Features of underground space formation at the base of high-rise buildings

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Abstract. The article discusses the relevance of high-rise construction and the factors that determine the possibility of large-scale development of underground space. The analysis of the engineering-and-geological conditions of the site, the trial design as a search for the optimal solution for the construction of foundations, the basic architectural and design solutions for the arrangement of the underground space at the base of a high-rise building, the design-basis justification of the stability of excavation pit shoring, the technology of geotechnical operations are given.

1. Introduction

The need for high-rise construction is growing every year without losing its relevance for a long time. The popular appeal of big cities and intensive population growth leads to higher-density development, which is a natural process of urbanization. The possibility of the megapolis growth "broadwise" is gradually running its course. This is due to the shortage of free urban areas, aggravation of the transport situation, the high cost of land, etc. The solution to this problem found its way into high-rise construction with integrated development of underground space, the whose main concept is the efficient use of the ground part of the city, namely, the preservation of green areas, improvement of the aesthetic qualities of the urban environment by means of increasing underground parking lots, etc.

Today, there are several dozens of high-rise buildings in Saint Petersburg, but not every one of them was designed with a developed underground space. For example, the Lider Tower, whose height is about 145 m, has only a "minus" ground floor under it that is designed to accommodate technical rooms. Given the traffic situation and the large number of vehicles, the lack of the required number of parking spaces is one of the main problems of the modern city. The construction of underground parking has a number of undeniable advantages, which include space saving in the conditions of already dense urban development, elimination of a large number of parked cars and the possibility of upgrading the ground part, thus creating the most comfortable living conditions for residents of the city.

From the point of view of designing, there is a question whether the construction of high-rise buildings is possible in the difficult geological conditions of Saint Petersburg. Based on the experience of past years and taking into account the successfully implemented projects, it can be concluded that high-rise construction is possible. This possibility is provided by state-of-the-art geotechnical technologies for construction of deep supports, for example, barrette piles. The construction of high-rise buildings and facilities may only be implement if they are reliably buried in soil foundation. Under a high-riser, a developed underground space shall be provided that would uniformly transfer the load from the superstructure to the foundation and reduce a pressure on the foundation soils due to the weight of extracted soil.

The purpose of this article is to analyze the features of the formation of underground space.

2. Analysis of engineering-and-geological conditions of construction site

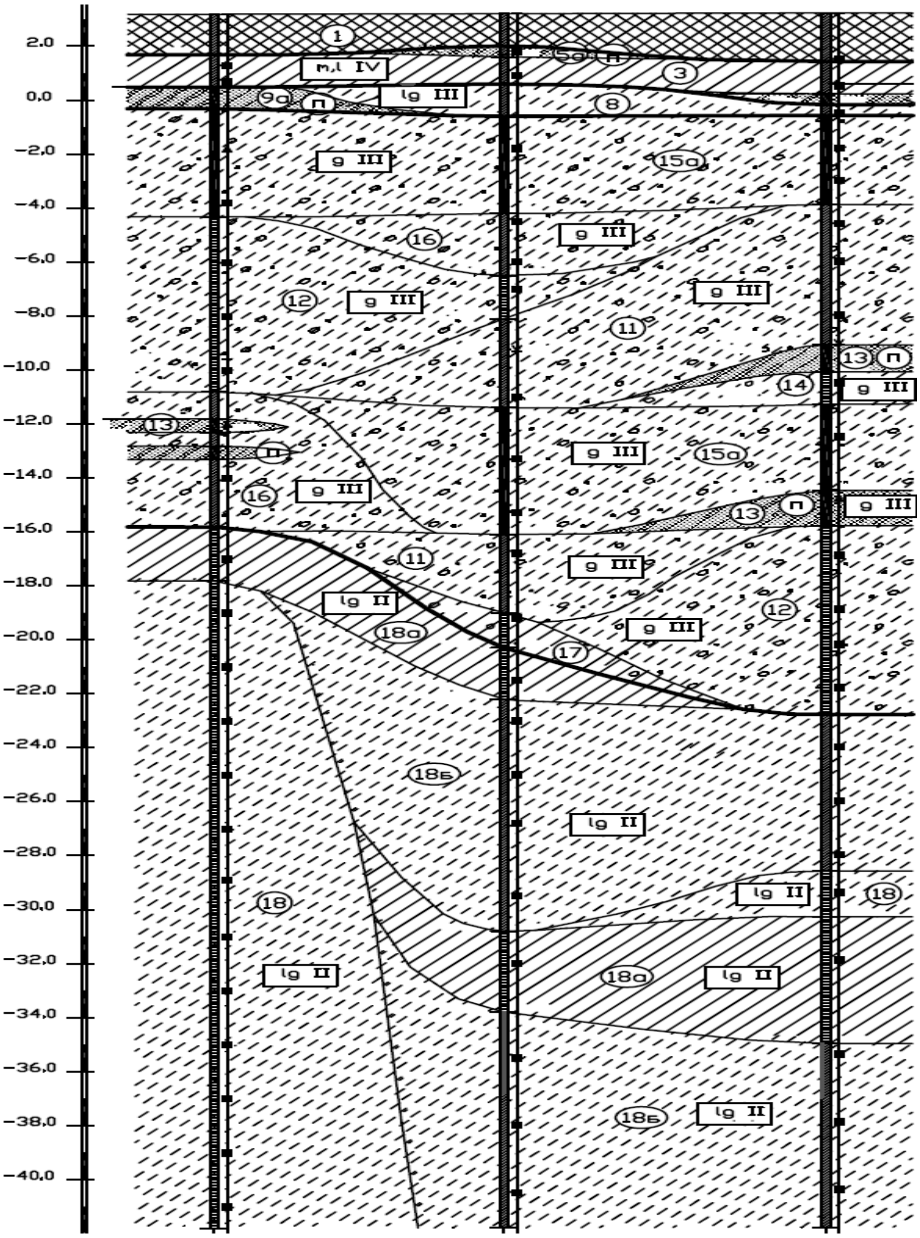

Figure 1. Engineering-and-geological section

According to the data of drilling and cone penetration test, the site is geologically formed to a depth of 45,00 m as follows:

Table 1. Soil properties

EGE No.	Soil description	E, MPa	Il	φ	c
1	Filled soils, consolidated	0.08	-		
3	Soft-plasticity clayey loam, thixotropic	8	0.54	18	17
8	Low-plasticity sandy loam, thixotropic	8	0.9	20	14
9a	Silty sands, compact	27	-	34	6
11	Low-plasticity sandy loam (IL<0,50), with 5-10% of gravel and pebble	13	0.25	26	38
12	Hard sandy loam, with 5-10% of gravel and pebble	15	-0.15	25	50
13	Silty sands, compact, with 5-10% of gravel and pebble	24	-	34	6
14	Hard sandy loam, with 10-15 % of gravel and pebble	19	-0.17	27	66
15	Low-plasticity sandy loam (IL> 0,50), with 10-15% of gravel and pebble	11	0.68	18	20
15a	Flowing sandy loam, with 10-15% of gravel and pebble	8	1.11	16	12
16	Low-plasticity sandy loam (IL<0,50), with 10-15% of gravel and pebble	18	0.26	27	47
17	Hard clayey loam, with 10-15% of gravel and pebble	16	-0.15	24	49
18	Hard sandy loam	16	-0.16	25	54
18a	Hard clayey loam	18	-0.24	24	72
18b	Low-plastic sandy loam	14	0.16	24	36

1. **t IV** - recent technogenic deposits represented by filled, consolidated (EGE 1).
2. **m, l IV-** recent marine and lacustrine deposits represented by soft-plasticity clayey loam, stratified and indistinctly stratified, thixotropic (EGE 3);
3. **lg III** - Upper Quarternary lacustrine-and-glacial deposits represented by low-plastic sandy loam, thixotropic (EGE 8), silty sand, compact (EGE 9a);
4. **g III** - Upper Quarternary glacial deposits represented by flowing sandy loam (EGE 15a), low-plastic sandy loam (IL>0,50) (EGE 15), low-plastic sandy loam (IL <0,50) (EGE 11, 16), hard sandy loam (EGE 12, 14), Silty sands, compact (EGE 13) and hard clayey loam (EGE 17);
5. **lg II -** Middle Quaternary lacustrine-and-glacial deposits represented by hard sandy loam (EGE 18), hard clayey loam (EGE 18a), low-plastic sandy loam (EGE 18b).

3. Main architectural and structural solutions for arrangement of underground space at base of high-rise building

As a development of underground space, a concept is considered to create a combined three-level underground parking under residential buildings, as well as a floor for commercial indoor spaces.

Cast-in-situ elevator shafts and stairwells serve as stiffening cores. In the underground part of the building along its perimeter there are pylons that absorb the load from the ground part and coaxially transmit it to the pile-barrettes. Between the high-rise buildings and underground parking, expansion joints are made due to a great difference in loads.

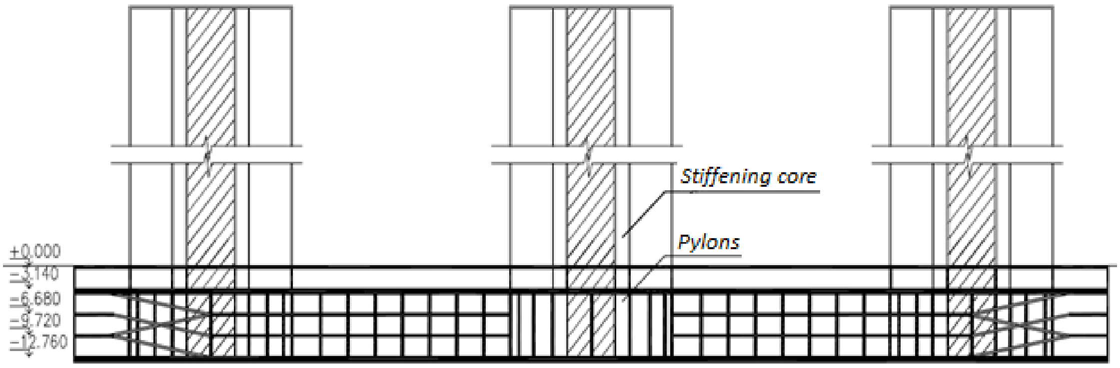

Figure 2. Architectural solution of underground space

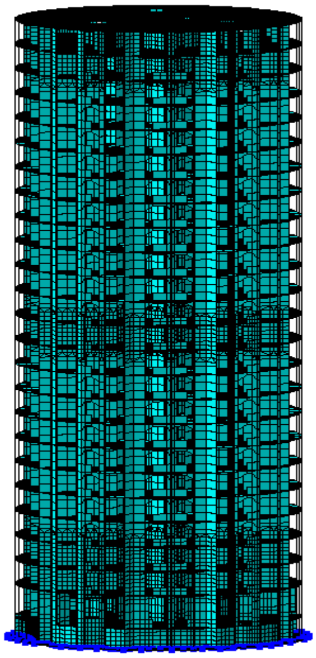

Figure 3. Computational model of superstructure

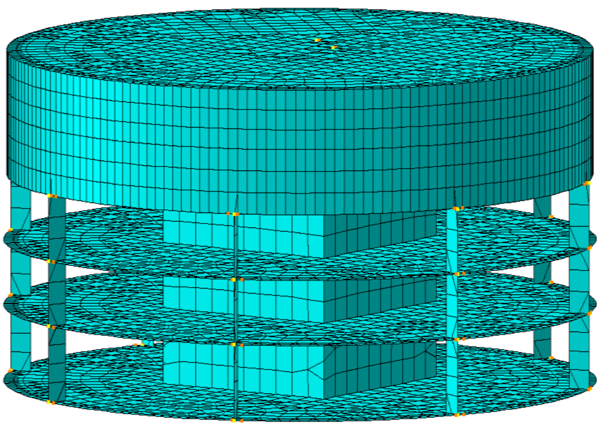

Figure 4. Computational model of substructure

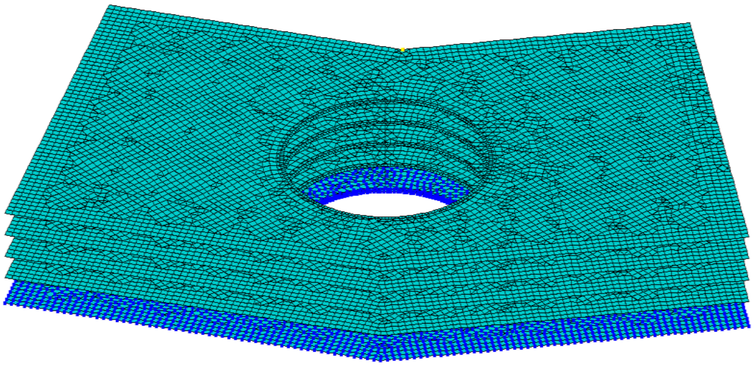

Figure 5. Computational model of underground parking

4. Trial design as search method for optimum solution for construction of foundations

Based on the data on the engineering-and-geological survey and on the loads transferred from the building to the foundation soil, let us consider an option of designing the foundation on barette piles.

Barette foundations are used in case of significant loads, which is characteristic of high-rise construction, thus being an alternative to drilled cast-in-situ piles. With the same cross-section area as circular pile, the barrette has the side surface area 2,5 times larger. It results in higher load-bearing capacity. Also, the great advantage of barrettes over drilled cast-in-situ piles is their smaller number and more economical price [1].

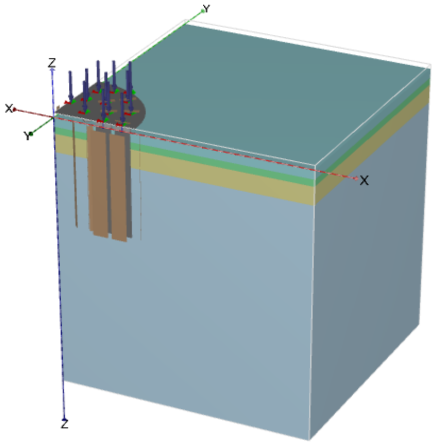

Figure 6. Computational model to determine settlement

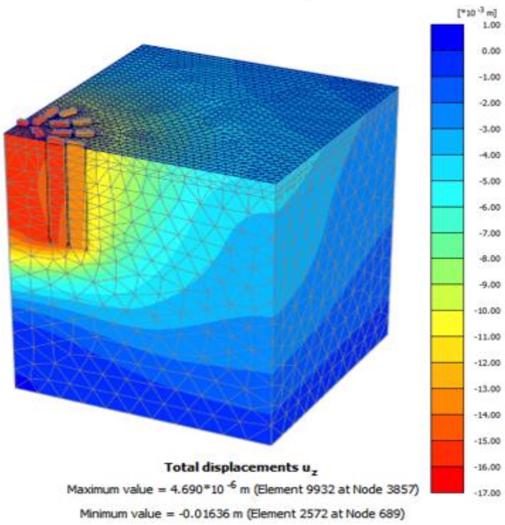

Figure 7. Settlement results for barrette piles

Table 2. Barrette piles. General information

Load from building (S=818 m^2) N	34500 t
Foundation soil	EGE-18b
Dimensions of barrette pile	3x1 m
Length	22.8 м
Quantity	43 ea.
Soil-specific load-bearing capacity of pile	10122,76 kN
Settlement	1,64 cm

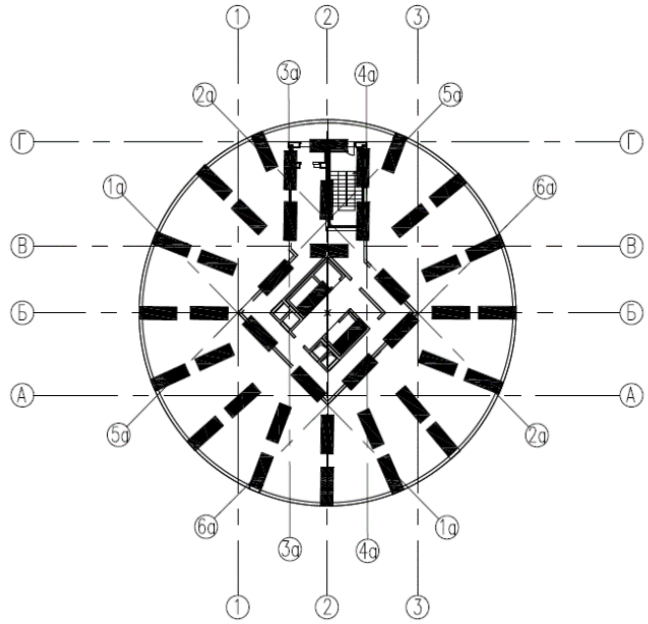

Figure 8. Layout of barrettes

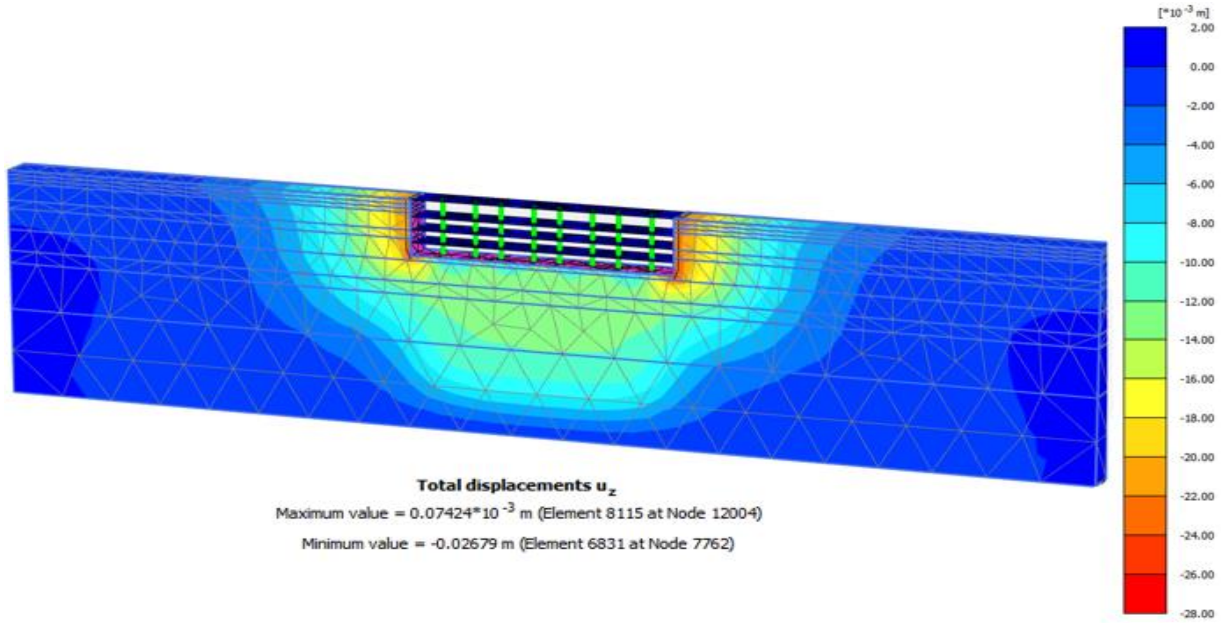

Figure 9. Settlement calculation for underground parking

Table 3. Parking. General information

Load from parking building (S=4784,76 m^2)	41500 t
Foundation soil	EGE-18
Pile Ø	600 mm
Length	19.6 м
Quantity	258 ea.
Soil-specific load-bearing capacity of pile	1911 kN
Settlement	2,68 cm

5. Design-basis justification of stability of excavation pit shoring to construct underground space for high-rise building

To construct a shoring of excavation pit 55x200 m, a diaphragm wall was selected with ground anchors as bracing system that are required to transfer the pulling forces to the soil layer. One of the main advantages of ground anchors is clearing of the excavation pit space from braces and struts, which makes the construction operations considerably simpler and faster.

Table 4. Shoring of excavation pit

Ground anchor	TITAN technology
Number of rows	3
Root embedding length	5 m
Root Ø	600 mm
Spacing	1,5 m
Soil-specific load-bearing capacity of anchor	750 kN
Diaphragm wall	600 mm
Height of diaphragm wall	22,5 m

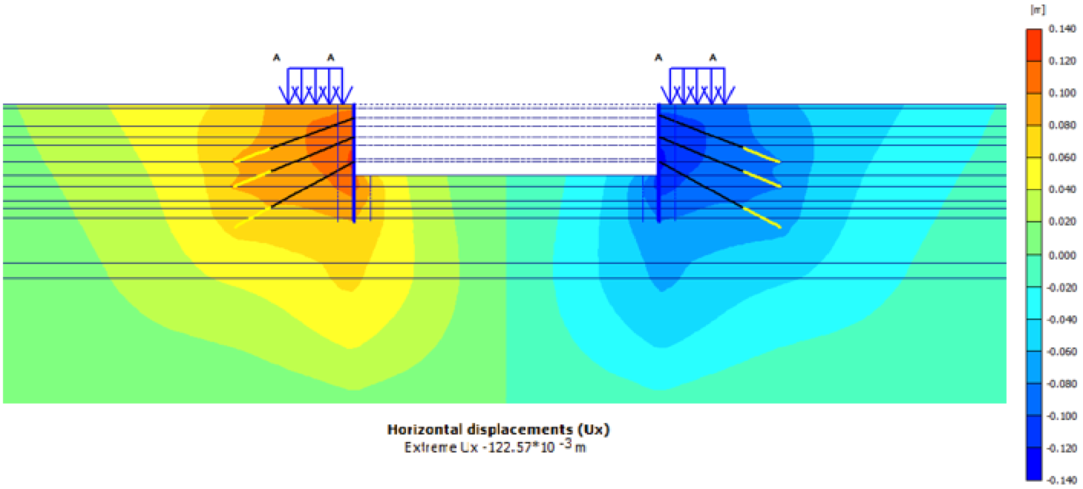

Figure 10. Horizontal displacements of shoring

A thickness of the diaphragm wall is taken to be 600 mm with support on soil: low-plastic sandy loam (modulus of deformation E = 14 MPa, index of liquidity IL = 0,16);
Computational model parameters of excavation pit wall:

- length 22,5 m;
- continuous multi-span beam buried in soil, supports in installation locations of ground anchors;
- uniformly distributed load from active soil pressure along the side surface of the wall;

load along the edge of the excavation pit from the possible installation of construction equipment, storage of materials, etc.

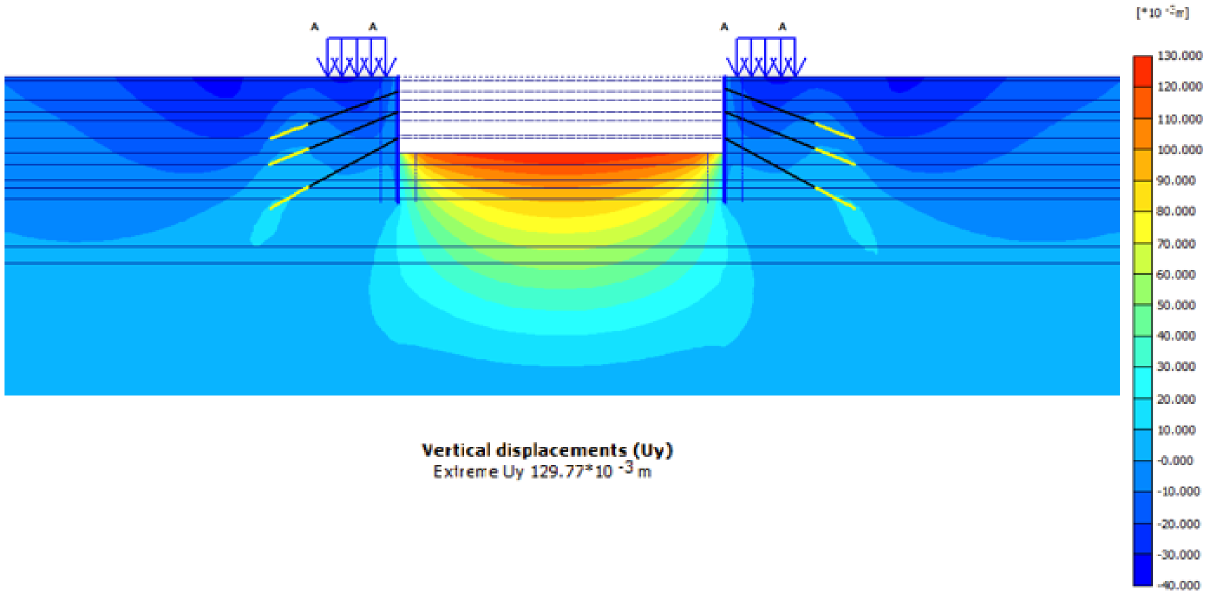

Figure 11. Vertical displacements of shoring

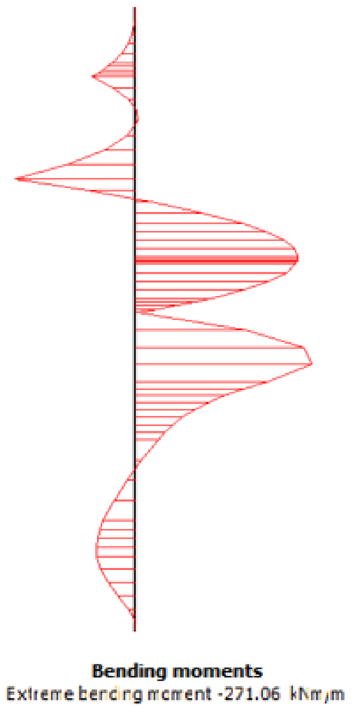

Figure 12. Diagram of bending moments

IOP Conf. Series: Materials Science and Engineering **775** (2020) 012025 doi:10.1088/1757-899X/775/1/012025

6. Technology of geotechnical operations

The construction of barrette piles is similar to the construction of the shoring structures "Diaphragm walls". The first stage is the construction of a guide wall, which serves as guide for the grab and provides the stability of the walls at the top. The base of the trench is levelled and compacted, after which the formwork panels are installed and the guide wall is reinforced and concreted. In the interval between the guides of the guide wall, the trench is excavated to full depth by separate work areas. Soil in the trench is excavated under slurry using flat two-leaf grab buckets on the rope hanger, dipper grabs, backhoe excavators with extended boom and a narrow bucket, as well as trench cutters. When concreting, separators are installed between the work areas to prevent concrete mix from entering from the work area being concreted to the next one. As a separator, it can be used a reinforced concrete pillar, or a reusable pipe that is removed after concrete has hardened in the work area before concreting the next work area. The reinforcement welded into the cages is lowered into slurry before concreting the work area. Concreting is carried out by the tremie pipe method.

Injected pre-stressed anchors are considered the most advanced and reliable as bracing system.

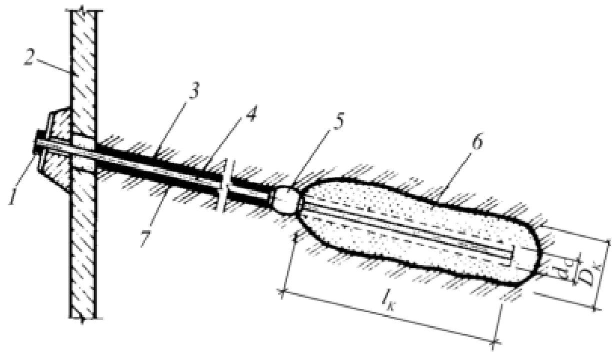

Figure 13. Injected anchor
1 - head;
2 - structure to be anchored;
3 - well;
4 - anchor bar;
5 - packer;
6 - area of injected soil;
7 - compound to protect bar against corrosion

Wells for anchors are drilled. Solid metal rods, pipes and cables are used as the carrier elements. When installing an injected anchor after the carrier has been lowered into the well, the lower part of the well is cut off by a plug (packer), and then sand-cement mixture is supplied under pressure, sometimes in in two steps: first, under a pressure of 0,3– 0,5 MPa, and then, under a pressure of 2–3 MPa. An area of compacted soil is created around the bottom of the well so that the anchor reaches a higher bearing capacity [2].

An integral part of the method of operations is the geotechnical monitoring, whose purpose is to provide a safe system of geotechnical operations during the construction of the excavation pit and substructure. The monitoring program includes: geodetic control of deformations of buildings of the surrounding development; system observations of deformations of the enclosing structures during the excavation of the pit with installation of inclinometry tubes and deformation telltales, monitoring of groundwater level fluctuation during construction, geological monitoring with the possibility of confirming the physical and mechanical properties of soils in the load-bearing layer of pile foundations and underpinning piles [3].

7. Conclusion

The presented analysis shows that the burial of the basement of a high-rise building combines two functions: structural - it is the foundation, and functional - arranged indoor spaces are used for consumer purposes.

Thus, when designing foundations for high-rise buildings, it is useful to take into account the possibility of developing the underground space by creating a combined option of the foundation construction.

When choosing a type of foundation for a high-rise building, it should be considered, in our opinion, the construction of barrettes among the other options in addition to the conventional methods. For high-rise buildings, the use of barrette-based foundation makes it possible to streamline a number of piles under the building as they have many times greater load-bearing capacity, and the very technological process of the barrette construction belongs to the category of low-impact technologies with minimum effect on surrounding soils and buildings.

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