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Analysis of mechanized tunneling parameters to determine the overcutting characteristics

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Abstract

Tunneling in urban conditions requires costly measures, in order to ensure the safety of existing buildings. On average, there are up to 17–20 buildings per 1 km of Moscow Subway Lines under construction. Analysis and comparison of geotechnical monitoring data and results of geotechnical estimations for underground construction using cut-and-cover and tunneling methods in conditions of high-density urban area shows an unsatisfactory correlation between estimated and actual data. This can be described in the following way: insufficient geotechnical survey data; discrepancy between the accepted estimation model and the actual behavior of soil under load; insufficient qualification of the construction workers; and overcutting. The study was aimed at solving the urgent scientific and engineering problem of determining the characteristics of overcutting during mechanized tunnel boring. At the first stage, the investigations were aimed at identifying the key reasons and factors which determine the quantitative parameters of overcutting in urban underground construction by tunneling. These factors include the following: mismatch between the cutting diameter and the outer lining diameter; displacement of the soil mass in front of the face; incomplete grouting of voids beyond the lining; incomplete filling of beyond-shield voids with clay mortar or slow-curing grouting mortar or no filling at all; and human factor (low qualifications of personnel). The overcutting coefficient was determined on the basis of the proposed empirical dependence of its values with regard to the depth of tunneling. The experimental data allowed the depth dependence of the overcutting coefficient for different tunneling depths to be defined, as well as for tunnel diameters from 4 to 10 meters in the case of mechanized tunnel boring machine (TBM) using the earth pressure balanced tunneling method. The practical importance of the studies consists in determining the range of the empirical overcutting coefficient variation from 0.5 % (for TBMs with nominal diameter of 10 m) up to 5 % (for TBMs with nominal diameter of 4 m). The development of organizational measures and justification of process solutions, aimed at ensuring the safety of the existing buildings in conjunction with the scientific and technical support of underground construction has led to a shortening of tunneling time between the Okskaya and Nizhegorodskaya stations of Nekrasovskaya Line of Moscow Subway by about six months. It has also provided savings of about 2.5 billion rubles.

Keywords

underground construction, tunneling, tunnel boring machine (TBM, blade shield), Herrenkneht, Robbins, geotechnical monitoring, overcutting, coefficient of overcutting

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СТРОИТЕЛЬСТВО ГОРНЫХ ПРЕДПРИЯТИЙ И ОСВОЕНИЕ ПОДЗЕМНОГО ПРОСТРАНСТВА

Научная статья

Анализ параметров механизированной проходки тоннелей для определения характеристик перебора грунта

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Аннотация

Ведение горнопроходческих работ в условиях современного города требует проведения дорогостоящих мероприятий по обеспечению сохранности существующих зданий. В среднем на 1 км строящейся линии метрополитена Москвы приходится до 17–20 зданий. Анализ и сопоставление данных геотехнического мониторинга с результатами геотехнических расчетов для подземного строительства открытым и закрытым способами в условиях плотной городской застройки продемонстрировал неудовлетворительную сходимость расчетных и фактических данных. Основными факторами этого явления являются: недостаточность данных инженерно-геологических изысканий; несоответствие принимаемой расчетной модели реальному поведению грунта под нагрузкой; недостаточная квалификация исполнителей; перебор грунта. Публикация направлена на решение актуальной научно-технической задачи определения характеристик перебора грунта при механизированной проходке тоннелей. На первом этапе исследования были направлены на идентификацию ключевых причин и факторов, определяющих количественные параметры перебора грунта в условиях подземного строительства в городах при закрытом способе горностроительных работ. Среди таких факторов выделяются следующие: несоответствие диаметра резания наружному диаметру обделки, перемещения грунтового массива перед забоем, неполное заполнение тампонажным раствором заобделочного пространства, неполное заполнение пространства за оболочкой щита глинистым или медленно твердеющим тампонажным раствором или их отсутствие, человеческий фактор (низкая квалификация персонала). Коэффициент перебора устанавливается на основе предложенной эмпирической зависимости его значений от глубины заложения тоннеля. Экспериментальные данные позволили установить зависимости коэффициента перебора при разных глубинах заложения тоннеля, а также при диаметрах тоннелей от 4 до 10 м для тоннелепроходческого механизированного комплекса с активным пригрузом забоя. Практическое значение проведенных исследований состоит в установлении диапазона изменения значений эмпирического коэффициента – от 0,5 % (для щитов с условным диаметром 10 м) до 5 % (для щитов условным диаметром 4 м). Разработка организационных мероприятий и обоснование технологических решений по обеспечению сохранности существующих зданий в комплексе с научно-техническим сопровождением подземного строительства позволила примерно на 6 месяцев сократить срок проходки перегонов между станциями «Окская» и «Нижегородская» Некрасовской линии Московского метрополитена, а также и обеспечить экономию порядка 2,5 млрд руб.

Ключевые слова

подземное строительство, проходка, тоннели, щитовой комплекс, Herrenkneht, Robbins, геотехнический мониторинг, перебор грунта, коэффициент перебора грунта

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Introduction

Tunneling in urban conditions requires costly measures, in order to ensure the safety of existing buildings. On average there are up to 17–20 buildings per 1 km of Moscow Subway Lines under construction. Analysis and comparison of geotechnical monitoring data and results of geotechnical estimations for underground construction by cut-and-cover and tunneling methods in conditions of high-density urban area shows an unsatisfactory correlation between estimated and actual data. This can be described in the following way: insufficient geotechnical survey data; discrepancy between the accepted estimation model and the actual behavior of soil under load; insufficient qualification of construction workers; and overcutting.

Analysis of the geotechnical monitoring data and comparison with the results of estimates determining the effect of underground construction on buildings and structures in the surrounding area show that with regard to facilities of this kind constructed by cut-and-cover method (C&C) in excavations up to 9–12 m deep, the correlation between the estimated and actual data does not exceed 60 %. With regard to the construction of subway facilities in excavations up to 35 m deep, this correlation amounted to up to 32 %. In the case of tunneling using tunnel boring machines with a nominal diameter of 6 m, the figure is 70 %, while using tunnel boring machines with nominal diameter of 10 m – 7 %. This data testifies to the necessity of improving both the estimation methods and the geotechnical monitoring techniques [2–4]. The main reasons for unsatisfactory convergence of the geotechnical estimations and actual geotechnical monitoring data were identified in earlier studies [5–7].

When modeling the tunneling method of construction, an important parameter, depending on the construction techniques, is overcutting. This design parameter is set during the modeling of soil mass strains as a characteristic of tunneling. It is equal to the ratio of the excavated area within the limits of the tunnel contour to the tunnel cross-sectional area [8].

It has been shown in historical studies that overcutting in the process of tunneling was caused by the following factors [9, 10]:

1. Cutting diameter mismatch with the lining outside diameter. In the case of using TBM with an external cutting tool (typical for majority of modern TBMs applying earth pressure balanced tunneling) rotor diameter is 3–5 % larger than the tunnel lining diameter on average.

2. Displacement of soil mass in front of the face. This factor is characteristic first of all for TBMs not performing earth pressure balanced tunneling, as well as in case of overcutting.

3. Overcutting may also occur due to human factor, i.e. insufficient personnel training.

4. Incomplete filling of beyond-shield voids with grouting mortar.

One more factor should be added to this list:

5. Lack of filling or incomplete filling of beyond-shield voids with clay mortar or slow-curing grouting mortar.

All the above factors indicate that overcutting leads to process strains of the surface [11].

Models for determining the overcutting coefficient in mechanized tunneling

The volume of soil loss (overcutting coefficient V_L) is commonly defined as the ratio of the surface subsidence area V_s to the cross-sectional area of the tunnel F_t:

$$V_L = \frac{V_s}{F_t} 100\%. \tag{1}$$

The key points in predicting the overcutting coefficient were outlined in earlier studies [9]. It was shown later that V_L can be determined only on the basis of field observation data, while for weak soil the value of soil losses does not exceed 2 % [12]. In [13], data is given for the dependence of V_L on the tunnel diameter, its depth and geotechnical conditions of the construction of tunnels with diameter up to 4 m at a depth up to 8.1 m.

Other studies [14, 15] show that during driving by TBM (with soil face balance weight) 9.15 m in diameter in water-saturated sand overlain by marl, V_L does not exceed 0.3-0.5 %. The existing regulatory documents in Russia[1] regulate the values of overcutting coefficient for tunnel construction up to 4 m in diameter in the range of 1.5 to 5.5 % depending on the type of soil in the face. These values are significantly higher than V_L, values obtained by foreign researchers [12, 14, 15].

When constructing subway tunnels by mechanized tunneling method in conditions of high-density urban area the following needs to be taken into account:

– tunnel depth is generally no less than 1*d* (*d* is the tunnel diameter) with sand or clay soils in the tunnel crown;

– TBMs with soil face balance weight are used mainly in subway soft ground tunneling (among all the Moscow TBM fleet, there are 24 TBMs with soil face balance weight and one with bentonite face balance weight). This assumes squeezing grouting mortar through the tail part of the casing simultaneously with TBM (shield) advancement.

Thus, the review of data from earlier studies allows it to be concluded that the overcutting coefficient depends on the following factors when applying mechanized tunneling:

– relative depth of tunneling h/d;

– cohesion of soil;

– ratio of the clearance between the cutting tool and the tunnel lining to the tunnel diameter.

Digital estimation models of technological processes and the rock (soil) mass conditions for designing TBM tunneling in urban areas are performed in PLAXIS, GEOWALL, COMSOL and other software systems [16, 17]. Determining the overcutting parameters while tunneling is also of great importance for improving reliability of the digital models.

Findings of geotechnical monitoring during main line tunneling

Let us consider the findings of monitoring during the tunneling of the Nekrasovskaya Line and the Western segment of the Great Ring Line (GRL) of the Moscow Subway as an example.

The tunneling of Western segment of the GRL was performed by "ROBBINS" TBM with soil balance weight, with a shield blade (work tool) diameter d_r of 6.6 m and tunnel diameter *d* of 6.3 m.

ζ factor characterizing the ratio of the clearance between the cutting tool and the tunnel lining to the tunnel diameter

$$\zeta = \frac{d_r - d}{d} \tag{2}$$

is equal to 0.048.

The tunneling was carried out in water-saturated fine/medium-grained sand.

[1] SP 249.1325800.2016 Underground utility systems. Design and construction by tunneling and C&C methods

The empirical overcutting coefficient V_{le} was calculated by the backward analysis method on the basis of the following formula:

$$V_{le} = \frac{s_f i \sqrt{2\pi}}{S}, \quad (3)$$

where s_f is actual subsidence in the observation point located at the distance i from the axis of the tunnel; S is the face area.

The reduced (equivalent) overcutting coefficient V_{Lp} was calculated through the following expression:

$$V_{Lp} = \frac{\sum_{i=1}^{n} V_{lp_i} S_i}{S}, \quad (4)$$

where S_i is the face area with overcutting coefficient V_{lp_i}.

The results of the overcutting coefficient calculation in the form of characteristic curves

$$V_L = f\left(\frac{h}{d_r}, \xi\right) \quad (5)$$

are shown in Figures 1 and 2.

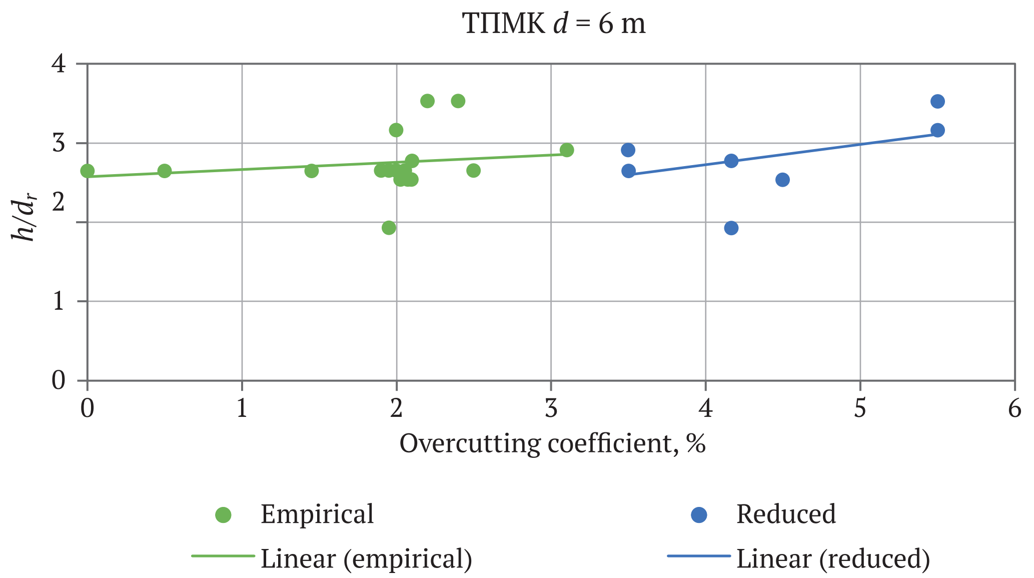

Fig. 1. Dependence of the empirical V_{le} and reduced V_{lp} overcutting coefficients on the relative depth of tunneling h/d_r with TBM with a nominal diameter of 6 m

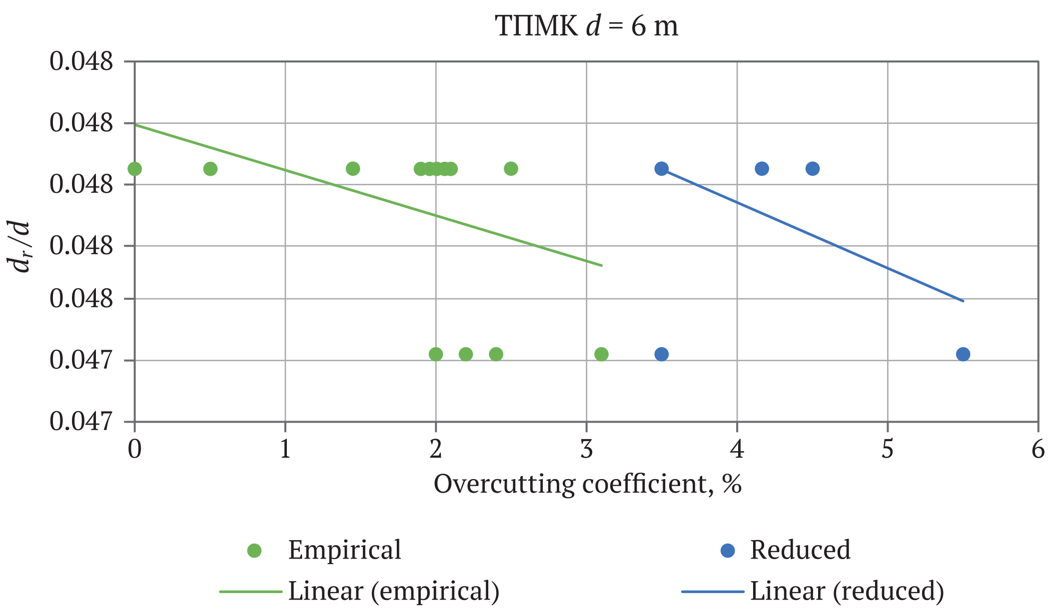

Fig. 2. Dependence of the empirical V_{le} and reduced V_{lp} overcutting coefficient on ζ factor for tunneling using TBM with nominal diameter of 6 m

During the construction of Nekrasovskaya Subway Line from Okskaya Ulitsa station to Stakhanovskaya Ulitsa station, a Herrenkneht TMB EPB with soil face balance weight and the work tool diameter d_r = 10.69 m was used. The diameter of the tunnel d = 10.3 m, and factor ζ = 0.038. The running (main line) tunnels are mainly located in Upper Jurassic clay, while the crown reveals Quaternary sediments almost throughout the whole length of the tunnels.

In the next segment from Kosino station to Yugo-vostochnaya station, tunneling was carried out using a Herrenkneht TMB EPB with soil face balance weight and work tool diameter d_r = 10.82 m. Diameter of the tunnel d = 10.5 m, and factor ζ = 0.03. The maximum additional subsidence of the building under whose foundations the TBM passed at a depth of 13 m, was 6.7 mm [18].

The values of empirical overcutting coefficient at these segments varied from 0.5 to 1.25 %, depending on the depth of tunneling and geotechnical conditions in the tunnel face.

Figs. 3 and 4 show generalized dependences (5) for tunnel boring machines with nominal diameter of 4–10 m.

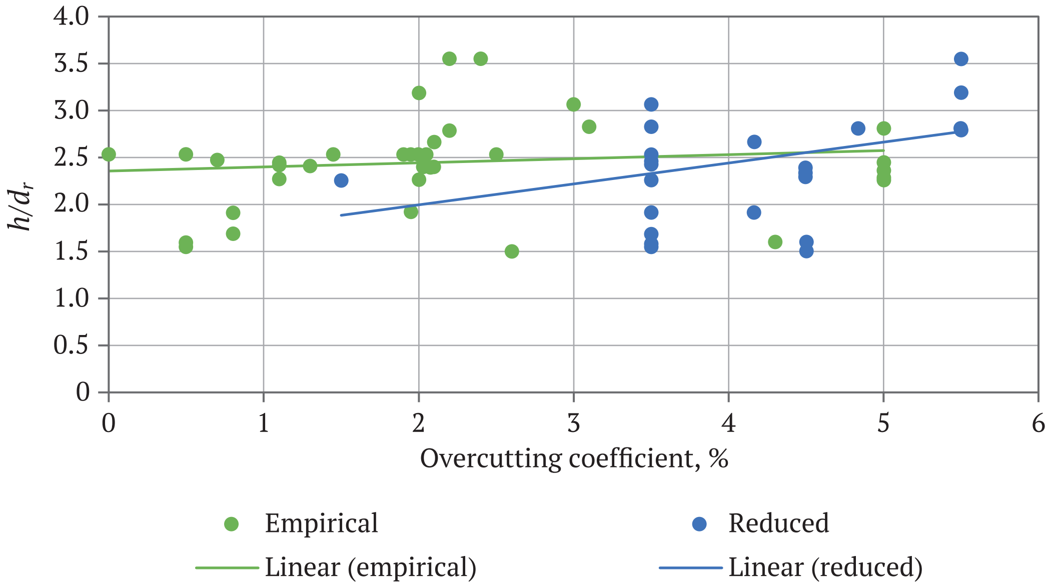

Fig. 3. Generalized dependence of the empirical V_{le} and reduced V_{lp} overcutting coefficients on the relative depth of tunneling h/d_r when tunneling at the diameter of 4–10 m using TBM with soil face balance weight

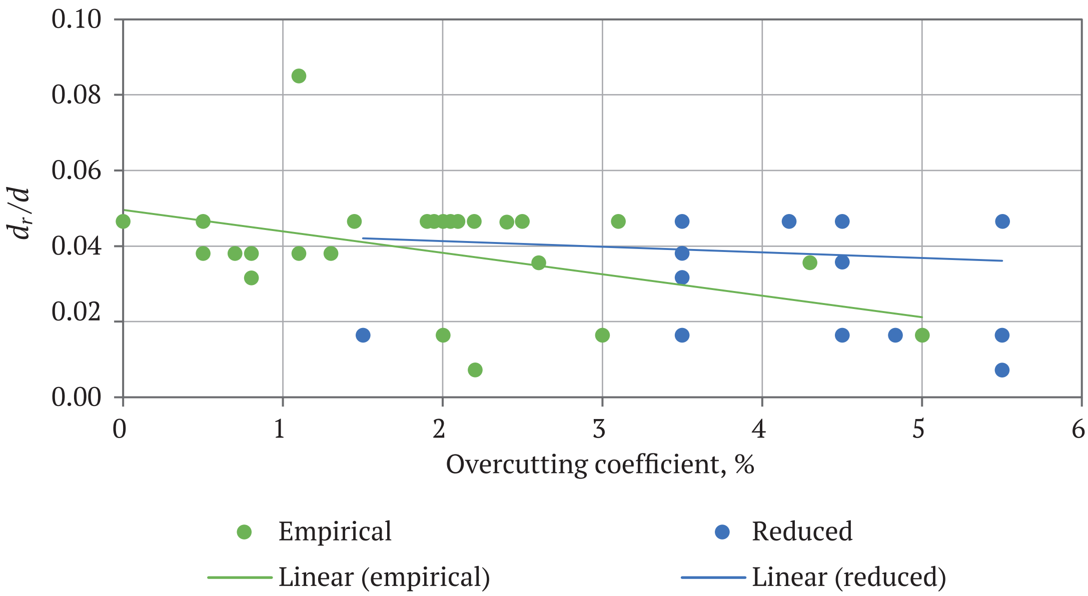

Fig. 4. Generalized dependence of the empirical V_{le} and reduced V_{lp} overcutting coefficients on ζ factor when tunneling at a diameter of 4–10 m using a TBM with soil face balance weight

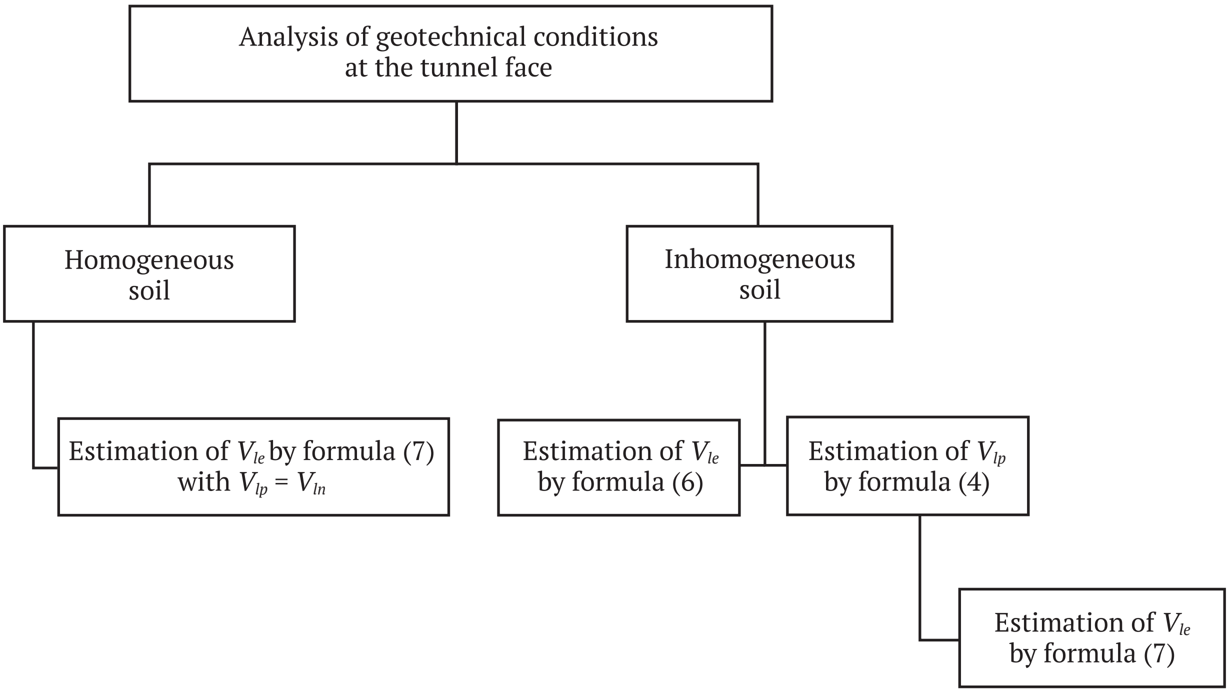

Fig. 5. Pattern of empirical overcutting coefficient V_{le} computation

It should be noted that the ζ factor is not a sufficiently reliable characteristic due to the constancy of ζ values for different types of TBMs. At the same time the value of overcutting coefficient depends on the TBM diameter.

The empirical values of the overcutting coefficient for TBMs with a nominal diameter of 4–10 m were determined by the backward analysis method. The empirical coefficient values vary in the range from 0.5 % (for TBM with nominal diameter of 10 m) to 5 % (for TBM with nominal diameter of 4 m). The characteristic curves shown in Fig. 3 allow overcutting coefficient to be calculated depending on the relative depth of tunneling (in mixed soils) according to the following empirical expression:

$$V_{le} = 0,49\frac{h}{d_r} + 0,96. \quad (6)$$

A similar dependence between the empirical and reduced overcutting coefficients is as follows:

$$V_{le} = 0.69V_{lp} + 0.53 \quad (7)$$

this allows, based on the normative values from SP 249.1325800.2016 “Underground utilities. Design and construction by tunneling and C&C” (Order of the Russian Ministry of Construction dated July 8, 2016 No. 485/pr), the empirical overcutting coefficient to be calculated, taking into account geotechnical conditions along the tunneling route.

Based on research findings, a pattern of the empirical overcutting coefficient V_{le} computation was proposed (as shown in Fig. 5). This pattern provides for computation of overcutting coefficient based on different dependencies. It takes into account the degree of soil homogeneity, determined on the basis of analysis of geotechnical conditions in the tunnel face.

Conclusion

The empirical values for overcutting coefficient in the case of TBMs with a nominal diameter of 4–10 m were determined by the backward analysis method. The empirical coefficient values vary in the range from 0.5 % (for TBMs with nominal diameter of 10 m) to 5 % (for TBMs with nominal diameter of 4 m). The computation pattern shown on Fig. 5 allows for the coefficient of overcutting at tunnel boring using TBMs with face balance weight to be determined, while taking into account the TBM diameter and the types of soil composing the tunnel face (homogenous/inhomogeneous).

The proposed method was successfully implemented during the construction of the Nekrasovskaya and Great Ring Lines of the Moscow Subway. Optimization of measures to ensure the safety of the existing buildings in conjunction with the scientific and technical support of underground construction allowed the time of tunneling between the Okskaya and Nizhegorodskaya stations of the Nekrasovskaya Line of the Moscow Subway to be shortened by about 6 months, as well as providing savings of about 2.5 billion rubles.

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