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Prediction of technological settlements for existing buildings during underground construction

Prévisions d'évolution technologique pour les bâtiments existants au cours de la construc-tion souterraine

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ABSTRACT: The paper contains results of scientific-research work on determining technological settlements during underground construction. There are suggested engineering methods for estimating technological settlements during construction of a diaphragm wall and sheet piles. Technological settlement values are determined for taking various types of mitigation measures for neighboring buildings (underpinning with piles, cut-off walls) considering geological conditions of two Russian cities. The prediction of additional settlements along a building with mitigation measures near a deep pit has been made.

RÉSUMÉ: L'article contient les résultats des travaux de recherche scientifique sur la détermination des tassements technologiques pendant la construction souterraine. Des méthodes d'ingénierie pour estimer le tassement technologique durant la construction de la paroi du diaphragme et le remplissage de la tôle ont été suggérées. Les valeurs de tassement technologique sont déterminées pour l'installation de divers types de mesures d'atténuation pour les bâtiments voisins (sous-sol avec des piles, murs de coupure) en tenant compte des conditions géologiques de deux villes russes. La prédiction de la colonisation supplémentaire le long de la construction avec des mesures d'atténuation près de la fosse profonde a été faite.

Keywords: technological settlement, cut-off walls, deep excavation pit, mitigation measures, sheet pile

1 INTRODUCTION

Underground space development in the conditions of congested urban areas causes additional deformations of surrounding buildings. It is connected not only with changes of strain-stress behavior of a soil bulk due to excavation for a deep pit or tunnel but also the influence of mechanic tools and protection measures on a soil bulk as well as underground structures and superstructures.

Vibration and blow impacts, as a rule, lead to additional consolidation of sandy soils, in particular, the loose ones, and can result in virbro-liquefaction of sandy soils. In soft clayey soils of small degree of lithification there could be observed soil destructuring, which causes reduction of strength and strain properties.

It leads to occurrence of technological settlements of the surface or buildings and structures in an area under the influence of underground construction. There has been conducted research, which allows predicting some types of technological settlements.

2 TECHNOLOGICAL SETTLEMENTS DURING INSTALLATION OF PIT FENCES

2.1 The factors influencing a value of technological settlements at construction a cut-off wall

When constructing a cut-off wall there is a need to differ technological settlements of the surface of a soil bulk without buildings (greenfield) and settlements of buildings, which rest upon shallow and deep foundations.

A size of the area, where technological settlements caused by cut-off wall construction manifest themselves, is defined by soil compressibility.

According to the research results of Russian specialists the settlements of the surface caused by construction of a cut-off wall (technological settlements) in soils of small or medium compression are observed at the distance of 5 m, in case of highly compressive soils - at 25 m and more. In particular, it is mentioned that soft clayey soils are prone to destructuring due to thixot-ropy, which results in an increase of the influ-ence area of underground facilities.

The works of Konykhov D.S. and Sviridov A.V.(2011), Mangushev R.A. and Sapin D.A. (2015), Shulyatjev O A et al (2016) prove that a value of technological settlements during construction of a cut-off wall is influenced by the following factors: different properties of clayey suspension and fluid concrete, parameters and types of equipment for making trenches, parameters of adjacent buildings and geotechnical conditions, a length of pour and rigidity of fencing.

2.2 Prediction of technological settlements at construction a cut-off wall

2.2.1 A fence in the form of a cut-off wall and one made of metal piles

The issues associated with prediction of settlements at construction of a cut-off wall using numerical methods are well reported in literature, for example, Ahmed Hosny Abdel-Rahman, Sayed Mohamed El-Sayed, 2009, Comodromos E.M. et al, 2013 etc.

Konykhov D.S. and Sviridov A.V. (2011) proposed to define a technological component of the additional settlement Sad,t at construction of a cut-off wall of the trench type during design according to formula (1):

$$\frac{L}{H_k} = 0{,}789 s_{ad.t}^{-0{,}73} \tag{1}$$

at driving metal piles using pheumodrifts – according to formula (2):

$$\frac{L}{H_k} = 0{,}041 s_{ad.t}^{2} - 1{,}027 s_{ad,t} + 6{,}226 \tag{2}$$

Where L is a distance from the external plane of a building foundation to a pit fence, H_k – a pit depth.

Sapin D.A. (2015) suggested an empirical expression for engineering evaluation of additional settlements of foundations of buildings caused by construction of a cut-off wall of the trench type (Figure 1):

$$S = \alpha A e^{-BL} \tag{3}$$

Where: S – a settlement of a building foundation adjacent to a pit; A and B –coefficients depending on geometrical parameters of a pour for a cut-off wall, clay mortar density and soil conditions are given in table 1; e – Euler constant (e =2.71); L – a distance from a cut-off wall to a building, m; α – adjustment factor equal to 1.3.

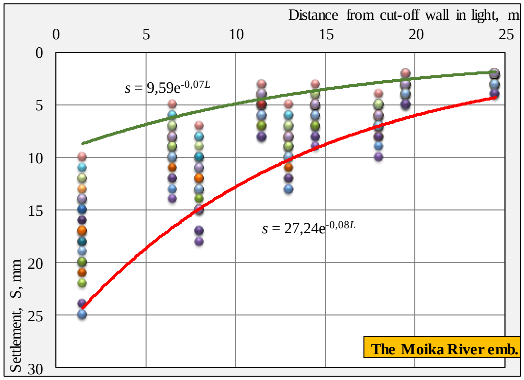

Figure 1. Technological settlements of existing buildings depending on a distance from a pit in St. Petersburg (Sapin D.A., 2015; Mangushev R.A., Nikiforova N.S., 2017)

Table 1. Coefficients A and B for geotechnical conditions in the central part of St. Petersburg

№	Pour parameters		γ, clay mortar, kN/m³	A, mm	B, m^{-1}
	***b* pour, m**	***l* pour, m**			
1	1.2	3.3	12.5	19	-0.07
2			11.7	23	-0.07
3			11	28	-0.08
4		2.6	12.5	17	-0.08
5			11.7	17	-0.07
6			11	22	-0.08
7		2	12.5	12	-0.07
8			11.7	16	-0.08
9			11	18	-0.07
10	1	3.3	12.5	17	-0.07
11			11.7	23	-0.08
12			11	27	-0.07
13		2.6	12.5	15	-0.08
14			11.7	19	-0.08
15			11	22	-0.08
16		2	12.5	11	-0.07
17			11.7	14	-0.07
18			11	18	-0.08
19	0.8	3.3	12.5	19	-0.08
20			11.7	22	-0.08
21			11	27	-0.08
22		2.6	12.5	15	-0.08
23			11.7	19	-0.09
24			11	22	-0.08
25		2	12.5	10	-0.07
26			11.7	14	-0.07
27			11	16	-0.08

There has been proposed an engineering method of calculation of a technological settlement of the surface during construction of a cut-off wall analogous to the method of corner points, which is known in soil mechanics (Mangushev R.A., Nikiforova N.S., 2017).

2.2.2 Pit fence made of jet-piles

Technological settlements of surrounding buildings at construction of a cut-off wall, which was made using jet grouting; at production of fences made of jet-piles in coarse-grained and medium-grained sands during construction of a transport tunnel in Lefortovo (Moscow) were 0.2...0.6cm. When constructing a pit fence for the second stage of the Mariinskiy Theatre in St. Petersburg in soft soils it was 0.5-0.6 cm (Figure 2).

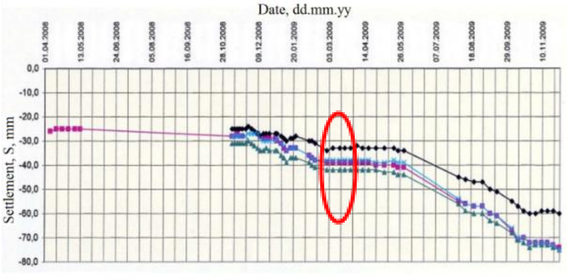

Figure 2. Technological settlements of buildings located in the area of influence of the pit of the second stage of the Mariinskiy Theatre in St. Petersburg (Mangushev R.A., Nikiforova N.S., 2017)

2.2.3 Technological settlements at construction of a fence for a pit in loose sands

Technological settlements due to construction of a cut-off wall in loose saturated sands adjacent to the building pit in the square of Tverskaya Zastava in Moscow reached 0.5...7.0cm, on the ground surface – 0.6cm, in spite of the fact that sands between the building foundations and cut-off wall was reinforced using the method of geocomposite (Mangushev R.A., Nikiforova N.S., 2017).

At construction of pit fences and pile foundations in saturated loose sand there is a need of strict compliance with requirements of special technological regulations and normative documents (Set of Rules 45.13330.2012).

In Moscow, a 9-storeyed building with an underground part (the pit depth - down to 4.0 m) was attached to the reconstructed 8-storeyed building with a basement. In order to preserve the existing building its strip foundations were underpinned with root pile of the diameter 18 cm and the length 16.8-17.5 m, cementation of the foundation body and "soil-foundation" contract as well as band reinforcement of walls in locations of existing cracks. Loose saturated sands of medium density of up to 4 m thickness constituted the soil of foundations.

Construction of the pit fence in two sides was implemented using the method of screwing a 8-m-long casing Ø377x7 with the spacing 1.0 m and its subsequent filling with a concrete mixture of B10 grade. The designed stated driving 69 casings with the spacing 1.0 m.

Construction of the pit fence using the method of casing screwing into a pre-drilled borehole (applying pilot auger drilling and soil loosening within a casing) led to over-normative differential settlement of the building –the maximum and minimum settlements of the building are 1.7 cm and 0.9 cm.

The pit fence along the building under reconstruction was made using CFA technology, however, it was accompanied with violation of the technical procedure of pile production–boreholes were poured with mortar only to a half of its height. The requirements of regulations on the terms of pile production and spacing between them were not met. As a result, there was softening of soil around reinforcing piles approximately at the half of their length that causes reduction of their bearing capacity and additional settle-ment of the building, which was 6.0 cm (figure 3), and resulted in cracking of its structures. The maximum relative difference of settlements reached 0.003.The additional limit values of settlements and relative difference of settlements of soil exceeded the ultimate values equal to 1.0 cm and 0.0007, respectively.

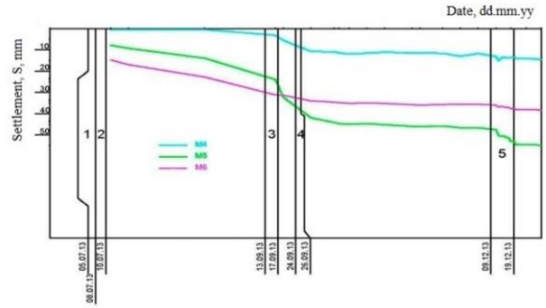

Figure 3. Technological settlements of the building under reconstruction in Moscow during construction of the pit fence and piles: 1 - using the method of driving a casing with an auger; 2 – the same for the building; 3,4 - using CFA method, 5 – piles under an additional house (Mangushev R.A., Nikiforova N.S., 2017)

2.3 Pit fence made of sheet piles

2.3.1 Technological settlements at jacking of sheet piles

While excavating deep pits adjacent to existing buildings it is necessary to use non-intrusive technologies of work execution, one of them is jacking of sheet piles. The main advantages of static jacking of sheet piles implies considerable reduction of vibrations and noise at driving.

There is an opinion on minimum influence of jacking of sheet piles on additional settlements of adjacent buildings.

The construction practice and results of geodetic observations of buildings in the central part of St. Petersburg show that in particular soils conditions there could be significant additional settlements of foundations of adjacent buildings at sheet pile jacking.

According to the investigations of Mangushev R.A. and Gursky A.V. (2016) conducted in two construction sites of St. Petersburg (in Vasilievsky Island and Glinka str.), the technological settlement of the building in Vasilievsky Island due to jacking of sheet piles, which fenced the pit, slightly exceeded 1 cm (figure 4). The other site, where there were conducted investigations of technological settlement at static jacking of sheet piles using the British maching Still Worker WP-150–0.6 m, was the construction of an apart-hotel in Glinka str. in St. Petersburg.

The main difference from the construction site in Vasilievsky Island is a deposit of highly compressive soils in the upper part of the geological profile which were cut with the constructed sheet pile wall, and poorly compressive soils below the front surface of the sheet pile. Therefore, the main deformations of adjacent buildings occurred due to settlement of soils cut with the sheet piles. The measured technological settlement of sheet pile jacking reached 2 cm.

It was found out that the value of technological settlements of buildings with spread footings could reach 1-3 cm at sheet-pile – building distance 0.6-1.0 m during construction of a pit fence of a cut-off screen of sheet piles jacked into soft clayey soils (Figure 4) overlain with sands in the upper part. An area of influence of jacking is equal to a length of sheet piles.

Figure 4. Jacking of sheet piles using the machine Giken U-Piller UP-150 at the distance of 0.63 m from the existing building in Vasilievsky Island in St. Petersburg (Mangushev R.A., Nikiforova N.S., 2017)

Based on the research conducted by Mangushev R.A. and Gursky A.V. (2016) there was developed an analytical method of calculation of technological settlements at jacking of sheet piles into soft clayey soils. The predicted technological settlements have been confirmed by the data of geotechnical monitoring.

2.3.2 Technological settlements at vibrodriving of sheet piles

Vibrodriving of sheet piles into thixotropic silty-clayey soils leads to occurrence of technological settlements due to their destructuring (Mangushev R.A., Konyushkov V.V., Sapin D.A. (2016). Construction of a pit fence using vibrodriving of 22-m-long sheet piles Larsen L5 UM in the proximity of adjacent buildings happened during construction of a multi-functional medical center located in the central part of St. Petersburg.

Sheet piles Larsen L5 UM were fixed at the depth 1.5 m from the ground surface by a system of casings with the spacing 6…6.5 m hanging on temporary piles (Figure 5).

Figure 5. Excavation of the second pit for the medical center (Mangushev R.A., Konyushkov V.V., Sapin D.A., 2016)

In the course of pit excavation there were vibration and dynamic processes – sheet piles were driven, heavy loaded transport moved along the pit edge.

These impacts lead to destructuring of thixotropic soft silty-clayey soils that was confirmed with the results of dynamic probing. According to the data of geodetic monitoring of the adjacent buildings, which were located at the distance 8 m and more from the pit received the settlements 0.3…0.4 cm due to sheet pile driving.

Due to soil destructuring strength properties of soils reduced that resulted in, on the one hand, the increase of the coefficient of active soil pressure of the pit fence, in some cases it soared up to 1.0, i.e. the soil obtained the properties of a viscous liquid, which transfers equal pressure in horizontal and vertical directions, on the other hand, the decrease of calculated soil resistance in the base of foundations. At constant load applied to the edge of foundations resulted in the increase of plastic zones that, in its turn was accompanied with additional settlements of foundations.

2.4 Additional settlement prediction along a building near a deep pit considering its technological part while taking mitigation measures

The methods of calculation of maximum values of technological settlements for different types of protective measures are given in section 13.3.5 of Geotechnical Engineer's Handbook (Ilyichev V.A., Mangushev R.A., 2016), the work of Ilyichev V A et all, 2017.

Numerical experiments on technological settlements defined while taking mitigation measures were conducted by Nikiforova N.S. and Konnov A.V., 2018. Numerical modelling was carried out in 2D V8 in the software complex Plaxis 2D, which implements the finite element method. Calculation in Plaxis 2D was conducted using the soil hardening model.

Using Matlab software the authors obtained empirical equations based on numerical modeling allowing to estimate the settlement of adjacent buildings after taking mitigation measures (micropile underpinning) near pit depth H_k =12m for two types of soil conditions (I type - medium-grained sand, medium density, II type - silty sand, loose).

The previous research of Ilyichev V A et all, 2017 showed that for micropiles the technological settlement is 60 % of the calculated settlement of a building.

The settlement of a building with micropile underpinning considering a technological settlement should be determined in equation (4).

$$S\left(\frac{x+L}{H_k},q\right) = K_T \cdot \left[K1 + K2\cdot\frac{x+L}{H_k} + K3\cdot q + K4\cdot\left(\frac{x+L}{H_k}\right)^2 + K5\cdot\frac{x+L}{H_k}\cdot q + K6\cdot\left(\frac{x+L}{H_k}\right)^3 + K7\cdot\left(\frac{x+L}{H_k}\right)^2\cdot q + K8\cdot\left(\frac{x+L}{H_k}\right)^4\right] \quad (4)$$

Where x is the coordinate along a length of a building, L is a distance from a building, q is a pressure under a building strip foundation (q=100, 200, 300 kPa), K_T – a coefficient considering a technological settlement.

Coefficients *K1-K9* of equation (4) for type I and II of soil conditions are given in Table 2.

Table 2. Equation (4) coefficients of settlement of a building with a protective measure (micropiles)

Coefficients							
K1	***K2***	***K3***	***K4***	***K5***	***K6***	***K7***	***K8***
Soil type I							
-22.74	22.71	-0.085	-8.59	0.057	1.42	-0.013	0.087
Soil type II							
-23.08	21.99	-0.093	-6.45	0.041	0.59	-0.004	0

3 CONCLUSIONS

There has been made a prediction of technological settlements for buildings and the surface near a deep pit during different kinds of underground works (construction of a diaphragm wall and driving of sheet piles, taking the mitigation measure for adjacent buildings and structures).

There has been made a prediction of additional settlements along a building with mitigation measures near a deep pit considering technological settlements.

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