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Efficient foundation pits solutions for restrained urban conditions

Vynnykov Yuriy[1], Kharchenko Maksym[2], Akopian Mkrtich[3*], Aniskin Aleksej[4]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0003-2164-9936
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-1621-2601
[3] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0002-5271-6639
[4] University North, Varaždin, Croatia https://orcid.org/0000-0002-9941-1947
*Corresponding author E-mail: armenia3579@gmail.com

There are presented analysis results of the new multi-story residential building construction's impact on the existing development, constructive and technological measures for the arrangement of an excavation, deeper than the existing foundations' footing level, with minimal costs and minimal negative impact on the surrounding buildings. In particular, its excavation stages, results of the excavation shoring strength calculation, as well as proposals for the technical condition monitoring of existing buildings in the process of new construction were introduced. The calculation of the new construction's impact, including the arrangement of the pit, was performed in a plane, nonlinear formulation by the finite element method (FEM). Numerical modeling of the system "base - foundations of the existing building - shoring construction" was performed using an elastic-plastic soil model with the Mohr-Coulomb strength criterion.

Keywords: soaked loess base, excavation shoring, spread foundation, pile foundation, settlement, stress-strained state, finite element method

Ефективні рішення влаштування котлованів у тісній забудові

Винников Ю.Л.[1], Харченко М.О.[2], Акопян М.К.[3*], Аніскін А.[4]

[1, 2, 3] Національний університет «Полтавська політехніка імені Юрія Кондратюка»,
[4] Північний університет, Вараждин, Хорватія
*Адреса для листування E-mail: armenia3579@gmail.com

Викладено результати аналізу впливу на існуючу забудову нового будівництва багатоповерхового житлового будинку, конструктивні й технологічні заходи з улаштування більш глибокого, ніж рівень підошви існуючих фундаментів котловану, за мінімальних затрат та мінімального негативного впливу на оточуючу забудову, зокрема, стадійність його відкопування, дані розрахунку міцності елементів огородження котловану, а також пропозиції щодо моніторингу технічного стану існуючих будівель у процесі будівництва. Грунти майданчику – переважно замоклі лесовані суглинки. Фундаменти існуючих будинків – стрічкові, а нового – із задавлених паль, об'єднаних залізобетонними ростверками: стрічковими під стінами та окремими під колонами. Розрахунок впливу нового будівництва, зокрема й влаштування котловану, виконано у плоскій нелінійній постановці методом скінченних елементів (МСЕ). Моделювання системи «основа – фундаменти існуючої будівлі – конструкція огородження» виконано із застосуванням пружно-пластичної моделі ґрунту з критерієм міцності Кулона – Мора. Наведено приклади результатів моделювання МСЕ деформацій грунтового масиву на різних стадіях улаштування огородження котловану. Розрахунками елементів огородження котловану з урахуванням стадійності виймання грунту та врахуванням мінімальних затрат, встановлено, що огородження котловану можливо влаштувати з шпунтових паль (двутаври №30Ш) з кроком 1 м та між ними дерев'яної забірки. Обгрунтовано, що для збільшення стійкості й зменшення деформацій вертикальних елементів огородження котлован на початкових стадіях слід розробляти котлован під захистом грунтової берми, а надалі – з встановленням обвязувальної балки, розкосів, підкосів і поступовим підведенням підлоги й зовнішньої стіни паркінгу. За результатами моделювання визначено, що максимальні горизонтальні переміщення огородження котловану на різних стадіях його влаштування коливаються від 0.8 до 2.3 см у зоні існуючих будівель. Максимальні вертикальні переміщення основ фундаментів існуючих будівель склали 0.8 см, що не перевищує допустимих за нормами величин.

Ключові слова: замокла лесована основа, огородження котловану, фундамент на природній основі, пальовий фундамент, осідання, напружено-деформований стан, метод скінчених елементів

Introduction

One of the current problems of modern construction in dense urban development is the danger of additional absolute and relative uneven deformation of the existing buildings' foundations, structures, and underground utilities due to new construction. Geotechnical experience shows that due to the impact of construction and operation of new facilities, the bases of the surrounding buildings' foundations are sometimes significantly deformed, and occasionally further operation of these buildings becomes dangerous [1-8].

Thus, a classic case of such influence in a weak soils environment was a five-story residential building built on piles, on the corner of Povitroflotsky and Peremohy avenues in Kyiv. Additional loading of its pile base from the side of the new five-storey building-insert on a slab foundation led to the emergency condition of the load-bearing structures of the adjacent part of the existing building.

Another problematic geoengineering task was not only to improve the design, installation, and execution of works in a deeper (compared to the level of the existing foundations' footing) excavation in the area of existing development [5, 7, 9, 10], but also to minimize the cost of protective measures.

Review of the research sources and publications

Limit additional absolute and relative bases' deformations of the surrounding structures' foundations, located in the influence area of deep pits or communications, depending on the type of these objects and their technical condition category [2, 5-7].

In the case of designing bases and foundations, as well as underground components of new buildings and structures or objects to be reconstructed, under conditions of dense urban development, geoengineering monitoring is performed to assess the impact of new buildings on the stress-strain state (SSS) of the surrounding soil, in particular, and foundations of the surrounding buildings. Under these conditions, graphical, analytical, graph-analytical, numerical, and other methods proved efficient in practice [1, 2, 4-7, 9-16].

If the excavation of the foundation pit with free slopes for the new construction is not justified by calculations, usually the excavation shoring of different types and technologies is used, for example [5, 7, 9-11, 13, 14, 16]:

– sheet piling (thin wooden, metal, reinforced concrete, plastic flat or profile retaining walls, the stability of which provided by the deep immuration in the ground or in combination with ground anchors, stiffeners, struts, etc.); retaining berms and unloading trenches have gained some popularity as a supplement to sheet piling, especially in conditions of weak soils; this option has a limit on the pits depth up to 5 - 6 m;

– excavation shoring such as "wall in the ground"; makes it possible to dig excavation of a considerable depth;

– shoring from tangent and secant drilled piles makes it possible to dig excavation of considerable depth;

– soil-cement excavation shoring made by deep soil mixing or jet cementation technology; has a limit on the excavation depth up to 5… 6 m;

– application of the Top-Down technology (vertical elements of shoring are arranged by the "wall in soil" technology, from drilled secant or drilled tangent piles), etc.; enables excavation of the deepest pits, including ones in the dense urban development.

As a rule, the choice of each design and the technological solution is influenced by several factors: geoengineering and hydrogeological conditions; technical state of existing buildings; economic; constructive, organizational-technological, many others [5, 7, 9-11, 13-16].

Definition of unsolved aspects of the problem

Each time the geoengineer must estimate the SSS of a rather complex and variable system in the development process, which includes the soil mass with the actual and projected groundwater level, existing foundations and superstructure of buildings in a certain technical condition, underground engineering networks, excavation at different stages and elements of its shoring, foundations of the new building and its load-bearing structures, take into account the cost of the proposed design solutions.

In particular, the efficiency and reliability of the above system are influenced by certain actual parameters of the excavation shoring, which are statistically variable: the increment and penetration depth of the shoring elements; geometric location of the capping beam; eccentricity of the excavation wall axis to the axis of the shoring's vertical element; geometric parameters of the existing surrounding buildings' foundations; physical and mechanical properties of the soils massif; technological issues during jacking the vertical elements; dynamic effects on the excavation edge; flooding of the excavation, etc.

Correct consideration of the possible variability of these factors, as well as the development of the excavation staging, can minimize the possible impact of new construction on surrounding buildings and existing networks with the required level of reliability and at the same time have minimal costs compared to alternative methods of excavation in certain conditions.

The existing regulative system of scientific and technical monitoring of buildings and structures [17] has not taken into account the features of the above-mentioned geoengineering problem yet.

Problem statement

Therefore, the purpose of the study is to minimize the impact of new construction to regulatory standards utilizing the actual construction site in dense development (number of surrounding residential buildings is more than one) with soaked loess loans and the excavation's bottom level deeper than the level of the existing foundations' footing at the cheapest possible excavation shoring solution.

In particular, the following tasks are highlighted:

– determining the area of the possible impact of new construction on the surrounding buildings;

– analysis of the new construction impact on the surrounding buildings with the definition of the allowable additional impact during performing the excavation;

– development of constructive and technological measures to minimize the possible impact of new construction on the surrounding buildings and existing underground networks;

– substantiation of the excavation workflow with minimization of the impact on existing buildings;

– calculation of strength and deformability of the elements of the excavation shoring taking into account the variability of the actual geometric parameters;

– development of recommendations for monitoring the technical condition of existing buildings in the process of new construction.

Basic material and results

The site of the full-scale object is located at the corner of Pushkin and Vatutina streets in Poltava (Fig. 1). The roadway of Vatutina street is 5.5 m away from the excavation, and Pushkina st. - 5.3 m.

The new building is one-section, eight-story, with public facilities on the ground floor and underground parking. The multi-story part is adjoined by a one-story underground car park through a contraction joint. The height of the underground floor is 3.9 m, and the depth of the excavation is over 4.0 m.

In construction terms, the new building is a framed monolithic structure from the foundation to the slab above the ground floor. Above that, it's a frameless structure with longitudinal and transverse load-bearing walls and interflooring of precast slabs. Its foundation is piles C140.35-8 (section 0.35x0.35 m, length 14 m), connected by a reinforced concrete spread grille under the walls and separate reinforced concrete grilles under the columns. The consequence class of the building is CC2.

From the analysis of the general plan and constructive parameters of the new building, it is possible to generalize that for the underground parking construction, it is necessary to dig an excavation 4.8 m deep (to a datum of 152.3 m) with vertical slopes.

Excavation and the new building foundations' performance will have an impact on existing buildings. Thus, the zone of negative influence (Fig. 1), in particular, includes the existing six-story residential building on Vatutina St. 9/68, five-story residential building on Pushkina St. 66A (at a distance of 7.2 m from the excavation), the roadway of Pushkina St. with a network of underground communications (taking into account the pillar crane area) and the roadway of Vatutina St., etc.

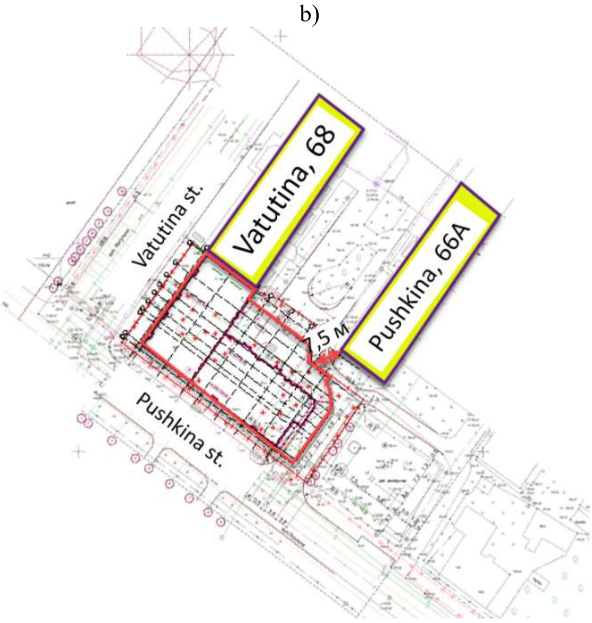
The building on Vatutina St. 9/68 has 6 floors, including the attic, and under the whole building, there is a basement (depth of the underground part - 2.2 m). Its shape in plain view is rectangular with overall axial dimensions 23.25x13.36 m and 18.5 m height. The structural scheme is frameless.

The load-bearing walls are longitudinal external and internal.

The foundations of load-bearing and self-supporting walls are spread monolithic reinforced concrete, shallow laying, on a natural base, the foundations footing depth from the ground level is 2.2 - 2.5 m. The bearing stratum of the base (Fig. 2) is an engineering geological element (EGE) heavy silty loam, stiff (EGE-2) loam with a thickness of up to 1.8 m. The spread foundation edge is 0.5 - 0.8 m away from the excavation. The general technical condition of the building is defined as "2" - satisfactory, and therefore the allowable additional settlement of its base from the influence of the new building should not exceed 20 mm, and their relative unevenness - 0.0015 [2].

a)

b)



c)

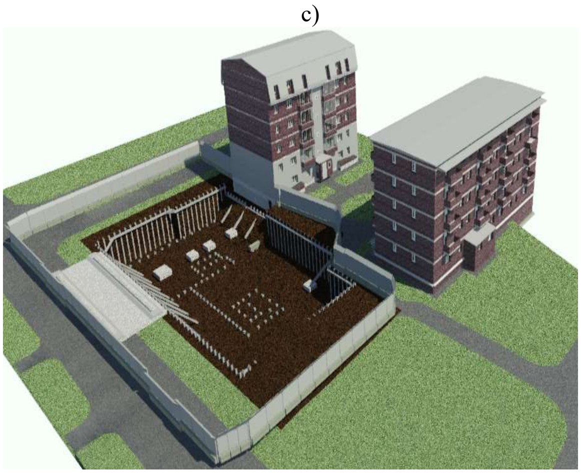


Figure 1 – Layout schematic of the site in:
a – full-scale conditions before the excavation;
b – in plain view;
c – in spatial dimension (design proposal)

A five-storey building on Pushkina St66A was built according to the 1-511 series, with a technical underground under the entire building. It has a rectangular shape in plan view with overall dimensions in the axes of 12.0x33.6 m. The load-bearing elements are external and internal longitudinal walls. Structural scheme - frameless with longitudinal load-bearing walls and stairwells in the form of stiffening cores. Foundations of walls - spread, precast reinforced concrete, a shallow foundation on a natural base. The bearing layer of their footing is EGE-2 (Fig. 2). The building is 7.2 m away from the edge of the future excavation. The general technical condition of the object - "2" - is satisfactory (as one that contains structures with the technical condition of category "2", but there are no structures of responsibility category A1, A or B with the technical condition of category "3" or "4"). Permissible additional settlement of its base from the influence of the new building should not exceed 10 mm, and their relative unevenness - 0.0015 [2].

Geomorphologically, the site is confined to the Poltava loess plateau. The thickness of the loess strata does not exceed 8 m on site. However, in the case of the soil massif soaking, settlement from the net weight is absent. Lithologically, the section up to a depth of 20 m is represented by silty heavy loams (EGE-2 and EGE-4 - stiff) and light (EGE-3 - fluxional, IGE-5a - soft-firm, IGE-5b - fluid-firm), as well as light silty, semi-hard clay (EGE-6). The layers are covered with bulk soil (EGE-1) with a thickness of 0.8 - 1.8 m. The soil strata are sufficiently sustained for the depth and area of the massif.

At the time of surveys and investigations, the groundwater level was recorded at 4.2 - 4.5 m below the ground surface (approximately at the level of the future excavation's bottom), it is expected to rise to 2.0 m.

According to the results of the existing buildings' investigation, the sections of the greatest influence of the new construction on these buildings and communications are highlighted (Figs. 3 and 4).

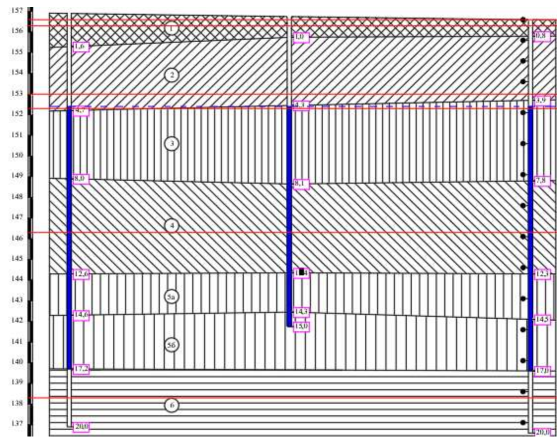


Figure 2 – Geotechnical cross-section of the site

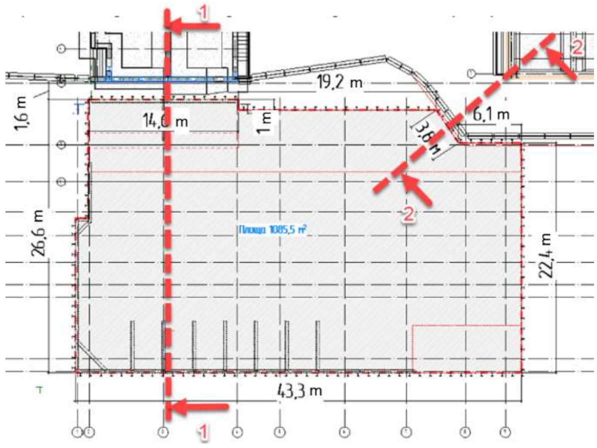


Figure 3 – Scheme of the design sections

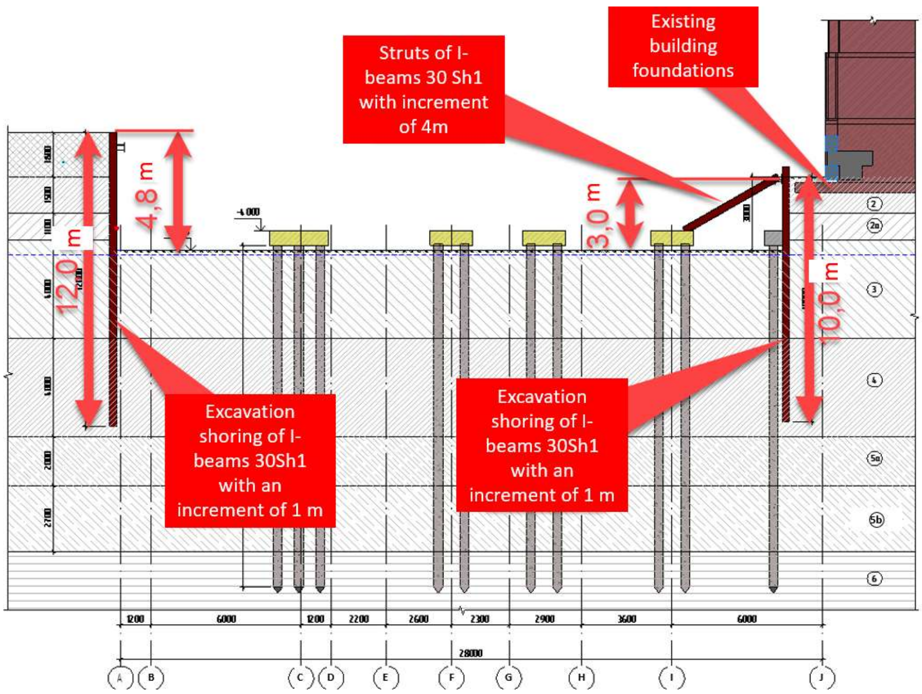


Figure 4 – Section 1-1 (6-storey building and tower crane for new construction along the axis «A»)

As an example we will consider results of only the basic calculations of the excavation shoring, influence of new construction on the existing building, checks of deformations during excavation, and an underground part of a new building on section 1-1 (passes through the six-storeyed building). Its foundations are 0.5 - 0.8 m from the edge of the excavation and the depth of the excavation in this section is 4.8 m (Fig. 4).

To reduce the load on the shoring, its depth was reduced by performing a preliminary ("pioneer") excavation with a depth of 1.8 m near the building. At the same time along with the existing building on Vatutina St., 9/68 there will be removed almost the entire bulk layer. Then from the bottom of the "pioneer" excavation vertical elements of the shoring will be pressed down (metal piles of I-beams 30Sh1 10 m long, with an increment of 1.0 - 1.5 m), between which a wooden fence and a capping beam will be installed. The proposed technology has the lowest cost compared to Larssen sheet piling and is arranged in the shortest time compared to drilling piles or "wall in the ground" (no need to wait for concrete to cure and it is possible to excavate the soil immediately after immersion of metal piles). It is expedient to create the offered protection on the following stages:

1 – immersion from the ground surface of pressed piles for a new building (before the arrangement of the excavation); erection of the vertical shoring elements along the contour of the excavation except for the area near the building (Fig. 5);

2 – digging the "pioneer" excavation to a depth of 1.8 m from the surface; pressing the piles of a shoring from I-beams 30Sh1 between excavation and the base of the existing building (fig. 6);

3 – excavation to the design depth under the protection of a soil berm 3.2 m wide with a slope of 45 - 50 ° (Fig. 7);

4 – an arrangement in the upper part of the shoring (0.5 m from the surface) of the capping distribution beam of I-beams 30Sh1, installation of I-beams 30Sh1 struts with an increment of 4 m on pre-arranged grilles of the future building (Fig. 8);

5 – works performance on arrangement of spread grilles under the parking wall, the parking floor arrangement, which will act as a spacer system and will accept the load from the shoring, it is also advisable to perform vertical reinforced concrete structures (pylons, walls) to the struts level and only after gaining strength with concrete to remove the struts and continue to perform monolithic work (Fig. 9).

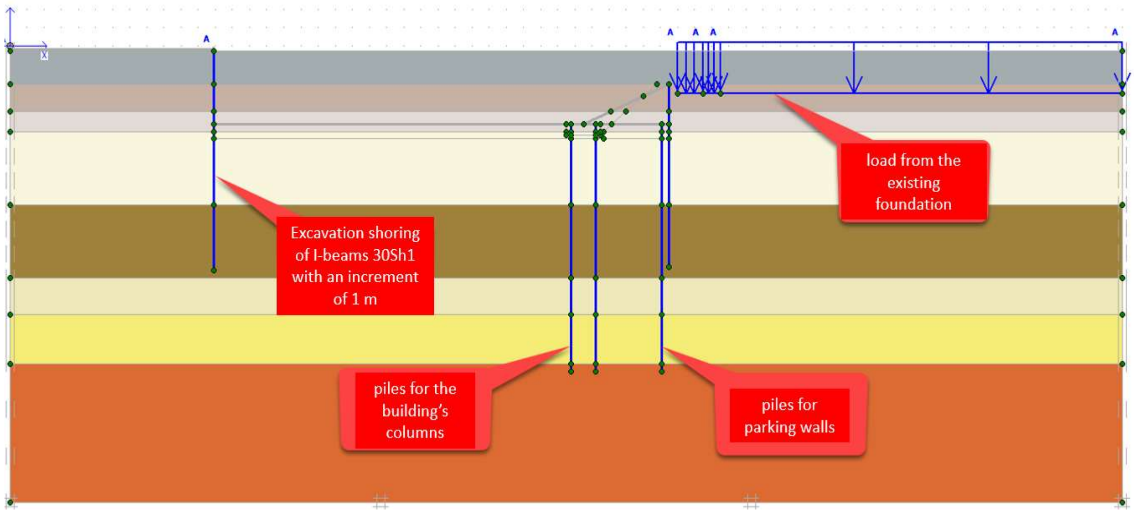


Figure 5 – Stage 1 of the excavation shoring erection in section 1-1

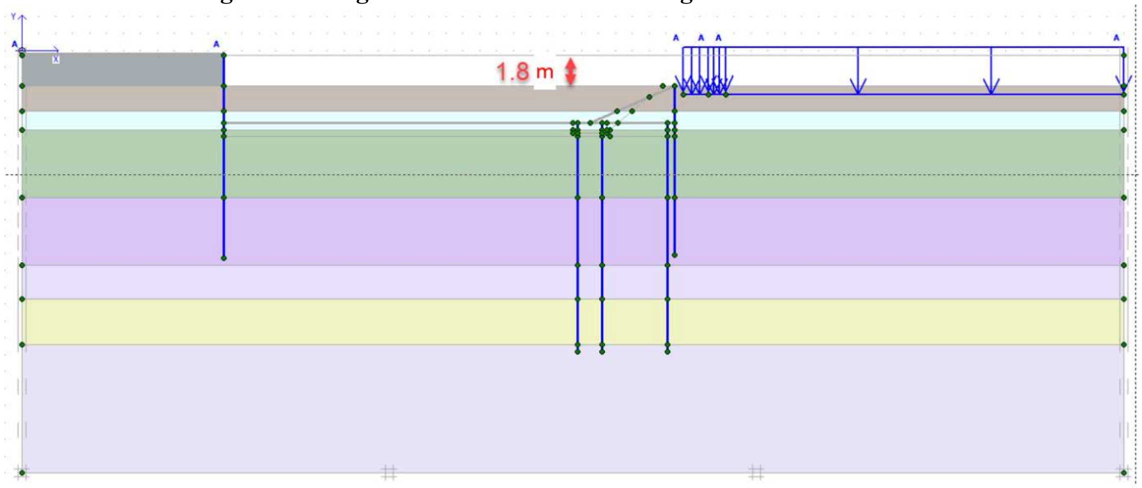


Figure 6 – Stage 2 of the excavation shoring erection in section 1-1

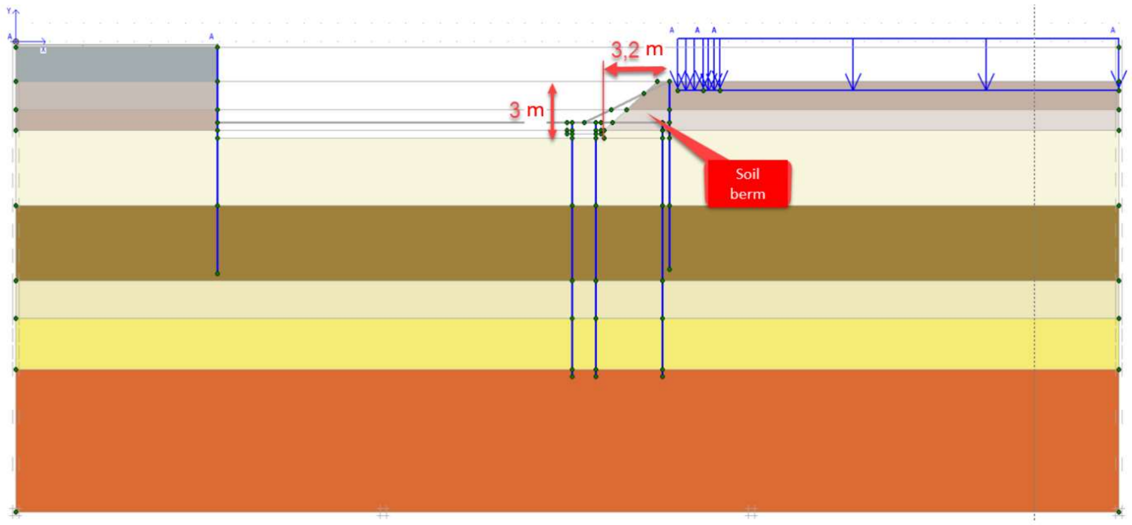


Figure 7 – Stage 3 of the excavation shoring erection in section 1-1

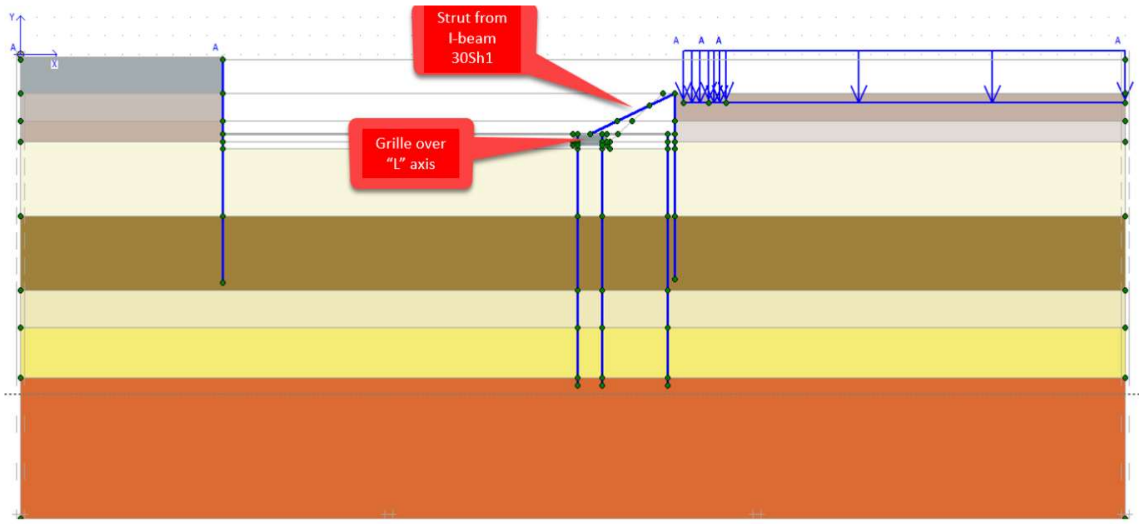


Figure 8 – Stage 4 of the excavation shoring erection in section 1-1

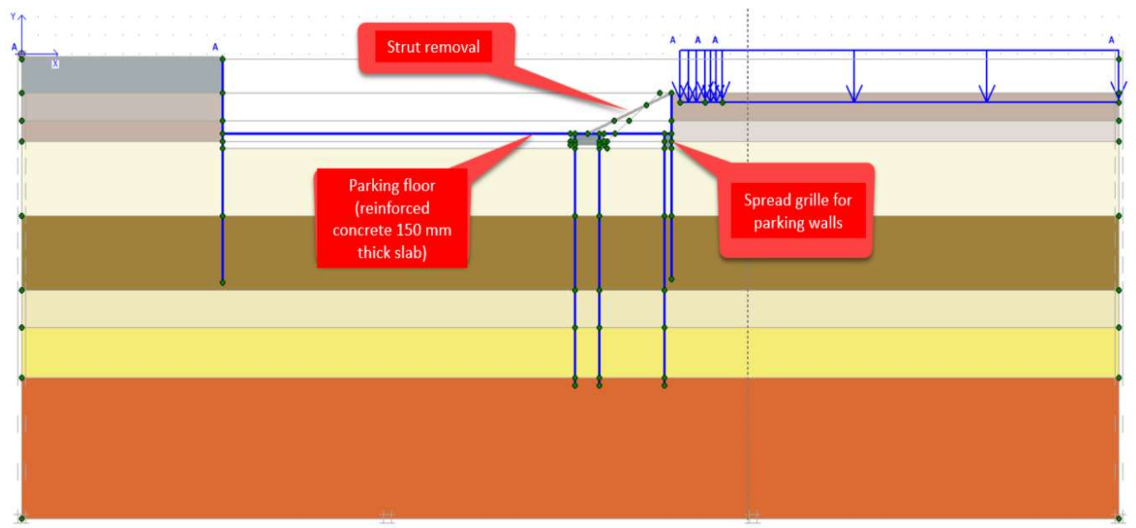


Figure 9 – Stage 5 of the excavation shoring erection in section 1-1

Similar studies were performed in cross-sections 2-2.

In the area where there are no communications and existing buildings, the criterion of calculation was taken as the strength and stability of the excavation shoring system. Horizontal displacements in this area should not exceed 10 cm. In the area of communications and buildings, horizontal displacements are limited so that the vertical deformations of the existing building foundations do not exceed the normative depending on the technical building's condition.

The spatial view of the excavation shoring is shown in Fig. 10.

The calculation of the new construction influence (namely the excavation in sections 1-1 and 2-2) was performed in a plane nonlinear formulation by the finite element method (FEM).

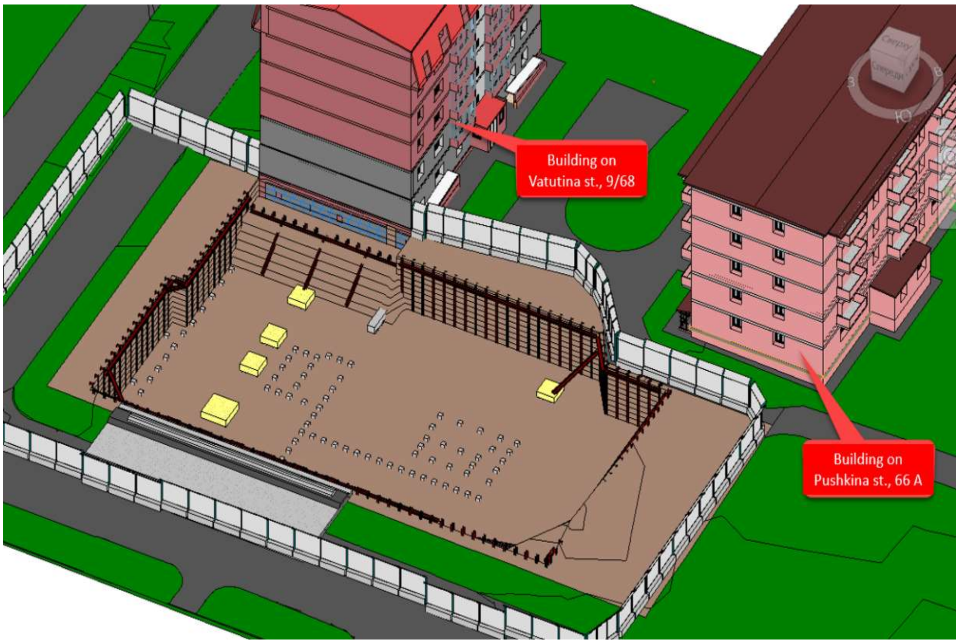


Figure 10 – Spatial view of the excavation and its shoring

To solve the problem, a software package for finite element analysis of geoengineering problems was used. Numerical modeling of the system "base - foundations of the existing building - construction of the shoring" was performed using a well-tested elastic-plastic model of the soil with the Coulomb - Mohr criterion of strength to solve similar problems.

Under these conditions, when using an elastic-plastic model of the soil with the strength criterion of Coulomb - Mohr, the known hypotheses of soil mechanics are accepted, such as:

1) the soil within each finite element is taken as a homogeneous isotropic medium;

2) at deformations, the integrity of a massif remains;

3) shapeshifting deformations are nonlinear;

4) vectors of the principal plastic deformations (and their velocities) and the principal stresses at a complex stress state are assumed to be coaxial;

5) load - simple (components of the stresses deviator increase in proportion to one parameter);

6) the coaxiality of stress and strain tensors are preserved.

The design schemes of the FEM for sections 1-1 modeling the influence of new construction at each stage are given in Fig. 5 - 9. In addition, at the initial stage, the initial stress state was modeled from the net weight of the foundation soils and existing buildings, but the deformations that occurred were zeroed because this SSS is the initial for further calculations.

Calculations of the excavation shoring elements, taking into account the stages of excavation, in particular, it is established that the shoring should be made of sheet piles (I-beams 30Sh), which should be pressed in increments of 1 m, with a wooden fence between them.

To increase the stability and reduce the deformation of the vertical elements, the development of the excavation is provided in the initial stages under the protection of the soil berm, and further - with the installation of capping beams, braces, struts, and gradual supply of the floor and outer wall of the parking lot.

Similar results of the massif's deformations at different stages of excavation shoring by FEM modeling were obtained for section 2-2 and in the area of the pillar crane.

For example, for section 2-2, excavation with minimization of the influence on the existing building is justified in the following stages:

1 – before the excavation from the surface of the site jacking the piles for the new building; immersion of vertical elements of shoring (I-beams 30Sh1) on an excavation contour; its excavation to the design mark under the protection of the berm from the ground (at an angle of about 55° with a width of 2.4 m at the base and 1.0 m at a depth of 2.4 m from the planning level); beyond the contour of the excavation arrangement of I-beams 30Sh1 capping beam at a depth of 2.4 m from the surface.

2 – installation of struts (I-beam 30Sh1), which on one side rest in the embedded part in the grilles (set in the process of concreting the grilles), and on the other one – in the capping beam; removal of the soil berm, due to which the load from the shoring is partially transferred to the foundations of the new building.

3 – works on the arrangement of spread grilles under a parking wall, the installation of its floor which will carry out a role of a spacer system and will accept loading from the shoring, it is also recommended to execute vertical reinforced concrete designs (pylons, walls) to the level of struts and only after concrete cures to remove struts and to continue performance of monolithic works.

For unloaded zones along axes 1, 9, and A it is advisable to arrange the excavation in stages:

1 – arrangement of excavation shoring from a platform surface from I-beams 30Sh1 12 m long pressed piles with an increment of 1.0 m;

2 – the pit excavation to a design depth of 4.8 m under the protection of a soil berm 2.0 m wide and 2.0 m high with a horizontal platform 1 m wide at the top;

3 – arrangement of a capping beam at a depth of 2.4 m from the surface, after which it is possible to cut the ground berm with grips up to 6 m and erect underground monolithic structures, including vertical (walls and pylons), etc.

There is also a shoring in the area of the pillar crane in the A axis – for the period of construction and installation works (the crane is located on the edge of the excavation between the axes 2 and 6) under the protection of a soil berm and struts with an increment of 4 m from double I-beams 30Sh1.

In fig. 11 some photos of the excavation shoring process are shown, and in Fig. 13 there are presented technological solutions for the erection of the underground part of the building in the area of the elements of the shoring.

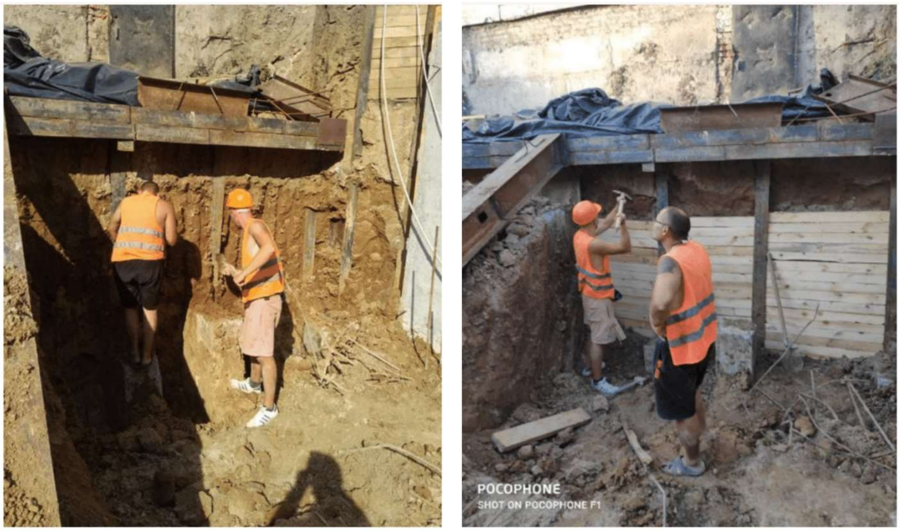


Figure 11 – Photo of the excavation shoring installation near the existing 5-story building

In order to minimize additional settlement of the existing building, it is planned to remove the strut of the excavation shoring only after installing not only the grille, but also after erecting a certain part of the vertical outer and transverse inner monolithic walls.

To confirm the calculated data on additional settlements of the foundations' base of the existing buildings, it is necessary to perform field observations in the excavation process.

The purpose of monitoring is to preserve the operational reliability and suitability of residential buildings bordering the new development zone. Its main task is periodic geodetic, including automated, surveys to quickly detect the deterioration of the technical buildings' condition or the approximation of actual (measured) sediments and slopes to their limits, control over the technology of excavation, and so on. Therefore, the following composition of geotechnical and geodetic monitoring in the process of construction of a new building was adopted:

– installation of settlement (wall) points and automated measuring and information system;

– system of instrumental (deformations measurement of foundations' bases by wall points) and visual (photo fixation) observations of existing structures;

– evaluating the results of observations and comparing them with the predicted data;

– development, if necessary, of measures to eliminate unacceptable deviations and negative consequences;

– control over the implementation of decisions.

The frequency of monitoring can be adjusted at different stages of new building construction with the deterioration of the technical condition of buildings or the approach of the measured settlements and slopes to the limit values.

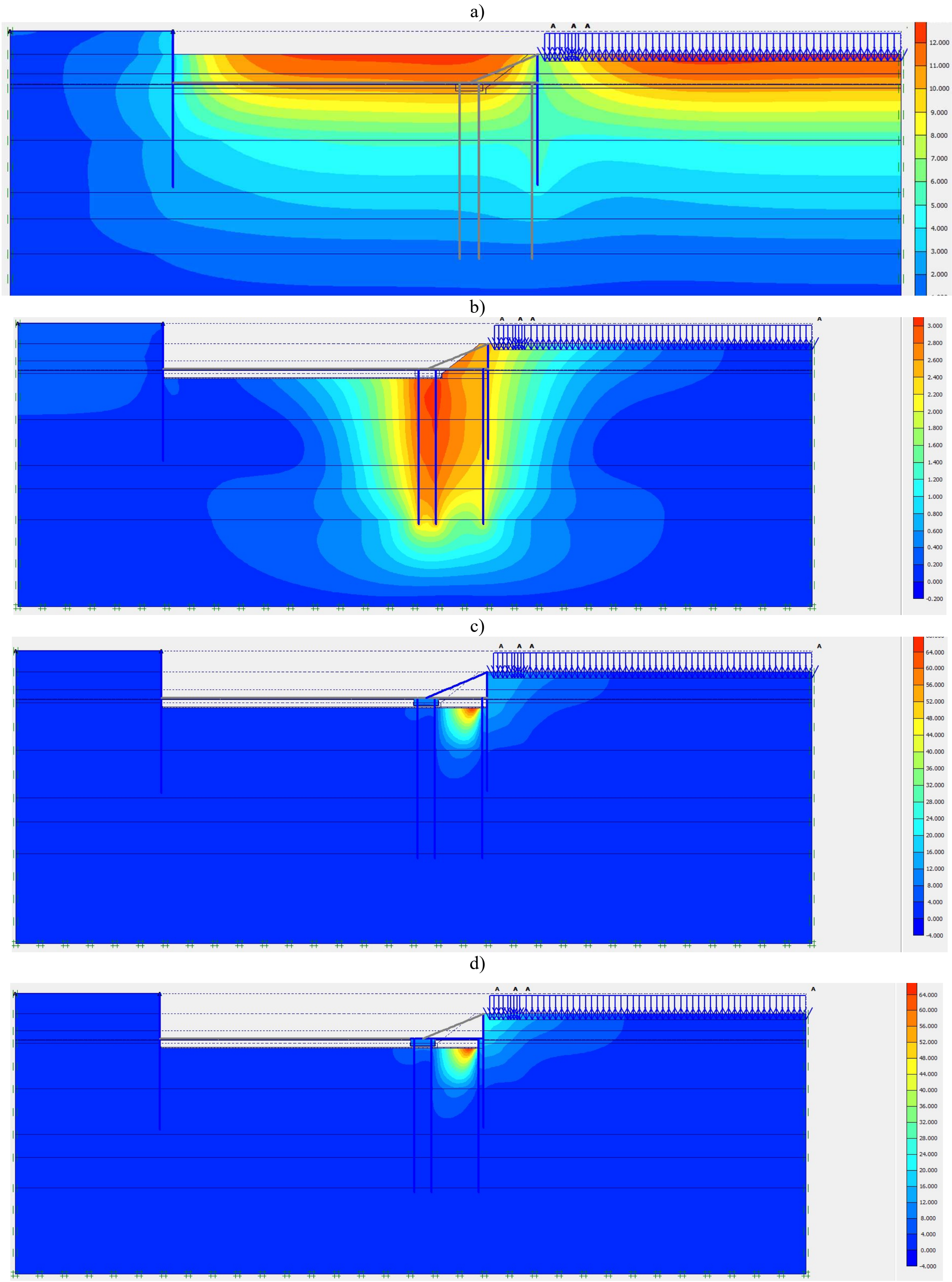


Figure 12 – Deformations of the soil mass according to the FEM modeling at the stages of excavation shoring performance:

a – execution of the "pioneer" excavation (maximum elevation of the bottom of the pit - up to 13 mm); b – arrangement of the excavation under the protection of the soil berm (maximum deformation - up to 3.2 mm at the bottom of the excavation); c – arrangement of a strut and removal of a soil berm (the maximum deformations - to 68 mm at the bottom of excavation from soil heaving); d – arrangement of the parking floor and spread grille and removal of the strut (maximum deformation - up to 68 mm at the bottom from the soil heaving, ie did not increase compared to the previous stage)

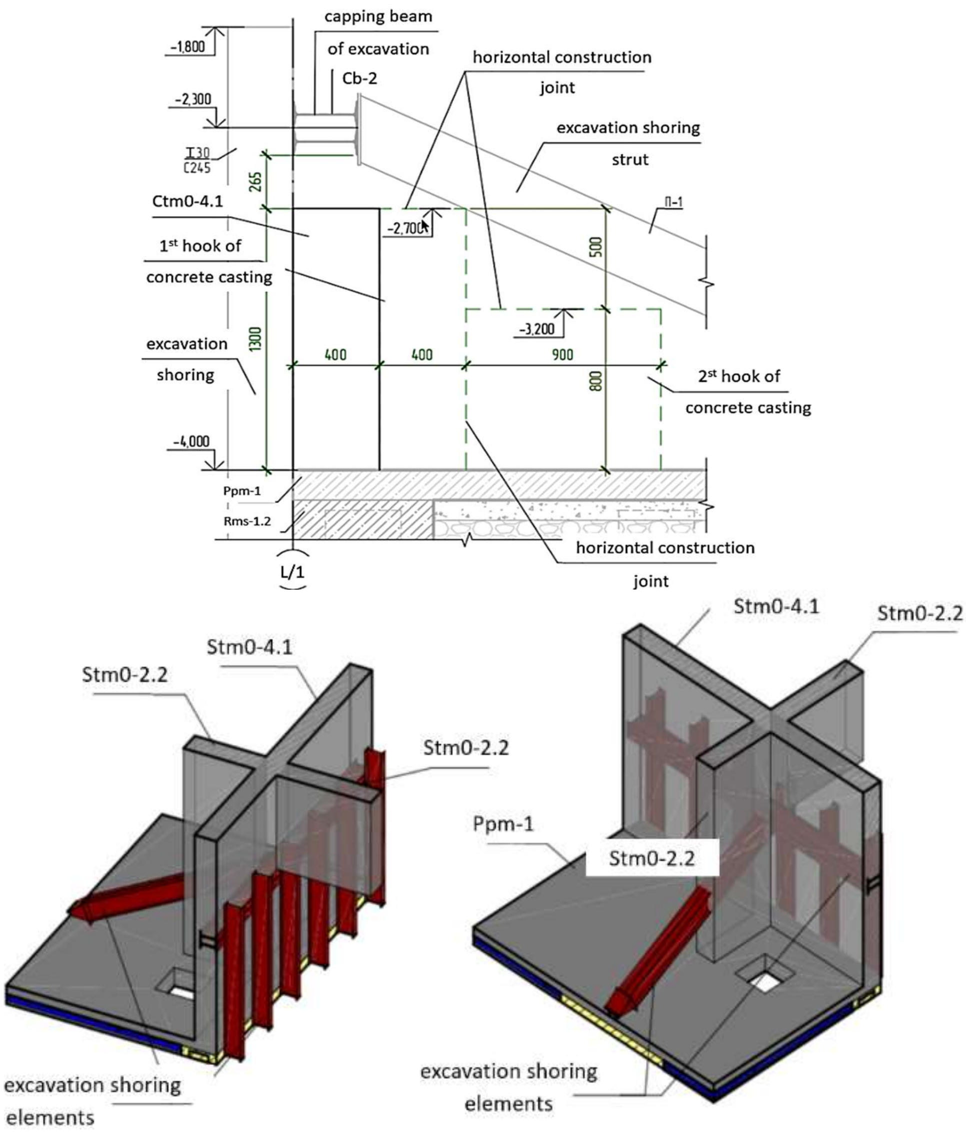


Figure 13 – Technological scheme of performance of the underground part of the building in the area of the shoring

Conclusions

Thus, on a typical full-scale object (multi-apartment residential building on piles) in the conditions of dense development (six- and five-story residential buildings on the shallow foundations and urban infrastructure) and soaked loess soil, it was minimized to regulatory requirements, the possible impact of new construction in a deeper excavation compared to the existing foundations level.

1. According to the results of the calculation of the excavation shoring stability in section 1-1 (depth 3 m taking into account the "pioneer" excavation with a depth of 1.8 m), it is established that its shoring can be made of vertical elements (I-beams 30Sh1) 10 m long with an increment of 1.0 m and struts with an increment of 4 m (from I-beams 30Sh1), between the elements, it should be created a wooden fence of boards with a thickness of 50 mm and connect with a capping beam (I-beam 30Sh1). The maximum additional settlement of the existing residential building foundations will not exceed 8 mm. This excavation technology is the cheapest.

2. According to the results of the calculation of the excavation shoring stability in section 2-2, it is determined that the shoring should be made of vertical elements (I-beams 30Sh1) 12 m long with an increment of 1.0 m and struts with an increment of 6 m, between the elements, a wooden fence of boards 50 mm thick should be made and connected by a capping beam (I-beam 30Sh1). The depth of the excavation is 4.7 m. The maximum additional settlement of the foundations of the existing building reaches 8.5 mm. In addition, it was found that after the arrangement of the parking floor and spread grille under its walls in the case of removal of the strut the foundations' settlement may increase to 12.5 mm, which is more than the maximum allowable value of 10 mm. Therefore, when carrying out work, the struts should not be removed until the vertical basement wall is erected to the bottom of the strut.

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