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SLOPE STABILITY ASSESSMENT OF HYDRAULIC-FILL SOIL DAMS AND FILL-UP EMBANKMENTS

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ОЦІНКА СТІЙКОСТІ УКОСІВ НАМИВНИХ ҐРУНТОВИХ ГРЕБЕЛЬ І НАСИПНИХ ДАМБ

Stability and technogenic safety of hydraulic-fill dams and filled-up soil embankments, used as geotechnical waterworks, represent an important scientific and applied concern.

Purpose. Investigating the stability of selected areas at the bottom slope of the hydraulic-fill soil dam of Seredniodniprovska hydroelectric power station and filled-up embankment for the Dnipro river bank protection. Research tasks include numerical simulation of geomechanical processes that take place in the dam body at the selected points from PK14 to PK16; revealing causes of funnel-shape subsidence areas on the dam slope surface; validation of the design procedure for soils slopes stability for assessment of the slope stability and soil dams assessment for justification of the Dnipro river bank protective measures.

Methodology. The paper utilizes a complex approach with the application of theoretical generalization of the laws of slope stability in hydraulic structures as well as numerical simulation of geomechanical processes in hydraulic-fill dams and filled-up soil embankments via Phase 2 finite element analysis software using Mohr-Coulomb failure criterion.

Findings. Modeling of geomechanical processes that occur in the soil body of the bottom slope of the fill dam of Seredniodniprovska hydroelectric power station is carried out. The calculation of the fill-up embankment slopes stability for river bank protection on the territory of the Dnipro is carried out.

Originality. The causes of the formation of funnel-shaped holes and piping phenomena on the surface of the deformed slope of the hydraulic-fill dam are determined. The regularities of change in the stability of slopes of fill-up embankments with a change in the height of the structure and slopes geometry are established.

Practical value. Lies in a reliable assessment of slope stability and safety of hydraulic-fill dams and fill-up embankments and the forecast of landslide-dangerous processes taking into consideration geometry and physical-mechanical properties of soil massif.

Keywords: *slope stability, hydraulic-fill dam, fill-up embankment, safety factor, Mohr-Coulomb failure criterion*

Introduction. Stability of hydraulic-fill and fill-up soil massifs serving as hydraulic engineering, protective and other engineering structures is always considered in the context of technogenic safety and potential emergency of catastrophic situations.

The hydraulic-fill dams and filled-up soil embankments as well as other protective geotechnical structures carry hidden potential risks of technogenic hazards from the very beginning of their exploitation. Thus, technogenic risks are associated with catastrophic bursting in dams and flooding of territories, and consequences associated with large-scale geodynamic processes in the form of landslides and geomorphological devastations of the landscape.

Therefore, the calculation of the stability of slopes of dams and dams of hydraulic structures using modern methods of numerical modeling is a tool for assessing technogenic safety.

Analysis of recent research and the objective of the article. Stability of man-made slopes of hydraulic-fill dams and filled-up soil embankments is conditioned by geometric parameters, rock strength properties, fracturing and stratification of the massif, groundwater regime and other factors.

One of the main causes of landslides and other types of deformations of slopes is the filtration of groundwater. Its influence is reduced to a change in the mechanical properties of rocks, change in the geomechanical state of the rock massif near the slopes, and the development of piping processes of soil particles removal.

Scientific works of many scientists in the field of geotechnics and foundation engineering by M. N. Goldstein, A. A. Tsarkov, I. I. Cherkasov, L. K. Ginzburg, V. B. Shvets, V. A. Mironenko, V. M. Shestakov, V. G. Shapoval, N. A. Tsytovich, T. K. Artemenko, S. A. Bychkov, N. A. Maksimova-Guliaeva and others dedicated to the prediction of landslide-dangerous situations in geotechnical systems, indicate the relevance and importance of the mentioned problem.

This paper deals with the case study of the stability of the bottom slope of the fill dam of Seredniodniprovska hydroelectric power station and the fill-up embankment slopes stability for river bank protection on the territory of Dnipro city.

The objective of the study is to investigate the relationship between the stability parameters of hydraulic-fill dams and fill-up embankments with the soil physical and mechanical properties, geometric parameters of these structures, watering conditions and external loads.

The paper includes the following tasks:

1. To carry out numerical simulation of geomechanical processes which take place in the soil layer of the bottom slope of the dam body at the selected points from PK14 to PK16 using the finite element analysis software Phase2.

2. To determine the reasons that have caused appearance of the failure holes on the slope surface, and assess the stability of the hydraulic dam by the given geometric parameters and soil physical properties and relevant hydrological processes.

3. To carry out an assessment of the bank reinforcement dam stability with the application of an improved methodology for calculating stability of filled-up soil embankments slopes for subsequent implementation in the project of Dnipro city coastline protection.

Stability of the bottom slope of the fill dam of Seredniodniprovska hydroelectric power station. The dam embankment of Seredniodniprovska hydroelectric power station (Fig. 1) is a part of the cascade of hydrotechnical structures situated along the Dnipro River. It serves both for making water head in upstream side and transportation via three railway lines on the dam top. Structurally, the dam consists of alluvial silt soils. Back of the dam is covered by concrete slabs with dimensions of 6.0×3.0×0.45 m for anti-filtration purposes.

As a result of long-continued time of dam exploitation and river wave dynamic impact essential deformations of concrete pavement in certain sites of the dam upper slope have been observed.

The joints between slabs become open to water filtration. Visual inspection and vibroacoustic diagnostics have revealed existence of voids under the concrete pavement and fractures with slab deformations in some sites of the right-bank dam. Average size of fractures covers the range from a few millimeters to a few centimeters. In whole, these factors decrease durability of the dam concrete pavement and facilitate unfavorable hydrological conditions resulting in slope deformations on the downstream side. The stability of slopes in some sites along the right-bank embankment is disturbed because of seepage processes inside the dam body.

There are two possible explanations regarding the nature of hydrological and geomechanical processes that cause slope instability. The first assumption is that the seepage process is followed by washing-out (piping) of soil and sand fine particles that weakens geomechanical skeleton and causes funnel-shaped subsidence areas down the slope and along the embankment with average diameter of 0.6–2.0 m (Fig. 2). According to another assumption the emergence of subsidence areas on the slope surface is bound with intensive seepage between two soil layers: silt loams of embankment body and silty clay loams in the foot of dam. In 2010, the site investigations (Usachenko, Shashenko, Kovrov, 2010) that were carried out for the dam stability assessment revealed the presence of local geomechanical deformations. Therefore, this work is aimed at validation of calculations and generalization of information on the stability of filled-up and alluvial massifs.

To simulate the stability of natural and technogenic slopes of hydraulic structures, a specialized geotechnical FEM software Phase 2 was used. This 2D finite element program for soil and rock applications can be used for a wide range of engineering projects and includes excavation design, slope stability, groundwater seepage, probabilistic analysis, consolidation, and dynamic analysis capabilities. The program allows calculating slope stability analyzing the process of decreasing the Shear Strength Reduction in the rock or soil massif. The Shear Strength Reduction feature in Phase 2 allows automatically calculating the Strength Reduction Factor (SRF) for the selected model, which is equivalent in its meaning to the slope stability safety factor [1].

The algorithm for calculating the safety factor includes iterative calculation of strength characteristics in all elements of the soil massif by means of a stepwise loading of the model. As a result, the stresses in the slope reach the ultimate shear strength and a landslide occurs. The process of PCR calculations is repeated until the moment of loss by the slope of the steady state and it is graphically expressed as the most probable slip surface along which the array moves. If the SRF>1, then the slope is in a stable state, and at the SRF<1 landslide processes take place.

The geometric parameters of the dam profile are plotted in the *Phase 2* interface (Fig. 3). The geometric model of the slope is divided into finite elements with assignment of specific soil mass physical-mechanical properties (Table 1) [1].

The physical-mechanical properties of the soils that form the dam body were assigned according to the field study data obtained from PJSC Ukrhydroproject (Ukraine).

According to the input data and taking into account Mohr-Coulomb failure criterion, the most important factors that determine the stability of the right-bank dam are the soil weight, cohesion and angle of internal friction.

According to design data the soil weight is assumed to be 1.6 t/m^3. At the same time, the density of sand particles, which is a mechanical skeleton, is 2.65 t/m^3, and the density of soil particles varies in the range of 1.55–2.12 t/m^3, depending on the granulometric composition of the sand fractions and the content of clay particles in the soil.

According to physical and mechanical characteristics, the soils that make up the body of the dam can be attributed to silted loams or to silted alluvial sands, for which the cohesion varies in the range of 14–20 kPa, and the angle of internal friction is 15–32°, with average value of 23° (V. A. Mironenko, V. M. Shestakov).

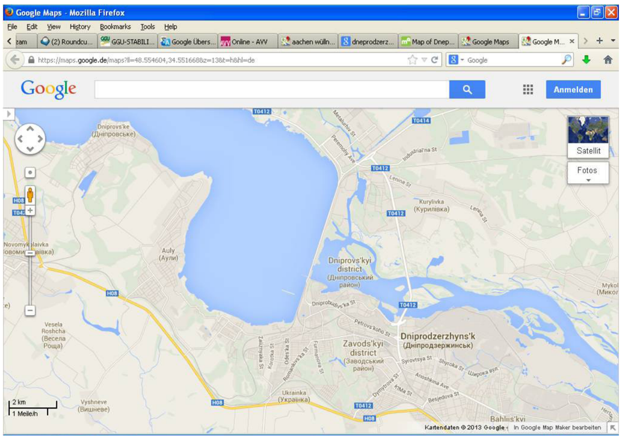

Fig. 1. The dam embankment of Seredniodniprovska hydroelectric power station (Source: Google Map)

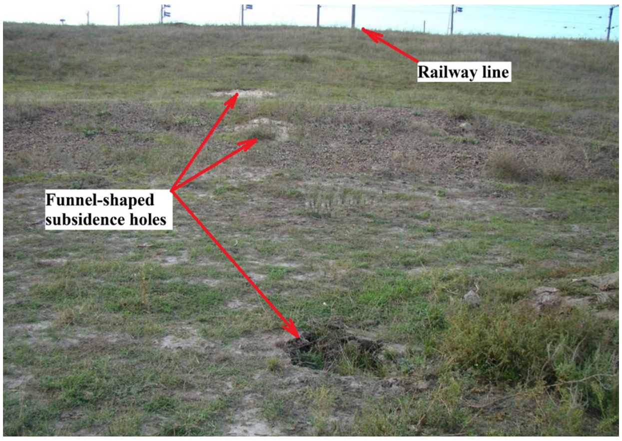

Fig. 2. Funnel-shaped subsidence areas on the downstream embankment slope

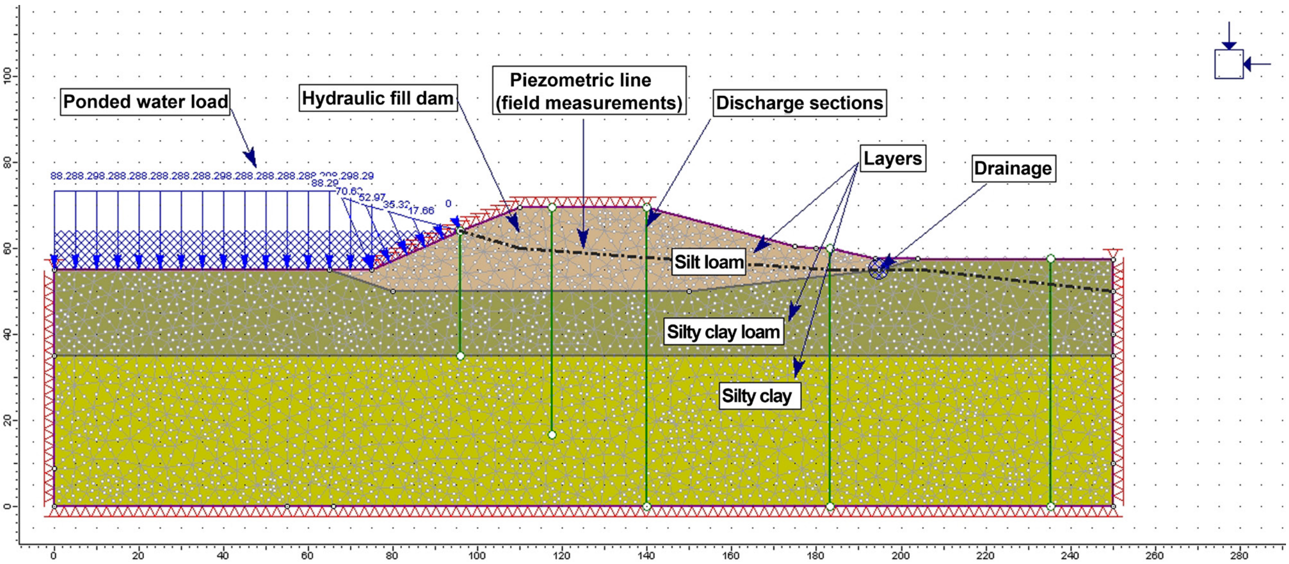

Fig. 3. Geometric profile of the hydraulic-fill dam (m)

Table 1

Geomechanical properties of the hydraulic-fill dam soil layers

Parameters	Units	Soil layers		
		Silt loam	Silty clay loam	Silty clay
Unit weight	kN/m^3	16.5	17.0	27.0
Poison's ratio	dimensionless	0.35	0.35	0.4
Deformation modulus	kN/m^3	20000	20000	20000
Tensile strength	kN/m^3	35.0	50.0	78.0
Friction angle	degrees	24	28	35
Cohesion	kN/m^3	21.5	36.0	72.0

The results of numerical simulation of geomechanical processes in the dam body show that the slope is stable as a whole and SRF = 3.6 (Fig. 4).

Fig. 4 shows the instability processes in the dam body with the appearance of excessive tensile stress zones. Thus, the maximum horizontal displacements in the investigated slope section are observed within the distance of 15.3 m down the slope, which corresponds to the actual subsidence sites on the slope surface. These subsidence zones were identified and examined by the staff of the Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine. The revealed deformations of the surface are caused by a rise in the level of the depression curve, which causes softening of the underlying soils and a weakening of their strength properties.

In turn, the long-term growth of horizontal tensile stress causes vertical displacements in the upper part of the slope, thereby creating a threat of the initiation of landslide processes.

Thus the possible occurrence of a slip surface in the slope is caused by the appearance of areas of increasing horizontal soil displacements in the central part of the slope due to decrease in the strength properties of the underlying soils, as well as at the upper hypsometric level +69.55 m due to increasing excessive horizontal and vertical tensile stresses directed from the slope toe upwards facilitate internal instability.

The zones with the most intense stresses identify the area of the probable displacement line in the slope, which, under given conditions, initiates a shift in the soil massif. The displacement line starts at some distance from the upper edge of the slope and leaves at a distance of 4.0 ± 0.5 m from the toe.

Groundwater flow is the most important factor in slope stability. Groundwater can affect slope stability by reducing strength, changing the bulk density and the mineral constituents content through chemical alteration and solution effects, generating pore pressure and erosion processes. Modeling hydrological parameters allowed determining filtration coefficients, direction of filtration vectors and location of the depression curve.

Fig. 5 shows total discharge velocity that decreases slightly from $2.25e^{-7}$ to $1.05e^{-7}$ m/s at the upstream and downstream slopes respectively. Flow vectors are indicative of the zones of the most intensive water streams.

The water flow depends on the hydraulic properties of the soil layers. The saturated permeability values for silt loams ($K_s = 1.25e^{-6}$ m/s) and silty clay loams ($K_s = 1.95e^{-7}$ m/s) differ significantly. The difference between inflow rate at the upper layer of the dam embankment and insufficient permeability of the silty clay loams cause the rising of groundwater level. Such changes of water table because of geological features and hydraulic properties as well as seasonal variations of discharge velocity can presumably impact slope stability at the downstream area.

As presented in Fig. 5, the water table (or phreatic surface) divides upper soil layer of the embankment dam into zones of positive and negative pore pressures. The dividing line is the groundwater table where the pressure is equal to atmospheric pressure. Below the groundwater table, the soil is fully saturated, and the pore pressure is above atmospheric pressure and positive in value – positive pore pressure. Above the groundwater table where the soil is unsaturated, the pore pressure is below atmospheric pressure and hence is negative in value – negative pore pressure (soil suction). Any changes in these pore pressures cause reduction of soil shear strength parameters and therefore have a tremendous effect on the slope stability.

The piezometric line obtained from field measurement goes down the slope above the calculated in Phase 2 water table and crossing it in the point of drainage pipe. Further phreatic line and piezometric line change positions and the water table falls down to the right side of the model.

Discharge sections as a user-defined feature that shows the steady state and volumetric flow rate, normal to the line segments to be calculated during a groundwater seepage analysis. The flow rate changes from $9.97e^{-7}$ to $7.45e^{-7}$ m^3/s at the upstream and downstream slope respectively.

A more detailed study of the hydraulic gradient in the dam body makes it possible to identify characteristic areas of excessive hydraulic head that are located between the depression curve and the slope surface and have the form of hemispheres (Fig. 6). Their average sizes vary in the range of 3–4 m, and the values of the hydraulic gradient at these points are comparable with those in the upstream level.

It is noteworthy that the location of the three regions of the high hydraulic gradient above the mark of the new tubular drainage practically coincides with the position of three subsidence areas in the considered slope section.

As can be seen from Fig. 6, the zones of the increased hydraulic gradient alternate with the zones of a lower gradient. It explains the occurrence of separate funnel-shape subsidence holes without continuous slip surface. According to one version of the authors, the cause of these areas is the infiltration of atmospheric precipitation and surface runoff.

Scientific results. Analyzing the results of modeling and comparing them with the field studies, it is obvious that mechanical piping occurs in the dam body. Removal of soil small particles through the pores of a coarse-grained skeleton can either be insignificant or lead to the destruction of the soil structure failure. The degree of piping development for a given soil massif is determined primarily by its heterogeneity and the filtration gradient. Thus, high filtration gradients that cause progressive piping can occur near the bottom slopes of the earth dams or in the areas of the dam base in the downstream. In the latter case, the risk of the dam stability may represent even a limited piping that leads to a decrease in the shear resistance for the rocks of the lower slope. Also it results in an increase in the base rocks compressibility followed by an irregular dam draft.

There is also an assumption that in weakly cemented rocks of the dam slopes, fracturing develops, as a result of which filtration erosion and removal of particles along the cracks occur. This process is of an erosive nature,

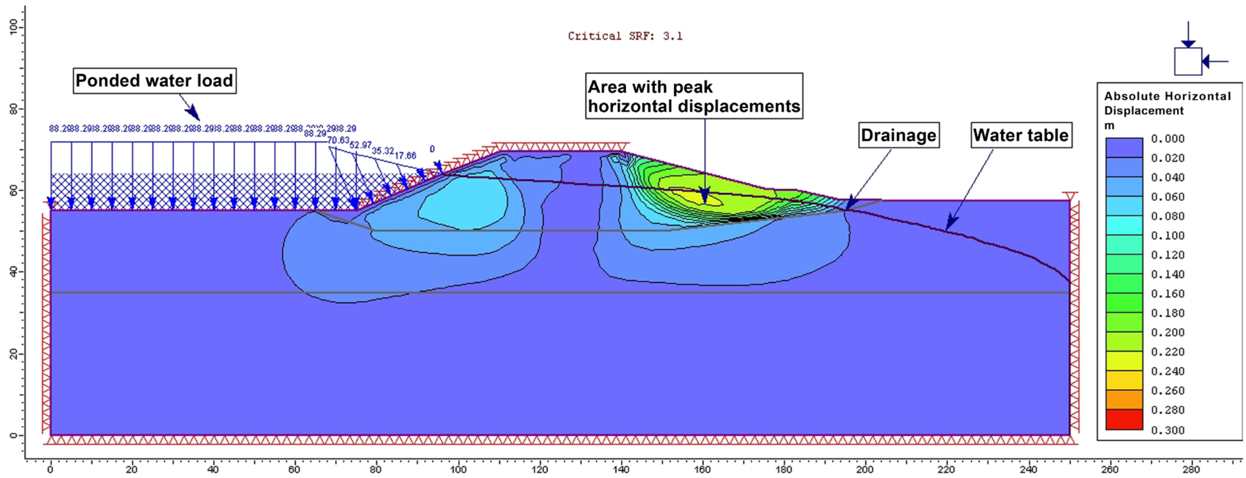

Fig. 4. Absolute horizontal displacements in the slope

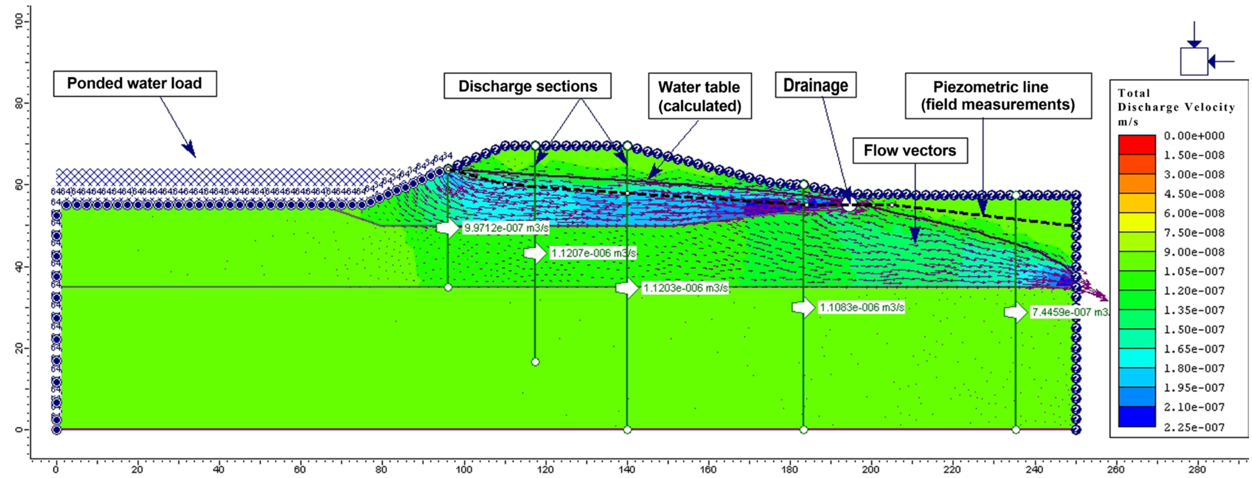

Fig. 5. Total discharge velocity in the dam body

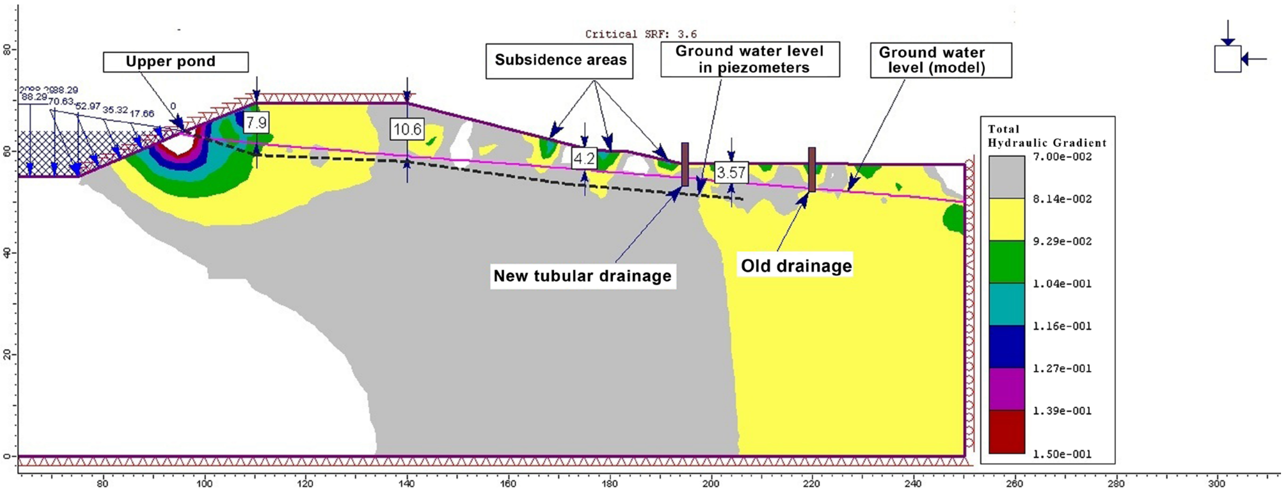

Fig. 6. Total hydraulic gradient in the dam body

and similar to some extent, to the erosion of the channel by an open flow. Under certain conditions, it can lead to the formation of underground cavities and failure funnels, the so-called "sandy karst", which actually takes place.

The influence of underground and surface waters on the strength of water-saturated clay rocks of hydraulic structures is revealed mainly in the process of their swelling. In clays with a hardening cohesion, these processes develop only when the swelling force exceeds the strength of the rigid structural bonds caused by cementing compounds. Soft bonded rocks are characterized by plastic deformations, relatively low strength and high compressibility, low permeability and high moisture capacity. All these properties are explained, first of all, by the presence of clay minerals in significant volumes represented by particles smaller than 0.001–0.002 mm. The huge specific surface area of such fine-dispersed systems leads to the development of internal forces of interaction between particles of a very special water-colloid type.

At the same time, the swelling process proceeds most intensively along cracks and especially bedding planes: intensive swelling often occurs only at the contacts of a clayey bed with aquifers and rapidly damps away from these contacts. One of the reasons for this phenomenon is that in many cases, especially in dense clays with hardening cohesion, the contact zone of the clay layer is disrupted by numerous micro-cracks along which the water enters the soil. Due to swelling phenomena, the contact zone of the clay layer often appears in the plastic state, which is one of the reasons for the occurrence of "contact landslides".

Clayey rocks and soils, corresponding to sandy loams and light loams in granular composition, undergo intensive swelling only near the surface of the filtering slopes because of small values of the maximum swelling stress. The process of swelling in such rocks on the slopes surface usually results in their complete loss of connectivity, and transformation into a fluid state, which leads to the shifting of swollen rocks by layers of 15–20 cm even at gentle slope angles (18–20 °).

In view of the fact that the swelling is associated with the filtration of water through clay rocks, its velocity depends on the filtration properties of the rocks: it flows in sandy and silty clays the most rapidly while in fatty clays – the most slowly. The swelling rate will increase with increasing gradients of water filtration through the layer of swollen clays. Therefore, in particular, the swelling is very intense when water flows down the surface of the slope of clay rocks, if previously all the water in them was in a capillary-tension state. Under the influence of surface waters, the capillary forces disappear, and the filtration of these waters into clays starts under a large gradient. As the liquid moves, the moisture of the clays increases, the gradient drops and, in the end, the filtration almost completely damps.

Swelling of clay rocks is enhanced when the tangential stress approaches to limiting values. In clayey rocks lying above the groundwater level, additional moistening always leads to deterioration in strength properties due to an increase in thickness of the hydrated shells, swelling and dissolution of the cementing compounds.

In clayey rocks with hardening cohesion, natural waters can cause dissolution or leaching of cement compounds. Such processes are the most characteristic for gypsum, carbonated and saline rocks (loess-like loams, marl clays, etc.) confined to the aeration zone when they experience additional moistening (for example, technical waters). Since in the construction of engineering structures, the rates of groundwater filtration often abruptly increase and water is desalinated due to recharge from surface water reservoirs. Then dissolution and leaching of cement compounds is possible in rocks with hardening cohesion. These circumstances are particularly important to consider when designing and assessing stability of hydraulic-fill dams.

Slope stability of the fill-up embankment for river bank protection in Dnipro city. Slope stability problem also occurs in the coastal areas of Dnipro city where the influence of the Dnipro River in the vicinity of coastline area can be quite dangerous. This fact causes a necessity to study the stability of embankment dam for design work on strengthening the coastline. Thus the purpose of the given investigation is the estimation of embankment dam stability using an improved methodology of slope stability calculation.

The object of this case study is a soil-fill dam for strengthening the coastline that is situated along the 9-B Naberezhna Peremohy Street in Dnipro city.

In accordance with the requirements of SNIP 2.06.05-84 "Earth dams" slope stability calculation of earth dams should be performed using circular cylindrical shear surfaces. The sustainability criteria and equation for slope stability coefficient k_s is the condition

$$k_s = \frac{R}{F} \geq \frac{\gamma_n \gamma f_c}{\gamma_c}, \qquad (1)$$

where F, R are calculated values of shear forces and moments of ultimate resistance or moments of forces tending to turn (to overturn) and retain building respectively; $\gamma_n = 1.1$ is the load safety factor; $\gamma_c = 0.95$ is the coefficient of working conditions [2].

According to the equation (1) the calculation of the dam lower slope stability was carried out on the basis of the hypothesis of the circular cylindrical sliding surface using standard and advanced methods. The first method was carried out using Electronic Manual of Engineer "ESPRI" software the safety factor was obtained as 2.299 (Fig. 7).

An improved approach is based on involving design soil characteristics and methods of mathematical statistics. The first step was to determine the appointment of the curvature center of the sliding surface using of the Electronic Manual of Engineer (Fig. 7). The values of

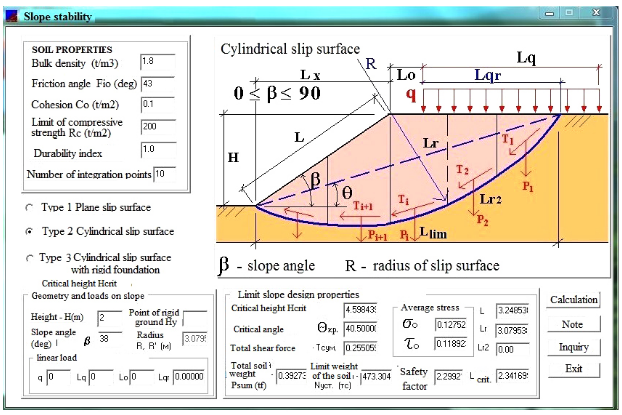

Fig. 7. The program window of Electronic Manual of Engineer "ESPRI" Software

the working length of the distributed load L_{qr} and radius R of the dam sliding surface were determined. The dam has the following soil characteristics: volume weight of the soil $\gamma = 1.8$ tf/m^3; internal friction angle $\varphi = 43°$; unit cohesion $c_0 = 0.01$ tf/m^2; limiting compressive stress $R_c = 200$ tf /m^2; loading safety factor is 1.0. According to DBN V.2.1–10–2009 "Foundations structures" the internal friction angle $\varphi_n = 43°$ for gravel and large sands with a porosity $P = 45$ %.

The geometrical parameters of the dam slope: height $H = 2$ m; the slope angle $\alpha = 38°$; the width of the upper base $a_1 = 1$ m; the width of the lower base $a_2 = 6.10$ m. The values of both $L_{qr} = 0$ and $L_0 = 0$ were obtained. The radius of the hazardous sliding surface $R = 3.08$ m. Then shape of the collapse curve was obtained using the obtained radius on design scheme (Fig. 8). Sliding wedge is formed by the area between this arc and the lower slope. According to calculations by circular cylindrical sliding surface method the area bounded by the shearing curve and external dam contours (sliding wedge) is divided by vertical lines into sections of width b, defining the angle of inclination α_i and volume V_i of each sector. The value of b was equal to 0.1 $R = 0.308$ m in the calculation.

Soil characteristics and the external load should be calculated to ensure the most unfavorable base working conditions in accordance with normative documents.

Therefore, the design loads and soil characteristics are determined by the formulas:

- if the characteristic is a part of the shearing forces

$$X_p = X^i \cdot (1+\rho);$$

- if the characteristic is a part of the retaining forces

$$X_p = X^H \cdot (1-\rho),$$

where X_p is design characteristic of soil; $X^н$ is normative soil characteristic; $\left(1 \pm \rho\right) = \dfrac{1}{\gamma_g}$ is the inverse value of the ground safety ratio (or overload ratio for determining the unit weight of soil and external loads); ρ is the accuracy ratio (the error) of the average value of characteristics determined in statistical analysis of the experimental data, $\rho = 0.1$.

The similar approach concerning assessment of landslide slopes stability based on MapInfo module is presented in the paper [3].

The difference from conventional technique of this is that the maximum and minimum values of the design characteristics of soil with the confidence probability equal to 0.95 are used in determining the shear and retaining forces, respectively. In practice only minimum values of the design characteristics of soil are used for calculating the retaining and shear forces. These design characteristics are obtained by the (1). Such approach leads to a distortion of the loading situation and increases the possibility of errors in the calculation results regarding slopes stability.

Therefore the design value of the retaining force R for the i^{th} sector is $R_i = R_i\, 0.9$.

The design value of the shear force F for the i^{th} sector is $F_i = F_i\, 1.1$.

Then the ground slope stability factor is

$$k_s = \sum R_i / \sum F_i = (0.9/1.1) \sum k_{si};$$

$$\sum k_{si} = \frac{R_1 \cos\alpha_1 tg\varphi + R_2 \cos\alpha_2 tg\varphi + ...}{F_1 \sin\alpha_1 + F_2 \sin\alpha_2 + ...}$$

$$\frac{..... + R_n \cos\alpha_n tg\varphi}{..... + F_n \sin\alpha_n}.$$

The data for each sector of the dam is shown in Table 2. Thereby the overall stability factor is $k_s = 1.39$.

Following this we verified the condition of the dam stability

$$k_s = \frac{R}{F} \geq \frac{\gamma_n \gamma f_c}{\gamma_c}; \;\; k_s = 1.39 \succ 1.2.$$

Thus condition is satisfied.

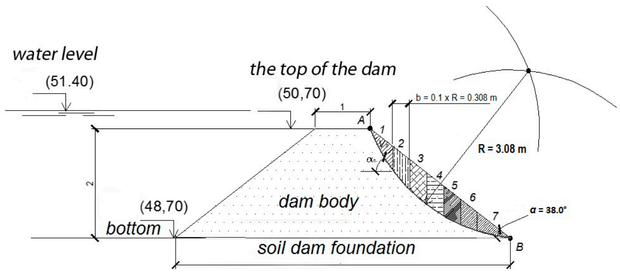

Fig. 8. Calculation scheme for the fill dam stability

Table 2

The data for each sector of the dam

The angle of sector inclination, α_i, ° degree	The angle of sector inclination, α, radian	The volume of the sector, V_i, m^3	The retaining force, R_i	The shearing force, F_i	Safety factor, k_s
61.7	1.076868	0.1069	0.09	0.17	
49.1	0.856957	0.1559	0.18	0.21	
41.0	0.715585	0.1782	0.24	0.21	
33.7	0.588176	0.1761	0.26	0.18	
27.0	0.471239	0.1582	0.25	0.13	
20.8	0.363028	0.1263	0.21	0.08	
12.0	0.209440	0.1105	0.19	0.04	
			1.42	**1.02**	**1.39**

Thus, according to the standard method for slope calculation based on the hypothesis of circular cylindrical sliding surface the slope stability factor 2.299 was obtained, which is 1.65 times higher than the result obtained by the improved method and equals 1.39. This result is supported by the results of test tasks for the calculation of rectangular limit height slope. The difference between the values provided by the calculations accounting and not accounting soil characteristics variation is 1.2–1.4 times [2]. Thus the proposed approach of calculation allows taking into account the most unfavorable slope condition and increasing the safety factor.

Conclusions. The paper presents results of two case-studies related to slope stability of hydraulic-fill dams and filled-up soil embankments via numerical simulation in geotechnical software Phase 2 and calculations in Electronic Manual of Engineer "ESPRI" software.

The appearance of deformations on the bottom slope of the fill dam of Seredniodniprovska hydroelectric power station is caused by several interrelated processes. The subsidence areas on the slope surface are emerged between two zones of moistening surface layer of the dam downstream. There are two primary causes for slope instability. The first one is directly connected to seepage processes being followed by piping fine particles of soil and sand that weakens geomechanical skeleton and causes funnel-shaped subsidence areas down the slope. The second cause is conditioned by the characteristic of dam construction and intensive seepage between two soil layers with different mechanical and hydraulic properties, namely, silt loams of embankment body and silty clay loams in the foot of the dam.

The second case study deals with slope stability assessment of the fill-up embankment for river bank protection in Dnipro city. The project results characterizing ground dam stability for the coastline protection show that the improved calculation technique takes into consideration the case of the most disadvantageous loading situation through a combination of minimal and maximum possible soil characteristics. It allows getting more reliable results than via the simplified approach generally used in the dam design practice. Based on investigation results recommendations for the implementation of the project for the local coastal line protection of Dnipro city have been carried out.

Further investigations will be focused on improving the calculation techniques related to determining condition relationships of unstable soil slopes.

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Стійкість і техногенна безпека намивних і насипних ґрунтових масивів, що служать в якості гідротехнічних та інженерних споруд, являє собою важливий науковий і прикладний напрям.

Мета. Полягає в дослідженні стійкості обраних ділянок низового укосу намивної греблі Середньодніпровської ГЕС і насипної дамби берегоукріплення р. Дніпро. Завдання дослідження включають: моделювання геомеханічних процесів, що мають місце у ґрунтовій товщі низового укосу греблі в межах від ПК 14 до ПК 16; виявлення причин появи на поверхні укосу греблі воронкоподібних провальних воронок; удосконалення методики розрахунку стійкості ґрунтових укосів і ґрунтових гребель для обґрунтування заходів із берегоукріплення р. Дніпро.

Методика. У роботі задіяний комплексний підхід з використанням аналізу й теоретичного узагальнення закономірностей стійкості укосів гідротехнічних споруд, а також чисельне моделювання геомеханічних процесів у намивних греблях і насипних ґрунтових дамбах із використанням критерію руйнування Мора-Кулона у програмі скінчено-елементного аналізу Phase 2.

Результати. Виконане чисельне моделювання гідрологічних і геомеханічних процесів у низовому укосі правобережної греблі Середньодніпровської ГЕС з урахуванням геометричних параметрів споруди, фізико-механічних властивостей ґрунтів і обводнення масиву. Виконано розрахунок стійкості укосів насипної ґрунтової греблі берегоукріплення р. Дніпро.

Наукова новизна. Визначені причини, що зумовлюють процеси суфозії та утворення воронкоподібних провалів на поверхні деформованого укосу намивної греблі. Встановлені закономірності зміни стійкості укосів насипних дамб при зміні висоти споруди й геометрії укосів.

Практична значимість. Полягає в достовірній оцінці стійкості укосів намивних гребель і насипних дамб, прогнозуванні зсувонебезпечних процесів з урахуванням геометричних параметрів і фізико-механічних властивостей масиву ґрунту.

Ключові слова: *стійкість укосів, намивна гребля, насипна дамба, коефіцієнт запасу стійкості, критерій руйнування Мора-Кулона*

Устойчивость и техногенная безопасность намывных и насыпных грунтовых массивов, служащих в качестве гидротехнических и инженерных сооружений, представляет важное научное и прикладное направление.

Цель. Исследование устойчивости выбранных участков низового откоса намывной плотины Среднеднепровской ГЭС и насыпной дамбы берегоукрепления р. Днепр. Задачи исследования включают: моделирование геомеханических процессов, имеющих место в грунтовой толще низового откоса плотины в пределах от ПК 14 до ПК 16; выявление причин появления на поверхности откоса плотины воронкообразных провальных воронок; усовершенствование методики расчета устойчивости грунтовых откосов и грунтовых плотин для обоснования мероприятий по берегоукреплению р. Днепр.

Методика. В работе задействован комплексный подход с использованием анализа и теоретического обобщения закономерностей устойчивости откосов гидротехнических сооружений, а также численное моделирование геомеханических процессов в намывных плотинах и насыпных грунтовых дамбах с использованием критерия разрушения Мора-Кулона в программе конечно-элементного анализа Phase 2.

Результаты. Выполнено численное моделирование гидрологических и геомеханических процессов в низовом откосе правобережной плотины Среднеднепровской ГЭС с учетом геометрических параметров сооружения, физико-механических свойств грунтов и обводненности массива. Выполнен расчет устойчивости откосов насыпной грунтовой плотины берегоукрепления р. Днепр.

Научная новизна. Определены причины, обусловливающие процессы суффозии и образование воронкообразных провалов на поверхности деформированного откоса намывной плотины. Установлены закономерности изменения устойчивости откосов насыпных дамб при изменении высоты сооружения и геометрии откосов.

Практическая значимость. Заключается в надежной оценке параметров устойчивости откосов намывных плотин и насыпных дамб, прогнозе оползнеопасных процессов с учетом геометрических параметров и физико-механических свойств массива грунта.

Ключевые слова: *устойчивость откосов, намывная плотина, насыпная дамба, коэффициент запаса устойчивости, критерий разрушения Мора-Кулона*

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