BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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JUSTIFICATION OF THE SELECTION AND CALCULATION OF THE DESIGN PARAMETERS ENSURING THE STABILITY OF THE SOIL SLOPE

Purpose. The article addresses the issue of ensuring the stability of a soil slope under natural and water-saturated conditions. The object of the study is the slope of the Tunnelna gully in Dnipro, for which a stability analysis was performed and the feasibility of using a retaining wall made of bored piles reinforced with ground anchors was justified. The purpose of the study is to substantiate the selection and calculation of the design parameters that ensure the stability of the soil slope and prevent deformations of the foundations and load-bearing elements of buildings located within the landslide-prone area. **Methodology.** The study is based on a combination of analytical methods for determining shear stress and numerical modeling using the Phase2 software package to identify the slip surface and the slope stability coefficient. The calculation of the parameters of bored piles and ground anchors was carried out using the LIRA-SAPR software and regulatory documents VBN, DSTU, and Eurocode 2. The modified Parchevskyi-Shashenko strength criterion was used as the failure criterion. **Findings**. The results of the study showed that in the natural state, the slope stability coefficient is K_{st}=1.30, while in the water-saturated state it is K_{st}=1.17, indicating the need for reinforcement. The proposed retaining wall, made of bored piles with a diameter of 500 mm and reinforced with anchors, increases the stability coefficient to K_{st}=2.01. The optimal location of the structure was determined to be 13 m from the back crack, with an embedment depth of the piles into the sandy soil of 6.67 m. **Originality** lies in the use of the modified Parchevskyi-Shashenko criterion for modeling the «soil – retaining wall with bored piles» system, which allows for a more accurate assessment of the stress-strain state and slope stability. A methodology for the integrated calculation of the «soil – piles – anchors» system, taking into account hydrogeological conditions, has been proposed. **Practical value** lies in the development of engineering-justified parameters for the retaining wall, which ensure the stability of an actual soil slope. The obtained results can be used in the design of retaining structures in landslide-prone areas. A comparison of design calculations showed that the use of Ukrainian standards allows for a 10 % reduction in reinforcement consumption (22 kg per element) compared to Eurocode 2.

Keywords: slope stability; bored piles; ground anchors; retaining wall; shear stress; Phase2, LIRA-SAPR, Parchevskyi-Shashenko criterion; building foundations

Introduction

The signs that a soil slope requires reinforcement include the following:

- visible migration of soil particles;
- water-eroded grooves;
- soil crumbling;
- presence of soil particle seepage at the foot of the slope after heavy rainfall.

To ensure the stability of soil slopes and prevent landslides, a number of engineering solutions exist. Their implementation depends mainly on the purpose, which determines differences in both materials and design (Причина, 2015). All stabiliza-

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tion methods, depending on the materials used, can be conventionally divided into three groups:

- natural;
- geomaterials;
- retaining and reinforcing structures.

Structures designed to prevent sudden slope collapse are retaining walls. Depending on the operating conditions, they are made of various materials and have different shapes and purposes. The materials used may include brick or rubble masonry, metal, wood, gabions, concrete or rubble concrete, and reinforced concrete.

This study considers a pile-anchor structure, which consists of rigid vertical reinforced concrete bored piles, arranged in at least two parallel rows on the slope of a hill in a staggered layout, and flexible reinforced concrete anchor ties. Depending on the situation, bored piles can also be used independently (Huang, 2023; Ghanshyam G. Tejani, Behnam Sadaghat, & Sumit Kumar, 2023).

The objective of the study is to calculate a protective structure that ensures the stability of the soil slope.

The object of the study is one of the slopes of the Tunnelna gully in the city of Dnipro. During the calculation, it should be taken into account that if the slope stability coefficient is less than K_{st}=1.25, it is necessary to justify the use of a retaining structure composed of bored piles.

The subject of the study involves the processes of stress-strain state formation in the soil mass and the retaining structure of the bored pile retaining wall, reinforced with ground anchors, under different levels of water saturation, as well as the regularities of the influence of the structure's parameters on the overall slope stability coefficient and on the stability of building foundations located within the landslide-prone area.

To achieve the stated goal, the following research methods were used: analytical method for determining slope stability based on calculating shear pressure using limit equilibrium equations; numerical modeling; engineering calculation of the bearing capacity of ground anchors; calculation of parameters of bored piles and the retaining wall using the LIRA-SAPR software environment, applying the modified Parchevskyi-Shashenko strength criterion; comparison of design results according to Ukrainian standards and Eurocode 2 to assess the influence of regulatory frameworks on material consumption.

Purpose

The purpose of the study is to substantiate the selection and calculation of the design parameters that ensure the stability of the soil slope and prevent deformations of the foundations and load-bearing elements of buildings located within the landslide-prone area.

Methodology

The slope layout is shown in Fig. 1, and the properties of the soils that compose it are presented in table 1. The problem of the calculation lies in the fact that the slope is stable in its natural state, but becomes unstable when fully saturated with water. In the natural state, the slope stability coefficient K_{st}=1.30>1.25, and in the water-saturated state $K_{st,sat}$ =1.17<1.25, which is lower than the design value. $K_{st,sat}$ =1.25.

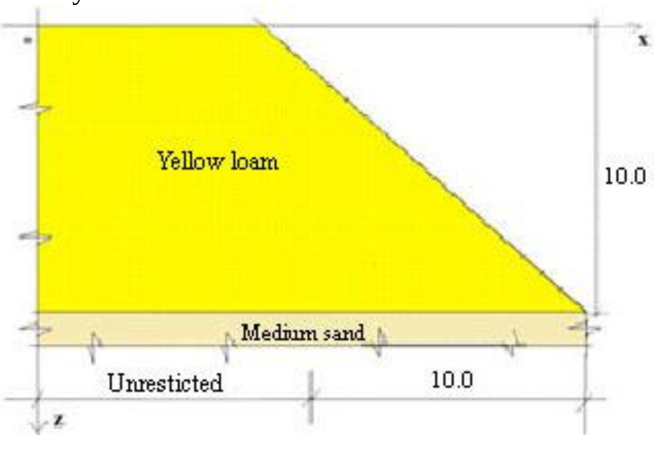

Fig. 1. The slope whose stability must be ensure

Table 1

Properties of the soils composing the slope

№	Name of the characteristic	Soil type	
		Yellow loam	Medium sand
1	Layer thickness, m	0-10	Unrestricted
2	Moisture content at the liquid limit W_L, rel. units.	0.32	-
3	Moisture content at the plastic limit W_p, rel. units	0.22	-
4	Plasticity index I_p, rel. units.	0.10	-
5	Natural moisture content W , rel. units	0.23	0.10
6	Moisture content at full saturation W_{sat}, rel. units	0.31	0.21
7	Liquidity index I_L / $I_{L,sat}$, rel. units	0.10/0.90	-
8	Soil particle density γ_S , rel. units	2.68	2.67
9	Soil density γ_I , rel. units	1.80	1.89
10	Dry soil density $\gamma_{d,I}$, rel. units	1.46	1.72
11	Water-saturated soil density $\gamma_{sat,I}$, rel. units	1.92	2.07
12	Density of water-saturated soil $\gamma_{sw,I}$, rel. units	0.92	1.08
13	Porosity coefficient e	0.83	0.55
14	Degree of saturation S_r / $S_{r,sat}$, rel. units	0.74/1.00	0.18/1.00
15	Internal friction angle φ / φ_{sat} , degrees	21/15	35/35
16	Cohesion c / c_{sat}, t/m^2	2,05/1,5	0,2/0,2
17	Modulus of overall deformation E / E_{sat}, t/m^2	1700/1500	4000/4000
18	Poisson’s ratio, rel. units	0.35	0.32

When determining the shear stress, the slope body was divided into 10 slices (Fig. 2). Within each slice, the following was calculated:

- length of the slip surface base;
- its inclination angle to the horizontal;
- weight of each soil slice P_i;
- shear T_{sd} and resisting T_{ud} soil slice forces in the natural state of the soil;
- shear $T_{sd,sat}$ and resisting $T_{ud,sat}$ soil slice forces in the water-saturated state of the soil in its natural condition K_{st};
- slope stability coefficient in the natural state $K_{st,sat}$.

During the calculations using the Phase2 software package, an approximate v value of the stability coefficient was obtained. $K_{st,sat}$ =1.21.

Thus, if the soil is in a water-saturated state, the slope is unstable.

To ensure the stability of the slope, a retaining wall made of bored piles with a diameter of 500 mm, reinforced with ground anchors spaced at two-meter intervals (Fig. 2), was designed (Palazzolo, Peres, Bordoni, Meisina, Creaco, & Cancelliere, 2021).

This type of retaining wall was chosen based on the following assumptions: in this case, the possibility of slip undercutting is excluded; retaining wall construction work can be performed using construction sections, which allows for additional safety when constructing the retaining wall.

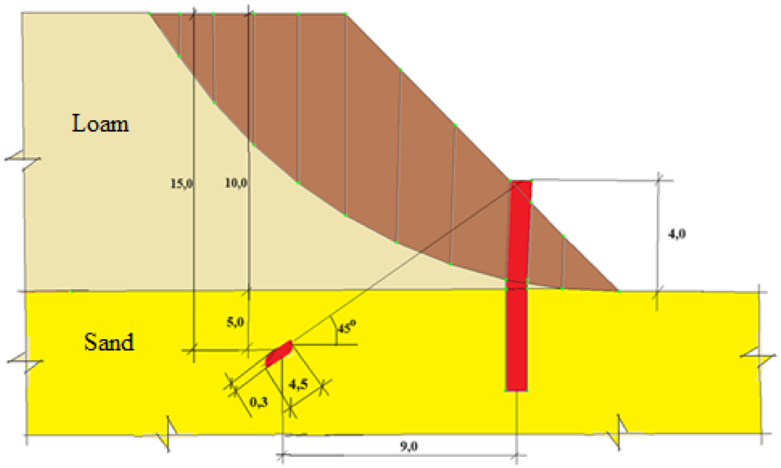

Fig. 2. Relative arrangement of the landslide, retaining wall, and ground anchor

Findings

The stability calculation of the retaining wall was carried out in the following sequence.

The shear stress curve for the fully saturated foundation was calculated as the difference between the resisting and shear forces using the following formula:

$$P_{on} = T_{ud,sat} - T_{sd,sat}.$$

This dependence is shown graphically in Fig. 3. The same figure also presents the dependencies on the surface coordinate and the thickness of the sliding mass. These data are necessary to justify the location of the retaining wall and the downward load of the ground anchor on it (Ivanova, Olishevska, Kravchenko, & Kulivar, 2025).

To assess the slope stability behind the retaining structure, the dependence of the stability coefficient of the remaining slope portion on the coordinate was constructed (Fig. 3). From Fig. 4, it can be seen that if the retaining wall is located 13 meters from the back crack, the stability coefficient of the soil mass behind the retaining wall will be $K_{st,sat}$=2.01>1.25, that is, in this case, the slope is stable.

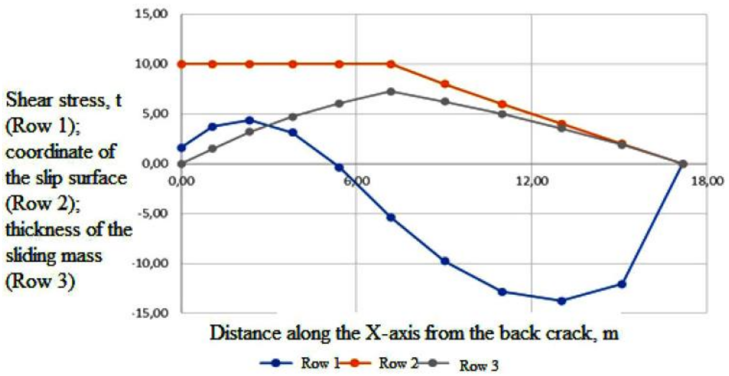

Fig. 3. Dependence of the stability coefficient of the remaining slope portion on the coordinate

The distance from the ground surface to the slip line at 13 meters from the back crack is 4 m, which corresponds to the height of the retaining wall (Fig. 2). The shear stress on the retaining wall at 13 meters from the back crack is 13.74 t per meter length of the retaining wall. The next step is to determine the bearing capacity of the ground anchor in the soil (Shapoval, Ivanova, Hapieiev, Yanko, & Barsukova, 2023). The calculation is carried out in accordance with VBN 506-88 (ВБН 506-88, 1988). The design load on the anchor, based on the bearing capacity of the foundation P_w should be determined from the condition:

$$P_w = \frac{P_d}{\gamma_n} = \frac{18.9}{1.4} = 13.5,$$

where P_w – design load on the anchor based on bearing capacity; P_w – working load of the anchor; γ_n – reliability coefficient according to the purpose of the structure, taken as 1.4 for permanent anchors.

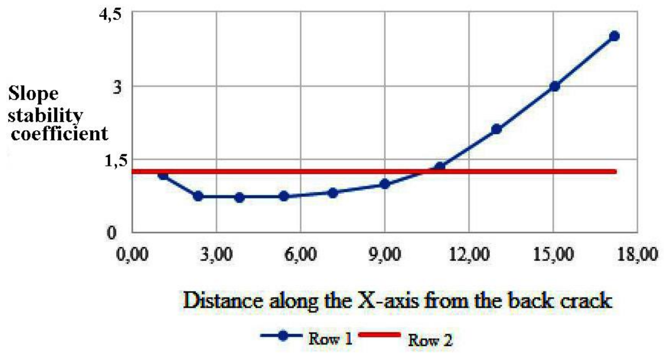

Fig. 4. Dependence of the slope stability coefficient in the water-saturated state on the distance from the back crack.
Row 1 – slope stability coefficient outside the retaining structure;
Row 2 – design value of the stability coefficient $K_{st,sat}$=1.25

The design load is determined using the following formula:

$$P_d = \pi \cdot D_k \cdot L_k \cdot (1+\sin\varphi) \cdot (\sigma_{od} \cdot \mathrm{tg}\varphi + c_1) \cdot K_p \cdot \gamma_c = 18.9$$

where D_k=0.3 m – anchor embedment (root) diameter; L_k=2 m – anchor embedment (root) length; φ=35° – design weighted average value of the soil internal friction angle along the anchor embedment length; c_1=2 kPa – design weighted average value of soil cohesion along the anchor embedment length; γ_c=0.72 – service condition coefficient for sandy soil; σ_{od} – average natural soil stress along the lateral surface of the anchor; K_p – coefficient depending on the ratio of borehole diameter to embedment diameter, natural stresses, and the strength and deformation characteristics of the soil (Ivanova, Radkevych, Olishevska, & Ma Tianwei, 2025).

Taking into account the inclination of the tie to the horizontal α=45° the projection of the resisting force on the horizontal axis is equal to:

$$R = P_{w,x} = P_w \cos 45^\circ = 13.51 \times 0.707 = 9.6\,\mathrm{t}$$

Anchors are spaced at one-meter intervals (Fig. 2). The next step was to calculate the embedment depth of the piles into the sandy soil below the slip surface. The calculation was carried out using the Jacobi scheme (ДСТУ-Н Б В.2.1-32:2014, 2014; ДСТУ-Н Б В.2.1-31:2014, 2014; ДСТУ-Н Б В.1.1-37:2016, 2017). The scheme of active and passive pressures and forces acting on the retaining wall according to the Jacobi scheme is shown in Fig. 5. To ensure the stability of the structure in Fig. 6, the sum of the projections of the forces acting on it along the horizontal axis Ox and the sum of moments about the rotation point O must be equal to zero (Fig. 6) (Masi, Segoni, & Tofani, 2021). Thus, to ensure the stability of the retaining wall, the following conditions must be satisfied:

$$\left.\begin{array}{l} \sum X = E'_p + E_{a2} + E_{a1} + E_{op} - E_p - R = 0 \\ \sum M = E_{a2}L_2 + E_{a1}L_3 + E_{op}(t_0+2) - E_pL_1 - R(t_0+4) = 0 \end{array}\right\}$$

The resultant force of the passive pressure E_p and the distance from the rotation center O to the point of application of this force L_1 determined using the following formula:

$$\left.\begin{array}{l} E_p = 0.399 \cdot t_o^2 + 0.768 \cdot t_o \\ L_1 = \dfrac{t_o \cdot (288 + 84.875 \cdot t_o)}{576 + 254.625 \cdot t_o} \end{array}\right\}$$

In Fig.5, the following are indicated: σ_{a1} – active pressure in loam soil, : σ_{a2} – the same in sand soil, : σ_p – passive pressure in sandy soil, P_{op} – shear stress, E_{op}=13.74 *t* – shear force on the retaining wall, E_{a1} – active force on the retaining wall from the loam soil side, E_{a2} – active force on the retaining wall from the sand soil side,

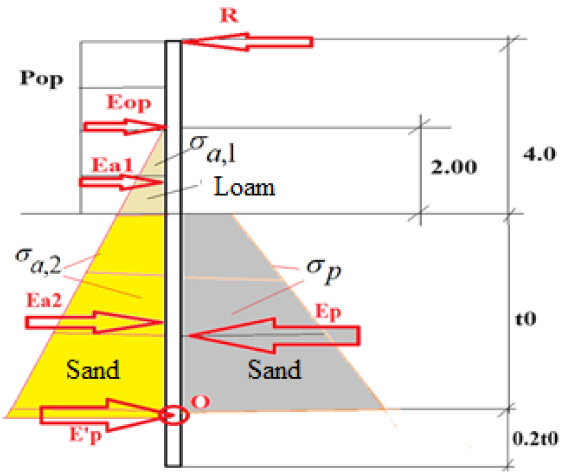

Fig. 5. Scheme of application of shear and resisting forces to the retaining wall

E_n – passive force on the retaining wall from the sand soil side, R=9.6 *t* – projection of the force in the ground anchor tie onto the horizontal axis, E_{p1} – unknown reaction at point O, 4 *m* – height from the top of the retaining wall to the slip surface line, 2 *m* – distance from the point of application of the shear force to the slip surface line, t_0 – unknown embedment depth of the retaining wall into the soil below the slip surface, $0.5t_0$ – unknown additional embedment depth of the retaining wall into the soil below the slip surface (Ivanova, Zhabchyk, Khoziaikina, & Hryhoriev, 2023).

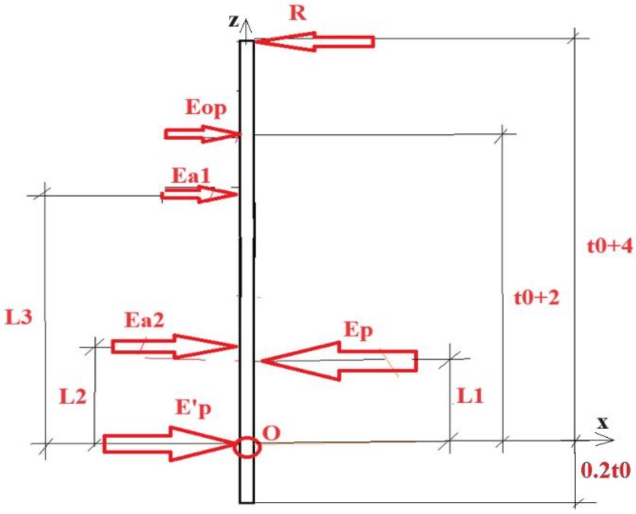

Fig. 6. Diagram for formulating the equilibrium equations

In Fig. 6, the following are indicated: L_1 – distance from the rotation point to the point of application of the force E_n, L_2 – distance from the rotation point to the point of application of the force E_{a2}, L_3, – distance from the rotation point to the point of application of the force E_{a1}.

The resultant force of the active pressure of the clayey soil on the retaining wall E_{a1} and the distance from the rotation center O to the point of application of this force L_3 are determined using the following formula: E_{a1}=2.18 t, L_3=0.653+t_0 m.

The resultant force of the active pressure E_{a2}, and the distance from the rotation center O to the point of application of this force L_2 are determined using the following formula:

$$\left.\begin{aligned} E_{a2} &= 1{,}87 \cdot t_0 + 0{,}28 \cdot t_0^2 \\ L_2 &= \frac{t_0 \cdot (5{,}61 + 0{,}561 \cdot t_0)}{11{,}2 + 1{,}68 \cdot t_0} \end{aligned}\right\}$$

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By substituting the values E_p, E_{a1}, E_{a2}, E_{op}, R, L_1, L_2 and L_3, and solving the resulting fifth-degree algebraic equation, we obtain: t_{01}=-6.67 m, t_{02}=-0.383 m, t_{03}=-3.519 m, t_{04}=1.694 m, t_{05}=2.789 m.

We take the largest value, that is:

$$t_0=t_{05}=2.789 \text{ m.}$$

Finally, the embedment depth of the retaining wall below the slip surface in sand soil is determined using the following formula:

$$t=1.2t_0=3.3468 \text{ m}$$

As a result, we adopt a retaining wall made of bored piles with a diameter of 500 mm and a length:

$$H=4+3.35=7.35 \text{ m}$$

The cross-sectional area of the ground anchor tie is determined based on formula (8) from DBN. (ДБН В.2.6-198:2014, 2014):

$$A_n \geq \frac{R\gamma_n}{R_y\gamma_c} = \frac{13.51\times1.25}{36000\times0.9} = 5.21 \text{ cm}^2$$

where A_n – cross-sectional area of the anchor tie; R=13.51 t – axial force in the anchor tie; γ_n=1.25 – reliability coefficient according to the responsibility level (class CC1, class A) (ДБН В.1.2-14:2018, 2018); R_y=360 MPa – design tensile strength of A400 class reinforcing steel; γ_c=0.9 – service condition coefficient (Table 5.1, (ДБН В.2.6-198:2014, 2014)).

The diameter of the anchor tie is:

$$d_n \geq \sqrt{\frac{4}{\pi}A_n} = \sqrt{\frac{4}{3.14}\times5.21} = 2.58 \text{ cm.}$$

Finally, we adopt anchor ties made of A400 class reinforcing steel with a diameter of $d_n = 28$ mm.

For the calculation and design of the retaining wall made of bored piles, the LIRA software package was used.

Originality and practical value

As the failure criterion, the modified Parchevskyi-Shashenko criterion was used. The model of the «foundation-retaining wall with bored pile» fragment is shown in Fig. 7, and the diagram of forces in the retaining wall elements is shown in Fig. 8. The piles are made of C16/20 concrete and reinforced with A400 class steel.

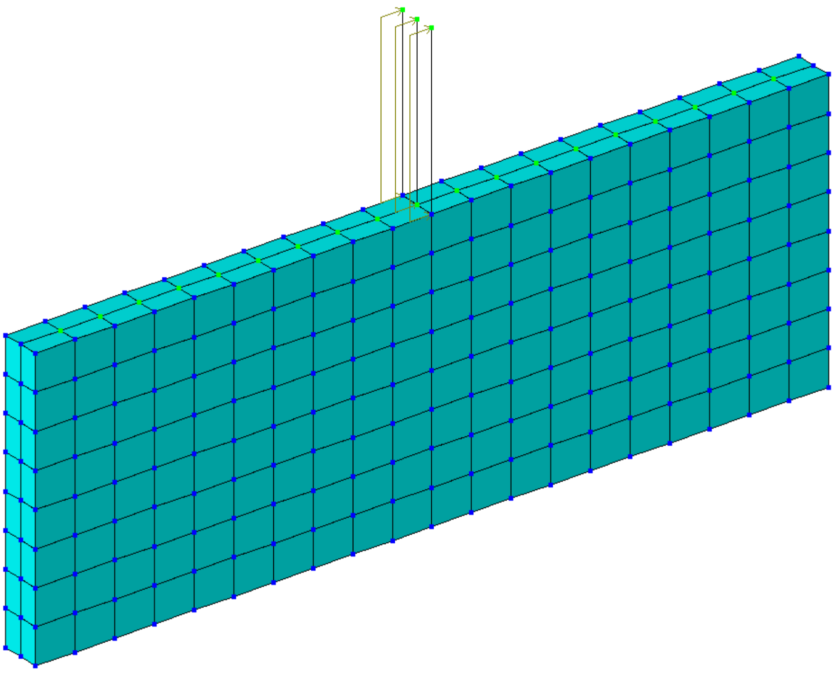

Fig. 7. Model of the «foundation-retaining wall with bored piles» fragment

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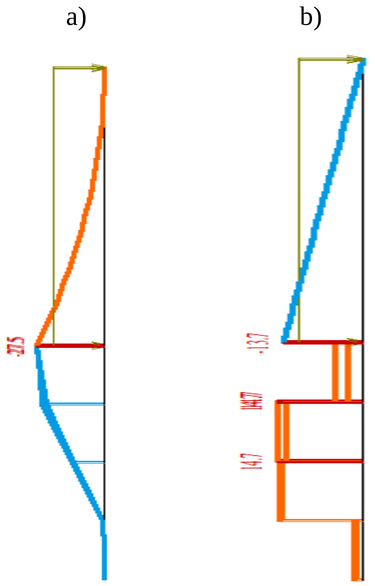

Fig. 8. Forces in the elements
of the retaining wall with bored piles:
a) bending moment diagram, b) shear force diagram

Based on the calculations, a working project drawing of the retaining wall element was developed in accordance with the requirements of DSTU (ДСТУ 3760:2019, 2019) and Eurocode 2 (ДСТУ-Н Б EN 1992-1-1:2010, 2011).

Conclusions

Based on analysis of methods for ensuring the stability of soil slopes, a pile structure with anchors was justified as the retaining construction for the soil conditions of the gully Tunnelna.

The modified Parchevskyi-Shashenko strength criterion allows:

- determining the shear stress on the retaining structures,
- calculating the bearing capacity of ground anchors in the soil,
- determining the embedment depth of retaining walls made of bored piles.

During the study, it was found that when designing elements of the retaining structure using Ukrainian building standards, 22 kg of reinforcement per element is required less than when using European standards (185 kg instead of 207 kg).

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ОБҐРУНТУВАННЯ ВИБОРУ ТА РОЗРАХУНОК ПАРАМЕТРІВ КОНСТРУКЦІЇ, ЩО ЗАБЕЗПЕЧУЄ СТІЙКІСТЬ ҐРУНТОВОГО СХИЛУ

Мета. У статті розглянуто питання забезпечення стійкості ґрунтового схилу в умовах природного та водонасиченого станів. Об’єктом дослідження є схил Тунельної балки у м. Дніпро, для якого виконано аналіз стійкості та обґрунтовано доцільність використання підпірної стінки з буронабивних паль, укріплених ґрунтовими анкерами. Метою роботи є обґрунтування вибору та розрахунок параметрів конструкції, що забезпечує стійкість ґрунтового схилу й запобігає деформаціям основ і несучих елементів будівель, розташованих у межах зсувонебезпечної ділянки. **Методика.** Дослідження базується на поєднанні аналітичних методів визначення зсувного тиску та чисельного моделювання в програмному комплексі Phase2 для визначення поверхні ковзання та коефіцієнта стійкості схилу. Розрахунок параметрів буронабивних паль і ґрунтових анкерів виконано з використанням програмного комплексу ЛІРА-САПР і нормативних документів ВСН, ДСТУ та Єврокоду 2. Як критерій руйнування застосовано модифікований критерій міцності Парчевського-Шашенка. **Результати.** Результати дослідження показали, що в природному стані коефіцієнт стійкості схилу становить K_{st} =1,30, а у водонасиченому стані K_{st} =1,17, що свідчить про необхідність укріплення. Запропонована підпірна стінка з буронабивних паль діаметром 500 мм, укріплена анкерами, забезпечує підвищення коефіцієнта стійкості до K_{st} =2,01. Визначено оптимальну відстань розташування конструкції – 13 м від закольної тріщини та глибину закладення паль у піщаний ґрунт – 6,67 м. **Наукова новизна** полягає у використанні модифікованого критерію Парчевського-Шашенка для моделювання системи «ґрунт - підпірна стіна з буронабивними палями», що дозволяє точніше оцінити напружено-деформований стан та стійкість схилу. Запропоновано методологію комплексного розрахунку системи «ґрунт - палі - анкери» з урахуванням гідрогеологічних умов. **Практична значимість** полягає в розробці інженерно обґрунтованих параметрів підпірної стіни, які забезпечують стійкість реального ґрунтового схилу. Отримані результати можуть бути використані при проектуванні підпірних конструкцій у зсувонебезпечних районах. Порівняння проектних розрахунків показало, що використання українських стандартів дозволяє зменшити витрату арматури на 10 % (22 кг на елемент) порівняно з Єврокодом 2.

Ключові слова: стійкість схилу; буронабивні палі; ґрунтові анкери; підпірна стінка; зсувний тиск; Phase2; ЛІРА-САПР; критерій Парчевського-Шашенка; основи будівель

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