D
At which boundary the displacement is reached / according to SP 249 / MC	7.5D	10.5D	8.5D	9.5D	7.5D	9.5D	9D	9D	7D	8D	11.5D	11.5D	10D	8D	12D	9.5D	4.5D	15.5D	2.5D
Distance to the center of the left tunnel, m	8.8	18.1	9.9	10.2	30.1	8.3	12.0	16.0	34.5	11.3	4.9	15.3	26.0	9.1	7.8	24.5	21.5	0	32.5
Distance to the center of the right tunnel, m	25.8	1.1	26.9	6.8	13.1	26.3	6.0	2.0	16.5	28.3	12.1	1.7	9.0	26.1	9.2	7.5	36.5	15	17.5

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Armen Z. Ter-Martirosyan – Vice-Rector, Doctor of Science, Professor; National National Research Moscow State University of Civil Engineering, 26, Yaroslavskoye Shosse, 129337 Moscow, Russia; Tel.: +7 (495) 025-28-65, доб. 2263; E-mail: gic-mgsu@mail.ru

Rustam H. Cherkesov – General Director, Institute Mosinzhproekt Limited Liability Company, 4/1, Sverchkov Ln, 101000 Moscow, Russia; Tel.: +7(495)225-19-40, доб. 1001; E-mail: Cherkesov.R@mosinzhproekt.ru.

Ilya O. Isaev – Director of Scientific and Technical Activities; Institute Mosinzhproekt Limited Liability Company, 4/1, Sverchkov Ln, 101000 Moscow, Russia; Tel.: +7(495) 225-19-40, доб. 6107; E-mail: IsaevIO@mosinzhproekt.ru.

Viktoriya V. Rud - graduate student; National Research Moscow State University of Civil Engineering, 26, Yaroslavskoye Shosse, 129337 Moscow, Russia; Tel.: +7-977-806-55-02; E-mail: victo-riadll@yandex.ru.

Mariya I. Ambrushkevich - master's student; National Research Moscow State Civil Engineering University, 26, Yaroslavskoye Shosse, 129337 Moscow, Russia; Tel.: +7-982-763-80-33; E-mail: m_ambrushkevich@mail.ru.

Тер-Мартиросян Армен Завенович – проректор, доктор технических наук, профессор кафедры механики грунтов, оснований и фундаментов; Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ), 129337, Россия, г. Москва, Ярославское шоссе, д. 26; Тел.: +7 (495) 025-28-65, доб. 2263; E-mail: gic-mgsu@mail.ru.

Черкесов Рустам Хасанович – генеральный директор; ООО Институт Мосинжпроект, 101000, Россия, г. Москва, Сверчков переулок, д. 4/1, стр.1; Тел.: +7(495)225-19-40, доб. 1001; E-mail: Cherkesov.R@mosinzhproekt.ru.

Исаев Илья Олегович - директор по научно-технической деятельности; ООО Институт Мосинжпроект, 101000, Россия, г. Москва, Сверчков переулок, д. 4/1, стр.1; Тел.: +7(495) 225-19-40, доб. 6107; E-mail: IsaevIO@mosinzhproekt.ru.

Рудь Виктория Владимировна – аспирант; Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ); 129337, Россия, г. Москва, Ярославское шоссе, д. 26; Тел.: +7-977-806-55-02; E-mail: victoriadll@yandex.ru.

Амбрушкевич Мария Игоревна – магистрант; Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ), 129337, Россия, г. Москва, Ярославское шоссе, д. 26; Тел: +7-982-763-80-33; E-mail: m_ambrushkevich@mail.ru.