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Deformations of the buildings located near foundation trenches and underground excavations and the measures for their reduction

La déformation des bâtiments prîs des foulles et des ouvrages souterraines et les mesures de leur reduction

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ABSTRACT
Empirical dependences are formulated on the basis of full-scale experiments which makes it possible to forecast the settlement of the buildings located within the zone affected by excavation of foundation trenches for the buildings having underground facilities in the congested urban housing environment of Moscow. The results of the research of buildings settlement values for different types of protective measures are demonstrated.

RÉSUMÉ
Sur la base des experiences natures cette article présente les dépendences empiriques quis permettent fair des pronostics des affaissements des bâtiments. Ces bâtiments se trouvent dans la zone d'influence de la foulle des objets avec la partie souterrain dans la condition urbaine exigu en Moscou. L'article présente les resultats des recherches des affaissements des bâtiments après application pour luis les mesures protecteur des types différents

1 INTRODUCTION

This research is based on full-scale experiments performed for identifying the regularities in deformation of foundations of the buildings located near foundation trenches and underground excavations. The aforesaid experiments have been performed by the Research Institute of Bases and Underground Structures (NIIOSP), with the authors participation, at Moscow construction sites. 17 objects with 73 buildings located in the affected areas have been studied in total. They include: the Third Transport Ring areas in Lefortovo and at Gagarin square, the objects with underground parking lots at Manezhnaya square; Petrovka Street, building 5; Leningradsky Prospect, building 39; Sadovnicheskaya Embankment, block 3 and many other objects.

2 FACTORS AND SETTLEMENTS

The following factors have impact on the value of deformation of the buildings located within the zone affected by excavation of foundation trenches for the buildings having underground facilities:

1. Foundation trench retaining structure type;
2. Building structures kind and condition (characterized by condition category);
3. Engineering and geological conditions at a construction site;
4. Foundation trench retaining structure fastening method;
5. Buildings relative remoteness from a foundation trench, with their foundations depth taken into account – m =(H-h)/L, (L – distance between the building and the underground facility, H – foundation trench depth, h – building foundation depth.

The following types of foundation trench retaining structures are used in Moscow:
«slurry wall» made with the use of trench method, "slurry wall" made of contiguous bored piles, retaining structure made of metal pipes (including screwed pipes) or flange beams with wooden fencing, retaining structure constructed of jet piles made according to jet technology and reinforced with metal pipes, retaining structure made of in-situ reinforced concrete with the use of partial foundation construction method in case of underground facilities construction under existing buildings or close to an existing building.

In this case retaining structures fastening is performed in the following ways: with the help of anchors or anchor structures (for instance, slabs with anchor piles), buntons made of metal pipes or floor slabs («top-down» method implying lower soil removal through the special openings left in floorings). One or several rows of anchors or buntons may be installed depending upon trench depth as well as engineering and geological conditions available at the construction site.

The existing buildings that used to be specific for the capital's downtown in the end of the XVIII century and the beginning/middle of the XIX century, were found in the zone affected by foundation trenches. Many of those buildings got the status of "monuments of architecture", "historical buildings" (constructed more than 100 years ago) or "old buildings" (constructed more than 50 years ago). As a rule, those were multistoried frameless buildings with load-bearing walls made of big blocks or bricks constructed without reinforcement at strip or isolated foundations, more rarely – at slab foundations. Those buildings often used to undergo reconstruction (for example, one or two more floors construction on the top of a building). Deformations of the buildings having the above-mentioned specific structural features are considered in the article.

Analyzing the neighboring buildings deformation, we split foundation trench retaining structures into two basic types:

1. Solid "slurry wall" made with the use of trench method, of contiguous bored piles, of jet piles (by «jet-grouting» method).
2. Sheet piling made of metal pipes or of flange beams with wooden fencing.

In order to identify the extent of the impact made by each of the aforesaid types of retaining structures, we have compared the buildings settlements dependences obtained on the basis of the measurements made at Moscow sites for the same values of $m = (H-h)/L$ for retaining structures fastening with buntons

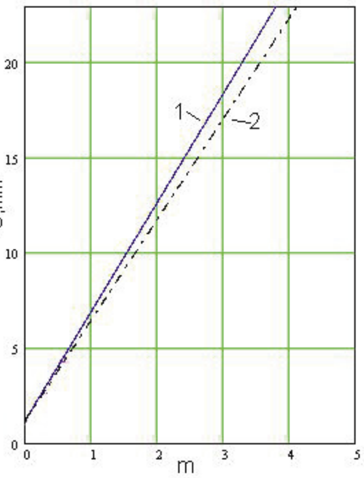

Figure 1. Comparison of experimental buildings settlements *S* dependence on *m* for retaining structures fastening with buntons made of metal pipes: 1 – for sheet piling made of metal pipes with wooden fencing, 2 – for "slurry walls" of different types.

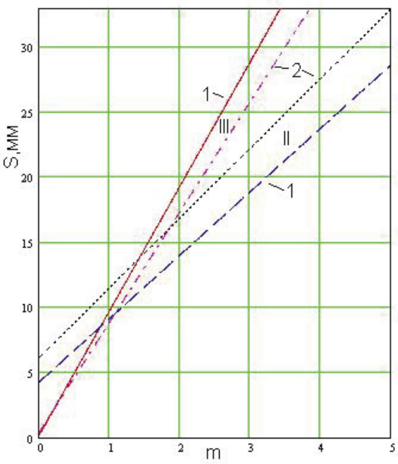

Figure 2. Comparison of buildings settlements *S* dependence on *m* for retaining structures fastening with buntons made of metal pipes for buildings of II and III structure category (1 – experimental dependences, 2 – calculated (PLAXIS, Brinkgreve and Vermeer, 1998) dependences).

made of metal pipes (Fig. 1). Settlement difference does not exceed 10%, which means that retaining structure type does not make a considerable impact on the neighboring buildings settlement.

The analysis of measured and calculated (Finite Elements Method (FEM) settlements (Brinkgreve and Vermeer, 1998) showed that building structures condition category influences building settlement only in case retaining structures are fastened with buntons made of metal pipes, with *m> 1,3* (Fig. 2). In case they are fastened with reinforced concrete floor structures and work is performed according to «top-down» method, buildings settlement insignificantly depends on building structures condition category.

Engineering and geological conditions available at a construction site also influence the settlement of the buildings located within the zone affected by underground facilities construction. According to soil structure, we have identified three most characteristic types of soil conditions available in Moscow (I – fill-up soil with underlying sand: from fine sand to semi-gravel, semi-dense and dense; II – fill-up soil with underlying loam and clay: from solid to tough; III - fill-up soil with underlying loose sand and sandy silt as well as soft and fluid clay). Fig.3, demonstrating *S* dependence on *m* for retaining structure fastening with anchors, shows that in softer soils (type III of engineering and geological conditions), having lower values of strength and deformation parameters, buildings settlements are higher than in stronger soils (types II and I of engineering and geological conditions). Experiments showed that this conclusion is also correct for other types of retaining structure fastening.

On the basis of these measurements and FEM method calculations (Brinkgreve, R.B.J. and Vermeer, P.A. 1998), generalized (for Moscow engineering and geological conditions) *S* dependences on *m* have been formulated for various kinds of retaining structure fastening (Fig.4). Fig. 4 shows that the maximal values of settlements are specific for neighboring buildings, with equal *m* value (foundation trench depth, foundation depth and distance to foundation trench), in case of anchor fastening of retaining structure; while the minimal values of settlements are specific for neighboring buildings in case of retaining structure fastening with floor structures. At the same time *m* parameter has maximal impact on the buildings settlement value in case of anchor fastening of retaining structure, and the minimal impact – in case of retaining structure fastening with reinforced-concrete floor structures (with the use of «top-down» method).

Measured settlements comparison with the settlements values, calculated by FEM method with the help of PLAXIS program (Brinkgreve and Vermeer, 1998) and with the use of Mohr-Coulomb elasto-plastic model within the framework of a flat task solution, demonstrated quite good convergence of both results.

Forecasted dependences analysis leads to the conclusion that calculations made by FEM method with the help of PLAXIS program and with the use of Mohr-Coulomb elasto-plastic model give up to 20% divergence for retaining structure fastening with anchors and reinforced-concrete floor structures, and 30% difference for retaining structure fastening with buntons made of metal pipes.

This conclusion is correct for the engineering and geological conditions specific for the central part of Moscow with the following physical and mechanical parameters of the soils underlying fill-up soil (type I: φ = 25…39° ; *c* = 0…4 kPa; *E* = 21…40 MPa; type II: φ = 14…19°; *c* = 25…55kPa; *E* = 18…28 MPa; type III: φ = 6…17° ; *c* = 1…48 kPa; *E* = 2…12 MPa). For the foundation bases formed by soft soils, buildings deformation values will be considerably bigger. The obtained results demonstrate better convergence as compared to those published in the article written by P.Mestat and E.Bourgeois (2002). The authors quote excerpts from MOMIS database: for "slurry wall" and sheet piling made of pipes the divergence between the calculated and measured values of surface settlement behind the foundation trench retaining structure reaches 100% because of applied soil models shortcomings, while the divergence between the calculated and measured values of horizontal shift of the retaining structure is 50%. The difference between our data and the data provided by P.Mestat and E.Bourgeois (2002) can probably be explained by the fact that they considered foundation trenches in soft soils as well. The authors note that the best results were provided by tough soil models.

S empiric dependences on *m* have been offered on the basis of experimental research (Table 1). Determining *S* dependence on *m* for different kinds of retaining structure fastenings, we selected the linear model. Pair correlation coefficient values exceeded critical values for selected significance level equal to 0.05.

Comparing the settlement values obtained for the offered empiric dependences with maximal permissible values, it is possible to determine the approximate scope of protective measures required for the buildings located within the zone affected by the foundation trench. This was made during the construction of the Third transport Ring section in Lefortovo, and this method is currently used at Moscow sites at preliminary stages of projects implementation. Empiric forecasted values comparison with the settlements of the buildings located in the zones affected by foundation trenches, measured after construction accomplishment, demonstrated quite satisfactory convergence. The choice of the method for an underground facility construction in the congested urban housing environment is often depends on neighboring buildings. Recommendations on retaining structure fastening type selection are given in Table 2, with maximum permissible value of existing buildings deformation taken into account

In order to reduce buildings settlements down to the permissible values, we have studied the efficiency of protective measures: buildings foundations reinforcement with piles and shut-off screens construction according to various technologies that have been used at Moscow sites. Bored injection piles, jacked piles and jet piles were considered for foundation body reinforcement, while rotary bored metal piles, bored injection piles and jet piles – for shut-off screens construction.

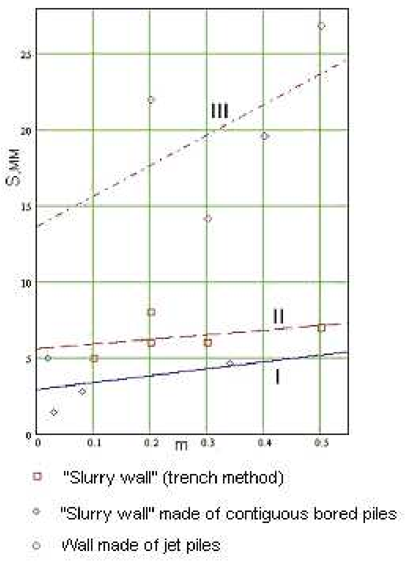

Figure 3. *S* dependence on *m* for different types of engineering and geological profile (I, II, III) in case of foundation trench retaining structure fastening with anchor structures and anchors.

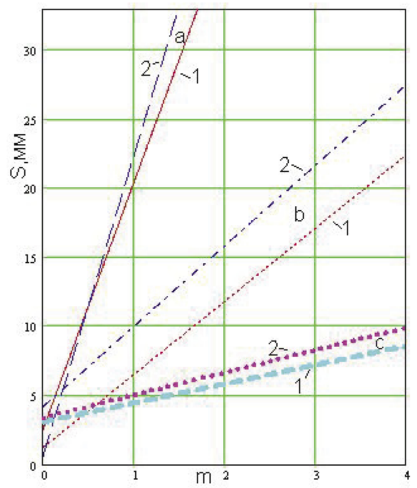

Figure 4. Buildings settlement *S* dependence on *m* (1 - experimental, 2 - calculated (with the help of PLAXIS [2] program)) for various types of foundation trench retaining structure fastening: **a** – with anchors, **b** – with buntons made of metal pipes, **c** – with reinforced-concrete floor structures ("top-down" method).

Table 1

Foundation trench retaining structure fastening type	*m* (structure condition category)	Forecasted settlement, mm (corellation coefficient)
Anchors or anchor structures	≤ 1.5 (I-IV)	$S_Φ$ = 2.55+17.86m (0.796)
Buntons made of metal pipes	≤5.0 (II)	$S_Φ$ =4.27 +4.87 m (0.633)
	≤3.4 (III)	$S_Φ$ =0.19 +9.65 m (0.801)
Reinforced-concrete floor structures. "Top-down» method	≤ 10.0 (II)	$S_Φ$ = 3.72 +1.23 m (0.779)
	≤ 10.0 (III)	$S_Φ$ =2.57 +1.42 m (0.701)

Table 2

Structure (building status)	Structures condition (category)	Type of en- gineer-ing and geological conditions	*m*	Foundation trench retaining structure fastening type
Multi-storied build-ings with load-bearing brick walls without reinforce-ment (old and modern ones)	I	I -III	≤1.7	A, R, P
		I, II	1.8 –6.0	R, P
			6.1-10.0	P
	II	I -III	≤0.5	A, R, P
			0.6-1.5	R, P
		I, II	1.6-4.0	R, P
			4.1-10.0	P
	III	I, II	≤0.4	A, R, P
			0.5-3.0	R, P
		I	3.1-4.0	R, P
			4.1-6.0	P
	IV	I -III	≤0.2	A, R, P
		I	0.2 –2.0	R, P
-«- (historical buildings and monuments)	II	I, II	≤0.4	A, R, P
			0.5-3.0	R, P
		I	3.1 –4.0	R, P
			4.1-6.0	P
	III	I -III	≤0.2	A, R, P
		I	0.2-2.0	R, P
	IV	I	≤0.2	R, P

Note to Table 2:

1. If *m* parameter exceeds the values specified in the table, buildings require protective measures.
2. Building structure condition category can be determined according to the table in Attachment 4 (Ilyichev et al,1998).

3 PROTECTIVE MEASURES AND BUILDINGS SETTLEMENTS

Protective measures application to the buildings located at pilot sites made it possible to reduce buildings settlements by 2-3 times as compared to the calculated values that exceeded maximum permissible values.

For instance, 40 mm settlements were forecasted to be caused by foundation trench excavation for the historical building located at 7/3, Znamensky Side-Street. After the building foundation reinforcement with bored injection piles and foundation trench excavation, the measured settlement appeared to be 13 mm, including 6 mm technological settlement caused by piles construction.

In case of construction of protective screens of various designs and reinforcement with piles, the measured settlements of the buildings located near foundation trenches ranged from 7 to 20 mm, on the average, with 5-8 mm technological settlements caused by shut-off screens construction and 4-10 technological settlements caused by piles construction. Settlements values are minimal in case jacked piles are used. It is determined that the technological settlement caused by protective measures makes 50-60% of the total settlement of the building, including the settlement resulting from underground excavation or foundation trench excavation. Sometimes protective measures cause settlements exceeding maximum permissible values, buildings structures get cracked and require post-settlement repair. However, without protective measures, the settlements caused by foundation trench excavation could lead to building destruction.

4 CONCLUSIONS

1. The most critical factors influencing settlement of the buildings located near foundation trenches are as follows: foundation trench retaining structure fastening type; buildings relative remoteness from the foundation trench, with their foundations depth taken into account; type of engineering and geological conditions. Less critical factors include: building structures category and foundation trench retaining structure type.
2. Affected buildings settlements empirical dependences on their relative remoteness from foundation trenches have been formulated, with their foundation depth taken into account, for various kinds of foundation trench retaining structure fastenings.
3. The values of settlements of the buildings located near foundation trenches have been researched for different kinds of protective measures. It has been determined that technological settlements caused by protective measures make 50-60% of the total settlements of the buildings located near foundation trenches, after foundation trench excavation.

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