

Settlement prediction for protected buildings nearby deep excavation

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Abstract. Increasing demand on new spaces in cities due to restrained urban conditions dictates development of underground construction including excavation of deep pits. So there is a need to prevent negative consequences caused by changes in a stress-strain condition of soil mass and additional settlement of foundations with underlying soil. A decrease in excessive settlements of building and their difference could be achieved by protection of a building with implementation of mitigation measures. The goal of the paper is to provide a method of settlement prediction for adjacent buildings in a zone of deep pit excavation for mitigation measure – underpinning of foundations with micropiles. Different factors affecting the settlement value (of building with micropiles) were considered. These factors are the distance from pit edge to a building, geology type, depth of excavation, height of the building etc. Also variation of settlement along a building was taken into account. A series of numerical experiments was conducted modelling these conditions. By methods of statistical analysis empirical equations were obtained allowing to predict the settlement of adjacent buildings underpinned with micropiles. These equations serve as a base for method aimed to determine building settlement in a zone of deep excavations impact with micropiles installed, also considering technological settlement. Technological settlement values were taken from similar case histories. Settlement prediction with the use of obtained equations could be useful at initial design phase to evaluate the use of micropiles to ensure permissible additional settlement values of adjacent buildings in a zone of deep excavation impact.

1. Introduction

Increasing demand on new spaces in cities due to restrained urban conditions dictates development of underground construction: new and as a part of renovation. Underground construction often includes excavation of deep pits. Herewith adjacent buildings and also ones of historical and cultural value turn out to be in an impact zone of such deep excavation. Additional settlement of adjacent buildings can reach up to 70% of general additional settlement during initial construction works on a new building [1]. So there is a need to estimate construction impact on such buildings and, if necessary, to prevent negative consequences caused by changes in a stress-strain condition of soil mass and additional settlement of foundations with underlying soil.

A decrease in excessive settlements of building and their difference could be achieved by protection of a building with implementation of mitigation measures. Some of them are aimed to increase the stiffness of deep excavation's support system, others affect the stress-strain condition of soil mass including adjacent building or belong to underpinning methods.



One of underpinning methods is the installation of micropiles. A distinctive feature of this type of piles is a small diameter. Micropiles of 80 – 250 mm in diameter are used in underpinning [3]. These piles are made with injection of fine-grained concrete into the borehole under pressure. Preliminary works includes drilling of the foundation, then a borehole, the pile stem is reinforced with the entire length or only at the top. One of the main advantages of such piles is that they can be installed in cramped conditions, which allows in some cases to be able to work right inside the basement of a building. The effectiveness of the micropile use for underpinning of buildings in various case histories is enlightened in Russian [4,5] and foreign researchers papers [6,7].

Additional settlement of a building with mitigation measures (including micropiles) in an impact zone of deep excavation can be evaluated, for example, using reduction coefficients [8]. But the goal of this paper is to provide another method of settlement prediction for adjacent buildings underpinned by micropiles in a zone of deep pit excavation. This method is based on empirical equations. To achieve this goal a series of numerical experiments was conducted.

2. Numerical experiments

2.1 Initial data

For numerical experiments the following situation was considered: a new construction is undergoing, a brick building of the surrounding development is located in the impact zone of deep pit excavation. In different experiments the characteristics of the building and the foundation pit were varied. The pit was 12 and 18 meters deep. The diaphragm wall was chosen as the most common solution in cramped conditions. The thickness of the diaphragm wall was 600 and 800 mm under various design conditions, it was assumed that it was buried in the confining bed. For supporting the foundation pit, a strut system was used consisting of steel pipes with a diameter of 325 to 630 mm with spacing of 8 m. The pressure under the strip foundation of the building q was set at 100, 200 and 300 kPa for 3, 5 and 7-storey buildings, respectively [9]. The building consisted of 5 spans of 6 m (in a plane perpendicular to the deep pit). The calculations were made for the distance from the building to the deep pit (L) equal to: 1m, $0.5Hk$, Hk , $2Hk$ where Hk is the pit depth.

Of the soil conditions typical for Moscow [10], type I (sand of medium grain size, medium density) and II (silty sand, loose) were considered. The thickness of a layer of an anthropogenic soil of each type was equal to 2 m. The level of underground waters was set on its lower border. The physical and mechanical characteristics of soils of each type are presented in Table. 1.

Table 1. Physical properties and soil strength

Soil type	Soil	Physical properties and soil strength				
		γ , kN/m ³	c , kPa	ϕ , °	E , MPa	ν
I	anthropogenic soil	16.5	1	12	10	0.35
	sand medium, medium density	19.7	2	36	30	0.3
II	anthropogenic soil	16.5	1	10	10	0.35
	silty sand, loose	16.7	1	20	12	0.30

The protective measure was carried out as building foundation underpinning with micropiles. In this series of numerical experiments, the underpinning of the building foundations with vertical micropiles with a diameter of 200 mm and a length of $0,8...1,2 H_k$ was considered.

2.2 Numerical modelling in Plaxis

Numerical modelling was carried out in 2D V8 in the software complex Plaxis 2D, which implements the finite element method. Calculation in the Plaxis 2D program was conducted using the Hardening soil model. The Hardening soil model is the most universal and suitable for many varieties of soils [11]. The main feature of this soil model is the dependence of the rigidity of the soil on stresses. Micropiles were set by plate elements with rigidity adjusted according to the pile step. The mesh of finite-element model for type I of ground conditions is shown in figure 1.

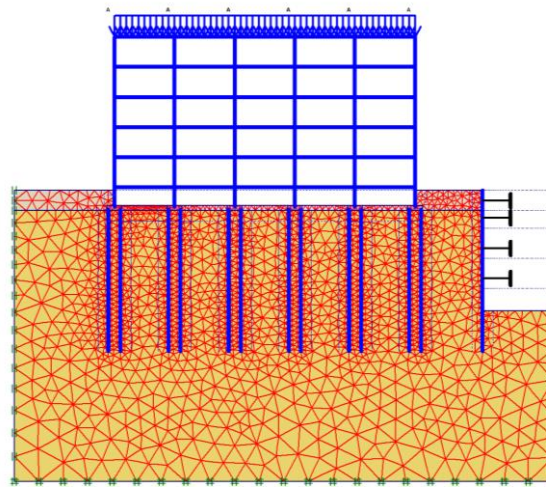


Figure 1. The mesh of finite-element model.
Building with foundations underpinned by
micropiles, located in the zone of deep
excavation ($H_k=12$ m) impact

24 numerical experiments were conducted to determine the additional settlement of the building in the zone of deep excavation impact. During the excavation stage additional settlement of the building with micropile underpinning and without it were defined. In this case, a number of values of the settlement along the entire length of the building was perpendicular to the deep pit.

3. Data analysis and obtaining of empirical equations

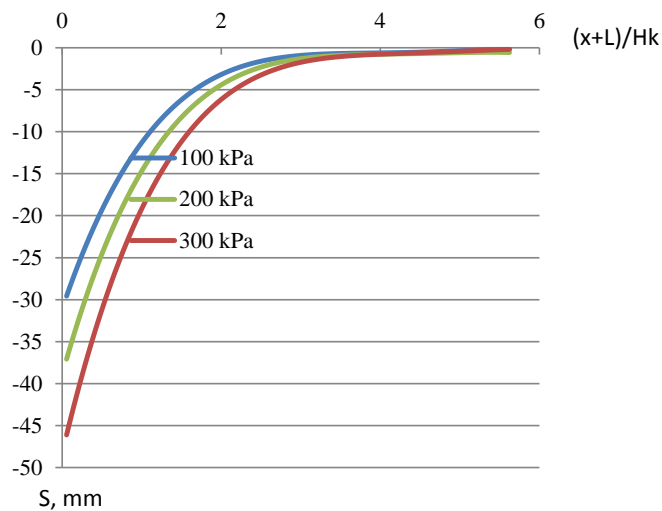
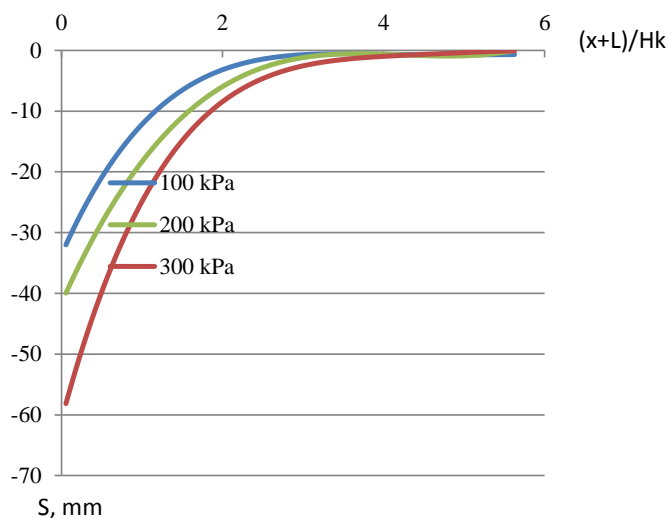
Statistical processing of modeling results was carried out using the Excel program of the Microsoft Office suite and the MATLAB application package. For the building underpinned with micropiles and without them, the dependences of additional settlement S from $(x + L) / H_k$, where x is the coordinate along the length of the building, L is the distance from the building to the deep pit. The curves depicting the dependence data were approximated (see figure 2,3) and empirical equations (1) were obtained for a building with micropiles.

$$S((x+L)/H_k) = K1((x+L)/H_k)^4 + K2((x+L)/H_k)^3 - K3((x+L)/H_k)^2 + K4((x+L)/H_k) + K5 \quad (1)$$

The coefficients $K1$ - $K5$ of equation (1) are given in Table 2. When using these coefficients, the resulting settlement will be measured in mm. This equation can be used in the range of values $(x + L) = [1 \text{ m}; 67.5 \text{ m}]$, $H_k = [12 \text{ m}; 18 \text{ m}]$.

Table 2. The coefficients of the settlement equation (1) of the building with a protective measure (micropiles)

Pressure q , kPa	Soil type	Coefficients				
		$K1$	$K2$	$K3$	$K4$	$K5$
100	I	-0.0814	1.4598	- 9.646	28.058	- 31.1
200		-0.0956	1.714	- 11.466	34.1	- 38.944
300		-0.0968	1.8271	- 12.846	40.228	- 48.3
100	II	-0.0787	1.4705	- 10.107	30.191	- 33.654
200		0	0.5606	- 7.1494	29.872	- 41.6
300		-0.1169	2.2026	- 15.561	49.449	- 60.85

**Figure 2.** Settlement of underpinned building (with micropiles) in relation to relative distance from excavation. Type I of soil condition, the pressure under the strip foundation of the building $q=100,200,300$ kPa**Figure 3.** Settlement of underpinned building (with micropiles) in relation to relative distance from excavation. Type II of soil condition, the pressure under the strip foundation of the building $q=100,200,300$ kPa

In the Matlab software for the functions of building settlement with micropiles, obtained in Excel by polynomial approximation, the dependence on the third variable - the pressure under a foundation q - was also obtained. The result was an empirical equation (2).

$$S((x+L)/H_k, q) = K1 + K2 \cdot (x+L)/H_k + K3 \cdot q + K4 \cdot ((x+L)/H_k)^2 + K5 \cdot (x+L)/H_k \cdot q + K6 \cdot ((x+L)/H_k)^3 + K7 \cdot ((x+L)/H_k)^2 \cdot q + K8 \cdot ((x+L)/H_k)^4 + K9 \cdot ((x+L)/H_k)^3 \cdot q \quad (2)$$

The coefficients $K1$ - $K9$ of equation (2) for type I and II of soil conditions are given in Table 3. When using these coefficients, the resulting settlement will be measured in mm. This equation can be used in the range of values $(x+L) = [1 \text{ m}; 67.5 \text{ m}]$, $H_k = [12 \text{ m}; 18 \text{ m}]$, $q = [100 \text{ kPa}; 300 \text{ kPa}]$.

For type I or II of soil conditions the settlement of building underpinned with micropiles can be determined by figure 4,5, or by the formula (2) using the table. 3 depending on the pressure q and $(x+L)/H_k$.

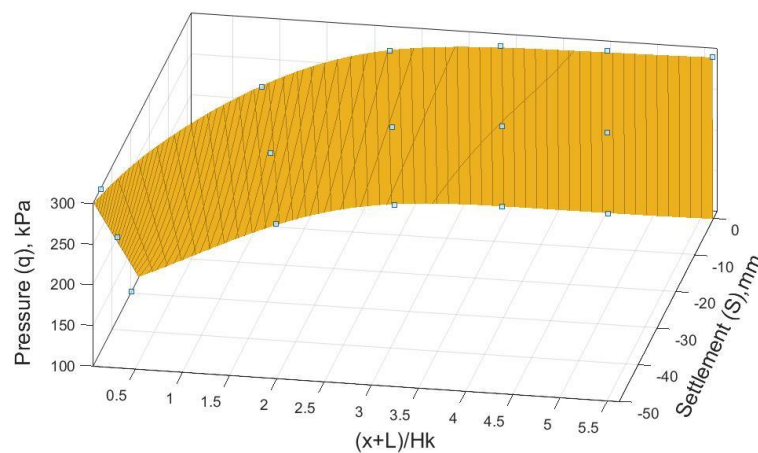


Figure 4. Calculated settlement of the underpinned building for I type of soil. $H_k = 12$ -18 m, $q = 100$ -300 kPa

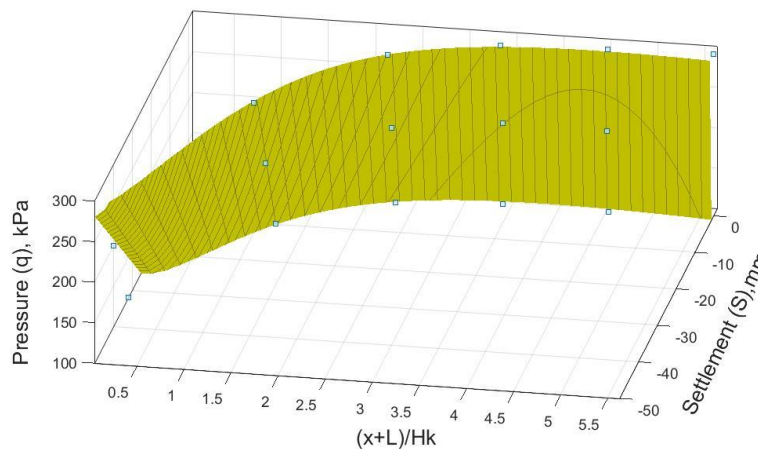


Figure 5. Calculated settlement of the underpinned building for II type of soil. $H_k = 12$ -18 m, $q = 100$ -300 kPa

Table 3. Equation (2) coefficients of the building settlement with a protective measure (micropiles)

Soil type	Coefficients								
	$K1$	$K2$	$K3$	$K4$	$K5$	$K6$	$K7$	$K8$	$K9$
I	-22.74	22.71	-0.08472	-8.592	0.05673	1.42	-0.01281	0.08611	0.0009645
II	-23.08	21.99	-0.09285	-6.451	0.04081	0.5861	-0.004387	0	0

4. Calculation method for deformations

In the course of construction work, including installation of mitigation measures, the deformations, including settlements, are occurred due to inaccurate process sequences. These settlements are defined by Russian experts as technological [1,12].

It's inevitable that settlement calculated by numerical methods tend to be less than settlement measured during geotechnical monitoring. Thus, to get closer to real values technological settlement should be considered in the calculation.

Technological settlement of existing buildings for the initial construction works is on average 40-60% of the total measured settlement. The biggest part of technological settlement is caused by installation of mitigation measures and retaining structure [1,13].

Previous research [14] showed that for micropiles technological settlement is 60 % of the calculated settlement of a building. The settlement of building with micropiles underpinning considering technological settlement should be determined by equation (3) or using figure 4,5 multiplying calculated settlement by coefficient $K_T=1.6$.

$$S((x+L)/H_k, q) = K_T \cdot [K1 + K2 \cdot (x+L)/H_k + K3 \cdot q + K4 \cdot ((x+L)/H_k)^2 + K5 \cdot (x+L)/H_k \cdot q + K6 \cdot ((x+L)/H_k)^3 + K7 \cdot ((x+L)/H_k)^2 \cdot q + K8 \cdot ((x+L)/H_k)^4 + K9 \cdot ((x+L)/H_k)^3 \cdot q] \quad (3)$$

As the result of conducted experiments, assistive tables, including building settlement with a mitigation measure (micropiles), were compiled for the given values of $L+x$, H_k , q and the type of soil conditions. The technological settlement is considered. As an example, one of the tables is given (see table 4).

Table 4. Additional settlement (including technological settlement) values for building with mitigation measure (micropiles). $H_k=16$ m, $q=250$ kPa and type I of soil conditions.

$x+L$, m	6	12	18	24	30	36	42
S , mm	-50.65	-35.54	-24.19	-15.92	-10.12	-6.25	-3.83

Analysing values in table 4 the effectiveness of micropiles to the neighboring buildings in the zone of deep excavation impact could be preliminary estimated. There is the range of permissible values from 0.5 cm (maximum settlement) for historic buildings category III of the technical state up to 3.0 cm for the multi-storey brick buildings of II category [15]. Thereby considering this range, it is possible to conclude that the use of micropile underpinning doesn't exceed the permissible settlement if $x+L \geq 18$ m, at a distance of 42 m from excavation doesn't exceed permissible value for historic buildings. To estimate the efficiency of underpinning table values should be compared with the settlement of a building with no mitigation measures, obtained numerically or by empirical-analytical method given in [16].

The described method could be useful at initial design phase to determine a necessity of foundation underpinning with micropiles.

5. Conclusions

1. Based on numerical modeling empirical equations were obtained allowing to estimate the settlement of adjacent buildings with installation of mitigation measure (micropiles underpinning)
2. The method for calculating a settlement is described considering a building in a zone of deep excavation impact with micropiles underpinning. Technological settlement was taken into account. At initial design phase the developed method allows to determine whether micropile underpinning for neighboring buildings decrease additional settlements to permissible values. In case of the negative response another mitigation measure should be realized.

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