A settlement calculation for neighbouring buildings with mitigation measures upon underground construction

Calcul des tassement des bâtiments avec des mesures de protection dans la zone d'influencée par travaux de construction souterrains

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ABSTRACT: The paper contains results of scientific-research work on determining of settlement reduction provided by the use of mitigation measures, investigating a technological part of settlement and proposing recommendations for applying "active" and "passive" mitigation measures for buildings in the zone of underground construction influence. Furthermore the method for preliminary calculation of neighbouring buildings' settlement with consideration of technological settlement was suggested.

RÉSUMÉ: Cet article contient les résultats des travaux de recherche. Le but de ce travail était de déterminer la valeur de la réduction de tassement a cause de mesures de protection effectués et l'étude des tassements technologiques. Des recommandations ont été faites sur l'utilisation des mesures de protection active et passive des bâtiments dans la zone d'influence de la construction souterraine. Outre cela pour les bâtiments environnants une méthode de calcul préliminaire des tassement tenant compte composante technologique a été proposé.

KEYWORDS: active and passive mitigation measures, underpinning, cut-off walls, deep excavation pit, compensation grouting.

1 INTRODUCTION

The development of underground space in large cities raises the problem of neighbouring buildings' preservation. To meet the requirements on additional deformations for such buildings active and passive mitigation measures should be considered to be used.

Passive mitigation measures affect the stress-strain condition of soil mass instantaneously, whereas active can provide this in time with certain possibility of control. Active measures includes: changing of foundation type, excavation of "discharging pit", strengthening of soils under foundation, cut-off walls and other measures, aimed to increase the stiffness of structures. Passive measures includes: installation of prestressed strutting structures, compensation grouting, controlled jet-grouting, vertical geotechnical barrier, injection of stiff concrete mixes outside of tunnel lining etc.

At the moment construction standards doesn't include methods of calculating the settlement of neighbouring buildings with application of mitigation measures and recommendations for the measures' selection.

2 SETTLEMENT CALCULATION FOR NEIGHBOURING BUILDINGS WITH MITIGATION MEASURES

2 .1 *Preliminary calculation of settlement*

To preliminary define a settlement for neighbouring buildings with active and passive mitigation measures (S_m) predicted settlement (S) must be multiplied by reduction coefficient K_c (Geotechnical Engineer's Handbook, 2016):

$$S_m = K_c S \quad (1)$$

where S is the predicted value of settlement for buildings without mitigation measures which can be obtained analytically or numerically.

2 .2 *Calculation of predicted settlement*

For buildings with strip footings (Ilyichev V.A. et al. 2007) proposed an equation for settlement calculation along a length of building:

$$S(x) = \kappa_r \left[\delta\varphi(x) + q / k \right] \quad (2)$$

where k is the subgrade reaction coefficient; q is the foundation pressure; κ_r is the coefficient, based on type of strutting structures for a pit;

$$\delta = \frac{A_1 f_1 H_k^5}{\alpha^4 + A_1 H_k^4};\ A_1 = \frac{k}{EJ}$$

$$\varphi(x) = \left[\psi\left(\frac{b}{\lambda} - 1\right)\eta_{II}(\xi) + \eta_{IV}(\xi) + e^{-b(x+L)} \right]$$

$$b = \frac{\alpha}{H_k};\ \psi = \frac{b^2 e^{-bL}}{2\lambda^2} \quad (3)$$

$$\eta_{II}(\xi) = e^{-\xi}\cos\xi;\ \ \eta_{IV}(\xi) = e^{-\xi}\sin\xi$$

$$\xi = \lambda x;\ \lambda = \sqrt[4]{\frac{k}{4EJ}}$$

where H_k denotes the excavation depth; x is the coordinate value along a length of building (x=0 on the nearest end of a building to a pit); α = 0,7552; f_l is the empirical coefficient, depending on max surface settlement compared to excavation depth; L is the distance between building and excavation pit; EJ is the stiffness of building.

2.3 *Defining of K_c coefficient*

Authors formed a data bank with settlement values of 52 buildings and utility systems protected with mitigation measures due to underground construction in Russia and worldwide.

As a result of comparing predicted and measured settlements of buildings with and without mitigation measures reduction coefficients (K_c) for predicted settlement without mitigation measures have been obtained for active and passive types of protection. Coefficients K_c were obtained by using methods of statistical analysis while processing collected archive data in conjunction with experiments' results.

Reduction coefficients K_c for settlement were obtained comparing predicted settlements of buildings with mitigation measures with predicted settlement values for buildings without any protection:

$$K_c = S_{pm} / S_p \quad (4)$$

where S_{pm} is the predicted settlement with mitigation measures, while S_p is the predicted settlement value without them.

Reduction coefficients K_{ct} for settlement were obtained comparing measured settlements of buildings with mitigation measures with predicted ones for buildings without any protection (see Eq. 5). These coefficients consider technological settlement (see Table 1). Deformations, including settlements, which occur due to inaccurate process sequences (in this case during installation of mitigation measures) are termed as technological deformations (settlements) by the Russian specialists.

$$K_{ct} = S_{mm} / S_p \quad (5)$$

where S_{mm} is the measured settlement of buildings with mitigation measures.

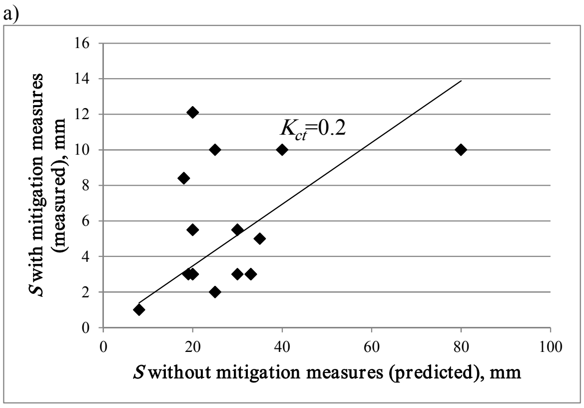
The dispersion of random variable X_i (reduction coefficient K_c) was calculated according to the following equation:

$$D = \frac{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n-1} \quad (6)$$

where n is the number of items in data set.

For examples of obtaining K_c and K_{ct} for passive and active mitigation measures see Figure 1.

a)



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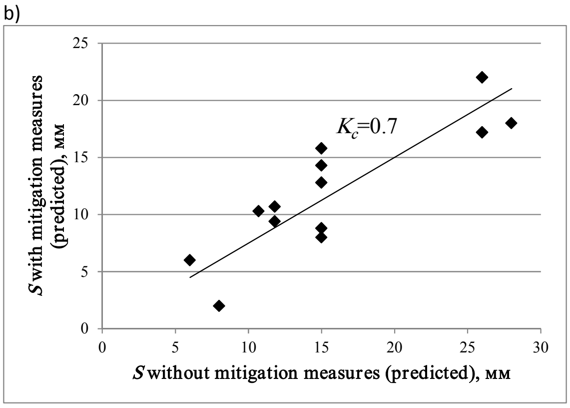

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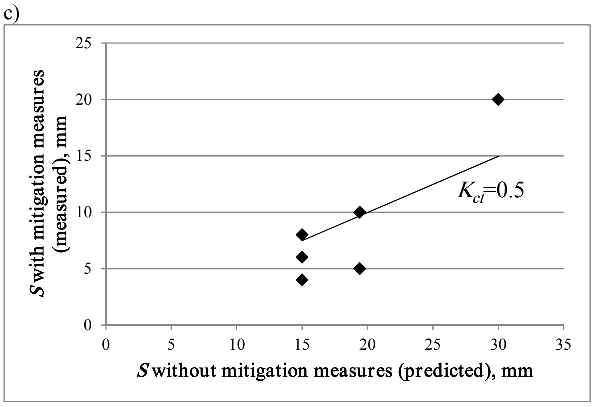

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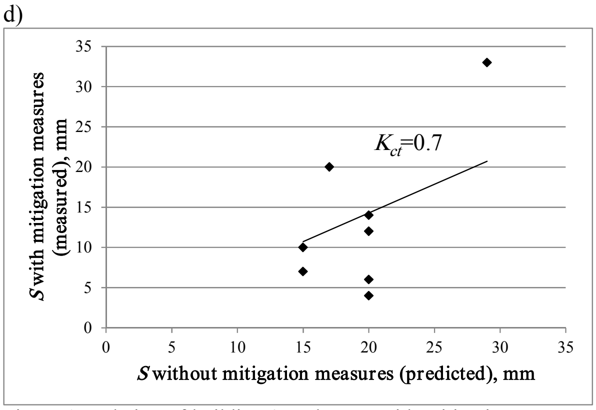


Figure 1. Relation of buildings' settlement with mitigation measures to settlement without them; *a* — compensation grouting, *b* — cut-off wall, *c* — jacked piles, *d* — jet grout columns.

2.4 *Investigating the technological part of the settlement*

The technological settlement of existing buildings during underground construction works equals 40–60 % from the total measured settlement. A big part of it is caused by installation of mitigation measures and construction of a support system (Leushin 2011).

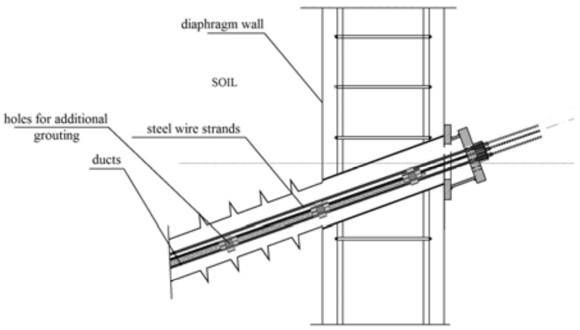
The research conducted during construction of six-level underground parking at Yartsevskaya st. in Moscow revealed 20 % amount from the predicted settlement for SBMA anchors with additional grouting (see Figure 3). A grout was injected by the use of polyvinylchloride pipes which are a part of SBMA anchorage system (see Figure 2). After it's installation each SBMA anchor was grouted primary and then secondary. Consider this consequence SBMA anchors with additional grouting could be related to active mitigation measures.

For micropiles data analyses revealed 60% amount of the technological settlement from the predicted settlement (see Figure 3).

Table 1. Reduction coefficients for settlement (K_{ct}) for active and passive mitigation measures.

Type of mitigation measure		K_{ct}	Dispersion D
Active	SBMA anchors with additional grouting[1]	0.5	0.09 ($n = 9$)
	Compensation grouting	0.2	0.03 ($n = 14$)
	Controlled jet-grouting	0.02–0.2	—
	Prestressed strutting structures (struts with jacks)	0.2	—
Passive	Micropiles	0.6	0.19 ($n = 22$)
	Jacked piles	0.5	0.03 ($n = 6$)
	Jet grout columns	0.7	0.013 ($n = 8$)
	Cut-off walls consisting of jet grout columns, bored piles or steel pipes (driven closely to a building)	0.4	0.03 ($n = 4$)
	Cut-off walls consisting of pipes (d=219 mm)	0.8	—

a)

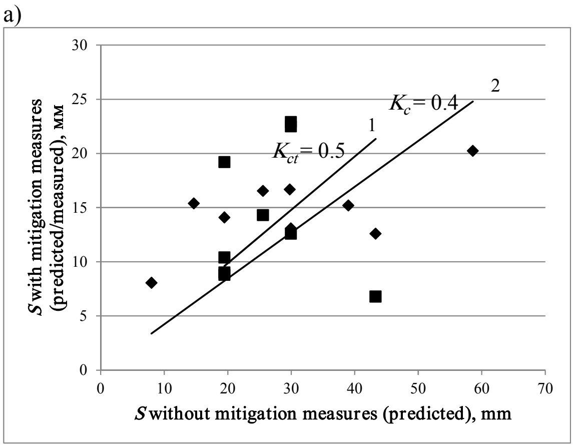


b)

Figure 2. SBMA anchors with additional grouting; *a* — scheme of anchor; *b* — photo of the site

A technological settlement caused by application of underpinning piles equals 20–40 % from the total settlement of the neighbouring building that already includes settlement influenced by excavation works (Nikiforova N.S. 2016). The minimal technological settlements are due to installation of jacked piles and maximum – of jet grout columns. For cut-off walls technological part of the settlement revealed to be 30-90%.

a)



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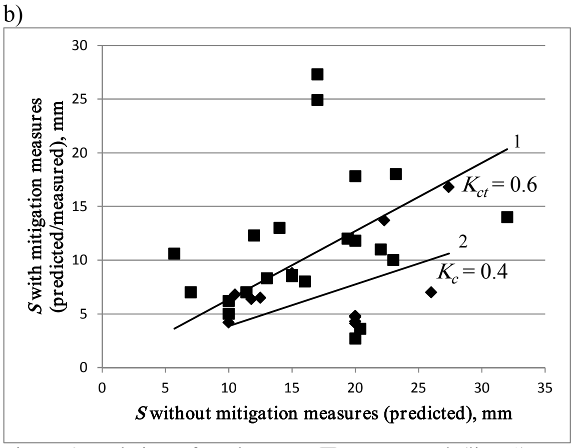

Figure 3. Relation of settlements: ■ – measured (line 1) and ◆– predicted (line 2); *a* — active protection (SBMA anchors with additional grouting), *b* — passive (micropiles).

3 RECOMMENDATIONS FOR THE SELECTION OF MEASURES

The required reduction coefficient ($K_{c.req}$) for settlement without protection measures was introduced (see Eq.7). It corresponds to the permissible value of settlement.

$$K_{c.req} = S^{max}_{ad,u} \big/ S_p \quad (7)$$

where $S^{max}_{ad,u}$ is the permissible additional settlement; S_p is the predicted value of settlement without mitigation measures.

Certain mitigation measure can be recommended to utilize if it's K_{ct} coefficient (see Table 1) satisfies the inequality $K_{ct} \le K_{c.req}$ (Nikiforova, Konnov 2016).

Recommended types of mitigation measures for buildings in the zone of the underground construction impact can be found in Table 2.

One of the major trends in underground construction is the application of active type of measures in case of building near historical sites or when access to adjacent buildings is impossible (Ilyichev et al. 2015).

[1] For utility systems

Table 2. Recommended mitigation measures for different types of buildings.

Type of building	Category of structures' condition	$K_{c.req}$	Recommended type	Mitigation measures
Monument, historical	III, II	0.3	Active	Compensation grouting; controlled jet-grouting ; compensatory micropiles; prestressed strutting structures
Monument, historical on reconstruction	III	0.75	Passive	Underpinning piles (micropiles, jet grout columns, jacked piles); Cut-off walls consisting of jet grout columns
Old, modern	III	0.5	Active	Compensation grouting; controlled jet-grouting ; compensatory micropiles; prestressed strutting structures
	III	0.5	Passive	Jacked piles; cut-off walls consisting of jet grout columns
	II	0.85	Passive	Underpinning piles (micropiles, jet grout columns, jacked piles); Cut-off walls consisting of jet grout columns

4 CONCLUSION

The forecast of buildings' settlements within a zone of excavation impact with mitigation measures was suggested. Active and passive types of measures were investigated. The technological part of the settlement was taken into consideration.

The recommendations for choosing a type of mitigation measure for adjacent buildings and structures were developed.

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