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Effectiveness of strengthening retaining structures based on the fan method of laying anchoring on urban underground facilities

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Abstract

The purpose of the work is study the construction of a retaining structure of the pit, in conditions of a significant height difference using a multi-tiered system of strand anchors. To assess the bearing capacity of the ascending anchorage, a combined approach to the formation of a multi-tiered anchorage is used.
Methodology. The methodological basis for calculating the strength of enclosing structures is a numerical solution of the problem of a beam bending lying on an elastic-plastic base and held by anchor structures as couplings. Modeling of an ascending anchor structure is implemented in the operating environment of the GeoWall program. Based on the optimization of the method of laying the anchorage, it is planned to include the system of ascending anchors replacing the ground anchors on the first two tiers of the structural reinforcement of the retaining structure in the operation.
Results. As a result of the analysis of the pit enclosure with a multi-tiered anchor system, it was stated that the ground anchors, on all four tiers, are not able to prevent soil decompaction around the excavation due to their malleability and, accordingly, the mobility of retaining structures.
The problem of reliability is solved by switching to an ascending method of laying anchors of the first and second tiers. The stability of the retaining structure is radically improved by increasing the bearing capacity of the ascending anchorage along the ground, due to the involvement of an array of soil in the work, an increase in holding forces with active reinforcement of the pile row.
Conclusions. The analysis of theoretical and experimental studies has shown that the practical result of the work is a radical change in the attachment scheme of retaining walls with a height difference of 15 m or more, due to the inclusion of an ascending anchorage system.

***Keywords*:** anchorage, ascending anchor design, active anchors, enclosing structure movement, retaining structures, fan method of laying anchorage, cement stone structure.

Introduction

The growth in the number of residents of our cities and the level of their needs in housing, recreation and living conditions is constantly increasing. The city is forced to develop deeper and deeper into the ground. The development of underground potential will allow for more efficient use of ground space, make the transport system more mobile, which will lead to a reduction in harmful emissions and noise levels and, as a result, to the renewal and improvement of the quality of life in the megapolis [1–4].

Russia has accumulated significant experience in the design and open cast construction of urban underground facilities, such as entertainment facilities, trade and catering enterprises, public utilities and consumer services, as well as a number of storage facilities, industrial buildings and structures, transport facilities systems.

It should be noted that many domestic ideas and technologies used in the development of underground space have no analogues abroad.

Nevertheless, when designing the pit enclosures, a number of complex tasks arise related to the step-by-step analysis of the stress-strain state of the surrounding array of soil, assessment of the impact of new construction on the subsidence of buildings and structures of the surrounding development, determination of reliable values of horizontal soil pressure.

Currently, there are many examples of the use of progressive enclosing and anchor structures with highly developed technologies. However, their implementation without a detailed analysis of the specific conditions of use can lead to very serious consequences [1, 5–7]. In one way, for example, in the process of opening the foundation pit of a new building of the

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Ministry of Foreign Affairs, the loss of prestressing in the anchors as a result of a long break in construction led to significant movements of the "slurry wall", the formation of cracks in the surrounding buildings.

During the construction of the pit of the underground part of the building in the Southwestern District of Moscow, a part of the "slurry wall" with an anchor attachment collapsed due to the discrepancy between the efforts in the anchor structures to the required values, due to the passage of prolonged and heavy rains.

An analysis of a number of reasons that caused accidents during the construction of deep pits allowed us to identify, in particular, the discrepancy between the bearing capacity of anchor structures and the calculated values, which is fully explained by the uncertainty of the static operation of the anchorage in the anchor sealing zone.

Anchorage during the construction of underground facilities liberates the interior space of the pits, thereby increasing the productivity of open working.

Meanwhile, in the case of the use of ground anchorage in urban underground construction, it is necessary to take into account a number of the following restrictive factors:

– the uncontrolled stage of injection of cement mortar into the root part of the anchor;

– uncertainty of the static operation of anchors, especially in cohesive and structurally unstable soils;

– the inability to compensate for the loss of anchor tension forces;

Table 1. Physical and mechanical characteristics of soils
Таблица 1. Физико-механические характеристики грунтов

IGE	Type of soil	h, m	ρ_I, g/sm^3	ρ_{satI}, g/sm^3	C_I, kPa	φ_I, degree	k_s, kN/m^3	λ_0	E, MPa	ν
1	Gruss sand	2,5	1,95	2,04	8,0	32,0	995	0,54	19,0	0,35
2	Refractory loam	7,2	1,92	2,05	37,0	28,0	1665	0,43	32,0	0,30
3	Gabbrodiorite of reduced strength	3,5	2,23	2,25	17,0	35,0	4000	0,33	40,0	0,25
4	Alsbachite of medium strength	10,0	2,30	2,35	19,0	36,0	5000	0,25	50,0	0,20

Table 2. Coupling parameters
Таблица 2. Параметры связей

Stage	Coupling type	Depth of installation, m	Coupling rigidity, kN/mm	Pitch, m	Angle of installation, degree	Tension force, kN
2	Anchor	3,0	19,4	1,5	10,0	40
3	Anchor	6,0	19,4	1,5	10,0	50
4	Anchor	9,0	20,6	1,5	10,0	110
5	Anchor	12,0	18,9	1,5	10,0	150

Table 3. Enclosure design parameters
Таблица. 3 Параметры конструкции ограждения

Enclosure design parameters	
Depth of pit, m	15
Length of enclosure, m	18
Depth of sealing, m	4
Type of enclosure Jet piles	
Pioneer pit parameters	
Offset, m	1
Depth, m	1
Angle of inclination, degree	45
Enclosure cross section parameters	
Number of rows	1
Pile pitch in a row, mm	700
Frame size, mm	920
Number of bars, sm^2	16
Cross-sectional area of reinforcing bars, sm^4 ...	78,540
Moment of inertia, MPa	83 125,810
Module of elasticity, MPa	200 000
Tensile strength, %	435
Reinforcement (row No.1)	50

– a complex process of assembling ground anchors, requiring a large number of components;

– low productivity of installation of ground anchors (2–3 pieces per shift) and, as a result, high cost of production work.

The object of the study is the construction of a retaining structure of the pit in conditions of a height difference of 15 meters.

The retaining structure consists of a number of soil-cement columns as elements of the enclosing structures of the pit wall. As a well-known anchor reinforcement of the enclosure, a variant of a multi-tiered system of strand anchors is considered.

At the same time, a combined approach to the formation of a multi-tiered anchorage is used to assess the bearing capacity of an ascending anchorage [8] and in order to increase the effectiveness of strengthening retaining structures with a large height difference.

When constructing deep pits, the task of choosing the attachment technology and the sequence of the pit arrangement, which allows to reduce the deformation of the enclosing structure and the soil massif, is particularly acute.

Research methodology

As an object of geotechnological analysis, a comprehensive calculation of the pit enclosure for strength, stability and checking the stability of the soil in the area of the buried part of the wall is considered.

The calculation of the pit enclosure reinforced with a system of multi-tiered anchorage is based on a numerical solution of the problem of a beam bending pinched by the lower end in an elastically plastic soil and held by anchors as couplings.

The design of the retaining walls is a series of split reinforced ground cement columns, erected on the basis of the technology of jet cementation of soils. During the opening of the foundation pit near the location of the retaining wall of the excavation, the soil surface is loaded with an active capacity of 20 kN/m². The seismicity of the area does not exceed 7 points.

In the GeoWall program, the pressure on the enclosure is calculated in accordance with the normative rules and regulations [9, 10]. The stability of the soil around the wall deepening is assessed by the limiting condition of the soil in the sealing zone. The passive pressure on the enclosure from the filled ground is taken into account. The elastic bending of the wall is modeled with the finite element method using the Lagrange variational formulation, taking into account the hypothesis of plane sections (Bernoulli's hypothesis). The engineering and geological conditions are given in table 1, the parameters of the enclosure are in table 2 and below table 3.

The design scheme of the enclosure reinforced with three tiers of ground strand anchors, injection type in the GeoWall program window is shown in fig. 1.

The work of the pit enclosure is considered in the conditions of heavy rains, which formed temporary accumulations of groundwater in the upper layer of sand. The retaining wall takes significant water pressure. Under these conditions, it is recommended to use preliminary dewatering, active drainage and jet cementation [11–14].

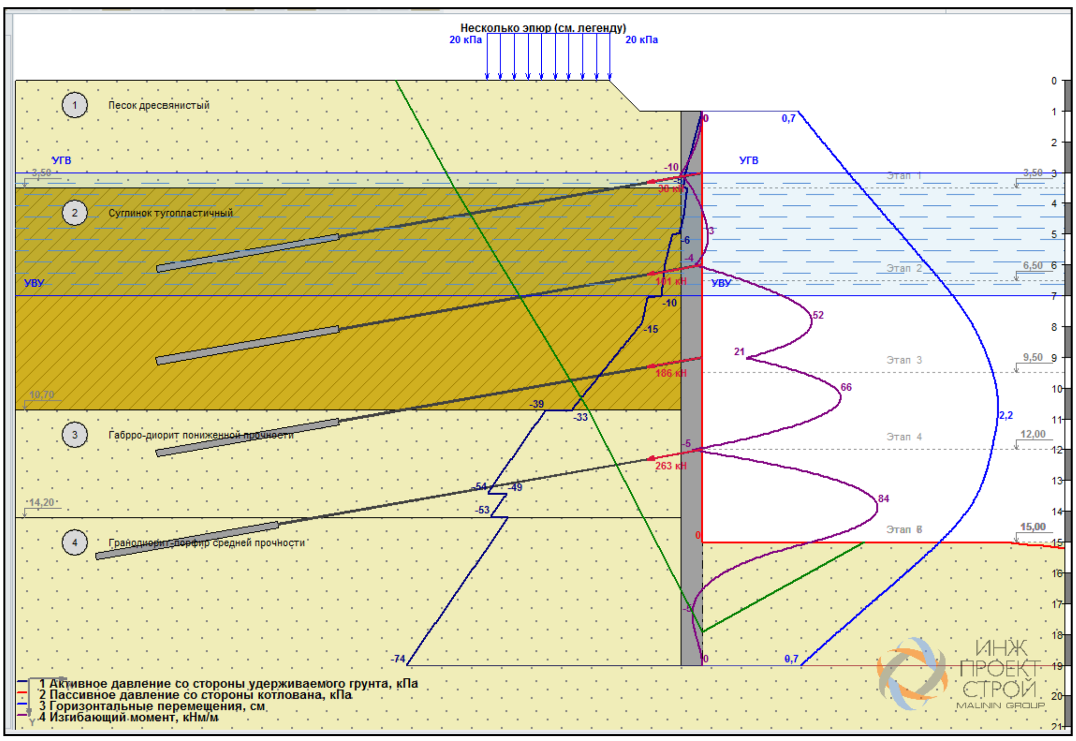

Figure 1. The design scheme of the pit enclosure, including the outlines of the diagram of active pressure from the retained soil, kPa, passive pressure from the pit, kPa, bending moments, kN · m/m, and horizontal movements of the soil displacement prism for stage 8 of the pit opening

Рисунок 1. Расчетная схема ограждения котлована, включая очертания эпюр активного давления со стороны удерживаемого грунта, кПа, пассивного давления со стороны котлована, кПа, изгибающих моментов, кН · м/м, и горизонтальных перемещений призмы сдвижения грунта для 8-го этапа вскрытия котлована

Table 4. Coupling parameters
Таблица 4. Параметры связей

Stage	Coupling type	Depth of installation, m	Coupling rigidity, kN/mm	Pitch, m	Angle of installation, degree	Tension force, kN
2	Anchor	3,0	33,0	1,5	–14,0	140
3	Anchor	6,0	25,0	1,5	–20,0	170
4	Anchor	9,0	20,6	1,5	10,0	110
5	Anchor	12,0	18,9	1,5	10,0	150

Table 5. Ground anchor parameters
Таблица 5. Параметры грунтовых анкеров

Parameter	Tier 1	Tier 2	Tier 3	Tier 4
Anchor type	Pipe-like	Pipe-like	Pipe-like	Pipe-like
Free length, m	10,5	16,0	12,0	14,0
Root length, m	1,0	1,1	6,0	6,0
Full length of the anchor, m	11,5	17,1	18,0	20,0
Borehole diameter, mm	210	210	210	210
Dimensions of the sides of the anchor plate/ diameter of the root, mm	1000	1100	230	230
Cross-sectional area of the anchor, mm^2	1810,0	1810,0	1476,0	1476,0
Elastisity force module, MPa	210 000	210 000	210 000	210 000
Traction strength limit, MPa	580	580	580	580

Table 6. Parameters of the soil concrete pile depending on the soil layer
Таблица 6. Параметры грунтобетонной сваи в зависимости от слоя грунта

Layer number	Soil type	Pile diameter, mm	Elastisity module, MPa	Compressive strength, MPa	Tensile strength, MPa
1	Gruss sand	1000	2700	24,4	1,7
2	Refractory loam	1000	2700	24,4	1,7
3	Gabbrodiorite of reduced strength	1000	2700	25,0	1,7
4	Alsbachite of medium strength	1000	3000	30,0	2,0

The results of the calculation as a whole should be considered unsatisfactory. Explanations are given in detail:

– the active load taken by active ground anchors does not ensure the reliability of the enclosure according to the conditions: the soil stability coefficients for the second, third and fourth tiers of anchors demonstrate values below the maximum permissible. Horizontal movements develop over the entire height of the piles and reach a maximum value at the level of the 4th tier, therefore, ground anchors are not able to prevent the decompaction of the retained array of soil due to their malleability.

Based on the optimization of the method of laying the anchorage, it is planned to include the system of ascending anchors replacing the ground anchors on the first two tiers of the structural reinforcement of the retaining structure in the operation. The need to include ground strand anchors in the work on the third and fourth tiers is caused by the proximity of buildings and structures of urban construction to the pit.

The simultaneous use of an ascending and descending method of laying anchorage is a fan method of anchoring the pit enclosure. Ascending anchors are installed on the upper tiers, and descending ground anchors are installed on the lower tiers. Thus, the arrangement of 1–2 rows of base anchor plates on the surface significantly liberates the space behind the foundation pit edge. The parameters of anchor structures and ground concrete piles are given in tables 4, 5, 6.

The cross section of the pit enclosure is shown in fig. 2.

In the process of modeling the complex calculation of the pit enclosure, 9 main stages of the pit construction were assigned, including 4 stages of installing active anchors in tiers and 5 stages of excavation of the pit.

The level of temporary groundwater is located at a depth of 3 m from the surface. The level of the water barrier is located on the roof of a loamy soil layer, at a depth of 7 m. Preliminary dewatering and active drainage are used.

The design scheme of the pit enclosure reinforced with a fan anchorage system, when anchoring the enclosure with ground descending and ascending anchors is used, is shown in fig. 3.

The problem of reliability of the enclosing system is solved by the transition to the use of an ascending method of laying anchors on the first and second tiers [15] while maintaining anchoring on the lower tiers with ground anchors.

The results of the calculation should be generally recognized as positive. The active load taken by the ascending anchors ensures the reliability of the enclosure according to the conditions: the stability coefficients of the anchorage on the ground reach high values, the effect of pre-tensioning of the anchors radically reduces horizontal movements and prevents

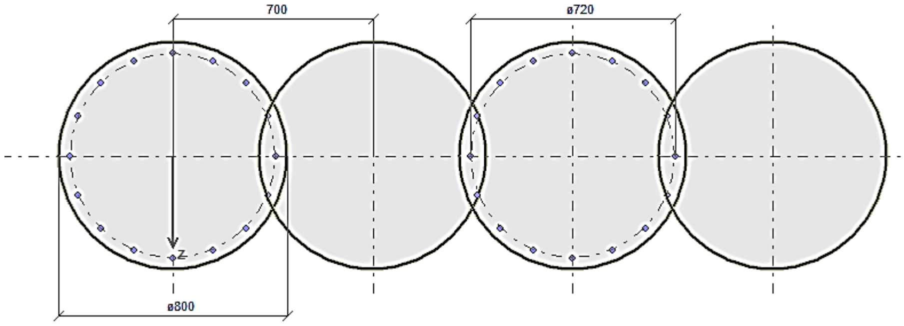

Figure 2. Diagram of the cross section of the pit fence
Рисунок 2. Схема поперечного сечения ограждения котлована

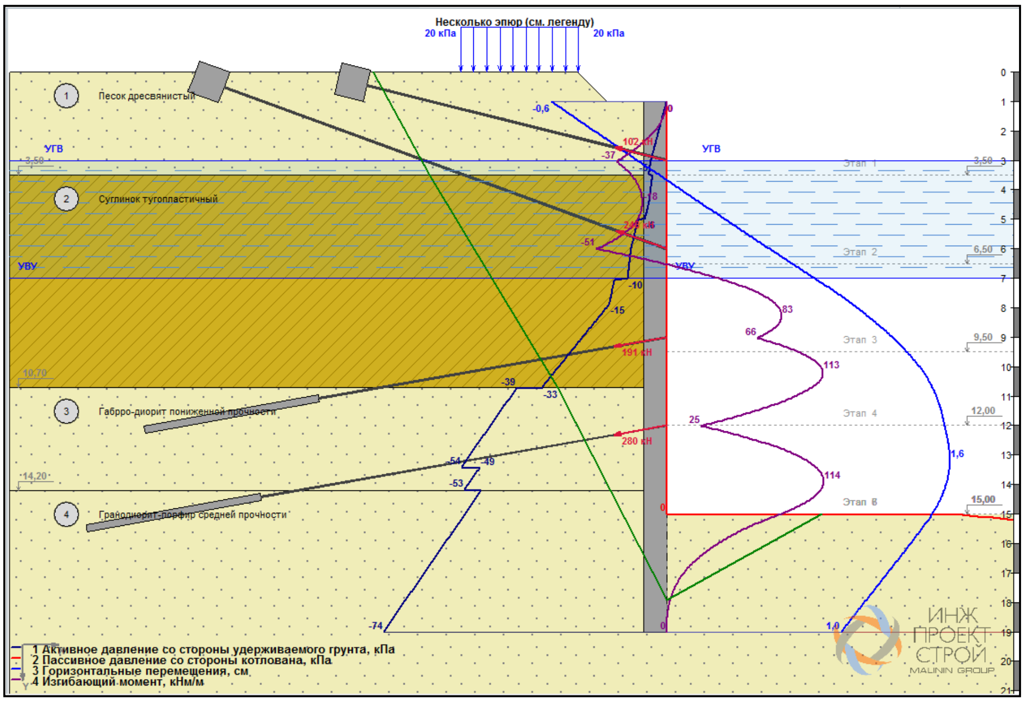

Figure 3. The design scheme of the pit enclosure, including the outlines of the diagram of active pressure from the retained soil, kPa, passive pressure from the pit, kPa, bending moments, kN · m/m and horizontal movements of the soil displacement prism for the 9th stage of the pit opening
Рисунок 3. Расчетная схема ограждения котлована, включая очертания эпюр активного давления со стороны удерживаемого грунта, кПа, пассивного давления со стороны котлована, кПа, изгибающих моментов, кН · м/м и горизонтальных перемещений призмы сдвижения грунта для 9-го этапа вскрытия котлована

soil decompaction around the pit. The operation of the ground anchors on the third and fourth tiers indicates a sufficient level of load-bearing capacity on the ground (Table 7).

Results. Analysis and discussion

The results of the calculation of the pit enclosure are shown in table 7.

As a result of the analysis of the pit enclosure reinforced with a multi-tiered anchor system, it was stated that the ground anchors, on all four tiers, are not able to prevent soil decompaction around the excavation due to their malleability and, accordingly, the mobility of retaining structures. At the same time, the calculated efforts of active soil anchors cannot be realized due to the limited bearing capacity on the ground.

Research practice shows that the maximum pressure for crimping the anchor seal, which can be obtained in sandy soils, is 2.1 MPa, and in clay soils it does not exceed 0,8 MPa.

In addition, it is not possible to obtain a cross-section of the root in loam layers with a diameter of more than 250 mm, due to the fact that in clay soils the structure of cement stone turns out to be porous, with the inclusion of unmixed soil particles and the strength of the solution does not exceed 8 MPa. Whereas in sandy, fractured rocky soils, intensive filtration of the liquid phase into the massif occurs [16, 17].

Thus, the development of horizontal movements of the pit enclosure during the opening of the excavation allows us to conclude that the anchor roots are creep with significantly less effort compared to the calculated ones. There is a high probability of overturning the structure when the anchorage is destroyed due to its insufficient bearing capacity on the ground. At the same time, the strength of concrete and reinforcing steel of ground cement columns, characterized by minimum reserve coefficients in concrete and metal, remains unclaimed

Table 7. The results of the calculation of the pit enclosure
Таблица 7. Результаты расчета ограждения котлована

Investigated parameters	Descending anchor system	Fan system of anchors
Pit depth, m	15,0	15,0
Number of tiers	4	4
Pile sealing depth *t*, m	4,0	4,0
Pitch of the anchors in the plan *L*, m	1,50	1,50
Calculated forces in anchors, kN	30; 101; 186; 263	102; 248; 191; 280
Maximum values of internal forces and movements		
Maximum bending moment in the pile, kN · m/m	141 (stage 3)	206 (stage 3)
Maximum cutting force in a ground concrete column, kN	92 (stage 3)	135 (stage 3)
Maximum horizontal movement, sm	2,2	1,6
Characteristics of the pile section		
Pile profile, type	Jet pile	Jet pile
The calculated resistance of the soil concrete according to IGE, sm^3	24; 24; 25; 30	24; 24; 25; 30
Rigidity of the reinforcing cage EA, MN	2678	2678
Stock coefficients of calculated components, for all tiers (9th stage of excavation)		
Minimum stock ratio in concrete piles	17,8	2,5
Minimum margin factor in the metal of the frame reinforcement	4,8	3,2
Coefficient of the anchor stock on the ground	2,10; 1,70; 1,80; 1,70	5,20; 2,90; 2,10; 2,10
Anchor stock ratio by material	13,2; 6,5; 4,5; 3,3	6,0; 4,0; 4,0; 3,1

(Table 7), due to the fact that long-term continuous movements of enclosing structures are developing.

The problem of reliability is solved by switching to an ascending method of laying anchors of the first and second tiers. The stability of the retaining structure is significantly improved with an increase in the bearing capacity of the ascending anchors along the ground, due to the involvement of an array of soil and an increase in holding forces due to the active reinforcement of the pile row and optimization of the method of laying anchorage.

The stability of the calculated forces of the active anchors throughout all stages of the pit opening is due to the acceptable pre-tensioning force and the optimal method of laying the ascending anchorage. The bearing capacity of the descending ground anchors is created by the friction force along the lateral surface of the root, whereas the bearing capacity of the anchor structures of the ascending type is provided both by the friction forces along the lateral surface of the anchor plate and by the reactive, frontal bearing pressure of the ground located at the base of the rear face of the base anchor plate. The use of an ascending anchorage, securely fixed with precast reinforced concrete base plates, makes it possible to achieve a significant reduction in labor intensity, a high degree of mechanization of work, a significant reduction in construction time and a reduction in its cost.

A feature of the assessment of the stability of the retained soil massif is the comparison of its calculated stress state with the maximum possible one [9, 11, 18]. The engineering method for assessing the stability of a retained soil massif is based on the concept of the K_{st} stability coefficient, which can generally be represented as the ratio of retaining and shear forces. Stability analysis is performed on the basis of the theory of limited equilibrium for prisms with a circular cylindrical sliding surface. The optimal position of each anchor, i. e. the laying zone, the dimensions and the stable position of the anchor seal are selected when calculating the loss of the overall stability of the "enclosure–anchor–soil" system based on the condition that the most dangerous sliding surface, of arbitrary geometry, passes through the bottom of the anchored structure.

The stability coefficient is calculated on the basis of the theory of marginal equilibrium, and is implemented for prisms with a circular cylindrical sliding surface using the methods of: tangential forces, Fellenius, Yanbu, Bishop, Morgenstern-Price, Shakhunyants. Stability analysis is based on the method of operational iteration of the enveloping sliding surfaces for displacement prisms characterized by stability coefficients. The limit value of the enclosure reaction is calculated as the minimum of three values:

– bending strength of the wall;
– shear strength of the wall;
– the ultimate wall sealing resistance.

Geological conditions of the retained soil massif, parameters of anchor couplings and parameters of enclosure structures (Tables 1, 2 and table 3 "Enclosure design parameters"). The main force factors of the prism compartments are presented in table 8.

The calculation of force factors and the coefficient of stability, taking into account the influence of ground anchors, is presented in table 9.

Stability coefficient:

$$K_{st} = \sum T_{\text{react}\,i} \cdot \lambda_i \,/\, \sum T_{\text{act}\,i\,(\text{shift})} \cdot \lambda_i = 995,4 \,/\, 943,7 = 1,055.$$

The shift stability of the pit enclosure when laying ground anchors in remote and deeply located soil layers is estimated by sorting through the areas formed by shift prisms using the Shakhunyants method.

The analysis of the stability of the pit enclosure based on the results of sorting through the enveloping sliding surfaces in order to search for a dangerous circular cylindrical sliding line

Table 8. The main force factors of the prism compartments
Таблица 8. Основные силовые факторы отсеков призмы

Parameters	The main force factors
i	Serial number of the compartment (numbering at zero)
G_i, kN/m	Weight of the i-compartment, $G_i = A_i\gamma_i$
T_i, kN/m	Tangential projection of the resultant active forces to the base of the i-compartment. In the simplest case $T_i = G_i \sin(\alpha_i)$
N_i, kN/m	Projection of the resultant active forces on the normal to the base of the i-compartment. In the simplest case $N_i = G_i \cos(\alpha_i)$
S_i, kN/m	The normal reaction of the base of the i-compartment. In the simplest case, in the absence of reinforcing elements and interaction forces between compartments $S_i = -N_i$
N_i tg φ_i, kN/m	The value of the conditional averaged friction force at the base of the i-compartment
$c_i l_i$, kN/m	The magnitude of the coupling force at the base of the i-compartment
$N_i \cdot$ tg $\varphi_i + c_i \cdot l_i$, kN/m	Tangential reaction of the base of the i-compartment. This is the limit value of the force of resistance to soil shift along the sliding surface of the i-compartment, without taking into account the influence of reinforcing elements
$T_{\text{act } i \text{ (shift)}}$, kN/m	The tangent projection of the resultant active forces to the base of the i-compartment, the direction of which coincides with the general direction of the shift
$T_{\text{act } i \text{ (retained)}}$, kN/m	Tangential projection of the resultant active forces to the base of the i-compartment, directed opposite to the general direction of the shift
$N_i \cdot$ tg $\varphi_i + c_i \cdot l_i$, kN/m	Tangential reaction of the base of the i-compartment. This is the limit value of the force of resistance to soil shift along the sliding surface of the i-compartment, without taking into account the influence of reinforcing elements
$N_{\text{arm } i} \cdot$ tg $\varphi_i + T_{\text{arm } i}$, kN/m	$N_{\text{arm } i}$, $T_{\text{arm } i}$ – the normal and tangent projections of the resultant forces in the armature
$T_{\text{react } i}$, kN/m	$T_{\text{react } i} = (N_i \cdot \text{tg } \varphi_i + c_i \cdot l_i) + (N_{\text{arm } i} \cdot \text{tg } \varphi_i + T_{\text{arm } i})$
λ_i	Numerical coefficient $\lambda_i = \cos(\varphi_i) / \cos(\alpha_i - \varphi_i)$

Table 9. Calculation of the stability coefficient using the Shakhunyants method
Таблица 9. Расчет коэффициента устойчивости по методу Шахунянца

i	$T_{\text{act } i \text{ (shift)}}$, kN/m	$T_{\text{act } i \text{ (retained)}}$, kN/m	$N_i \cdot$ tg $\varphi_i + c_i \cdot l_i$, kN/m	$N_{\text{arm } i} \cdot$ tg $\varphi_i + T_{\text{arm } i}$, kN/m	$T_{\text{react } i}$, kN/m	λ_i	$T_{\text{act } i \text{ (shift)}} \cdot \lambda_i$, kN/m	$T_{\text{react } i} \cdot \lambda_i$, kN/m
0	11,5	0,0	21,4	0,0	21,4	1,39	15,9	29,6
1	20,3	0,0	12,2	0,0	12,2	1,20	24,4	14,7
2	24,7	0,0	11,8	0,0	11,8	1,13	27,9	13,3
3	28,0	0,0	12,3	0,0	12,3	1,08	30,2	13,3
4	30,6	0,0	13,3	0,0	13,3	1,04	31,9	13,8
5	32,7	0,0	14,3	0,0	14,3	1,01	33,1	14,5
6	34,4	0,0	15,5	0,0	15,5	0,99	34,0	15,3
7	35,9	0,0	16,7	0,0	16,7	0,97	34,7	16,2
8	37,1	0,0	17,9	0,0	17,9	0,95	35,3	17,0
9	38,1	0,0	19,1	0,0	19,1	0,94	35,7	17,9
10	38,9	0,0	20,4	0,0	20,4	0,92	35,9	18,8
11	39,6	0,0	21,6	0,0	21,6	0,91	36,1	19,7
12	40,1	0,0	22,8	0,0	22,8	0,90	36,2	20,6
13	40,5	0,0	24,0	0,0	24,0	0,89	36,2	21,5
14	40,7	0,0	25,2	0,0	25,2	0,89	36,1	22,3
15	40,9	0,0	26,3	0,0	26,3	0,88	36,0	23,2
16	40,9	0,0	27,5	0,0	27,5	0,87	35,8	24,0
17	40,9	0,0	28,6	0,0	28,6	0,87	35,6	24,9
18	40,8	0,0	29,7	0,0	29,7	0,87	35,3	25,7
19	40,6	0,0	30,7	0,0	30,7	0,86	35,0	26,5
20	40,3	0,0	31,8	0,0	31,8	0,86	34,6	27,3
21	40,0	0,0	32,8	0,0	32,8	0,86	34,2	28,1
22	39,6	0,0	33,8	0,0	33,8	0,85	33,8	28,9
23	39,1	0,0	34,8	0,0	34,8	0,85	33,3	29,6
24	38,6	0,0	35,7	0,0	35,7	0,85	32,8	30,4
25	37,5	0,0	36,2	0,0	36,2	0,85	31,8	30,7
26	33,3	0,0	33,7	0,0	33,7	0,85	28,3	28,6
27	32,1	0,0	33,8	0,0	33,8	0,85	27,2	28,7
28	30,9	0,0	33,9	0,0	33,9	0,85	26,2	28,8
29	0,0	229,5	171,5	1,5	402,5	0,85	0,0	341,5
Итого	1028,3	229,5	889,3	1,5	1120,3		943,7	995,4

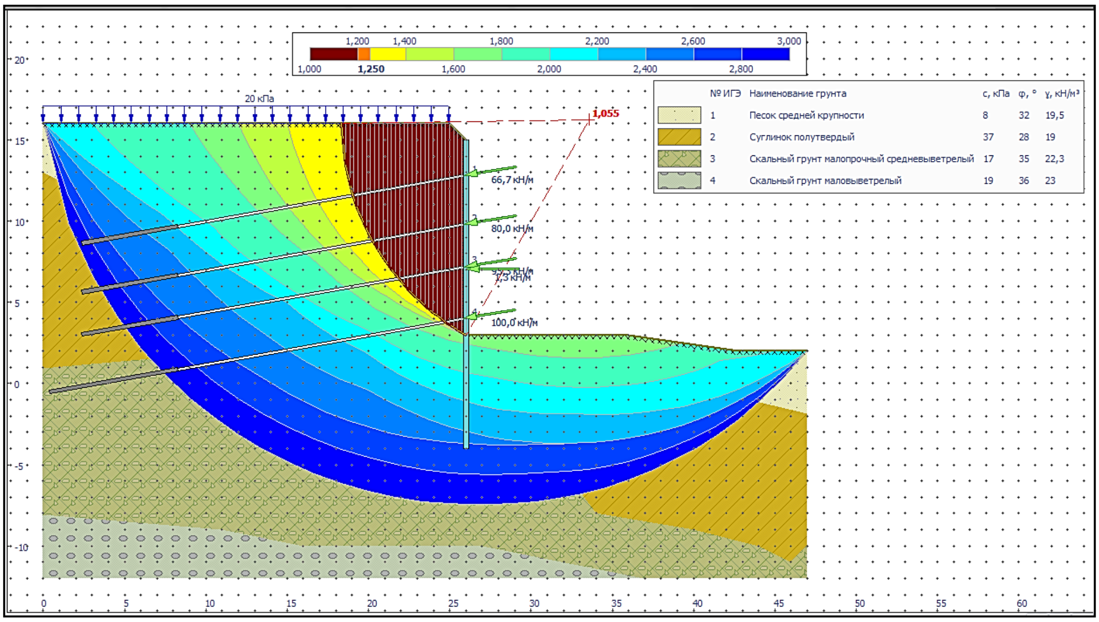

Figure 4. Analysis of the shift stability of the pit enclosure using the Shakhunyants method in the conditions of a complex geological structure of the retained soil massif when laying ground anchors in remote and deeply located soil layers
Рисунок 4. Анализ устойчивости на сдвиг ограждения котлована по методу Шахунянца в условиях сложного геологического строения удерживаемого массива грунта при заложении грунтовых анкеров в удаленные и глубоко расположенные слои грунта

Table 10. The Shakhunyants method
Таблица 10. Метод Шахунянца

i	$T_{act\ i\ (shift)}$, kN/m	$T_{act\ i\ (retained)}$, kN/m	$N_i \cdot \mathrm{tg}\ \varphi_i + c_i \cdot l_i$, kN/m	$N_{arm\ i} \cdot \mathrm{tg}\ \varphi_i + T_{arm\ i}$, kN/m	$T_{react\ i}$, kN/m	λ_i	$T_{act\ i\ (shift)} \cdot \lambda_i$, kN/m	$T_{react\ i} \cdot \lambda_i$, kN/m
0	11,5	0,0	21,4	0,0	21,4	1,39	15,9	29,6
1	20,3	0,0	12,2	0,0	12,2	1,20	24,4	14,7
2	24,7	0,0	11,8	0,0	11,8	1,13	27,9	13,3
3	28,0	0,0	12,3	0,0	12,3	1,08	30,2	13,3
4	30,6	0,0	13,3	0,0	13,3	1,04	31,9	13,8
5	32,7	0,0	14,3	0,0	14,3	1,01	33,1	14,5
6	34,4	0,0	15,5	0,0	15,5	0,99	34,0	15,3
7	35,9	0,0	16,7	0,0	16,7	0,97	34,7	16,2
8	37,1	0,0	17,9	0,0	17,9	0,95	35,3	17,0
9	38,1	0,0	19,1	0,0	19,1	0,94	35,7	17,9
10	38,9	0,0	20,4	0,0	20,4	0,92	35,9	18,8
11	39,6	0,0	21,6	0,0	21,6	0,91	36,1	19,7
12	40,1	0,0	22,8	0,0	22,8	0,90	36,2	20,6
13	40,5	0,0	24,0	0,0	24,0	0,89	36,2	21,5
14	40,7	0,0	25,2	0,0	25,2	0,89	36,1	22,3
15	40,9	0,0	26,3	0,0	26,3	0,88	36,0	23,2
16	40,9	0,0	27,5	0,0	27,5	0,87	35,8	24,0
17	40,9	0,0	28,6	0,0	28,6	0,87	35,6	24,9
18	40,8	0,0	29,7	0,0	29,7	0,87	35,3	25,7
19	40,6	0,0	30,7	0,0	30,7	0,86	35,0	26,5
20	40,3	0,0	31,8	0,0	31,8	0,86	34,6	27,3
21	40,0	0,0	32,8	0,0	32,8	0,86	34,2	28,1
22	39,6	0,0	33,8	0,0	33,8	0,85	33,8	28,9
23	39,1	0,0	34,8	0,0	34,8	0,85	33,3	29,6
24	38,6	0,0	35,7	0,0	35,7	0,85	32,8	30,4
25	37,5	0,0	36,2	0,0	36,2	0,85	31,8	30,7
26	33,3	0,0	33,7	0,0	33,7	0,85	28,3	28,6
27	32,1	0,0	33,8	0,0	33,8	0,85	27,2	28,7
28	30,9	0,0	33,9	0,0	33,9	0,85	26,2	28,8
29	0,0	627,1	209,0	442,0	1278,1	0,85	0,0	1084,3
Итого	1028,3	627,1	926,7	442,0	1995,8		943,7	1738,3

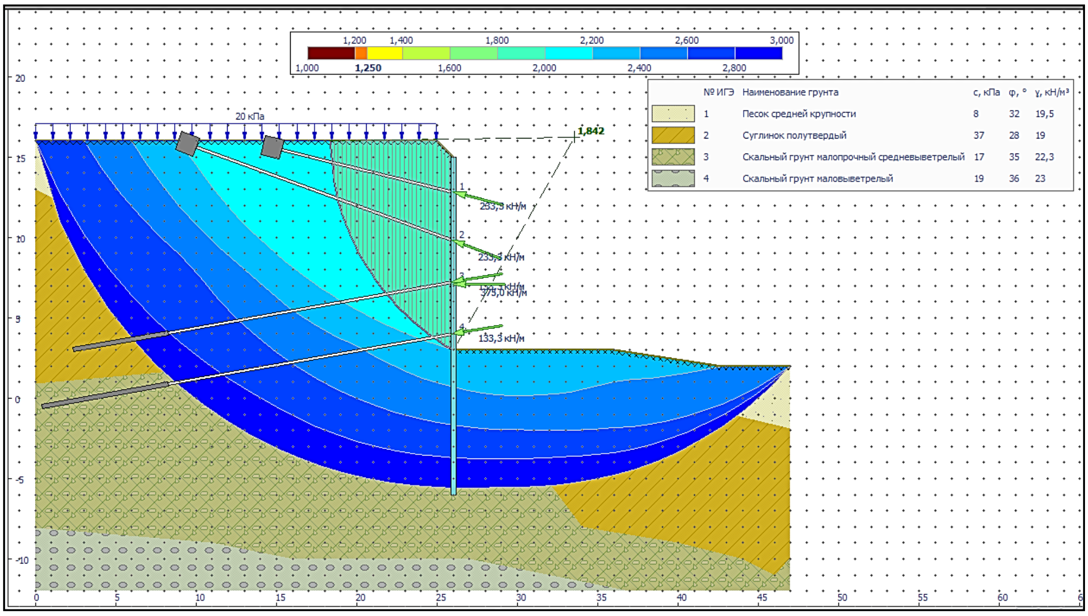

Figure 5. Analysis of the stability of the pit enclosure using the Shakhunyants method in conditions of a complex geological structure of the retained soil massif when laying ascending anchors on the 1st and 2nd tiers outside the possible shift prism

Рисунок 5. Анализ устойчивости ограждения котлована по методу Шахунянца в условиях сложного геологического строения удерживаемого массива грунта при заложении восходящих анкеров на 1-м и 2-м ярусах за пределами возможной призмы сдвижения

Table 11. The results of the assessment of the enclosure stability and the retained soil massif

Таблица 11. Результаты оценки устойчивости ограждения и удерживаемого массива грунта

Calculation methods	Values of the stability coefficient	
	Laying of ground anchors	Laying anchors with a fan method
Fellenius method	**0,839**	**1,774**
Bishop method	**1,185**	**1,925**
Yanbu method	**1,148**	**2,296**
Morgenstern-Price method	**1,190**	**2,023**
Shakhunyants method	**1,055**	**1,842**
The method of tangential forces	**1,172**	**3,208**

showed the existence of a contour of the formed shift prism with a stability coefficient K_{st} = 1,055, below the normative, maximum permissible value [K_{st}] = 1,250.

The calculation of the force factors and the stability coefficient for the fan method of laying the anchorage is presented in table 10.

Stability coefficient:

$$K_{st} = \sum T_{\text{react}\, i} \,/\, \sum T_{\text{act}\, i\,(\text{shift})} \cdot \lambda_i = 1738,3 / 943,7 = 1,842.$$

The increase in the stability of the retaining structure is due to the involvement of an array of soil located at the base of the rear faces of the base anchor plates, an ascending anchorage.

The analysis of the stability of the pit enclosure based on the results of sorting through the enveloping sliding surfaces in order to search for a dangerous circular cylindrical shift prism revealed the contour of the formed prism with a stability coefficient K_{st} = 1,842, above the normative, maximum permissible value [K_{st}] = 1,250.

As a result of assigning the optimal position of each anchor relative to the areas of the formed prisms, clarifying the zone of laying of each tier of anchors, as well as the size and stable position of the base anchor plates, the stability of the retained soil massif and the pit enclosure is ensured (Fig. 5).

The results of the assessment of the stability of the retaining structure based on the search for the most dangerous circular cylindrical shift prism are presented in table 11.

The problem of achieving stability is solved by switching to a fan method of laying anchors. The stability of the retaining structure is significantly improved with an increase in the bearing capacity of the ascending anchors along the ground, due to the involvement of an array of soil in the work, a significant increase in holding forces due to the active reinforcement of the pile row.

Conclusions

The practical result of the work is a radical change in the attachment scheme of retaining walls with a height difference of 15 m or more, thanks to the inclusion of an ascending anchorage system. The rationality of such a scheme is to increase the bearing capacity of the anchorage on the ground, increase the strength of attachment the upper tiers of anchors, and reduce labor costs. The possibility of visual control over the condition of the sealing nodes and the extractability of anchor bars, achieving a high level of manufacturability, safety of work and preservation of the surrounding buildings, which ensures the development of the most effective, economically efficient and high-tech production processes in the open cast construction of urban underground structures.

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Эффективность усиления подпорных сооружений на основе веерного способа заложения анкерной крепи на городских подземных объектах

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Аннотация

Цель работы. В качестве объекта исследования рассматривается строительство подпорного сооружения котлована в условиях значительного перепада высот с использованием многоярусной системы прядевых анкеров. Для оценки несущей способности восходящей анкерной крепи используется комбинированный подход к формированию многоярусной анкерной крепи.

Методология. Методической основой расчета на прочность ограждающих конструкций служит численное решение задачи изгиба балки, лежащей на упругопластическом основании и удерживаемой анкерными конструкциями в качестве связей. Моделирование восходящей анкерной конструкции реализуется в операционной среде программы GeoWall. На основе оптимизации способа заложения анкерной крепи предусматривается включение в работу системы восходящих анкеров, заменяющих грунтовые анкеры на первых двух ярусах конструктивного усиления подпорного сооружения.

Результаты. В результате анализа ограждения котлована многоярусной системой анкеров установлено, что грунтовые анкеры на всех четырех ярусах не способны предотвратить разуплотнение грунта вокруг котлована по причине их податливости и, соответственно, подвижности подпорных сооружений. Проблему надежности решает переход на восходящий способ заложения анкеров первого и второго яруса. Устойчивость подпорного сооружения радикально повышается за счет увеличения несущей способности восходящей анкерной крепи по грунту благодаря вовлечению в работу массива грунта, увеличению удерживающих сил при активном усилении свайного ряда.

Выводы. Анализ теоретических и экспериментальных исследований показал, что практическим результатом работы является радикальное изменение схемы крепления подпорных стен с перепадом высот от 15 м и более благодаря включению в работу системы восходящей анкерной крепи.

***Ключевые слова*:** анкерная крепь, конструкция восходящего анкера, активные анкеры, перемещение ограждающей конструкции, подпорные сооружения, веерный способ заложения анкерной крепи, структура цементного камня.

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