



Construction of Underground and Multi-story Car Parks in High-density Urban Areas

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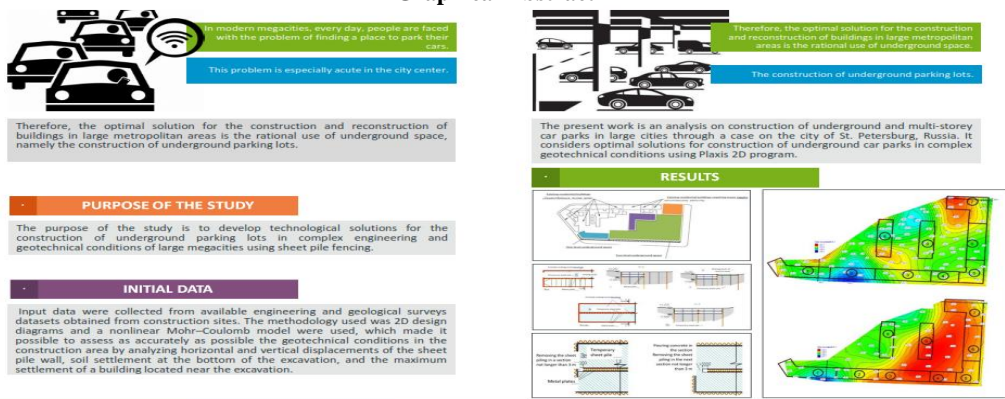
Complex Geotechnical Conditions

A B S T R A C T

In modern megacities, every day, people are faced with the problem of finding a place to park the cars, this problem is especially acute in the city center. The number of existing parking spaces is sorely lacking in view of the rapid growth in the number of cars. Therefore, the optimal solution for the construction and reconstruction of buildings in large metropolitan areas is the rational use of underground space, namely the construction of underground parking lots. The present work is an analysis on construction of underground and multi-story car parks in large cities through a case on the city of St. Petersburg, Russia. It considers optimal solutions for construction of underground car parks in complex geotechnical conditions using Plaxis 2D program. The purpose of the study is to develop technological solutions for the construction of underground parking lots in complex engineering and geological conditions of large megacities with the use of sheet pile fencing. Input data were collected from available engineering and geological surveys datasets obtained from construction sites. The methodology used was 2D design diagrams and a nonlinear Mohr–Coulomb model was used, which made it possible to assess as accurately as possible the geotechnical conditions in the construction area by analyzing horizontal and vertical displacements of the sheet pile wall, soil settlement at the bottom of the excavation, and the maximum settlement of a building located near the excavation. As a result, professional recommendations were developed for construction of underground and multi-story car parks in complex geotechnical conditions: it is necessary to carry out complex geotechnical support of construction; when constructing a pit in difficult engineering and geological conditions, construct a pit with metal spacer systems (open pit); when constructing a pit near existing buildings and structures, it is very important to take into account the relative position of the base of the foundation and the pit being constructed; accurately and reliably perform calculations in the design and implementation of the construction of underground parking as part of new construction or reconstruction of previously constructed buildings in difficult engineering and geological conditions. The authors of the article have developed new technological solutions that are of great scientific and practical significance to improve the reliability and safety of preserved architectural monuments during the construction of underground parking lots, as well as the safety of neighboring buildings that may be affected by construction or reconstruction.

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Graphical Abstract



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1. INTRODUCTION

In countries with advanced economies, underground parking is gaining more and more popularity due to the lack of space on the surface and the growing number of cars. Some cities in Asia already include in their city policy the presence of underground garages under certain standards under all new buildings.

In Europe, one of the deepest car parks in Leiden, the Netherlands, is about 22 meters deep, which corresponds to a 7-storey building. In China, in the city of Hangzhou, an automatic 12-level parking with a depth of about 40 meters for 200 cars was built. Obviously, with the growth in the number of cars, underground parking lots will only deepen. The University of Minnesota Civil Engineering Faculty building stands out from public buildings, which has 7 underground floors, and it was built back in 1983.

Continuous global growth of urban areas and high-rise construction with underground story requires attention to lowering development footprint in order to preserve natural landscapes that makes it important to provide sufficient spaces, such as, for vegetated open areas and car parks .

Modern cities are facing major issues with acute shortage of parking spaces, especially in city centres due constant growth in the number of cars. On the other hand, while parked vehicles impose negative impacts on lawns, grass verges and general environmental situation, double-parking constructions also occupy spaces for cars to pass by and negatively influence the road safety.

Therefore, efficient use of underground spaces, including development of underground car parks, deems to provide optimal solution for construction and renovation of buildings in large cities. However, a range of difficulties commonly arise in underground parking construction, such as, due to high density in city centers and complex geotechnical conditions (1-8).

Figure 1 shows the past twenty years history of investment and leading countries, including China, the Republic of Korea, Japan, the USA, France, Taiwan, Canada, and Germany, in development of innovative technologies for underground parking construction.

Note that Intelligent Polytron Technologies (China), Beijing Zhongyan Zhibo Technology (China) and Hangzhou Haoche Technology (China) are major companies that lead in the development of innovations for underground parking construction are shown in Figures 2 and 3.

Over a long period of operation of residential buildings, the requirements for living conditions have also changed, which led to obsolescence of residential buildings of old buildings. The elimination of factors of physical and moral depreciation of residential buildings of old buildings occurs during their overhaul and reconstruction. In the case of cultural heritage objects, this is an adaptation for modern use. A demanded and

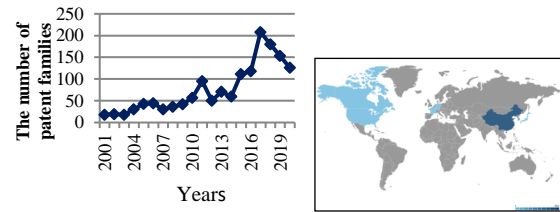


Figure 1. Investment trends over the past twenty years (Left) and Leading countries (Right) in underground parking construction technologies

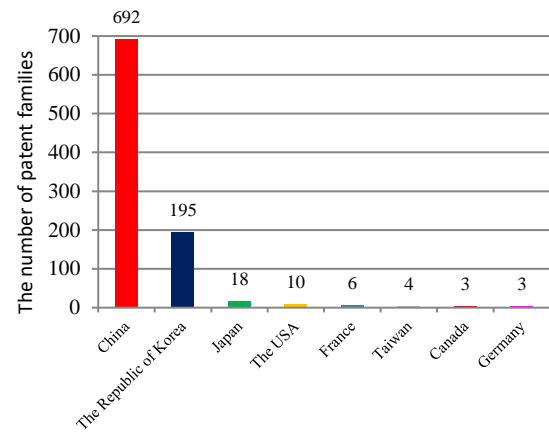


Figure 2. Patent families in the field of underground parking construction by country

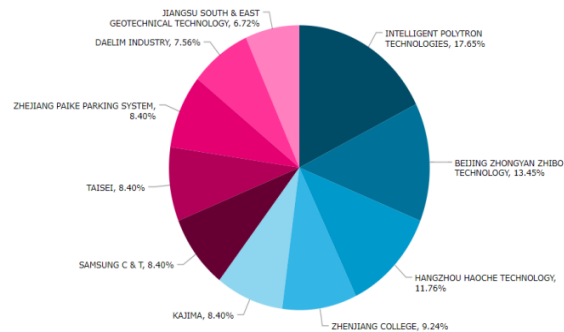


Figure 3. Shares of key players in the development of innovative technologies for underground parking construction

justified action to improve the investment attractiveness and quality of life of citizens living in the central districts of the city is underground parking, the construction of which should create zones of comfortable stay by eliminating car parking in courtyards and on adjacent streets (9, 10).

Today, underground parking lots are an essential element of the infrastructure of any urban facility: a shopping mall, business center or residential building. The cost of real estate directly depends on the characteristics and capacity of the parking lot.

The advantages of underground parking lots are obvious: they save free space, can be located under roads and buildings, and sanitary and hygienic requirements for their location are much milder compared to the norms for surface parking lots and garages. Underground parking lots also save energy by reducing energy consumption due to the constant temperature of the air underground (provided the building is well insulated). The disadvantage of underground parking lots is the high cost of their construction. It is necessary to take into account internal communications, hydrogeological conditions and other factors. On the other hand, designing an underground parking lot allows to effectively use the remaining area of the structure for residential, office and commercial purposes. In the development of the central districts of the city for a number of reasons should be preferred to underground parking above ground traditional format. Designing an underground parking lot requires many details to be taken into account. First of all, these include safety, ease of use, manufacturability, waterproofing, availability of necessary engineering systems, sufficient width of entrances and exits, ceiling height and much more. Often it is not easy to comply with all the requirements, and therefore the construction of underground parking should involve professionals (11, 12)

The most important characteristic of the site for building an underground parking lot is the hydrogeological conditions, in particular, water currents and soil composition. The problems of stabilization of weak soils in Russia were studied by many research scientists (13-21). Numerous works by Dashko et al. (22) are devoted to the issues of justification of building construction in complex engineering-geological and hydrogeological conditions of St. Petersburg. These features can limit the depth of the parking lot and significantly complicate construction works (13).

It is also necessary to take into account the possible impact of the new construction on the foundations of nearby buildings, as well as various urban planning restrictions.

2. DATA COLLECTION AND METHODOLOGY

Depending on the geotechnical conditions and density of urban development, countries use different innovative approaches and technologies in underground parking construction. For instance, in dense urban areas, sheet piling has become a popular choice in construction of underground car parks since it does not have a negative effect on the surrounding buildings and structures .

Sheet piles have a relatively high moment of resistance in relation to their cross-sectional area and a small thickness (Figure 4).

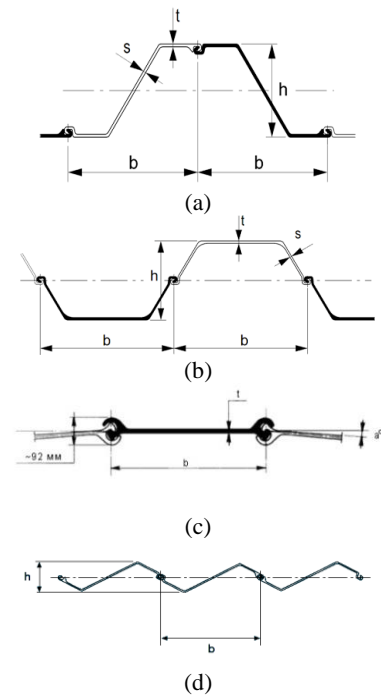


Figure 4. Types of sheet piling (a – Z-type sheet pile; b – U-type sheet pile; c – flat sheet pile; d- jagged wall of Z-type sheet piles)

In constructing sheet pile walls, metal profiles are most often used, which vary in their cross-sections and interlock types. Hook-type interlocks provide for ease of installation and produce a strong connection between two elements, ensuring the strength of the structure (14-16).

Sheet piles are commonly used as permanent structural elements in substructures and other applications. For example, in order to build a block of flats with four floors and one underground level in a densely populated area in France, stringent requirements were imposed on the construction site, which were partly due to its being located close to a tramway track and other buildings, including a 19th-century monastery (23-33). The allowable deflection of the sheet pile wall was limited to 20 mm and a fifty-year service life had to be guaranteed for the steel elements. To protect the nearby high-voltage power lines, a nine-metre-high barrier was built (Figure 5).

As retaining walls made of steel sheet piles take up only a minimum of space, it made them the ideal retaining-wall solution for a new underground car park. The original design included sheet piles as temporary retaining elements and a permanent concrete wall. Later, changes were made to the project to use sheet piles as permanent elements. In addition to improving the watertightness of the excavation, the sheet pile wall also resists lateral earth pressure, including traffic and tram loads.

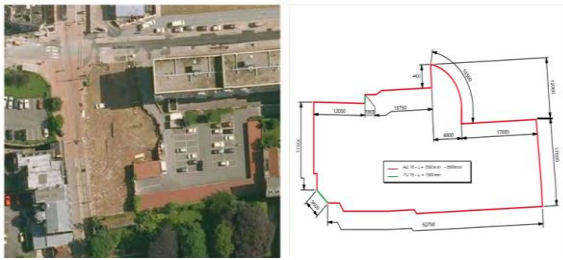


Figure 5. Plan of the construction site of the block of flats with an AZ 18 sheet pile wall that surrounded the excavation during the construction phase and was subsequently left in place to serve as the outer wall of the underground car park

The vertical loads were taken by a deep foundation of bored concrete piles. Several boreholes were drilled to a depth of up to 16 m. Soil analysis revealed the following soil layers (top to bottom):

- one metre of made ground;
- up to seven metres of silty to clayey river sand (angle of internal friction: 20-28°, cohesion up to 20 kN/m²);
- groundwater 1.5 m below ground level (El. +40.30 m);
- hard clayey substratum down to the well bottom.

Before driving the sheet piles, the clayey soils were loosened with a 460-mm-diameter drill. The project mainly used AZ 18 profiles, as well as several PU 18 sheet piles, with both types being made of S 240 GP steel. The AZ and PU sheet piles with a length of 7.5 to 8.5 m were driven into the hard clayey substratum using a rig-mounted ABI vibratory hammer (MRZV 925).

To prevent damage to surrounding buildings, the city had introduced strict vibration limits. Therefore, special equipment was installed at the construction site to measure the vibration level.

After the sheet piles were driven into the clayey substratum, an RC capping beam was poured onto the piles.

To carry the horizontal reaction of the retaining walls during construction, large-diameter steel tubes were bolted to the capping beam.

The sheet piles were left in the ground as a permanent part of the building, and the top slab of the car park served as bracing. Rebars were fixed to the sheet piles prior to pouring the slab of the car park, ensuring proper connection. The access ramp also has sheet pile retaining walls. The AZ 18 retaining wall has a total length of approximately 150 m.

In order to ensure the watertightness of the excavation and that of the future underground car park, several sealing measures were taken. The common AZ 18 double pile locks were welded together. In addition, the leading locks installed below the bottom slab were filled with a bituminous sealant.

After the installation of the steel sheet piles, excavation work began inside the retaining wall. To be able to work in the dry, the water table was lowered by two metres using pumps inside the excavation.

During the excavation operations, parts of the interlocks visible from the inside of the excavation were seal-welded.

To complete the car park waterproofing system, a small horizontal drainage system was created. Since the upper structure rests on concrete partitions, the connection between the bottom slab and the sheet piles did not have to take great loads.

As a result, 140 tonnes of steel sheet piles with a capping beam were installed within six weeks despite the complex shape of the excavation.

In the United States, during the construction of a mixed-use development consisting of 416 condominium residences with a large underground car park for 970 cars, geotechnical surveys revealed water at a depth of three metres below ground within the four-metre-thick layer of limestone. Beneath the limestone, there was a three-metre layer of loose sand, which lay over dense limestone and sandstone.

Instead of conventional temporary excavation support and an in-situ concrete wall, a bottom-up solution relying on sheet piles was chosen for the project as it provided for significant savings in construction costs and time. Being used as permanent retaining elements, sheet piles greatly simplified the construction process. First, a separate foundation system made of concrete bearing columns was constructed for seven seven-story houses. The sheet piles of the retaining wall for the 7.5-metre-deep excavation for the two-level underground car park were driven through the limestone until the design elevation was reached (Figure 6).

The construction was carried out using steel sheet piles as permanent retaining elements after the completion of excavation work and as temporary separation walls as the site was divided into several construction bays. Subdivision into several sections helped to reduce the concrete pour for the bottom slab, reaching manageable sizes.

About 3,000 metric tons of steel sheet piles were installed using a crane-mounted vibratory hammer.

About half of the piles remained in the ground at the end of construction as the permanent outer wall of the basement floor.

Nine-metre-long AZ 26 sheet piles with a web / flange thickness of 12.2 / 13.0 mm were selected to provide penetration through the hard soil to the design depth. A high-pressure pile equipped with a driving shoe was driven ahead of the sheet pile line to fragment the limestone, making it possible to drive the sheet piles without damage.

After pile driving was completed, formwork was installed at the heads of the sheet piles and a concrete cap was poured. Temporary ground anchors were incorporated in the capping beam that had been drilled into the sheet piles to provide temporary support until the 84 floor slabs were poured. A 1.2-metre-thick slab was then installed to provide the seal needed to start

construction in the dry. The sheet piles, which started experiencing pressure as the water drained, were pressed against the concrete, sealing off water from below that was trying to seep through the interface between concrete and steel (17, 34-36).

The middle interlocks of the AZ 26 double piles had been welded before installation. After pumping out groundwater, the remaining interlocks were seal-welded. When the sealing was completed, the piles that served as permanent walls were cleaned and an aesthetic coating was applied (17, 18).

It looks to be more about case studies in France and USA and not related to the case study in St. Petersburg in which the data were used to as input to the present study .

Input data were collected from several underground car parks construction projects in St. Petersburg, Russia with complex geotechnical conditions especially in the city centre with high density of buildings many of which are of architectural and historical interest. Also, the city centre is characterized by weak clayey soils, and old river beds can be quite often found underground.

One of the most significant features of engineering-geological conditions of St. Petersburg, which must be taken into account in the construction of underground parking lots, is the distribution of weak clay soils. These sediments of lake-marine and lake-glacial genesis are capable of changing their behavior when the natural composition is disturbed. The impacts typical of a construction site in many cases lead to the disturbance of their natural structure. In this case, the soil ceases to work as a quasi-solid body and turns into a liquid-like medium. Therefore, it is necessary to develop technological solutions aimed at improving the reliability and safety of underground parking lots, as well as neighboring buildings and preserved architectural monuments.

Case-1

This case includes a residential development consisting of three buildings located within an area of 26,085 m² where two-level and one-level underground car parks were designed to be located at a depth of 8 m. During the construction, a pile foundation was driven. Loads per pile ranged from 120 to 150 tons, with loads on a pile group exceeding 300 tons. The piles were driven to a depth of 25 to 30 m (Figure 7).

The construction site is surrounded with four to five story 20th-century brick residential buildings. To the



Figure 6. Construction site with steel sheet piles used as permanent and temporary retaining elements

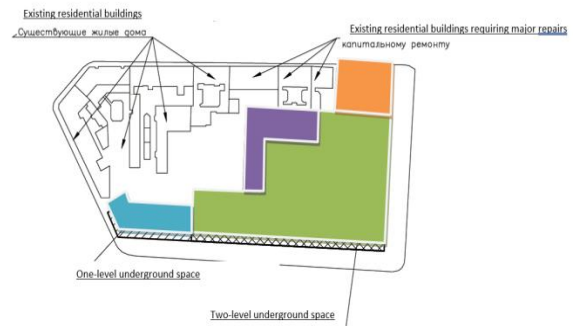


Figure 7. A building under construction with an underground car park in the central part of St. Petersburg

north and west. The buildings rest on strip rubble foundations, locally exhibit significant deformations in the form of oblique cracks, considered to be in critical condition with their foundations need to be reinforced to maintain their stability.

Moreover, the territory experienced demolition of non-residential buildings of two to three story while remains of their concrete foundations still left on the ground. The territory can be used to implement reconstruction projects and build new structures provided they comply with height restriction laws and create frontage for the block.

The underground car park consists of five sections separated by contraction joints and is separated from the main part of the building by settlement joints.

When performing calculations of underground parking lots, it is necessary to take into account the engineering and geological conditions of the construction site. The most important indicators for calculations are the characteristics of soils at the construction site, which were laid in the basis of calculations of the presented study.

When constructing buildings and structures in dense urban areas, it is necessary to take measures to monitor the condition of buildings and structures located near the object under construction. To do this, terms of reference are drawn up, which should contain a rationale for monitoring operations, goals and objectives, parameters of the newly constructed building, parameters of existing buildings and structures within the area of influence, geotechnical conditions on site, and technical monitoring requirements (19-23).

Before starting the construction of new facilities, nearby buildings and structures must be inspected to check their external and internal state and the quality of their foundations. Particular attention should be paid to structures that were built several centuries ago and have not undergone major repairs.

Usually, there are several inspection stages :

- object monitoring (visual observation system, geodetic control);
- geological and hydrogeological monitoring,

- environmental and biological monitoring;
- analytical monitoring.

When construction works are carried out in a residential area, it is necessary to conduct geotechnical monitoring throughout the entire construction period of all objects located within a 30-metre radius from the construction site.

To prevent subsidence and soil compaction within the area of influence, soils under buildings and structures located in this area should be constantly monitored (24, 25). Also, geodetic monitoring needs to be performed in order to reveal irreversible processes in soils and predict settlement and tilt of buildings.

When erecting buildings and structures in complex geotechnical conditions, it is necessary to have a reliable forecast of the absolute and differential values of settlements. Therefore, in order to ensure the most accurate forecast, these values should be calculated for both foundations and superstructures.

For a newly constructed building, it is important to make sure that settlement is kept to a minimum. In the case being considered, this is due to the fact that the building is adjacent to other buildings, for which there is a settlement limit of 2 to 3 cm since they belong to Categories II and III in terms of their health.

In this geotechnical situation, it is advisable to consider a deep pile foundation solution for the projected development (26-28).

Geological surveys revealed the following soil types are presented in Table 1.

TABLE 1. Geological description of the construction site (up to a depth of 47.2 m)

| N. n/n | Soil type | Designation |
|--------|--|-------------|
| 1. | Modern quaternary (QIV) deposits represented by man-made soils (tIV) (fill soils) | SL1 |
| 2. | Lacustrine and marine (ImIV) deposits (loose silty sands) | SL2 |
| 3. | Low-peat soils | SL3 |
| 4. | Silty sands (medium density) | SL4 |
| 5. | Soft sandy loams | SL5 |
| 6. | Fine and dense sands | SL6 |
| 7. | Very soft clay loams with interlayers of soft clay loam | SL7 |
| 8. | Upper quaternary (QIII) deposits of glaciolacustrine (lgIII) genesis represented by very soft clay loams with interlayers of soft clay loam; banded formations | SL8 |
| 9. | Soft clay loams, laminated | SL9 |
| 10. | Soft sandy loams, indistinct lamination | SL10 |
| 11. | Deposits of Glacial (gIII) genesis represented by hard sandy loams | SL11 |

| N. n/n | Soil type | Designation |
|--------|--|-------------|
| 12. | Silty sands (high density) | SL12 |
| 13. | Soft sandy loams with interlayers of hard sandy loams | SL13 |
| 14. | Middle Quaternary (QIII) sediments of glaciolacustrine (lgII) genesis represented by stiff clay loams with interlayers of semi-hard clay loams | SL14 |
| 15. | Deposits of Glacial (gII) genesis represented by hard sandy loams with soft interlayers | SL15 |

For a pile foundation, such soils as hard sandy loams of Glacial (gIII) genesis (SL11), as well as silty dense sands (SL12) lying at a depth of 19.8 to 24.9 m can be considered as a support layer for the piles (absolute elevation ranging from -14.7 to -22.0 m), as well as glaciolacustrine (lgII) soils ranging from stiff to hard loams (SL13, 14 and 15). However, soil layers SL11 and SL12 are not good options since their geology is irregular with inconsistent thickness values. As the upper layers are represented by moraine deposits, they have low bearing capacity, which also makes them unsuitable as support layers for piles. Based on the results of cone penetration tests, it is advisable to drive the piles down to layers SL13 and SL15 since these soils are located at a depth of more than 30 m from the surface.

Figure 8 (a, b) shows depth contour lines for the roofs of the layers of SL13 and SL15 layers, which are used as a support layer for piles.

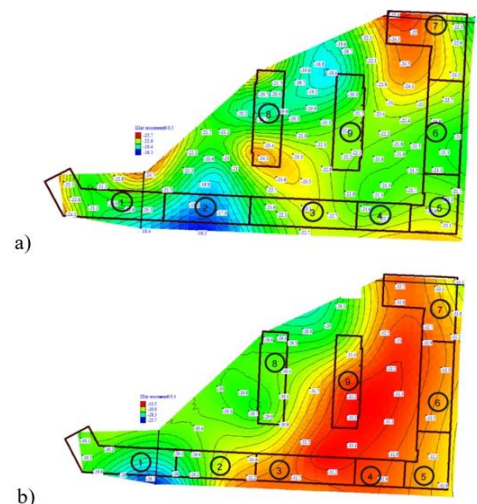


Figure 8. Depth contour lines for the roofs of the layers represented by: a) soft sandy loams with interlayers of hard sandy loams (gIII) (SL13) used as a support layer for piles in Sections 2, 3, 4, 5, 6, 8, 9; b) hard sandy loams with soft interlayers (SL15) and hard clay loams (SL16) used as a support layer for piles in Sections 1 and 7

The design depth (taking into account the depth of the capping beam) of the one-level underground car park will be about 5.2 m, and that of the two-level car park will be about 8.0 m.

When constructing a two-level underground car park, two excavation types can be used: top-down excavations and excavations with internal bracing.

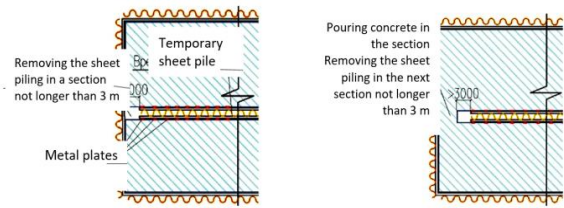
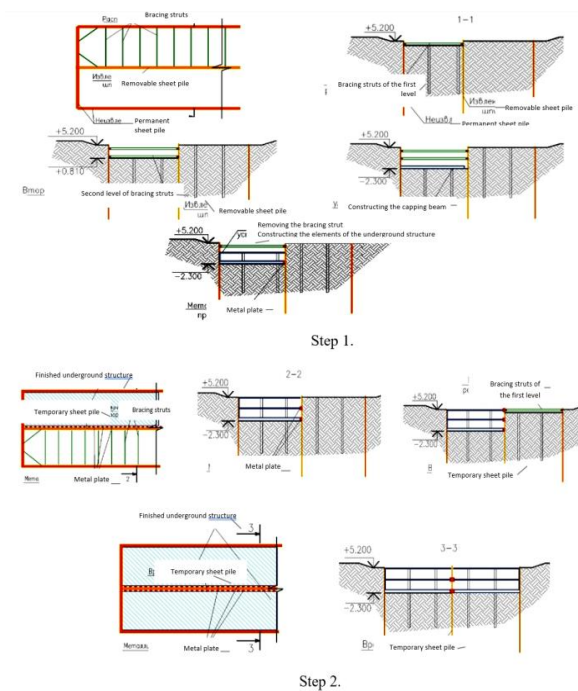
In the case under consideration, it was decided to use a braced excavation with operations being performed in separate sections (29-32).

The sequence of operations in constructing the two-level underground car park is as follows: at the first step, a two-level metal bracing system is installed in the first trench, which serves as protection in constructing the underground car park; then, operations continue in a parallel trench; at the final step, the elements of the RC structures installed in the two parallel trenches are connected to form an underground structure in the following sequence (Figure 9):

- In each section, bracing struts are installed between the elements of two underground structures at a length of 3-4 m;
- The elements of the sheet piling are removed;
- Concrete is poured in the free space the two sections;
- The operations are repeated.

The advantages of using this method include the following:

- excavation operations can be carried out in the required sequence and order;
- excavation costs are reduced;
- it becomes possible to install expansion and contraction joints;



Step 3.

Figure 9. Steps in the construction of two-level underground facilities for separate sections using metal struts and temporary sheet piling

-there is no need to excavate the soil over the whole excavation area;

-if needed, it is possible to quickly suspend operations in one individual section .

The main disadvantages of this method include:

-the need for transporting and hauling a large number of sheet piles and installing a large number of bracing systems (33-35).

3. RESULTS AND DISCUSSION

To calculate the parameters of the sheet pile wall in the excavation being discussed, the Plaxis 2D software was used. This software calculates stress and strain in an array using the finite element method.

To minimize the impact of the two-level underground car park on existing buildings and structures, the following engineering solutions were developed:

-reinforcing the foundations and superstructures of nearby buildings in order to start work on the construction of the excavation;

-using permanent sheet piles to protect the excavation walls (sheet piles with a length of 24 metres);

-using a one-level or two-level bracing system made of pipes;

-testing piles before starting work to strengthen the foundations, main piles, and sheet piles, and digging a test excavation;

-monitoring the settlements of buildings and structures located in the area of influence, the level of vibration, and horizontal displacements of the sheet piles (17, 36).

The mathematical calculations were performed using 2D design schemes and the nonlinear Mora-Coulomb model, which made it possible to evaluate as accurately as possible the engineering-geological conditions in the construction area by analyzing the horizontal and vertical displacements of the sheet pile wall, the soil settlement at the bottom of the excavation, and the maximum settlement of the building located near the excavation.

The Coulomb-Mohr theory allowed us to describe mathematically the dependence of tangential stresses of a material on the magnitude of applied normal stresses,

as well as to describe the dependence of ultimate tangential stresses on the average normal stress, since this theory is due to internal friction in a solid body. The Coulomb-Meer theory in the world practice is usually used to analyze the bearing capacity of soil masses. Under loading, soils work predominantly in shear along the surface with the lowest bearing capacity. Therefore, shear strength is the defining strength characteristic for soils. Failure is realized at the moment when the magnitude of shear (tangential) stress reaches the shear strength of the soil. Therefore, the relationship between normal stresses and tangential stresses is the strength criterion for soils.

Traditionally, analytical solutions based on the theory of limit equilibrium are used to calculate pit enclosures. In the considered case it is necessary to take into account the possibility of incomplete realization of active and passive pressures. For this purpose, it is necessary, one way or another, to set a nonlinear function of pressure dependence on wall displacement.

The simplest way of approximation of this function is the introduction of a bedding coefficient linking the values of pressure and wall displacement before reaching the active (when moving in the direction of pressure) or passive pressure (when moving in the opposite direction). To perform the calculation, special finite elements are used, whose deformability is determined by the value of the bed coefficient, and when the value of active or passive pressure is reached in the element, a nonlinear problem is solved by the method of initial stresses. In this connection, it is necessary to use models that take into account the difference of soil operation at the loading and unloading stages.

As observations of the deformations of envelope structures show, a characteristic feature of the operation of such structures is the long development of deformations in time. Calculation methods that do not take into account the time factor actually assume that after each excavation stage deformation occurs for a long period of time (until the "final" deformations are reached). In field conditions, excavation of an excavation pit may be performed relatively quickly, in which case the expected "final" deformations at all stages may not have time to develop. As a result, consideration of the time factor can have a significant impact on the nature of the performance of the envelope structure. Thus, as follows from this brief review of the theoretical assumptions of the calculation of pit envelope structures, this problem is a rather complex scientific and theoretical problem.

Based on the used Coulomb-Mohr model, the variables used in the calculations are the specific cohesion of the soil, which characterizes the resistance of the soil to shear (shear) in the absence of normal stresses at the shear (shear) site, soil characteristics, normal and tangential stresses.

Since the Plaxis 2D program was used to perform the calculations, which is a powerful and convenient finite element software package designed for two-dimensional calculations of deformations and stability of construction objects, the geometry was modeled with standard types of structural elements and loads using CAD drawing tools, which made it possible to quickly and efficiently create a finite element model. The Plaxis 2D program calculations are based on an ideal-elastic-plastic model with the Mohr-Coulomb strength criterion.

The Staged Construction mode allowed modeling the construction process by activating and deactivating soil clusters and structural elements at each stage of the calculation. Verified and stable iterative computation procedures were used. Using multi-threaded computing and a 64-bit computational kernel, Plaxis was able to compute this complex geotechnical model.

The Output program was used to output the data, which provides a variety of ways to display forces, displacements, stresses, and flows in the form of contours, vectors, and tables. Using the Curve manager option, graphs of different types of results at different stages of the calculation were created.

When calculating sheet pile parameters, 2D design diagrams were used. In calculations, the following three situations were considered: retaining wall at an elevation of +0.560 m; retaining wall at an elevation of -2.500 m; retaining wall in a complex section at an elevation of -2.500 m (adjacent building at a distance of 2.5 m).

The soil parameters used in the Plaxis 2D model when calculating the parameters of the retaining wall at an elevation of +0.560 m are presented in Table 2. The elevation of the surface is +6.000 m.

For the one-level car park, AZ 42-700N sheet piles are used. The cross-sectional area of each profile (S) is 259 cm²/m, the moment of inertia (I) is 104,930 cm³/m, the wall mass (m) is 203 kg/m², the elastic modulus (E) is 200,000 MPa, and the moment of resistance (W) is 4,205 cm³/m. The bracing struts are made of 720x10 mm metal pipes located at an elevation of +4.700 m.

Based on the calculation results, it was found that the horizontal displacement of the sheet pile wall was 12 mm. It was also found that at the bottom of the excavation, there is an upward movement of soil by 166 mm, which is caused by the poor mechanical properties of the soils. The maximum settlement of the soil near the excavation was found to be 20 mm, which meets the requirements.

The soil parameters used in the Plaxis 2D model when calculating the parameters of the retaining wall at an elevation of -2.500 m are presented in Table 3. The elevation of the surface is +6.000 m.

For the two-level car park, HZ 1080M A-12 / AZ19-700N sheet piles are used. The cross-sectional area of each profile (S) is 324.8 cm²/m, the moment of inertia (I) is 445,330 cm³/m, the wall mass (m) is 270 kg/m², the

TABLE 2. Soil parameters for Problem 1

| Designation | Elevation, m | Bulk density, kN/m ³ | Volumetric frame weight, kN/m ³ | Modulus of deformation, kN/m ² | Angle of internal friction, ° | Poisson's ratio | Cohesion, kPa |
|-------------|--------------|---------------------------------|--|---|-------------------------------|-----------------|---------------|
| SL1 | +6.000 | 16.3 | 11.0 | 5,000 | 4 | 0.3 | 11 |
| SL2 | +4.500 | 17.8 | 13.2 | 5,000 | 23 | 0.3 | 1 |
| SL3 | +3.500 | 16.3 | 10.2 | 3,000 | 5 | 0.3 | 11.3 |
| SL4 | +0.500 | 19.7 | 15.4 | 15,000 | 28 | 0.3 | 3 |
| SL5 | -1.000 | 19.3 | 14.7 | 6,700 | 9 | 0.34 | 8 |
| SL6 | -3.000 | 20.7 | 17.0 | 38,000 | 35 | 0.3 | 3 |
| SL7 | -4.000 | 19.4 | 14.9 | 6,000 | 8 | 0.37 | 6 |
| SL8 | -10.000 | 18.2 | 1.29 | 5,000 | 3 | 0.37 | 6 |
| SL9 | -13.500 | 19.1 | 14.5 | 8,000 | 7 | 0.37 | 6 |
| SL10 | -17.500 | 19.9 | 15.8 | 11,000 | 10 | 0.34 | 31 |
| SL11 | -18.000 | 22.1 | 19.0 | 21,000 | 22 | 0.34 | 6 |
| SL12 | -24.500 | 21.0 | 17.5 | 34,000 | 33 | 0.3 | 7 |
| SL13 | -28.500 | 21.8 | 18.8 | 18,000 | 20 | 0.34 | 25 |

TABLE 3. Soil parameters for Problem 2

| Designation | Elevation, m | Bulk density, kN/m ³ | Volumetric frame weight, kN/m ³ | Modulus of deformation, kN/m ² | Angle of internal friction, ° | Poisson's ratio | Cohesion, kPa |
|-------------|--------------|---------------------------------|--|---|-------------------------------|-----------------|---------------|
| SL1 | +6.000 | 16.3 | 11.0 | 5,000 | 4 | 0.3 | 11 |
| SL2 | +4.500 | 17.8 | 13.2 | 5,000 | 23 | 0.3 | 1 |
| SL3 | +3.000 | 16.3 | 10.2 | 3,000 | 5 | 0.3 | 11.3 |
| SL4 | +0.500 | 19.7 | 15.4 | 15,000 | 28 | 0.3 | 3 |
| SL5 | -1.000 | 19.3 | 14.7 | 6,700 | 9 | 0.34 | 8 |
| SL6 | -2.000 | 20.7 | 17.0 | 38,000 | 35 | 0.3 | 3 |
| SL7 | -3.000 | 19.4 | 14.9 | 6,000 | 8 | 0.37 | 6 |
| SL8 | -6.000 | 18.2 | 1.29 | 5,000 | 3 | 0.37 | 6 |
| SL9 | -9.000 | 19.1 | 14.5 | 8,000 | 7 | 0.37 | 6 |
| SL10 | -15.000 | 19.9 | 15.8 | 11,000 | 10 | 0.34 | 31 |
| SL11 | -18.000 | 22.1 | 19.0 | 21,000 | 22 | 0.34 | 6 |
| SL12 | -23.000 | 21.0 | 17.5 | 34,000 | 33 | 0.3 | 7 |
| SL13 | -30.000 | 21.8 | 18.8 | 18,000 | 20 | 0.34 | 25 |

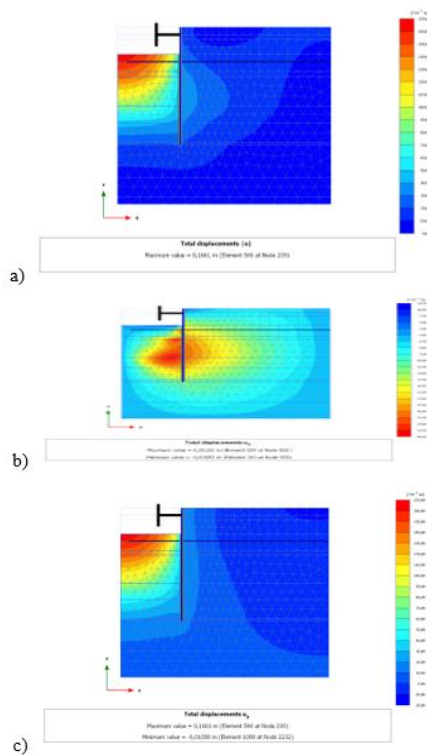


Figure 10. Calculation results for Problem 1: a) total displacements; b) total displacements along the x-axis; c) total displacements along the y-axis

elastic modulus (E) is 200,000 MPa, and the moment of resistance (W) is 7,790 cm³/m.

The bracing struts are made of 720x10 mm metal pipes, with the first level located at an elevation of +4.700 m, and the second one at an elevation of +2.250 m.

Based on the calculation results, it was found that the horizontal displacement of the sheet pile wall was 20 mm. At the bottom of the excavation, there is an upward movement of soil by 292 mm, which is caused by the poor mechanical properties of the soils. The maximum settlement of the soil near the excavation was found to be 20 mm, which meets the requirements.

The soil parameters used in the Plaxis 2D model when calculating the parameters of the retaining wall at an elevation of -2.500 m (with an adjacent building at a distance of 2.5 m) are presented in Table 4. The elevation of the surface is +6.000 m.

In this case, a combination of AU-14 sheet piles and 820x10 mm pipe piles reinforced with 40k5 I-beams and filled with B20 concrete is used.

Sheet pile parameters in this case are as follows: the cross-sectional area (S) is 132 cm²/m, the wall mass (m) is 104 kg/m², the moment of inertia (I) is 28,680 cm⁴/m, the moment of resistance (W) is 1,405 cm³/m, and the elastic modulus (E) is 200,000 MPa.

Composite pile parameters are as follows: the cross-sectional area (S) is 5,278 cm²/m, the wall mass (m) is 1,248 kg/m², the axial stiffness (EA) is 20,790,262

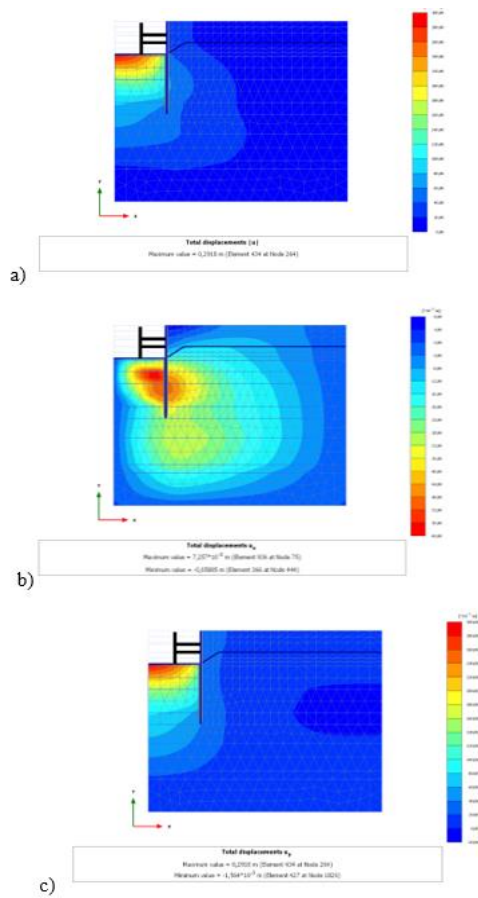


Figure 11. Calculation results for Problem 2: a) total displacements; b) total displacements along the x-axis; c) total displacements along the y-axis

TABLE 4. Soil parameters for Problem 3

| Designation | Elevation, m | Bulk density, kN/m ³ | Volumetric frame weight, kN/m ³ | Modulus of deformation, kN/m ² | Angle of internal friction, ° | Poisson's ratio | Cohesion, kPa |
|-------------|--------------|---------------------------------|--|---|-------------------------------|-----------------|---------------|
| SL1 | +6.000 | 16.3 | 11.0 | 5,000 | 4 | 0.3 | 11 |
| SL2 | +4.500 | 17.8 | 13.2 | 5,000 | 23 | 0.3 | 1 |
| SL3 | +3.000 | 16.3 | 10.2 | 3,000 | 5 | 0.3 | 11.3 |
| SL4 | +0.500 | 19.7 | 15.4 | 15,000 | 28 | 0.3 | 3 |
| SL5 | -1.000 | 19.3 | 14.7 | 6,700 | 9 | 0.34 | 8 |
| SL6 | -2.000 | 20.7 | 17.0 | 38,000 | 35 | 0.3 | 3 |
| SL7 | -3.000 | 19.4 | 14.9 | 6,000 | 8 | 0.37 | 6 |
| SL8 | -6.000 | 18.2 | 1.29 | 5,000 | 3 | 0.37 | 6 |
| SL9 | -9.000 | 19.1 | 14.5 | 8,000 | 7 | 0.37 | 6 |
| SL10 | -15.000 | 19.9 | 15.8 | 11,000 | 10 | 0.34 | 31 |

| | | | | | | | |
|------|---------|------|------|--------|----|------|----|
| SL11 | -18.000 | 22.1 | 19.0 | 21,000 | 22 | 0.34 | 6 |
| SL12 | -23.000 | 21.0 | 17.5 | 34,000 | 33 | 0.3 | 7 |
| SL13 | -30.000 | 21.8 | 18.8 | 18,000 | 20 | 0.34 | 25 |

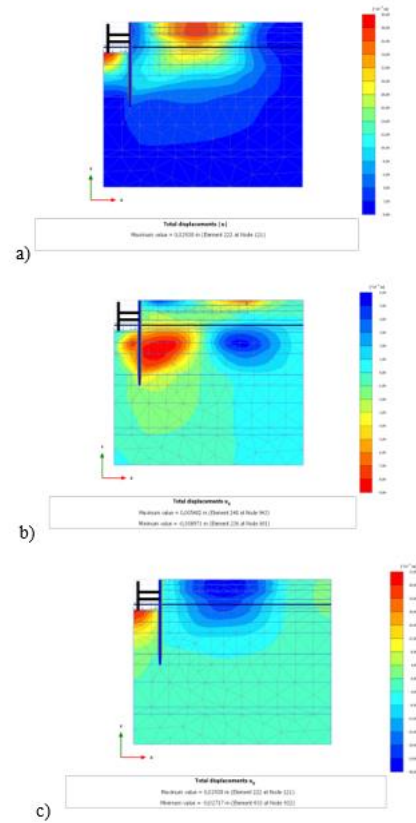


Figure 12. Calculation results for Problem 3: a) total displacements; b) total displacements along the x-axis; c) total displacements along the y-axis

kN/m², and the bending stiffness (EI) is 1,046,064 kN/m².

The bracing struts are made of 720x10 mm metal pipes, with the first level located at an elevation of +4.700 m, and the second one at an elevation of +2.250 m.

In Plaxis 2D, two slabs located at a minimum distance from each other were used in solving this problem. Between the slabs, the space is filled with elastic soil, which only transfers the load from one slab to another.

Based on the calculation results, it was found that the horizontal displacement of the sheet pile wall was 6 mm. At the bottom of the excavation, there is an upward movement of soil by 32 mm, which is caused by the poor mechanical properties of the soils. The maximum settlement of the building located at a distance of 2 metres from the excavation was found to be 30 mm, which meets the requirements.

Poor mechanical properties of soils will cause changes in the initial stress state, which will lead to a loss

of stability of the soil layer adjacent to the foundation. This will especially affect the part of the foundation that is directly adjacent to the excavation. What is the most dangerous is that in the process of excavation, plastic soil deformations may develop, with the foundation footing of the existing building being squeezed out towards the excavation. Therefore, when constructing an excavation near existing buildings and structures, it is very important to take into account the relative positions of the foundation footings and the excavation being constructed.

It is also very important to understand that the slightest mistake in the design or implementation stage of a project for building a new underground car park or renovating buildings in difficult geotechnical conditions can lead to the destruction of objects of architectural interest that have survived to this day, as well as to the resettlement of the surrounding residential buildings.

It can be seen from the earlier researches of the authors of the article that numerical analysis allows to determine quite accurately the parameters of interest, namely, to predict the development of settlements due to improved soil models taking into account its nonlinear operation under the action of load, to determine the stress-strain state of the system "soil mass - sheet pile wall - surrounding building", and also that when designing underground engineering facilities in complex engineering-geological conditions it is best to use for mathematical calculations the following parameters: «soil mass - sheet pile wall - surrounding building».

Objectivity and correctness of the authors' judgments are confirmed by the use of proven methods of mathematical modeling, implemented in the engineering software package Plaxis 2D, as well as positive results of experimental studies in full-scale conditions. The results of this study are confirmed by the fact that the calculated values coincide with the experimental data by 92%. According to the results of the calculations, it was found that the horizontal displacements of the sheet pile wall in the 1st, 2nd and 3rd problem were: 12 mm, 20 mm and 6 mm, respectively. Whereas in-situ measurements of sheet pile wall displacement showed values of 11, 19 and 5 mm. The same convergence was shown by the calculated soil displacement values and calculations of the maximum settlement of the soil near the excavation. This confirms the reliability of the calculations.

The innovativeness of the performed research consists in the use of new approaches and solutions for the construction of underground parking lots and multi-level parking lots in complex engineering and geological conditions of megacities.

4. CONCLUSIONS

To ensure the safety of objects of architectural interest during the construction of underground parking lots and

the safety of nearby buildings that may be affected by construction or renovation works, it is necessary to conduct comprehensive geotechnical monitoring. Due to the complexity and multifactor nature of geotechnical problems, it is possible to find a solution in most cases only using modern numerical methods based on physical and geomechanical nonlinear models.

Objectivity and correctness of the authors' judgments are confirmed by the application of proven methods of mathematical modeling, implemented in the engineering software package Plaxis 2D, as well as positive results of experimental and field studies.

The results of this study are confirmed by the fact that the calculated values coincide with the experimental data by 92%. According to the results of the calculations, it was found that the horizontal displacement of the spindle wall at setting 1, 2 and 3 tasks amounted to: 12 mm, 20 mm and 6 mm, respectively. At the same time, field measurements of the spindle wall displacement showed values of 11, 19 and 5 mm. The same convergence was shown by the ground motion calculation and the calculation of the maximum settlement of the ground near the pit. This confirms the accuracy of the calculations.

The results presented in the paper are of great scientific and practical importance for improving the reliability and safety of preserved architectural monuments during the construction of underground parking lots, as well as the safety of neighboring buildings that may be affected by construction or reconstruction.

The results of tests and calculations can be used by companies engaged in the design and construction of underground parking lots in complex engineering and geological conditions, as well as by organizations engaged in the control of serviceability of structures, design of the zero cycle of foundations and earthworks. The results can be used by scientific-technical and research institutes in the implementation of similar projects, as well as in the educational process of training specialists of the highest category.

5. ACKNOWLEDGMENT

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Persian Abstract

چکیده

در کلان شهرهای مدرن، هر روز مردم با مشکل یافتن مکانی برای پارک خودروها مواجه می شوند، این مشکل به ویژه در مرکز شهر حادثتر است. با توجه به رشد سریع تعداد خودروها، تعداد فضاهای پارک موجود به شدت کم است. بنابراین راه حل بهینه برای ساخت و ساز و بازسازی ساختمان ها در کلانشهرهای بزرگ، استفاده منطقی از فضای زیرزمینی، یعنی احداث پارکینگ های زیرزمینی است. کار حاضر تحلیلی بر ساخت پارکینگ های زیرزمینی و چند طبقه در شهرهای بزرگ از طریق پرونده ای در شهر سن پترزبورگ روسیه است. راه حل های بهینه برای ساخت پارکینگ های زیرزمینی در شرایط پیچیده ژئوتکنیکی با استفاده از برنامه Plaxis 2D در نظر گرفته است. هدف از این مطالعه توسعه راه حل های فناورانه برای ساخت پارکینگ های زیرزمینی در شرایط پیچیده مهندسی و زمین شناسی کلانشهرهای بزرگ با استفاده از حصار شمع ورق می باشد. داده های ورودی از مجموعه داده های مهندسی و بررسی های زمین شناسی موجود به دست آمده از سایت های ساخت و ساز جمع آوری شد. روش مورد استفاده، نمودارهای طراحی دو بعدی و یک مدل غیر خطی موهر-کلمب بود که امکان ارزیابی دقیق ترین شرایط ژئوتکنیکی در منطقه ساخت و ساز را با تجزیه و تحلیل جابجایی های افقی و عمودی دیوار شمع ورق، نشست خاک در منطقه فراهم کرد. پایین حفاری، و حداکثر استقرار یک ساختمان واقع در نزدیکی حفاری. در نتیجه، توصیه های حرفه ای برای ساخت پارکینگ های زیرزمینی و چند طبقه در شرایط پیچیده ژئوتکنیکی ارائه شد: لازم است پشتیبانی ژئوتکنیکی پیچیده ساخت و ساز انجام شود. هنگام ساخت یک گودال در شرایط سخت مهندسی و زمین شناسی، یک گودال با سیستم های فلزی فاصله ساز (چال باز) بسازید. هنگام ساخت گودال در نزدیکی ساختمان ها و سازه های موجود، توجه به موقعیت نسبی پایه فونداسیون و گودال در حال ساخت بسیار مهم است. انجام محاسبات دقیق و مطمئن در طراحی و اجرای ساخت پارکینگ زیرزمینی به عنوان بخشی از ساخت و ساز جدید یا بازسازی ساختمان های قبلی ساخته شده در شرایط سخت مهندسی و زمین شناسی. نویسندگان مقاله راه حل های فن آوری جدیدی را ایجاد کرده اند که از اهمیت علمی و عملی زیادی برای بهبود قابلیت اطمینان و ایمنی بناهای معماری حفظ شده در طول ساخت پارکینگ های زیرزمینی و همچنین ایمنی ساختمان های مجاور که ممکن است تحت تأثیر ساخت و ساز قرار گیرند، ایجاد کرده اند.