http://www.moderntechno.de/index.php/meit/article/view/meit40-02-050
DOI: 10.30890/2567-5273.2025-40-02-050

УДК 624.131

PROTECTION OF THE STATE GEOSITE – "PYVYKHA" MOUNTAIN UNDER THE CONDITIONS OF THE DEVELOPMENT OF SLIDING PROCESSES

ЗАХИСТ ДЕРЖАВНОГО ГЕОЛОГІЧНОГО ПАМЯТНИКА – ГОРИ «ПИВИХА» В УМОВАХ РОЗВИТКУ ЗСУВНИХ ПРОЦЕСІВ

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Abstract. *To preserve the state geosite – Pyvykha Mountain, the authors have developed a set of measures to strengthen the landslide slope. However, the work is complicated by the possibility of rockslides and rock collapses, which threatens the equipment and people carrying out strengthening of the shore. After a detailed analysis and generalization of the results of the engineering and geological surveys conducted in this area, the most landslide-hazard zones of the slopes were selected and the stress-strain state of the slope was studied with the help of the Plaxis software complex, considering the possibility of a landslide. According to the simulation results, dangerous zones have been determined within which soil collapses are possible. It was concluded that the presence of people and equipment in these areas should be limited as much as possible.*

Keywords: *landslide, stability of slopes, displacement of soil.*

Introduction.

On the left bank of the Kremenchug Reservoir, near the village of Hradizhsk, there is one of the most picturesque places not only in Poltava Oblast, but also in all of Ukraine – Pyvykha Mountain. The mountain has a long history. According to legend, there was once a settlement of Pyva here, which belonged to the Pyva boyars (nobles). In 1489, the King of Poland Casimir IV presented lands and various grounds, located around Pyvykha Mountain, to Pustynno-Mykolaivskyi Monastery in Kyiv, whose monks in the 16th century founded Pyvhorodskyi Mykolaivskyi Monastery here. The monastery on Pyvykha Mountain became a religious and political centre for the Ukrainian people in the liberation war for their statehood. However, it was later destroyed. In 2008, Pyvykha represented Poltava Oblast at the All-Ukrainian competition "Seven Natural Wonders of Ukraine". The aesthetic appeal of Pyvykha Mountain is no less than the appeal of well-known places on the Crimean coast. Unfortunately, the destruction of the mountain has become more active recently, in which anthropogenic factors play a dominant role.

After the construction of the Kremenchug Reservoir in the late 1960s, Pyvykha Mountain gradually collapses. Every year, water absorbs about 7 meters of the mountain. Today, more than 600 meters of Pyvykha have been washed away. People find the remains of an ancient monastery, washed away by the waters of the Dnieper River. Now the State is trying to save the mountain in every possible way. Fortification works are being carried out along the shore, consisting mainly of anti-erosion plantations.

Figure 1 - General view of Pyvykha Mountain

Source https://funtime.kiev.ua/u/i/gallery/2019/06/gora-piviha-8-5d0bf03510066.jpg

Main part.

Almost all well-known geologists, without exception, devoted their attention to the study of the phenomenon of Pyvykha Mountain in the late 19th and early 20th centuries. At that time, Pyvykha Mountain, together with such well-known natural objects as Kanevsky dislocations (Cherkasy region), Vysachkivskyi Hill, Kalytka Mountain, were considered part of the Karpinskii lines, which united the Carpathians, the folded Donbas, the Caucasus and Mangyshlak into a single tectonic chain. According to D. Sobolev, Pyvykha Mountain is an example of glacial dissection of the surface. The most prominent among the numerous works, dedicated to Pyvykha at the beginning of the last century, are the publications of geologists V. Riznichenko and B. Lichkov. Later (in the early 1970s) generalizations were performed by the team of the Institute of Geological Sciences of the National Academy of Sciences of Ukraine. This work was part of a series of works on the study of the Chornobyl and Kamianka-Irpinski dislocations. In the late 1980s, an assumption was put forward regarding the geostructural conditioning of the position of the dislocations of Pyvykha Mountain and others. It was suggested that they are connected with linear morphostructural zones, the zone of influence of which includes various dislocated sections of the Dnieper Valley.

Marl, clay, sand, and crystalline gypsum can be found in the cleavages of Pyvykha. In the region, only on the territory of Pyvykha there are places where blue marl – a rare limestone rock used in construction – comes to the surface.

In order to study the possibility of preserving Pyvykha Mountain in its current state, we carried out engineering and geological studies, which included the collection and systematization of previous studies and the conduct of additional fieldwork and laboratory tests of soil samples taken along the entire length of the coast.

In terms of orography, the territory is located on the border of the Dnieper uplift and the left-bank Dnieper depression. From a geomorphological point of view, the protected territory is a ledge in the floodplain terrace of the Dnieper River with markings of the Earth’s surface 95-150 m.

Soils. The geological structure of the site includes Quaternary and Paleogene sediments.

The Quaternary sediments consist of a complex of alluvial sandy-clay deposits, Quaternary loams and clays, glacial, eolian-deluvial loess soils, with a total thickness of 25-30 m. The Quaternary deposits are underlain by greenish-gray and light blue marls of the Kyiv suite, with a thickness of more than 46 m.

In the lower part of the slope, where bank protection is being carried out, a shoal was formed by the accumulation of sediments of the reservoir, which is composed of sands with a thickness of 4-10 m.

On the site, 12 formations (axial sections) were selected for detailed study, aimed at determination of the topography of the slope, the layers of soils that make it up, as well as the physical and mechanical properties of the soils. A fragment of the scheme with the axial sections, according to which the research was carried out, is shown in figure 2.

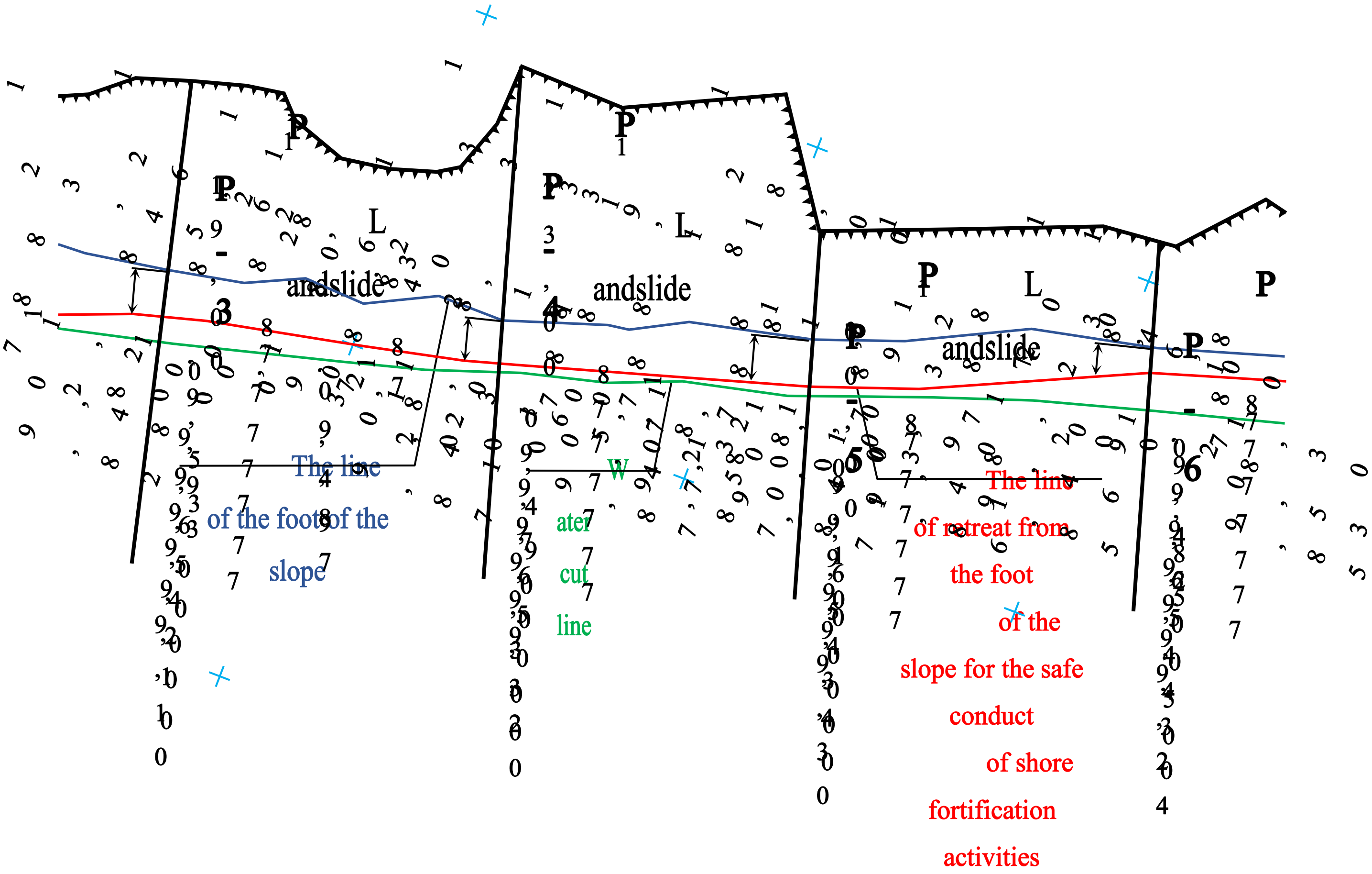

Figure 2 - A fragment of the scheme with axial sections PP-3, PP-4, PP-5, PP-6

Author's development

As a result of research work, and study of archival and stock materials, the following layering of soils was established:

IGE-1 – soil-vegetation layer with a thickness of 0,1 – 0,3 m;

IGE-2 – fine yellow-grey sand of medium degree of water saturation, of medium density; with a capacity of 4 – 8 m;

IGE-7 – fine dark grey sand, of medium density, with a low degree of water saturation, with a thickness of 2-4 m;

IGE-11^{а} and **IGE-12**^{а} – yellow-brown, semi-hard loam, 2,0-3,2 m thick;

IGE-13^{а} − brown, hard clay, 15-20 m thick;

IGE-13 − fawn, hard, silt loam, with a thickness of 2,8 – 3,1 m.

IGE- 13^{б} – yellow-grey, dusty sand of medium density, with a low degree of water saturation, 5-6 m thick;

IGE-13^{в} – sandy loam, hard, 2-3 m thick;

IGE-22 – marl, semi-hard clay, more than 46 m thick.

The hydrogeological conditions of the territory are characterized by the presence of a permanent non-pressure aquifer of the soil type, the discharge of which occurs towards the reservoir behind the depressions in the water-resistant layer. IGE =22 serves as a waterproof layer.

Physical and mechanical characteristics of the soils were determined based on the study of archival and stock materials and in laboratory conditions by methods of determining long-term and structural cohesion.

In the process of the reconnaissance survey of the slope section, its condition was visually established. The photo (Figure 3) clearly shows that the slope is sliding, which is evidenced by numerous cuts, and local divisions of individual soil pillars. At the foot of the slope, there are massive blocks of destruction products that have not yet been washed away by water. This confirms the continuity of the slope destruction process and, as a result, the great danger for people and construction equipment, who can be in the action area of the landslide.

Figure 3 - Landslide processes in the form of landslides-collapses of rock blocks

Source https://ic.pics.livejournal.com/zov_24/61703616/306609/306609_original.jpg

Tests.

The Plaxis software complex was used to determine the stability of the slope.

Plaxis is a software package designed to calculate stability and determine deformations of geotechnical structures using a mathematical apparatus in the form of the finite element method. The design of geotechnical structures requires the development of discrete models to simulate the non-linear, rheological behaviour of the soil. Since the soil conditions are represented by the layering of rocks with different properties and characteristics, and the rocks themselves are three-phase systems, special calculations are needed to model the pore pressure in different versions. The task was implemented with the help of the Plaxis complex, because it has special capabilities for working with many aspects of complex geotechnical structures.

The software complex has all the possibilities of input-output of information on the screen in a user-friendly interface (in tabular and graphic form – in the form of graphs and drawings). It also allows you to consider the nonlinearity of the base deformation processes, using the elastic-plastic model of the soil.

The following prerequisites are adopted in the formulation of the elastic-plastic problem:

- the considered manifestations of nonlinearity include plastic deformation of a change in shape under a complex stress state, unimpeded deformation during stretching, displacement along a given surface;

- in a complex stress state (compression with displacement), the general deformations include linear (elastic) and plastic parts and the plastic component of the deformations occurs after the stress state reaches the strength limit and corresponds to the Mohr-Coulomb condition for a plane problem:

$$\frac{1}{2}(\sigma_1 - \sigma_2) + \frac{1}{2}(\sigma_1 + \sigma_2)\sin\varphi - c\cdot\cos\varphi = 0, \qquad (1)$$

Discretization of the computational domain when solving a nonlinear problem is performed using the finite element method.

The Plaxis software complex allows you to consider the stress-strain state with simultaneous application of all loads or step-by-step application. The initial stress state reached by the system before the application of the load can be taken into account.

Finite elements in the form of elastic-plastic plates of triangular cross-section are used in the calculations. Stress components are determined only in the centres of continuous finite elements modelling the soil, and displacements – in grid nodes.

The information entered consists of the following arrays of output data:

- coordinates of nodes;
- links (nodes with zero displacements and nodes with equal displacements);
- description of loads (magnitude, direction and points (nodes) to which it is applied);
- description of finite elements (numbers of nodes, cross-sectional areas and moments of inertia of rods; physical and mechanical characteristics of soils, the angle of inclination of the sliding surface, natural and initial stress state);
- the maximum number of iteration cycles.

The following calculation results are printed:

- movement of nodes;
- stress components in the centres of continuous finite elements;
- longitudinal and transverse forces and moments at the ends of rod elements.

The peculiarity of the method under consideration is the performance of calculations on the limit states of both groups on the same calculation scheme with the same soil model. In practice, the calculation can be performed by stepwise loading: the active load is given a value that corresponds to the calculation based on the limit states of the second group, and then the forces are increased to the dimensions of the most unfavourable calculated values.

The central issue of the calculation of foundations and soil structures according to the limit states of the first group is the assessment of the possibility of a loss of strength and stability due to the development of significant displacements and the admissibility of plastic deformations of the soil. The coincidence of the iterative process, that is, a solution that satisfies all the established requirements (with respect to the permissible incoherence), indicates that a static stress state has been obtained, which excludes the loss of strength and stability.

The elastic-plastic problem under consideration is set so that the properties of the soil environment, which are taken into account in the calculation, could be described by realistically determined characteristics. When preparing the initial data of the elastic-plastic calculation, six basic parameters of each layer are required: specific weight γ, modulus of deformation E, Poisson’s ratio ν, angle of internal friction φ, specific adhesion c, and dilatancy parameter.

The use of soil reliability coefficients only for parameters γ, φ, c and E when using average characteristics is enough to ensure the necessary reliability of the calculation results.

The calculation of the stability of the slope is carried out according to the following calculation scheme, which involves changing the soil strength characteristics until the slope reaches a state of ultimate equilibrium. With this approach, the slope stability coefficient is defined as the ratio of the initial strength characteristics to their limit values:

$$K_{st} = \frac{c+\sigma\cdot\tan\varphi}{c_r+\tan\varphi_r}, \quad (2)$$

Where c and φ are the input strength parameters, σ is the normal component of the actual stress. The parameters c_r and φ_r are the reduced strength parameters that ensure slope stability. In this approach, the adhesion and the tangent of the friction angle are taken in the same proportion:

$$\frac{c}{c_r} = \frac{\tan\varphi}{\tan\varphi_r} = \sum M_{sf}, \tag{3}$$

The reduction of strength parameters is controlled by the common factor ΣM_{sf}. This parameter is increased in a stepwise method until failure occurs. The reliability factor is then defined as the value of ΣM_{sf} at failure, provided that failure results in a more or less constant value for the number of successive iterations.

The calculation of the stability of the slope in the area of the village of Hradizhsk, Globyn district, Poltava region, was carried out to determine the safe distance from the foot of the slope for shore fortifications. The safe distance in this case was determined from the condition of loss of stability of the slope or possible soil collapse when the slope is moistened. That is, shore-fortification structures and mechanisms for their arrangement must be placed at such a distance from the foot of the slope that would ensure their safe operation in the event of possible falls of ground or landslides.

At the time of this work, landslides and falls of ground are observed on the slope at a distance of 3-5 m from the foot. However, with an unfavourable combination of some factors, the soil massif, bounded by the slope, can go into an unbalanced state and lose its stability. At the same time, the movement of the soil can take place over a slightly greater distance.

The main reasons for the loss of stability are:

- arrangement of an unacceptably steep slope or undercutting the slope that is in a state close to the boundary condition;
- increase in external load (construction of structures, storage of materials, etc.);
- a change in the stress-deformed state (increase in the specific gravity of the soil with an increase in its humidity or vice versa, the effect of the balancing effect of water on the soil);
- a decrease in the calculated characteristics of soil strength and its resistance to displacement due to, for example, an increase in humidity;

- manifestation of hydrodynamic pressure, seismic forces and various dynamic forces (traffic, pile driving, etc.).

As part of the work, we performed the calculation of the slope, which is located in the area of the village of Hradizhsk, Globyn district, Poltava region, according to 12 sections. The calculation scheme includes the cross-sectional area of the slope with the corresponding soil layers and boundary conditions. As an example, Figure 4 shows the calculation scheme of the PP-5 cross-section, divided by a grid of finite elements.

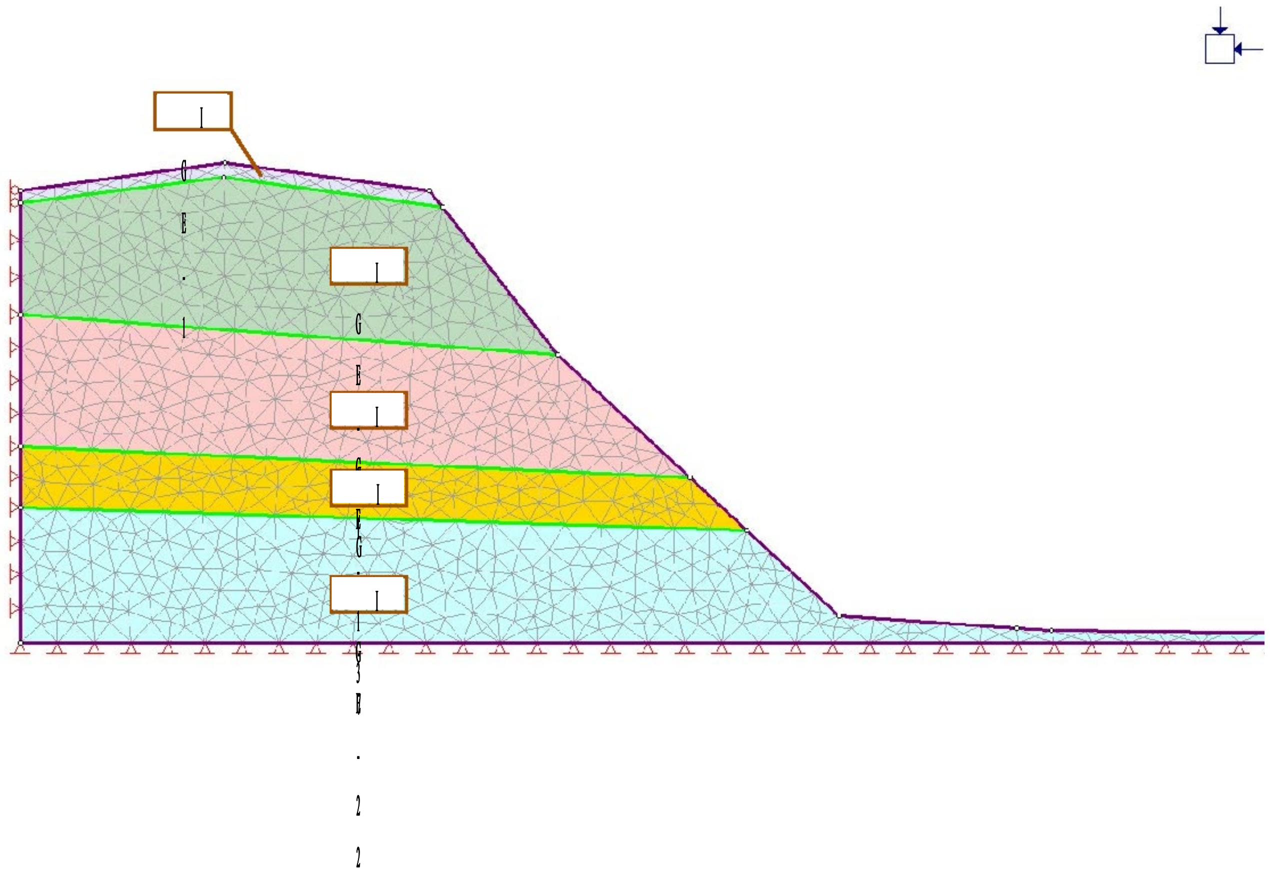

Figure 4 - Calculation scheme of the PP-5 cross-section

Author's development

The results of the calculations are presented in Table 1.

The critical values of the stability coefficient on the slope sections are significantly smaller than 1, indicating the emergency condition of this slope.

Thus, as a result of calculations based on 12 calculation schemes corresponding to 12 sections of the slope, the following data were obtained:

- slope stability coefficients;

- the most landslide-hazard zones according to the results of calculations on 12 sections;
- a safe distance from the foot of the slope for shore protection works.

Table 1 - Values of slope stability and maximum displacements of the soil massif from its foot.

Cross section number	The coefficient of stability of the slope in critical condition, K_{st}	Maximum displacements of the soil massif from the foot of the slope at the coefficient of stability of the slope K_{st}=1,0, m
PP-1	**0,23**	**25,8**
PP-2	**0,10**	**12,4**
PP-3	**0,17**	**12,8**
PP-4	**0,18**	**12,0**
PP-5	**0,11**	**12,8**
PP-6	**0,19**	**7,2**
PP-7	**0,12**	**10,6**
PP-8	**0,12**	**15,1**
PP-9	**0,09**	**6,8**
PP-10	**0,14**	**11,2**
PP-11	**0,14**	**9,0**
PP-12	**0,23**	**22,7**

Author's development

Based on the study of the location of the zones with maximum shear stresses in the sections, we obtained the most probable positions of the sliding planes of the soils that make up the slope.

Conclusions.

As a result of the conducted research, the following main conclusions can be drawn.

1. Quaternary and Paleogene sediments can be traced in the geological structure of the slope area. The Quaternary sediments consist of a complex of alluvial sandy-clay deposits, represented by Quaternary loams and clays of glacial and eolian-deluvial origin, with a total thickness of 25-30 m. Quaternary sediments are underlain by greenish-gray and light blue marls of the Kyiv suite, with a thickness of more than 46

m. In the lower part of the slope, where the bank protection is projected, a shoal was formed by the accumulation of sediments of the reservoir, which is composed of sands with a thickness of 4-10 m.

2. In the process of reconnaissance survey of the slope section, it was visually established that it should be classified according to DBN B.1.1-46:2017 as a sliding slope. This is evidenced by numerous cuts and local separations of individual soil pillars. At the foot of the slope, there are massive blocks of alteration products that have not yet been washed away by water, this confirms the continuity of the process of destruction of the slope and, as a result, the great danger for people and construction equipment in the area of action of the landslide.

3. In accordance with the technical task of the customer, it is necessary to ensure the safe conduct of construction works to strengthen the banks of the reservoir under specific conditions. For this, it was necessary to determine the zone at the foot of the slope, which is likely to suffer from the collapse of rocks due to landslide processes.

4. The location of the dangerous zone, within which shifts and collapses of the rocks of the slope are possible, is determined by mathematical modeling of the sliding processes of the slope with the help of the Plaxis software complex, which uses a discrete model for modeling the nonlinear, rheological behavior of the soil. Triangular finite elements were used in the calculations. Stress components were determined only in the centers of continuous finite elements simulating the soil, displacements – in grid nodes.

5. As a result of the conducted research, a diagram of the slope of the reservoir bank was constructed on a topographic basis with the definition of a danger zone within which landslides are possible. The presence of people and all technical means is prohibited in this zone, with the exception of those that are used to monitor the state of the slope in automatic mode.

6. To monitor the state of the slope, it is recommended to use the modern "Monitoring" system, designed by the State Enterprise "State Research Institute of Building Constructions", Kyiv.

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Анотація. *На лівому березі Кременчуцького водосховища поблизу с.м.т. Градизьк розташована одна із найбільш мальовничих місцин не лише Полтавщини, а і усієї України – гора Пивиха. Окрім естетичного гора має ще й історичне значення. У 1489 році король Польщі Казимир IV подарував землі і різні угіддя, розташовані довкола гори Пивихи, Київському Пустинно-Миколаївському монастирю, ченці якого у XVI ст. заснували тут Пивгородський Миколаївський монастир. І хоч пізніше монастир на Пивисі, що був релігійно-політичним осередком українського народу у визвольній війні за свою державність, був зруйнований, його значення в історії спонукає нас до збереження даної місцини.*

Після зведення в кінці 1960-х років Кременчуцького водосховища Пивиха поступово руйнується. Щорік вода поглинає близько 7 метрів гори. Сьогодні вже розмито понад 600 метрів Пивихи. Люди знаходять залишки древнього монастиря, які вимиваються дніпровськими хвилями. Тепер гору всіляко прагнуть зберегти. Вздовж берега проводяться укріплювальні роботи, що складаються, в основному, з протиерозійних насаджень.

Дослідженням феномену гори Пивихи, що проводились з кінця XIX століття, присвятили свою увагу практично всі без винятку відомі українські вчені-геологи, а узагальнення даних були виконані колективом Інституту геологічних наук НАН України. У подальшому проводились роботи щодо детального вивчення інженерно-геологічних умов території та розробки проекту укріплення берегів Кременчуцького водосховища.

У відслоненнях Пивихи присутні мергель, глина, пісок, кристалічний гіпс. У регіоні лише на території Пивихи є місця виходу на денну поверхню блакитного мергелю – рідкісної вапнякової породи, яка використовується в будівництві.

Для вивчення можливості збереження гори Пивиха у сучасному стані були проведені інженерно-геологічні дослідження, що включали збирання та систематизацію раніше проведених вишукувань та проведення додаткових польових робіт і лабораторних випробувань зразків ґрунтів, відібраних по всій довжині узбережжя.

В геологічній будові ділянки приймають участь відклади четвертинної та палеогенової систем. Відклади четвертинної системи складаються комплексом алювіальних піщано-глинистих відкладів, суглинками та глинами четвертинного віку, льодовиковими, еолово-делювіальними лесовими ґрунтами, загальною потужністю 25 – 30 м. Підстилаються четвертинні відклади зеленувато-сірими і світло-голубими мергелями київської світи, потужністю більш ніж 46 м.

Метою проведених досліджень було визначення стану схилу узбережжя Кременчуцького водосховища та надання рекомендацій щодо безпечного проведення робіт по берегоукріпленню.

На ділянці для детального вивчення було виділено 12 створів (профілів), за якими виконувалися роботи з визначення топографії схилу, нашарувань грунтів, що його складають, а також фізико-механічних властивостей ґрунтів. У результаті проведення вишукувальних робіт, вивчення архівних та фондових матеріалів встановлено нашарування ґрунтів, що включає більше 20 елементів. Гідрогеологічні умови території характеризуються наявністю постійного безнапірного водоносного горизонту ґрунтового типу, розвантаження якого відбувається у бік водосховища за улоговинами у водотривкому шарі.

В процесі рекогносцировки ділянки схилу візуально встановлено, що схил зсувний. Про це свідчать численні заколи, місцеві відділення окремих стовпів ґрунту. У підніжжі схилу розташовані масивні брили продуктів руйнування, які ще не розмиті водою. Це підтверджує безперервність процесу руйнування схилу і, внаслідок цього, велику небезпеку при знаходженні в зоні дії зсуву людей і будівельної техніки.

Для визначення стійкості схилу було застосовано програмний комплекс Plaxis – програмний пакет, який призначений для розрахунку стійкості та визначення деформацій геотехнічних споруд з використанням математичного апарату у вигляді методу скінчених елементів.

Пружно-пластична задача, що розглядається, поставлена так, щоб властивості ґрунтового середовища, які враховуються в розрахунку, могли бути описані реально визначеними характеристиками. При підготуванні вихідних даних пружно-пластичного розрахунку необхідні шість основних параметрів кожного шару: питома вага γ, модуль деформації E, коефіцієнт Пуассона ν, кут внутрішнього тертя φ, питоме зчеплення c, параметр дилатансії.

В рамках проведення роботи було виконано розрахунок схилу, що розташований в районі селища Градизьк Глобинського району Полтавської області за 12 профілями, у результаті чого отримані коефіцієнти стійкості схилу та визначені найбільш зсувонебезпечні зони і безпечна відстань від підніжжя схилу для проведення берегоукріплювальних робіт.

Ключові слова: *зсув, стійкість схилів, переміщення ґрунту.*