The Field Investigation of the Influence of Deep Excavation Construction Fence on the Mechanical and Strength Characteristics of Soil

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(Received 2 / 10 / 2023. Accepted 13 / 11 / 2023)

□ ABSTRACT □

In the course of excavating a thick layer of soft, weak soil in St. Petersburg, Russia, instabilities were encountered in a 21 m long sheet pile excavation fence made of AU Arcelor 18. In light of the rather large depth (12 m) and areal extent (150 m by 80 m) of the excavation, such instabilities presented a significant challenge for the geotechnical engineers. The stability of the sheet pile was increased by constructing vertical and horizontal diaphragms in close proximity by jet grouting. This process can, however, alter the properties of the foundation soil in the vicinity of the excavation fence. To better ascertain how such properties can potentially be altered, excavations involving similar soils from neighboring building were simulated using the PLAXIS finite element program. This paper reviews the results of soil property tests performed in conjunction with the construction of the aforementioned large excavation, as well as the neighboring buildings. The need for continuous monitoring of geotechnical conditions using the methods of static sounding, so as to assess the zone of construction influence and to forecast the mutual influence of the structure being constructed on the surrounding buildings, is discussed.

Keywords: excavation pit, soil characteristics, static sounding, numerical methods of calculation.

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التحقق الحقلي لتأثير جدار تدعيم حفرية تأسيس عميقة على الخواص الميكانيكية للتربة ومتانتها

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(تاريخ الإيداع 2 / 10 / 2023. قُبِل للنشر في 13/ 11 / 2023)

□ ملخّص □

أثناء حفر حفرة تأسيس في طبقة سميكة من التربة الناعمة والضعيفة في سانت بطرسبرغ، روسيا، تمت مواجهة حالات عدم استقرار في جدار تدعيم الحفرية المؤلفة من أوتاد بطول 21 مترًا مصنوع من AU Arcelor 18. عند حفر حفرة التأسيس التي أبعادها (150 مترًا × 80 مترًا) وعمقها (12 مترًا) نشأت مشكلة أمام المهندسين الجيوتكنيكيين متمثلة بعدم استقرار جوانب الحفرية. تمت زيادة ثبات الأوتاد المحيطية من خلال إنشاء عوارض رأسية وأفقية ملاصقة للأوتاد في جدار الحفرية. يمكن لهذه العملية أن تغير خصائص تربة التأسيس في المنطقة المجاورة لجدار تدعيم الحفرية. للتأكد بشكل أفضل من كيفية تغيير هذه الخصائص، تمت نمذجة حفريات لمباني مجاورة تربتها مماثلة لتربة الحفرية باستخدام برنامج العناصر المحدودة PLAXIS. يستعرض هذا البحث نتائج خواص التربة التي تم اختبارها بالتزامن مع إنشاء الحفرية العميقة المذكورة أعلاه، بالإضافة إلى النتائج المأخوذة من المباني المجاورة. تمت مناقشة الحاجة إلى المراقبة المستمرة للظروف الجيوتكنيكية باستخدام طرق السبر الستاتيكية، وذلك لتقييم منطقة تأثير البناء والتنبؤ بالتأثير المتبادل لجدار التدعيم الذي يتم تشييده على المباني المحيطة.

الكلمات المفتاحية :حفرة التأسيس، خصائص التربة، السبر الستاتيكي، الطرق العددية للحساب.

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INTRODUCTION:

The modern large volume underground construction in the conditions of the compact urban development requires to consider the effect of technogenic factors on the change of soil properties during the construction. These changes occur in the soil under the foundation of the constructing building and outside this building in the zone effected by this construction. It is most important to consider these changes during the excavation of large volume pit in difficult geotechnical conditions.

Such information allows to make geotechnical calculations and to specify stress and deformation properties of the soil in order to forecast the settlement of the erecting and adjacent buildings during the crucial stages of the pit excavation.

The technogenic effect on the soil under foundation may be of local and general (territory) character. Local changes in the soil under the foundation during the piling work made according different technologies are discussed in previous articles [1,2].

This article discusses changes of soil properties while the construction of the excavation pit of the size 150 x 80 m and the depth 12,5 m in the soft soil conditions of St. Petersburg and adjacent buildings.

2. THE MAIN CONSTRUCTIVE ELEMENTS OF STRUCTURES IN THE UNDERGROUND PART AND IN THE ADJACENT BUILDINGS

The protective and strutting devices of the excavation pit include:

- metal sheet piling made from AU Arcelor 18 penetrated to the depth of 21 m by vibration;
- protective “slurry wall” made from piles and reinforced by steal shape structures installed on distance 1,0 m from one to another. The Jet grouting “soil mix wall” with installed steel shape structures and the sheet piling on top are joined by reinforced concrete beam 2,3 m wide and 1,15 m high;
- longitudinal soil-cement diaphragm on the depth of 11,5 – 14 m is made by Jet-grouting technology. The design strength of the diaphragm material for uniaxis compression is at least 1,0 MPa, the deformation modulus is at least 400 MPa;
- temporary bored piles with a length of 29 m long, diameter 600 mm arranged inside the excavation pit on a grid with a pitch of 6m x 6m;
- permanent bored piles having the diameter from 800 *mm* up to 1200 *mm* are the constant structures of the slab of pile cap grillage and arranged below the bottom of the excavation pit;
- strutting reinforced concrete plates, erected as the pit is developed at the levels - 4,41 and -11,1*m* (top of the plate). The plate at the level – 4,41 has a thickness of 400 *mm* and is supported by temporary piles. The plate at the level of -11,1 has a thickness 1200 *mm* and its base is permanent bored piles;
- strapping beams at the level – 8,11 *m* and sections of transverse walls in order to provide additional rigidity of the foundation pit fence at this level.

The adjacent 4-7 floor buildings were constructed earlier 1917 and have cross and longitudinal bearing walls and strip foundations. The nearest to the pit are 4-5 floors buildings at a distance of 14 m.

The influence of works related to the vibro penetration of the sheet piles, the erection of permanent and temporary piles, the creation of vertical and horizontal diaphragms by Jet grouting technology could lead to the serious changes of the physicomechanical properties and strength characteristics of soil in the foundation pit and beyond.

According to the preliminary design surveys of 2005, the engineering and geological structure of the construction sites is characterized by the following soil layers:
- fill soil layer (L1) 1,5 – 3,4 *m* deep composed from small debris, sand of different grain size and plastic sand clays;
- under the fill soil layer there are sea-lake deposits , composed from silty sand (L2) 2,4-4,4 *m* thick and clay-sand (L3)1,2- 2,0 *m* thick. The sea-lake sand and sandy clay are characterized by thixotropic properties. The underlying sea glaciers deposits are represented by belt, fluid sandy clay (L4). The thickness of lake–glaciers deposits is 3,4-8,3 *m*. These soils as well as litorin sediments belong to thixotropic soil;
- glacial deposits are represented by sandy clays with sand lenses (L 5) with a thickness of 0,7 to 4,9 *m*, light silty sandy loam with lenses and sand interlayers of different sizes grain (L6) with a thickness of 1,7 to 9,3 *m*, light grey-greenish-gray sandy clays with interlayers of sand and gravel of semi-solid consistency (L7) with a thickness of 0,9 to 6,1 m.

The glaciers deposits are laid on stiff proterozoy bluish-gray (Vendian complex of the Upper Kotlin subformation) , greenish-gray and bluish-green silty clays, the roof of which was uncovered at a depth of 22,4-28 *m.*

The roof of primary clay to a depth of 27.2 -32.7 *m* is affected by glacial dislocation, there are characterized by inclusions of rear gravel (L8). Below are fine stiff clays. (L9).

Site construction stratigraphy cross section are given on Fig. 1.

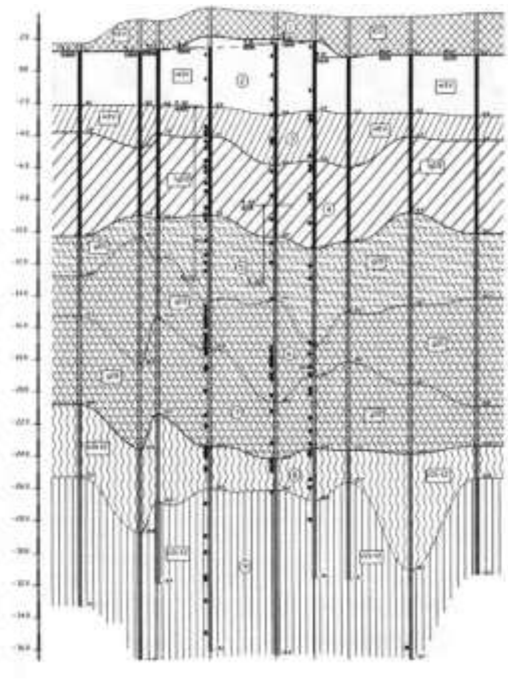

Figure 1(Site construction stratigraphy cross section)

3. SOIL TEST METHODS

An assessment of the effect of the underground construction on soil properties was done by comparative analysis of the results of static sounding obtained in 2005 and 2009.

In 2005, the static sounding test was performed by the “Iziskatel” Company in the course of design studies. The sounding was done by a CPT sounds probe of the Swedish company “Geotech AB“, which corresponds to type II of the Russian classification [6].

In 2009, static sounding was done by r

Research and Development Center for Geotechnology of St. Petersburg State University of Architecture and Civil Engineering as a part of scientific and technical supervision program for construction. The sounding was carried out in the period after completion of the installation of piles, sheet piling and excavation of the pit up to 2/3 its depth, that is, before the most critical stage of the work was performed – opening of the lower part of the pit.
Taking into account the intensity of the pit excavation according to the “Top-Down” method and confined construction site area, the tests were done using the modern multi-channel probe CPT -U of Swedish “Geotech AB” PROBE No. 3531. The sounde penetration was done by the Swedish small-size self-propelled geotechnical installation RIG 204 D of the company “Geotech AB” (Fig 2, 3).

Figure 2 (Static sounding of soil at site № 1)

Figure 3 (Penetrations of the sound at the site № 3)

To conduct soil testing by the method of static sounding, 4 sites were selected - one inside the excavation pit and three outside it. At each of them, from 6 to 14 points of static sounding were performed, located at a distance of 1 *m* minimum from each other. (Fig 4).

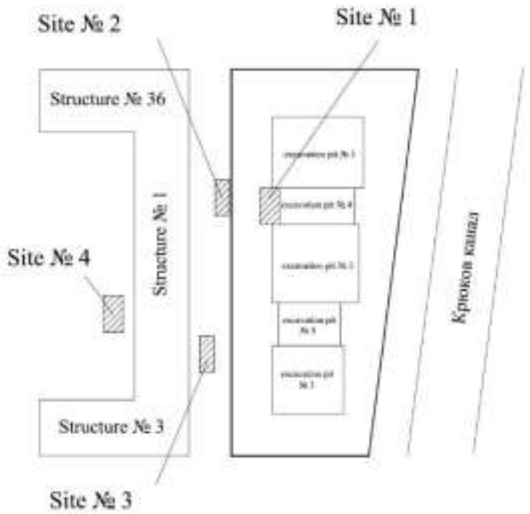

Figure 4 (Scheme of location of static sounding sites)

The location of sounding points at each site is assumed to be linear along the foundation pit so that in the sections remote from the fence at the different distances, average soil characteristics from sheet piling are recorded.

The main parameters used for testing physical and mechanical properties were the resistance of the soil to cone penetration qc and friction along the side surface f_s. The additional parameters of soil characteristics were porous pressure u , temperature t , inclination angle from the vertical position of the sounde T. These parameters were used for estimating the sounding conditions, inhomogeneity and variability of soil properties. Taking into account the possibility of changing the composition and soil type under the influence of technogenic impact, the test of the stability of the soil type was done for each engineering and geological element according to P.K. Robertson et al. using q_c and R_f = (f_c/q_c)x100% [3].

The assessment of the physical and mechanical characteristics of soils was carried out using the tables and nomograms [4,5].

4. TEST RESULTS OF THE CHANGE OF SOIL CHARACTERISTICS

The registered numeric parameters at the sounding points, their comparison with previous results of static sounding made in 2005, and statistical treatment of the data set made it possible to construct graphs of changes in the average values of the investigated parameters for each site of investigation.

So, at the site № 1, located inside the pit at a depth of 4 m, 14 sounding points were completed. The soil of this site were most of all subjected to intensive construction impacts when vibrating of the sheet pile penetration was effected, while installing permanent and temporary drilled piles made under casing with an auger and screw using SOB and DDS technologies. Besides, the longitudinal and vertical soil- cement diaphragms in the soil were made using “jet grouting” technology.

In Fig. 5 the changes of the parameters q_c and f_s depending on the depth is given for this site. The roof of the longitudinal soil cement diaphragm was fixed at the depth of 7,7 m.

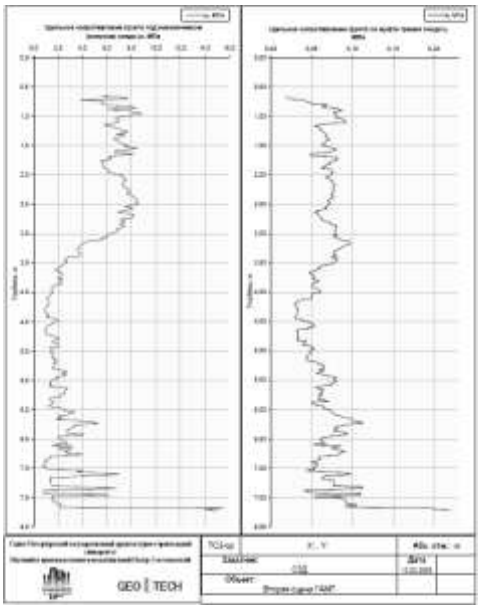

Figure 5 (The diagram of the average value qc and fs.)

At site № 2, located at the distance 2,6 m from the pit, 10 sounding points were done. The sounding was done at a distance 0,3 m from the side surface of the reinforced concrete binding beam of the outside pit protection. The soils here were affected by vibro penetration of sheet piles and by the construction of vertical walls in the ground which were made by jet grouting technology. In addition, soils at this site are influenced by load from the adjacent building. .

At the site № 3, located at a distance of 5,6 *m* from the pit, 8 sounding points were made located at a distance of 3,3 *m* from the outside face of the reinforced concrete binding beam of the external pit fence

At the farthest site № 4 located inside the courtyard of a residential building at a distance of 25 *m* from the pit, 6 sounding points were completed.

The average value of q_c and f_s at the depth of 2,3 – 21,4 *m* at this site are shown in Fig 6.

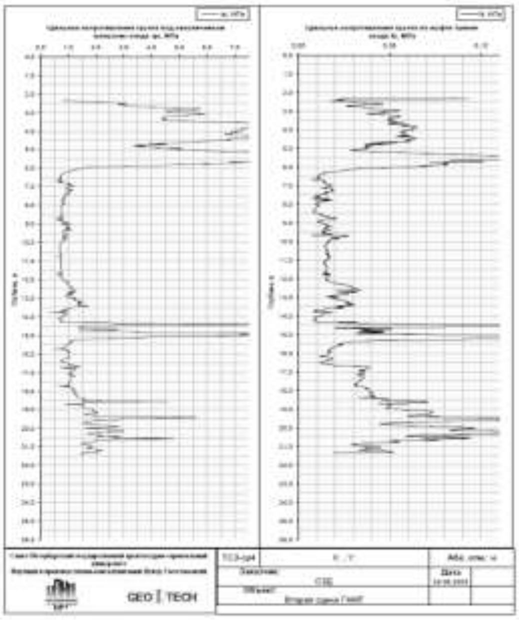

Figure 6 (The diagram of the average value qc and fs)

For the comparative analysis of the changes in soil due to the construction, the average values of q_c, f_s and R_f for each type of soils were obtained on the basis of sounding test results.
The diagrams of the average value of these parameters for each soil type are given in Fig.7 in comparison with engineering and geological data.
The average values of q_c and f_s were obtained in 2005 from the sounding data at 8 points located along Minsk Lane between sites № 1, 2 and № 3.

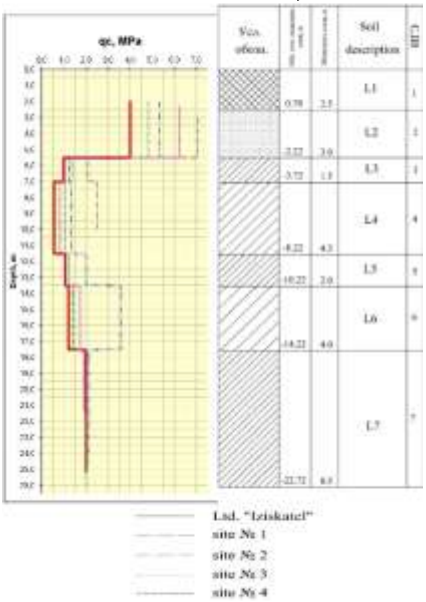

Figure 7 (Average qc values at the sites №1-№4 measured in 2009 compared with the corresponding values measured in 2005.)

The analysis of the mentioned data showed that the upper part of the soil inside the pit at soil lays L 2,3 and 4 was most affected by industrial impacts during construction. The comparison of the diagrams shows that soil resistance to the static sounding at the site 1 increased by more than 2 times due to construction works.
Outside the pit on the distance of 0,3 m from reinforced concrete binding beam the most significant increase in soil resistance q_c, f_s occurred in sandy clay in the soil lays L5 and L6.
At a distance of 3,3 m from the foundation pit fence the soil resistance to sounding increased by not more than 50% against soil resistance measured before the start of the construction.
The registered changes of the soil properties in terms of increasing occurred only up to the depth 17,5 m in the soil lays L 2 ….6.
The increase of strength and deformation soil properties received in the second sounding can be explained by soil consolidation at soil lays L 2….6 due to technogenic effect caused by installing of a large number of piles, restoration of structural links and also partial hardening of soils during manufacture of cement-soil diaphragm by Jet grouting method.
Below, in the glaciers sandy clays of L 7, the change in soil resistance to sounding is not significant.

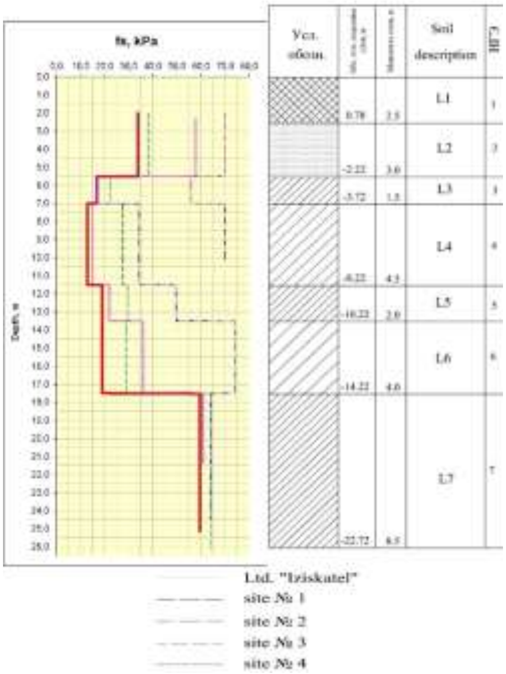

Figure 8 . (Average fs values at the sites № 1-№4 measured in 2009 compared with the corresponding values measured in 2005)

Verification of possible changes in the type of soil was made for L 2….7 by the average values of the parameters q_c and R_f . The results of the test show that there is no any changes in the type soil under the influence of construction. This conclusion allowed to use in further calculations the data received in former tests and new data with different values of physical and mechanical properties.

After statistical treatment of the results of soil static sounding using tables and specifications nomograms [5,6] the specified values of deformation modulus *E*, specific cohesion *c* and angle of inner friction φ of soil in the construction site were received (Table 1,2,3).

Table 1 (Specified values of deformation modulus E, MPa based on results of static sounding)

№	E, MPa			
№	2005	Nnumber of site		
L	г.	№ 1	№ 2	№ 3
2	12,0	21,0	16,0	14,4
3	7,0	14,0	9,0	10,0
4	3,5	17,5	10,0	7,0
5	9,3	-	11,5	9,8
6	9,3	-	15,0	9,6
7	12,0	-	12,0	12,0

Table 2 (Specified values of specific cohesion c, KPa based on results of static sounding)

№	c, KPa	
№	2005 г.	Number of site

L		№ 1	№ 2	№ 3
2	-	-	-	-
3	20,0	30,0	23,0	23,0
4	17,0	29,0	23,2	20,5
5	25,0	-	34,0	27,0
6	25,0	-	43,0	30,0
7	35,0	-	35,0	36,0

Table 3 (Specified values of angle of inner friction φ based on results of static sounding)

№ № L	φ, degrees			
	2005 г.	Number of site		
		№ 1	№ 2	№ 3
2	29,0	31,4	30,2	29,8
3	15,4	15,7	15,5	15,5
4	9,8	10,0	10,0	9,9
5	25,0	-	25,0	25,0
6	25,0	-	25,5	25,0
7	26,0	-	25,0	25,5

The values of soil properties changed as a result of technogenic impact for each of the elements and for each of the zones considered were used for an updated geotechnical forecast of the stress-strain state of the soil of the foundation pit base and the surrounding soil mass during the phased construction of a building under construction with an assessment of the effect on the adjacent buildings. The calculations were done according to the FEM program "PLAXIS' using 24 engineering and geological elements (Fig. 9).

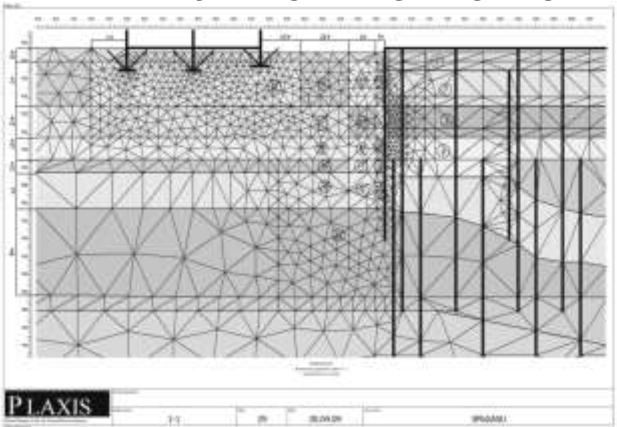

Figure 9 (The settlement diagram of the changed earth basis)

Recommendations and Conclusions

1. The method of static sounding and the analysis of the results made it possible to proper time to estimate the changes in soil properties in the foundation pit of the building under construction and around caused by technogenic effect.
2. The increase of the strength and deformation values of soil registered at the second sounding can be explained by soil compaction caused by technogenic impact during the

erection of a large number bored piles, restoration of the structural binds and partial compaction of soil while manufacturing cement-soil diaphragm by jet grouting method.
3. The use of the results of altered soil characteristics in the finite element calculations using the PLAXIS program made it possible to more reliably evaluate the stress-strain state of the soil massive and to predict the stability and deformation of the building under construction and neighboring buildings.

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