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APPROACHES TO ASSESSING THE STABILITY OF BANK PROTECTION STRUCTURES OF WATERBODIES: ANALYSIS OF CONSTRUCTIONS AND MODELS FOR THEIR CALCULATION

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Анотація: *The article analyzes the theoretical foundations for determining the stress state in a soil mass and the design of fastening the bank slope of reservoirs. Scientific research and theoretical principles on determining the forces that act on a bank protection structure have been systematized. Methodological approaches to the static calculation of bank protection for indirectly vertical structures are proposed, taking into account the relationship between the load on the structure and its deformation.*

The purpose of the research is to ensure the stability and reliability of bank protection structures and to substantiate directions for improving technical solutions in modern conditions.

The work analyzes the use of various types of slope fastenings for bank protection structures in accordance with the requirements of State construction standards. It is proposed to focus research on sheet piling shore fastenings, as a modern and progressive technology for bank protection. The "soil massif – fastening structure" system is considered as a calculation model in the form of a one-sided type, which is an elastic element, which makes it possible to apply the modern apparatus of the theory of elasticity in considering this problem. This makes it possible to accept a linear relationship between stress and strain and obtain sufficient accuracy, which is confirmed by the available results of domestic and foreign research. For calculations of deformations, and assessment of the strength and stability of soil massifs and foundations, it is proposed to pay direct attention to the characteristics of the mechanical properties of soils, while three stages of foundation deformation are considered.

The formulated differential equations of the equilibrium of the soil massif make it possible to solve a wide range of issues related to the limit equilibrium and to obtain the calculated parameters of the pressure of earth masses on the retaining walls of shore fortifications of the oblique-vertical type. The results of the research analysis are recommended for use in determining the main loads on hydraulic structures, substantiating technical solutions for the development and improvement of slope and slope-vertical types of bank protection of reservoirs.

Key words: *bank protection, stress state, theory of elasticity, soil mass, calculation model, stability*

Relevance of research. Bank protection structures as part of anti-slide and anti-landslide measures are used in areas where the bases of the slopes are placed in contact with the water mirrors of seas, lakes, reservoirs or rivers, to protect native shores or stabilize landslides, expand or preserve existing beaches. In connection with the change in the hydrological and geological situation, the increase in anthropogenic load and climate change, the conditions for ensuring the stability and reliability of the bank portection structures are an urgent task.

The spread of bank destruction processes, especially in the cascade of the Dnieper reservoirs, is the most representative of the objects, which requires the introduction of changes and renewal of the provisions of the existing methodological and regulatory documentation on the assessment of the processes of statics and dynamics of soil massifs and the calculation of bank fortification structures, their design, construction and operation. The accumulated experience in the operation of bank protection of reservoirs indicates the insufficient durability of the fastening structures used, both slope and vertical types. This is explained by the fact that during the design and construction of various types of bank protection structures, their stability and reliability were not sufficiently taken into account.

Determining the stress state of the interaction between the soil mass of the slope and the fasteners is a very complex statistically uncertain problem of structural mechanics. In practice, when determining the soil pressure on the construction of fasteners, the theory of limit equilibrium of granular bodies, proposed by C. Coulomb back in 1766, is used. This theory, as the practice of construction and operation of hydraulic structures shows, provides a solution with a certain margin of safety.

This is especially true for flexible fastening structures, both slope and vertical types, which under operating conditions are significantly different from the basic provisions laid down in the Coulomb theory. Therefore, there is a need to improve the methodology for calculating inclined-vertical structures, which would take into account the different rigidity and operating conditions of bank protection structures.

Purpose of research. Ensuring the stability and reliability of bank protection structures and substantiating directions for improving technical solutions in modern conditions.

Analysis of recent research and publications. The basis of Coulon's theory of the limiting equilibrium of granular bodies is the hypothesis that a granular body is a homogeneous continuous medium that perceives only compaction itself, and also that when the system is at "rest" (equilibrium), the resulting stress deviates by an angle less than – φ of the internal friction of the soil mass).

Coulon's theory reflects only one statistical side of the problem of pressure of a granular medium, and to a certain extent does not cover its kinematic side, that is, it excludes consideration of deformation and displacement from the processConsequently, the condition has been accepted that the movement of the fastener structure is sufficient for the occurrence of a state of limiting equilibrium of the backfill behind it. This means that the fastener structure and backfill are not in normal operating condition, but are in the initial stages of destruction. In 1840, Ponsele carried out scientific research and practical solutions to this problem, regarding the pressure on the retaining wall, graphic materials were proposed for determining the force acting on the structure of the fastener.

P.P. Argunov reduced the problem of determining the pressure on a vertical smooth wall to the problem of the theory of elasticity with the superimposition of solutions for two planes, one of which has a vertical plane and the other horizontal, which made it possible to determine the pressure on the structure depending on its displacement [1]. N.K. Snitko developed a method taking into account the joint movement of the retaining structure and its base [2]. I.E. Byaler obtained a general solution to the linear theory of elasticity for soil pressure on structures of any rigidity, including anchor and cantilever ones, taking into account their joint deformation of the backfill soil [3]. Later I.Ya. Beler, M.Ya. Borodyansky presented a new method for calculating retaining walls, based on the joint work of the retaining wall and soil backfill [4]. G.E. Lazebnyk, E.P. Chernysheva gave a solution for determining the influence of the shape of lateral soil pressure supports on forces in sheet pile anchor retaining walls [5]. A.I. Beleush outlined the basics of calculating retaining structures and the effectiveness of their operation in securing landslide slopes [6]. A.M. Ryzhev provided solutions to problems of nonlinear mechanics and physical modeling of the foundations of structures [7]. Yu.M. Kalyukh proposed modern information technologies, mathematical methods of studying and forecasting the evolution of processes in dangerous areas and objects [8, 9]. M.T. Kuzlo proposed calculation schemes and models for assessing the state of water-saturated soil massifs and foundations [10].

Based on the analysis of theoretical principles, it can be argued that the combined fastening of slopes of reservoirs is made in the form of a slope-vertical structure and has several advantages compared to classic fastening slopes, which are determined by hydraulic and static calculations. This design is widely used in hydraulic engineering. For example, strengthening the banks of the Dnieper reservoir cascade [11].

It is known that soils on the banks of reservoirs are a nonlinear elastic medium. Therefore, to obtain a more reliable solution for the selection and justification of calculations of slope-vertical structures of bank protection structures, it is necessary to develop new methodological approaches that would take into account both the rigidity of the structures and the nonlinear elasticity of the soil of the slopes and operating conditions.

Materials and methods of research. A slope is an artificially created surface that limits a natural soil massif, a recess, or an embankment. Slopes are formed during the construction of various types of embankments (roadbeds, dams, earthen dams, etc.), excavations (pits, trenches, canals, quarries), or during the repurposing of territories. On the sea and river coasts, hydraulic retaining walls and embankment shore fortifications are built to protect the slopes of enclosing dams or coastal slopes from the destructive effects of waves and storm currents [12].

It is allowed to use the following types of oblique fastenings of shore fortification structures in accordance with the requirements of State Construction Standard DBN V.2.4.-3:2010 [13]:

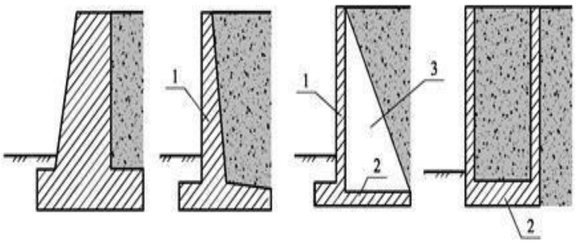
- impermeable concrete, reinforced concrete from prefabricated slabs or in the form of a continuous coating;
- permeable concrete, reinforced concrete from prefabricated elements in the form of a diagonal-stepped structure with a wave chamber;
- stacking from shaped or ordinary blocks;
- stone overlays and paving, including from mountain mass.

Depending on the design and purpose, hydraulic retaining walls are of the following types:

1. Gravity – erected on rock and non-rock foundations (Figure 1), made of monolithic or prefabricated concrete and reinforced concrete.

Retaining walls of this type, as a rule, are part of the structures of the pressure front of hydraulic units, mooring structures, and embankments;

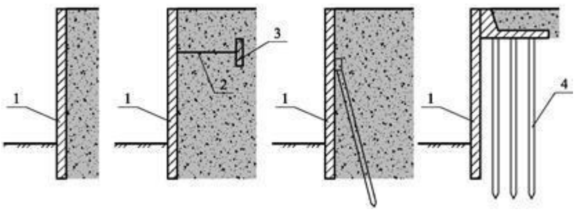
Gravity-retaining walls resist soil pressure due to their significant self-weight and the weight of the soil within the wall dimensions.



a *b* *c* *d*

Fig. 1. Types of gravity retaining walls:

a) massive, b) corner, c) buttress, d) shell;
1 – plate (face element), 2 – foundation plate,
3 – buttress (rib)



a *b* *c* *d*

Fig. 2. Types of sheet piling and pile retaining walls:

a) anchorless; b) anchored in the slab; c) anchored to the inclined pile; d) on a pile foundation;
1 – sheet pile, 2 – rod (rod), 3 – slab, 4 – piles

2. Sheet piling and pile retaining walls – are erected on a base that allows the deepening of sheet piles or piles (Figure 2). They are part of berth buildings, embankments and other hydraulic structures.

The strength of sheet piling and pile retaining walls is ensured by resistance to bending, and stability – mainly by resistance to bulging of the foundation soil.

Consequently, sheet piles generally act as flexible retaining structures. This means that they hold the soil, resist shifting and overturning due to embedding in the soil mass or the design of the fasteners (spacers, anchors). Thus, sheet piling structures operate either according to a cantilever design scheme or a beam design scheme (in the presence of spacers or anchors). Spacers and anchors should be used in cases where the operation of sheet piles according to the cantilever scheme does not provide the required durability, strength, rigidity, and deformability. As a rule, when the height of the retained difference is more than 5 m, fastening structures are required. In addition, it should be understood that the operation of a sheet pile using a cantilever scheme requires the presence of sufficiently strong soils into which the sheet pile can be deepened.

Calculation of sheet piling comes down mainly to determining its length and type, as well as the parameters of the anchor or spacer support, if necessary. Therefore, we are considering a problem of models for calculating sheet piling bank protection.

Models used for calculating natural slopes, bank protection slopes, combined into four groups:

- soils are considered as a continuous linear elastic medium that does not correspond to their natural state;
- soils in the form of a continuous incompressible single-phase medium, each point of which is in a state of maximum stress (theory of V.V. Sokolovsky);
- deformation-free models of the hardened compartment of the soil collapse, which is taken as an absolutely rigid body;
- soils as a solid, deformed, elastic-plastic, heterogeneous and strengthening medium, at each point of which it is possible to determine both stresses and strains from single positions.

The fourth nonlinear calculation model is complex, but it is the most progressive, both theoretically and in numerical implementation [14]. Compared to the other three models, it more fully reflects the natural soils' properties.

The paper presents approaches to the calculation of sheet pile fastening by the graph-analytical method – the Blum-Lohmeyer method. At the same time, the calculation is performed in the following order: the total soil pressure plot is divided into 10-12 layers. The areas of each layer are calculated, which are replaced by concentrated forces and laid in the center of gravity of the layers, taking into account the direction.

The stability of bank protection structures is checked using deep shear schemes using the K. Terzaghi method, in which calculations are reduced to determine the safety factor for the overall stability of the structure. When calculating the stability of slopes, it is important to establish the most dangerous position of the sliding surface, the stability of which is assessed by calculation methods, for example, the method of circular cylindrical surfaces of a leaning slope of horizontal forces.

Assessing the stability of a bank protection structure based on solutions to the elastic-plastic problem of nonlinear soil mechanics – establishing the relationship between the load and the deformation of the foundation. When calculating the stability of slopes based on deformations, the soil is considered as a structurally stable body, the deformation of which is assessed based on the theory of creep.

To calculate deformations, and assess the strength and stability of soil masses and foundations, we consider the characteristics of the mechanical properties of soils. By mechanical properties of soils, mean their behavior under the influence of external load or a change in their physical state. The mechanical properties of soil depend on the mineral and granulometric composition, physical state (density, humidity, temperature) and structural features.

Research results and their discussion.

The stability of bank protection slopes from the point of view of deformation development and offsets. Under natural conditions, the soil is affected by tension from its weight. Deformations usually occur upon completion of the processes of soil creation and diagenesis, external load, etc. If the soil is located in the base of massif then under the influence of the weight of the structure, stress arises, which leads to additional deformation of the soil. Soil deformations under load are accompanied by complex processes: compression of solid particles, compression of water and air that are in the pores of the soil, destruction of bonds between particles and their mutual displacement, changes in the thickness of water films, and squeezing out free water from soil pores [15]. Research by domestic and foreign scientists established stages of deformation of foundations, in which at each stage deformations of a certain type occur in the soil, affecting the nature of the dependence of subsidence on loading or pressure along the base of the foundation $p = F(A)$. The following stages of base deformation have been identified (Fig. 3):

I – compaction stage;
II – shift stage;
III – stage of destruction.

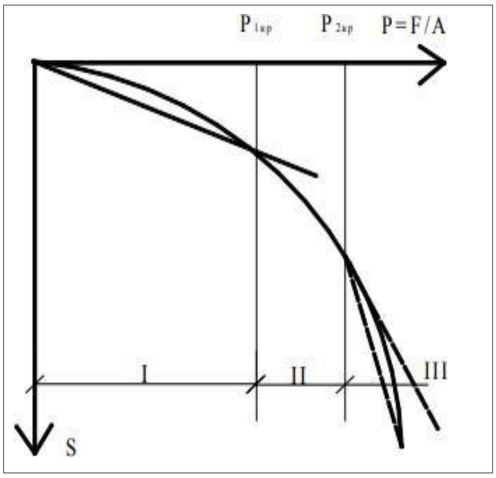


Fig. 3. Stages of base deformation:
I – compaction; II – shift; III – destruction

In the first stage, the deformations are insignificant. The movements of soil particles are directed mainly vertically and a zone (core) of compacted soil is formed under the sole. The dependence $S = f/(p)$ in this section is close to linear. In the second stage, the nature of the deformation changes: the soil is squeezed out from under the edges of the foundation and areas are formed in which the strength of the soil is exhausted – shear zones. As they develop, the increment in subsidence increasingly outpaces the increment in pressure, which is described by the nonlinear relationship $S = f/(p)$.

The exit of the displacement areas to the soil surface leads to the beginning of the III stage – the destruction of the base with failure settlement.

Analyzing the graph (Fig. 3), it becomes necessary to theoretically determine the pressures (loads) that cause the transition of the base from one stage of deformation to another.

Taking into account deformation properties, and indicators of soil mechanics, which describe mechanical properties, the main regularities of soil mechanics are established, which are listed in Table 1.

1. The main regularities of soil mechanics

The law	**Indicators**	**Note**
Deformation characteristics		
Law of compaction	*m*0 – compressibility coefficient; *mv* – relative compressibility coefficient; *E*0 – modulus of total deformation	When calculating the foundation using the second group of limit states or deformations
Strength characteristics		
Coulon's law	φ – angle of internal friction; C – specific adhesion	When calculating the stability of the foundation, the first group of limit states
Water permeability		
Darcy's Law	*kf* – filtration coefficient; *cv* – consolidation coefficient	Calculation of base subsidence over time, other filtration calculations

Methods based on solving a system of equations of the theory of limit equilibrium with the construction of a grid of slip lines in the soil mass forming the slope. Quantitatively, the degree of slope stability is usually characterized by a stability or reliability coefficient, determined by the ratio:

$$C_{st} = F_{hodl} \,/\, F_{destr} \qquad (1)$$

where F_{hold} – a factor that takes into account the action of all forces that ensure stability;

F_{destr} – also, causing the slope to collapse.

The essence of the factors – forces or moments of forces – depends on the shape of the probable slope failure and, consequently, on the adopted design scheme.

By definition (1), when $C_{st} > 1$ the slope is stable, when $C_{st} < 1$ it is unstable, and when $C_{st} = 1$ there is a limiting equilibrium.

Having specified the value of C_{st}, you can determine the slope contour corresponding to it. The basis for assigning a stability coefficient can be regulatory recommendations (usually $C_{st} = 1{,}2–1{,}5$), as well as special pre-design studies. For the simplest but most common structures, methods for calculating the stability of slopes at limiting equiaction are often used.

Conditions for the limit equation of a granular body. In the case of hydraulic engineering constructions, a granular body (medium) includes solid homogeneous parts (soil, crushed stone), characterized by friction and adhesion coefficients. The amount of internal friction of a granular medium is estimated by the angle of internal friction – φ, and the amount of adhesion – by the adhesion coefficient – *C*.

The stability of a bulk body (medium) is ensured provided that at each point of it (the body) the following inequality is satisfied:

$$/\tau_n/ \le \delta_n \,\mathrm{tg}\varphi + C, \qquad (2)$$

That is, with (2), the magnitude of the tangential stress in the massif, which causes displacement (sliding) of parts of the soil along any sliding plane, will be less than the sum of the friction and adhesion forces on the same plane. The condition for limiting equation in this case can be written in the form

$$/\tau_n/ = \delta n \,\mathrm{tg}\varphi + K, \qquad (3)$$

and the plane corresponding to this condition is the sliding plane.

The magnitude of the stresses and the coefficient of adhesion from the Coulon-Mohr circle are determined by the dependence:

$$/\tau_n/ = \frac{\delta 1 - \delta 3}{2}\cos\varphi$$

$$/\tau_n/ = \frac{\delta 1 - \delta 2}{2} - \frac{\delta 1 - \delta 3}{2} * \sin\varphi, \qquad (4)$$

$$K = \frac{\delta 1 - \delta 3}{2} * \frac{1}{\cos\varphi} - \frac{\delta 1 - \delta 3}{2} * \mathrm{tg}\varphi,$$

where δ1 – δ3 – normal stress.

Then the limit equilibrium condition can be expressed as a dependence:

$$(\delta_x - \delta_y)^2 + 4\tau^2_{xy} = (\delta_x + \delta_y + 2K\,\mathrm{tg}\varphi)^2 * \sin\varphi \quad (5)$$

at φ = 0, that is, for a medium with perfect adhesion, the condition takes the form:

$$(\delta_x - \delta_y)^2 + 4\tau^2_{xy} = 4K^2. \qquad (6)$$

Which coincides with the plasticity condition (5).

The deformation equilibrium equation and condition (5) constitute the basic equation of statics of a granular mass (medium), which can be expressed by the equations:

$$\frac{d\delta_y}{d\delta_x} + \frac{d\tau_{xy}}{\delta_x} = 0\,;$$

$$\frac{d\delta_y}{d_y} + \frac{d\tau_{xy}}{\delta_x} = \gamma\,;$$

$$(\delta_x - \delta_y)^2 + 4\,\tau^2_{xy} = (\delta_x + \delta_y) + \\ + 2K\,\mathrm{tg}\varphi^2)\ *\ \sin^2\varphi, \qquad (7)$$

where: γ, φ, К – volumetric weight, friction angle, specific adhesion of bulk medium.

Equation (7) allows for solving a wide range of issues related to the ultimate equilibrium of earth masses.

Discussion of the results. The results of the analysis of the stability of bank protection slopes and static calculations of bank protection structures indicate that the magnitude of the forces accepted by the structure varies widely depending on the physical and mechanical properties of the soil, the structure of the structure and the methods of construction work. It is impossible to take into account all factors. Therefore, it is proposed to exclude less important components from consideration and focus in the calculation theory on the components of the system – the interaction of fastener structures with the soil mass. The bank protection design, when interacting with the soil mass, absorbs part of the loading, thereby ensuring the stability of the soil mass, and also contributing to the equilibrium process. Consequently, the fastener structure and the earth mass are load-bearing components of a single system, and the stresses arising in the system are constantly interconnected. The above makes it possible to apply the modern apparatus of the theory of elasticity based on the linear relationship between stress and deformation through the use of differential equilibrium equations for the soil massif.

Conclusions. Methodological approaches are proposed for the static calculation of bank protection of sloped-vertical structures, taking into account the relationship between the load on the structure and its deformation.

The system "soil mass – fastener construction" is considered a one-sided calculation model, which is presented as an elastic element, which allows the use of modern elasticity theory. Accepting a linear relationship between stress and deformation simplifies the calculation of loads with obtaining stability indicators of bank protection structures with sufficient accuracy, which is confirmed by the available materials from the results of domestic and foreign research. Differential equations of equilibrium of the soil massif are formulated, which allows solving a wide range of issues related to limit equilibrium and obtaining calculation parameters of the pressure of soil masses on the retaining walls of shore fortifications of the slope-vertical type.

The research results are recommended for use in determining the main loads on hydrotechnical structures and justifying technical solutions for the development and improvement of oblique and oblique-vertical types of shore fortification of reservoirs.

References

1. Arhunov, P.P. (1942). A combined application of the theory of elastic and plastic deformations to calculate soil pressure on retaining walls [Metod kombynyrovannoho prymenenyia teoryy upruhykh y plastycheskykh deformatsyi k raschetu davlenyia hrunta na podpornye steny]. *Yzvestyia AN SSSR, OTN.* 10 [in russian].
2. Snytko, N. K. (1963). Static and dynamic soil pressure and calculation of retaining walls [Statycheskoe y dynamycheskoe davlenye hruntov y raschet podpornykh stenok]. Lenynhrad – Moskva : Hosstroiyzdat [in russian].
3. Klein, H.K. (1996). Ground pressure on a structure depends on its movements [Davlenye hrunta na sooruzhenye v zavysymosty ot ykh peremeshchenyi]. 1, 1996 [in russian].
4. Beliar, Y.Ia., & Borodianskyi, M.Ia. (1970). Calculation of retaining walls of any stiffness [Raschet podpornykh stenok liuboi zhestkosty]. *Yzv. Vuzov "Stroytelstvo y arkhytektura"*, 8 [in russian].
5. Lazebnyk, H.E., & Chernysheva, E.Y. (1966). On the influence of the shape of lateral soil pressure diagrams on the forces in sheet pile anchor retaining walls [O vlyianyy formy epiur bokovoho davlenyia hrunta na usylyia v shpuntovykh ankernykh podpornykh stenkakh]. *Hydrotekhnycheskoe stroytelstvo,* 5 [in russian].
6. Byleush, A.Y. (1984). Theoretical basis for the calculation of retaining structures and the effectiveness of their operation when securing landslide slopes [Teoretycheskye osnovy rascheta uderzhyvaiushchykh sooruzhenyi y effektyvnost ykh raboty pry zakreplenyy opolznevykh sklonov: Avtoref. dys. d-ra tekhn. nauk.], L: VNYYH ym. B.E. Vedeneeva [in russian].
7. Ryzhov, A.M. (1992). Introduction to nonlinear mechanics and physical modeling of foundations [Vvedenye v nelyneinuiu mekhanyku y fyzycheskoe modelyrovanye osnovanyi]. Zaporozhe: Vydavets [in russian].
8. Kaliukh, Yu.Y., & Vovk, O.A. (1978). Theoretical concept and practical implementation of monitoring of building structures of Unit IV of the Chernobyl Nuclear Power Plant [Teoretycheskaia

kontseptsyia praktycheskaia realyzatsyia monytorynha stroytelnykh konstruktsyi IV bloka Chernobylskoi atomnoi stantsyy]. *III Szkola geomehaniki Glivice – ustron Poland*, 81–86 [in russian].

9. Kaliukh, Yu.Y. (1999). Application of modern information technologies, mathematical methods and sensitive elements for studying and predicting the evolution of process-hazardous territories and objects [Prymenenye sovremennykh ynformatsyonnykh tekhnolohyi, matematycheskykh metodov y chuvstvytelnykh элementov yzuchenyia y prohnozyrovanyia эvoliutsyy protsessoopasnykh terrytoryi y obъektov. Nauchnometodycheskoe posobye]. Kyev: Znanye Ukrayna [in russian].

10. Kuzlo, M. T. (2019). Experimental and theoretical studies of deformations of soil massifs under the influence of man-made factors: monograph. [Eksperymentalni ta teoretychni doslidzhennia deformatsii gruntovykh masyviv pry dii tekhnohennykh faktoriv : monohrafiia]. Rivne: Nats. un-t vod. hosp-va ta pryrodokorystuvannia, 181 p. [in Ukrainian].

11. Panasiuk, I.V., Tomiltseva, A.I., Zub, L.M., Maltsev, V.I., Dolynskyi, V.L., Dubniak, S. S., Dubniak, S. A., Struzhko, A.O., & Zbitniev, A.A. (2012). Efficiency and ecological role of shore fortification structures on the Dnieper reservoirs. [Efektyvnist ta ekolohichna rol berehoukripliuvalnykh sporud na dniprovskykh vodoskhovyshchakh]. Kyiv: KNUTD, 120 p. Retrieved from: https://www.researchgate.net/profile/Lesya-Zub2/publication/299468906_Efektivnist_ta_ekologicna_rol_beregoukripluvalnihsporud_nadniprovskih_vodoshovisah/links/56fa4ab808ae7c1fda319e91/Efektivnist-taekologicna-rol-beregoukripluvalnih-sporud-na-dniprovskih-vodoshovisah.pdf [in Ukrainian].

12. Khoziaikina, N. V., & Smyrnova, M. S. (2018). Analysis of methods for assessing the stability of slopes and slopes, which are used as the foundations of buildings and structures [Analiz metodiv otsinky stiikosti skhyliv i ukosiv, yaki vykorystovuiutsia v yakosti osnov budivel ta sporud Materialy konferentsii "Perspektyvy rozvytku budivelnykh tekhnolohii"], Dnipro: NTU "Dniprovska politekhnika". Retrieved from: https://ir.nmu.org.ua/handle/123456789/152332 [in Ukrainian].

13. DBN V.2.4-3:2010 Hydrotechnical, energy and reclamation systems and structures, underground mining. Waterworks. Substantive provisions [Hidrotekhnichni, enerhetychni ta melioratyvni systemy i sporudy, pidzemni hirnychi vyrobky. Hidrotekhnichni sporudy. Osnovni polozhennia] [in Ukrainian].

14. Syplyvets, O. O. (2020). Mathematical modeling of joint work of supporting structures and soil massif in conditions of dense urban development [Matematychne modeliuvannia spilnoi roboty pidpirnykh sporud i hruntovoho masyvu v umovakh shchilnoi miskoi zabudovy: Dysertatsiia na zdobuttia naukovoho stupenia kand. tekhn. nauk: 05.23.01.] Odesa: Odes. nats. mor. un-t. Retrieved from: https://onmu.org.ua/ua/spetsializovana-vchenarada-d-41-060-01/dissertation-repository.html [in Ukrainian].

15. Buhrov, A.K., Narbut, P.M., & Spydyn, V.P. (1987). Study of soils under triaxial compression conditions [Yssledovanye hruntov vuslovyiakh trekhosnoho szhatyia]. Leningrad: Stroyizdat [in russian].

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ПІДХОДИ ДО ОЦІНЮВАННЯ СТІЙКОСТІ СПОРУД БЕРЕГОУКРІПЛЕННЯ ВОДОЙМ: АНАЛІЗ КОНСТРУКЦІЙ І МОДЕЛЕЙ ЇХ РОЗРАХУНКУ

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Анотація. *У статті наведено результати аналізу теоретичних основ визначення напруженого стану в ґрунтовому масиві і конструкції кріплення берегового укосу водойм. Систематизовано наукові дослідження і теоретичні положення з визначення зусиль діючих на конструкції кріплень. Запропоновано методичні підходи до статичного розрахунку берегоукріплень укісно-вертикальних конструкцій з урахуванням взаємозв'язку між навантаженням на конструкцію та її деформацією.*

Метою досліджень визначено забезпечення стійкості та надійності конструкцій берегоукріплень та обґрунтування напрямів удосконалення технічних рішень у сучасних умовах.

У роботі проаналізовано застосовування різних типів укісних кріплень берегоукріплювальних споруд відповідно до вимог Державних будівельних норм. Запропоновано зосередити дослідження на шпунтових кріпленнях берегів, як на сучасній і прогресивній технології берегоукріплення. Система «ґрунтовий масив – конструкція кріплення» розглядається як розрахункова модель у вигляді одностороннього типу, який являє собою як пружний елемент, що дає можливість у розгляді цієї задачі застосувати сучасний апарат теорії пружності. Це дає можливість прийняти лінійну залежність між напругою і деформацією та отримати достатню точність, що підтверджується наявними результатами вітчизняних та закордонних досліджень. Для розрахунків деформацій, оцінювання міцності та стійкості ґрунтових масивів і основ запропоновано приділяти безпосередню увагу характеристикам механічних властивостей ґрунтів, при цьому розглянуто три стадії деформації основ. Сформульовані диференціальні рівняння рівноваги ґрунтового масиву, дають змогу вирішити широкий спектр питань, пов’язаних з граничною рівнодією та отримати розрахункові параметри тиску земляних мас на підпірні стінки берегоукріплень укісно-вертикального типу. Результати аналізу досліджень рекомендовано для використання у визначенні основних навантажень на гідротехнічні споруди, обґрунтуванні технічних рішень з розробки та удосконалення конструкцій укісного й укісно-вертикального типів берегоукріплення водойм.

Ключові слова: *берегоукріплення, напружений стан, теорія пружності, ґрунтовий масив, модель розрахунку, стійкість*