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HYDRO AND GEOMECHANICAL STABILITY ASSESSMENT OF THE BUND WALL BOTTOM SLOPE OF THE DNIPROVSK TAILING DUMP

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ABSTRACT

Purpose. The objective is to assess the stability of bund wall components of a hydro-technical structure under the conditions of a tailing dump which hydrodynamic mode has been disrupted during operation. The specified data on the geomechanical state, physical and mechanical properties have been used of both the bund wall material and that of the soil base.

Methods. Mathematical modeling by means of finite element method has been used to assess the hydro and geomechanical stability of bund wall components of a tailing dump (flood-breaking dam). The most reliable software Phase 2 v.8.0 was used for simulating. The modeling takes into consideration the influence of hydrostatic weighing forces and hydrodynamic pressure as well as nonstabilized state of water-logged rocks in the bund wall body.

Findings. Based on the results of assessments, geomechanical stability margin of the bund wall components of a tailing dump has been determined. It has been shown that on an equal height of the bund wall, the areas with insignificant angles of bottom slopes horizontal equivalent are characterized by the greater stability margin, and their resistance to shear deformation factor is comparable to the strength of alluvial sands shear in the base of a dam. In this context, stability margin is connected with the controlling influence on the bund wall state of water-logged soils, located above the ground water table in the dam body.

Originality. It has been determined that the hydro and geomechanical state of the bund wall components of the hydro and technical structure is influenced by the occurrence within the bounds of the tailing dump bund wall of alternately water-logged rock material intervals located above the ground water fixed position.

Practical implications. The results of modeling the tailing dump hydro and geomechanical state, which consider the multifactor conditioning of hydrodynamic and deformation processes in a body of the bund wall components, are the basis to substantiate a complex of engineering measures directed at the ensuring further safe operation of the hydro and technical structure.

Keywords: *technical structure, bund wall, geomechanical stability, numerical modeling, stability margin*

1. INTRODUCTION

Industrial activity, covering for a long time almost the entire Dnipropetrovsk region has led to the formation of a new type of landscape – anthropogenic. The technogenic landscape, the features of formation and structure of which are determined by human's productive activity with the use of powerful technical means, has been formed also within the area of the Dniprovsk tailing dump (Tymoshchuk, Sherstiuk, & Tishkov, 2013).

Geomorphologically, the Dniprovsk tailing dump is located in the valley of the Dnipro River within its right-bank terrace. Its construction was carried out by way of the bund walls erection along the perimeter of a natural ravine located on the watered bank of the Konoplianka River in the immediate vicinity of the Dnipro River.

At present, the relief in the area of the tailing dump has undergone significant changes. As a result of technogenic transformations (warehousing and waste planning), the natural surface on most of the tailing damp is blocked by a layer of filled-up soils of different genesis.

The existing imperfection of the tailing dump construction, which is connected with its insufficient protection from the effects of atmospheric precipitation, wind and water erosion, the lack of anti-filtration screens in the base and in the dam, has determined the need for additional studies aimed at identification of its current state and substantiation of the necessary engineering measures of protective nature (Buiskikh & Zamoshch, 2010; Krupskaya, Bubnova, Zvereva, & Krupskiy, 2011; Epov, Yurkevich, Bortnikova, Karin, & Saeva, 2017).

One of the features for the stability assessment of the bottom slopes of the tailing dump bund wall components (retaining prisms and flood-breaking dam) is the necessity to consider the hydrostatic weighing forces and hydrodynamic pressure, as well as the possible influence on its stability of non-stabilized state of water-logged soils in a body of the bund wall (Mironenko & Strelskiy, 1989; Galperin, 2003; Xu et al., 2013).

During the development of hydro and geomechanical models of the bund wall areas of a tailing dump, the data of prospect boring, the results of study of the physical and mechanical properties of soils under laboratory conditions, the data of reference documents and the results of published scientific research were used (Ignjatovic, Djurdjevac-Ignjatovic, & Ljubojev, 2013).

The deformation elastoplastic model of the medium, implemented on the basis of the finite element method, used in the stability assessment, is a generalization of the elastic and rigid-plastic medium with internal friction and joins the two theories on which modern rock mechanics is based: the theory of elasticity and the theory of the limiting state (Duncan, 2000).

The procedure of numerical solution in the finite element method is based on the prerequisite for force interaction between the elements of the modeled domain only in the node points (Whiteley, 2017). In this case, the continuity condition of the medium is satisfied by the inseparability of the nodal constraints between the elements.

In the structural base of numerical algorithm lies the rigidity matrix of the system, formed from the rigidity matrixes of the elements and linking the known nodal forces and unknown nodal displacements into the system of linear equations. The result of the numerical solution is the determination of the model nodes displacements proceeding from the given nodal forces determined by the external load and own weight of the model elements (contour and bulk forces). Based on the set values of displacements, axial, major deformations and stresses corresponding to them are calculated. The model used and its software implementation provide a possibility to study the areas of discontinuities fixed in stretching strain areas (Huang, 2013; Abellán et al., 2013; Yang, Hou, Tao, Peng, & Shi, 2015).

The method of derating the strength parameters in the stability margin assessment of rock massif, which was implemented in conjunction with the finite element method, provides the possibility of simultaneous determination of the slip surface position and the stability factor in the absence of any restrictions on the failure mechanism geometry. According to the method used, the design factor of stability margin C_S (1) is found out from the ratio of the maximum possible soil strength τ_{active} to the minimum value, sufficient to maintain equilibrium $\tau_{critical}$ (1):

$$C_S = \frac{\tau_{active}}{\tau_{critical}}. \tag{1}$$

If formula (1) is represented as a standard Coulomb condition, then it takes the form (2):

$$C_S = \frac{\sigma_n tg\varphi + C}{\sigma_n tg\varphi_r + C_r}, \tag{2}$$

where:

C and φ – the initial parameters of strength – respectively, the specific cohesion and internal friction angle;

σ_n – the actual normal stress;

C_r and φ_r – the strength parameters, decreased during the calculation to the minimum values sufficient to maintain equilibrium.

An essential advantage of using this method is its unity with other possibilities of numerical modeling. This allows to take into account the embedded part of the slopes when calculating the stability on soft (compressible) soils, with regard to consolidation processes of the base and its hardening. And also it makes possible to perform stability calculation with account of excess interstitial pressure, forming a "respud" in the central part of the slopes and stimulating a decrease in their stability.

2. MAIN PART

The modeling technique was provided for the solution of direct geomechanical problems (Chanyshev & Abdulin, 2014; Sánchez, Wang, Briaud, & Douglas, 2014), which, at the first stage, consisted in assessment of the stress-strain state of the bund wall areas, at the second stage – in assessment of their stability margin using the method of derating the strength parameters. The most reliable software Phase 2 v.8.0 is used for simulating.

When assessing the geomechanical stability of the bund wall, the calculated profiles 1 – 1, 2 – 2, 3 – 3 and 4 – 4 were accepted in calculations, set off through the specific areas of the tailing dump in the direction of the most probable development of negative deformation processes (Fig. 1).

The dimensions of the models in accordance with the calculated profiles are determined from the condition of minimization of their contours effect on the stress-strain state of the modeled massif and cover the areas of 350.0 m length with the thickness of the soil stratum from 14.0 m at the bottom slope of the bund wall to 35.0 m – in boundaries of the tailing dump pond.

To ensure the spatial determination of the modeled domain, zero displacements are specified at the lateral boundaries of the model and along its lower contour, and the force interaction between the elements of the model was determined by gravitational (bulk) forces in the soil stratum.

In general, the numerical model within the bounds of assessed areas is represented by triangular elements of seven types in accordance with the geologic-lithological structure of the soil stratum in the base of a tailing dump, rock refuse and phosphogypsum stocked in the tailing dump pond, rock material in a body of the bund wall.

The main parameters determining the state of the modeled massif and its behavior under the conditions of elastoplastic deformation were specific gravity γ, deformation modulus E, Poisson's ratio ν, specific cohesion C and internal friction angle φ, that is, the set of characteristics obtained during the standard complex of geotechnical research.

Values of deformation and strength characteristics of lithological varieties in the numerical model are accepted on the results of laboratory determinations, data of actual standards and studies performed on similar sites.

Figure 1. The layout of the calculated profiles within the bounds of the outer bund wall of the Dniprovsk tailing dump

To study the physical and mechanical properties of the rock material in a body of the bund wall during the drilling of exploratory boreholes, a geological-engineering testing was carried out with the selection of 25 undisturbed structure samples and subsequent determination under laboratory conditions of the basic physical and mechanical properties of soils, which build up the dam.

According to the testing data, the material, which builds up the dam is represented mainly by one nomenclature of soil – heavy, yellowish-brown and fawn-brown sandy loams, with inclusions of sandy and loamy material, of heterogeneous structure, slightly wet in the upper part of a dam and water-logged in its lower part, often with inclusions of humus material. In the samples selected from the dam base, in some cases there occurred carbonaceous material.

Determination of the deformation characteristics of soils for tested intervals was performed under conditions of compression, and strength characteristics – under conditions of rapid unconsolidated-drained shear. For one of the tested intervals, a control test of soils was carried out under triaxial compression conditions according to the unconsolidated undrained scheme of loading. This yielded results, which were close to the results of tests in a shear device: deformation modulus $E = 16.3$ MPa, specific cohesion $C = 13.79$ kPa, internal friction angle $\varphi = 19°$ (Fig. 2).

Based on the results of analysis and generalization of these laboratory determinations, the characteristics of physical and mechanical properties of soils have been grouped for states characterized by the degree of their water saturation: slightly wet and wet with a degree of humidity $S_r < 0.8$ and water-logged with a degree of humidity $S_r > 0.8$:

– for sandy loam with a degree of humidity $S_r < 0.8$: $\gamma = 18.2$ kN/m^3, $E = 13.65$ MPa, $C = 20.98$ kPa, $\varphi = 4.17$ </s>;

– for sandy loam with a degree of humidity $S_r > 0.8$: $\gamma = 19.4$ kN/m^3, $E = 11.46$ MPa, $C = 14.43$ kPa, $\varphi = 23.33$ </s>.

The values of parameters of physical and mechanical properties of rock material, which were determined in this way are accepted as normative when substantiating the design parameters of the numerical model and assessing the stability of the bund wall for depth intervals, respectively, above and below ground water table.

The physical and mechanical properties of granites in the base of alluvial sands, which in the numerical model represent a rigid incompressible base, are taken from reference data and are set as equal for the fractured granites: specific gravity $\gamma = 25.5$ kN/m^3, deformation modulus $E = 4.5 \times 10^4$ MPa, Poisson's ratio $\nu = 0.12$, specific cohesion $C = 110.0$ MPa, internal friction angle $\varphi = 32$ </s>.

The physical and mechanical properties of the base soils, stocked in the rock refuse tailing dump pond and that of phosphogypsum strata, which superposes them are determined in accordance with DBN-B.2.1-10-2009 recommendations.

In conformity with DBN-B.2.1-10-2009, their normative values are adopted as deformation (deformation modulus E) and strength (specific cohesion C and internal friction angle φ) properties characteristics of alluvial sands and loams under conditions of their natural occurrence:

– for intermediate size sands with porosity stratification factor $e = 0.55$: $E = 40.0$ MPa, $C = 2.0$ kPa, $\varphi = 38°$ (Table 1);

– for loams at $e = 0.65$ and consistency index $0.50 \le \mathrm{IL} \le 0.75$: $E = 17.0$ MPa (Table 3), $C = 25$ kPa, $\varphi = 19°$ (Table 2).

Similarly, the deformation and strength characteristics of radioactive waste, stocked in the tailing dump pond are determined, which are classified by their nomenclature as sandy loams. According to DBN-B.2.1-10-2009, sandy loams at $e = 0.65$ and consistency index of $0.25 \le \mathrm{IL} \le 0.75$ are characterized by a deformation modulus $E = 16.0$ MPa (Table 3), specific cohesion $C = 13.0$ kPa and internal friction angle $\varphi = 24°$ (Table 2).

For phosphogypsum, the values of the basic physical and mechanical properties are determined according to the data of studies on similar site (Ivochkina, 2013).

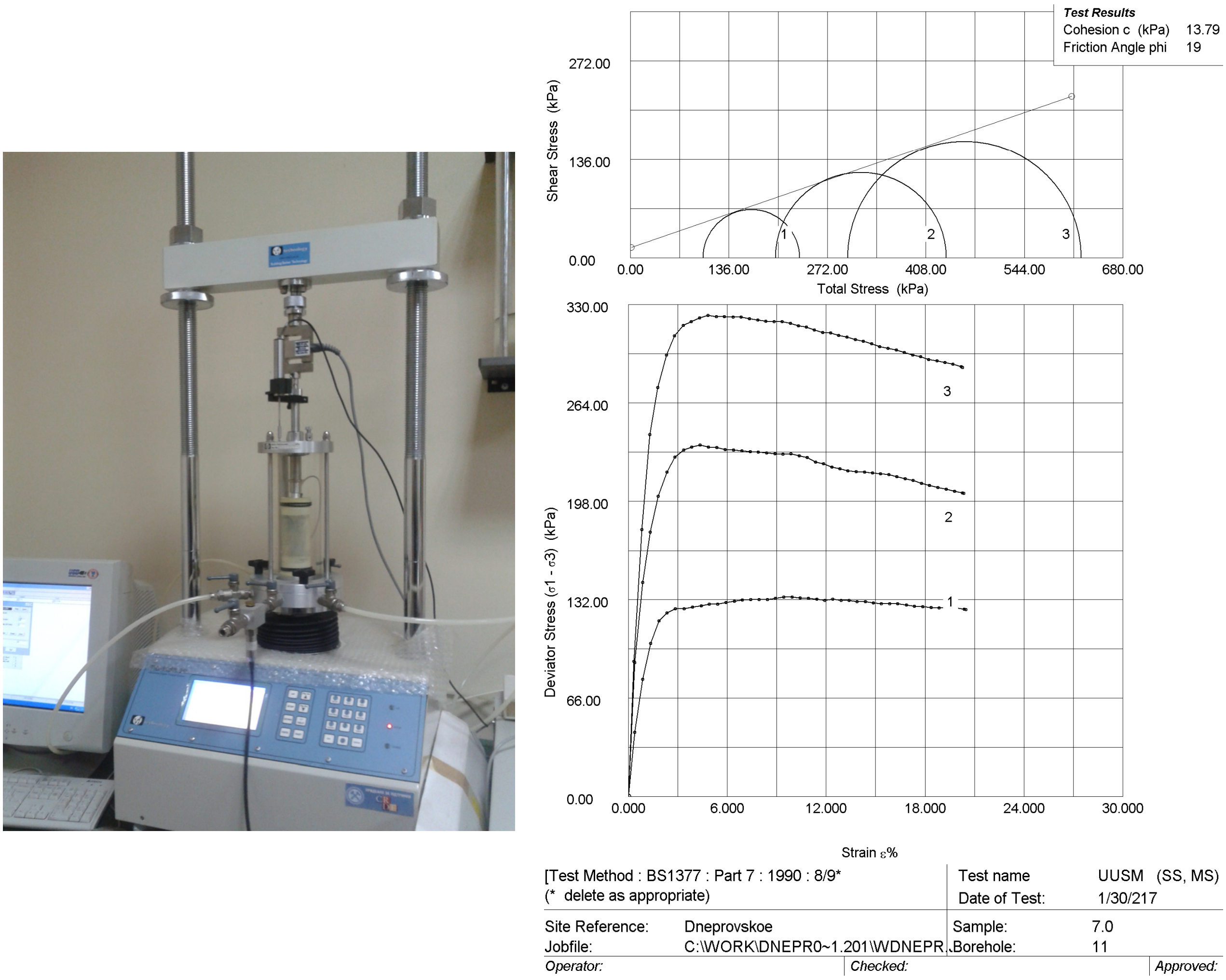

Figure 2. Testing of soils under conditions of triaxial compression according to the unconsolidated undrained scheme of loading

Table 1. Calculated values of physical and mechanical properties of base soils, stocked waste and bund wall material

Name	Specific weight, γ, kN/m^3	Modulus of deformation, E, kPa	Poisson's ratio, v	Specific cohesion, C, kPa	Internal friction angle, φ, °
Granite	25.5	45000000	0.12	110000.0	32.0
Sand	17.0	40000	0.30	1.3	34.5
Clayish soil	19.0	17000	0.35	16.7	15.7
Phosphogypsum	15.0	15000	0.30	18.7	27.8
Rock refuse	18.0	16000	0.30	8.7	20.9
Dam (sand loam $S_r < 0.8$)	18.2	13650	0.30	14.0	21.0
Dam (sand loam $S_r \geq 0.8$)	19.4	11460	0.30	9.6	20.3

Table 2. Calculated values of the stability margin factors of the bund wall bottom slope

Alternate solutions	Stability factor, C_S			
	Calculated profiles			
	1 – 1	2 – 2	3 – 3	4 – 4
The dam is in a non-watered state	2.93	3.09	3.32	1.83
Dam is in the current position of the ground water table	2.71	2.77	3.02	1.78
Dam is in the existing position of the ground water table and with derated strength parameters above the water level	2.29	2.48	2.75	1.57

Table 3. Calculated values of the stability margin factors of the bund wall bottom slope in the detailing area

Bund wall state	Stability factor, C_S			
	Calculated sections (prospecting profiles)			
	I – I	II – II	III – III	IV – IV
The existing position of the ground water table with derated strength parameters above the water level	1.91	1.59	1.85	1.78

According to these data, phosphogypsum, represented by calcium sulfate dihydrate, is characterized by the values of deformation modulus $E = 15.0$ MPa, specific cohesion $C = 28.0$ kPa and internal friction angle $\varphi = 32°$ in the rock dump for consolidated differences.

The calculated values of deformation and strength properties of soil differences used in assessing the bund wall stability, which were determined both from the data of laboratory studies and by their physical properties in accordance with the DBN-B.2.1-10-2009 requirements, and were adopted with the consideration of the safety coefficient on the ground γ_g, which is equal for the calculations of the load-bearing capacity:

– for specific cohesion $\gamma_g (c) = 1.5$;

– for internal friction angle of sand $\gamma_g (\varphi) = 1.1$;

– for internal friction angle of clay soils $\gamma_g (\varphi) = 1.15$.

The values of physical and mechanical properties accepted for calculation, which were determined with account of the safety coefficient on the ground γ_g and used in the numerical model in assessing the hydro and geomechanical bund wall stability, are given in Table 1.

The performed calculations of the hydro and geomechanical bund wall stability of the Dniprovsk tailing dump showed that its stress-strain state is determined by geometrical dimensions of the dam and by horizontal equivalents within the bounds of the modeled areas, by the position of the ground water initial level and by the distribution of deformation and strength characteristics of the rock material in the section of the bund wall.

Analysis of the results of calculations showed that, on an equal height of the bund wall within the bounds of assessed areas, the areas with insignificant angles of bottom slopes horizontal equivalent from 1:3.4 to 1:2.0 are characterized by greater stability margin, and their resistance to shear deformation factor is comparable to the strength of alluvial sands shear in the base of a dam (Table 2).

With an increase in the angle of horizontal equivalent to 1:1.3, the shear deformation factor occurs directly in a body of the dam, with their maximum values concentration within the bounds of bottom slope areas. Under these conditions, an influence grows on the assessed area stability of a possible rise in the ground water table and related decrease in the deformation and strength characteristics of the rock material, which builds up a bund wall body.

In Figure 3, it is shown the position of displacement surfaces in the bund wall under non-watered condition, with the existing position of the ground water table and under the condition of derating the strength parameters of the rock material above the water level to the values, corresponding to its water-logged state in the direction of 4 – 4 profile, which corresponds to the section with the minimal value of the stability factor.

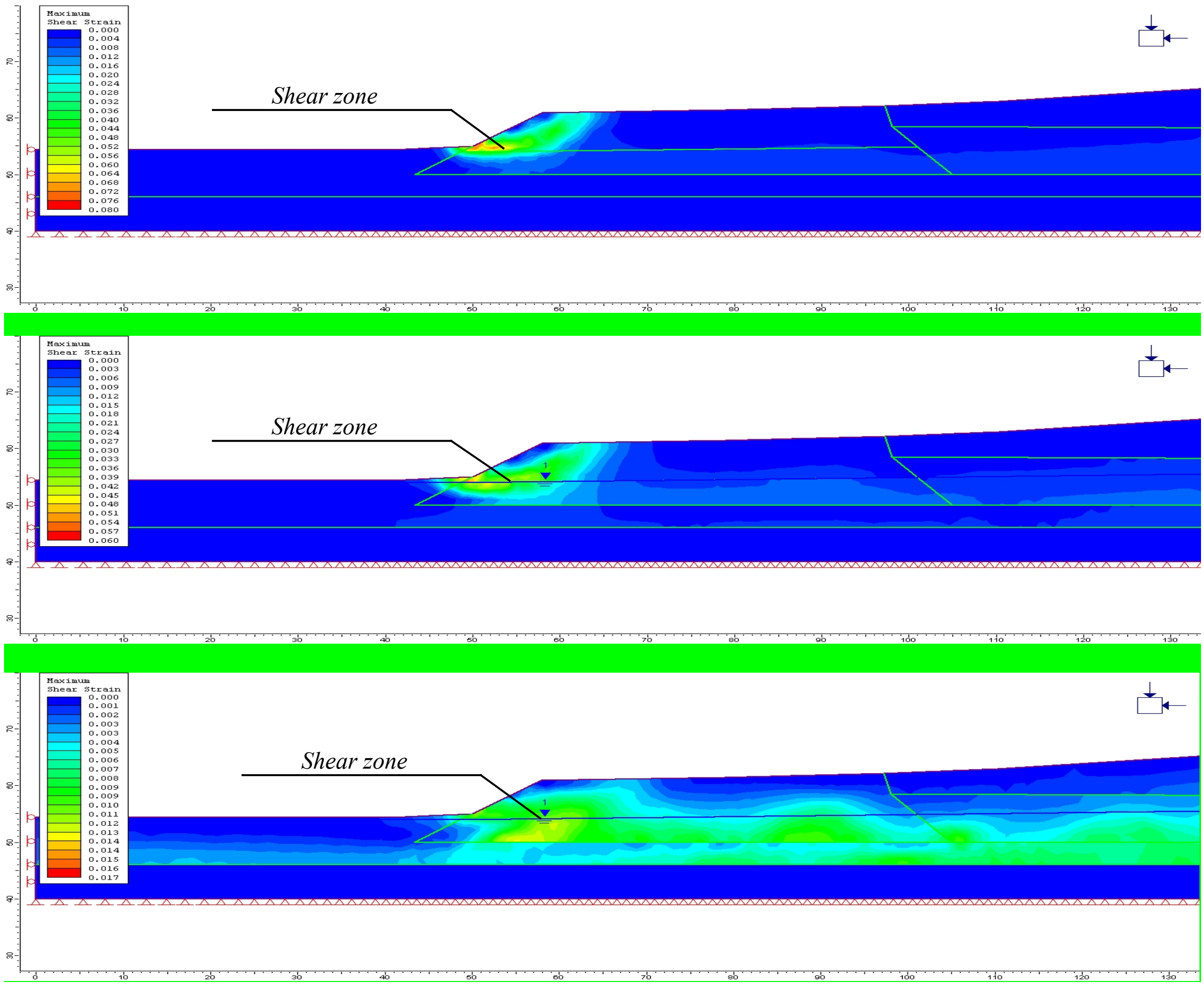

Figure 3. The nature of shear deformation of the bund wall bottom slope, profile 4 – 4: 1 – in non-watered state ($C_S = 1.83$); 2 – in existing position of the ground water table ($C_S = 1.78$); 3 – when derating the strength parameters of the dam material above the ground water table to the values, corresponding to their water-logged state ($C_S = 1.57$)

To assess the hydro and geomechanical stability of the bund wall area, within which the minimal stability factor value is obtained, the more detailed representation of the bottom slopes is performed, with consideration of their geometry specifics and changes of physical and mechanical properties of rock material in depth, according to the data of prospect boring and geological-engineering testing.

The calculated sections II, II – II, III – III and IV – IV, carried out in accordance with the position of prospecting profiles I – I (wells Nos. 13, 14, 15), II – II (wells Nos. 10, 11, 12), III – III (wells Nos. 7, 8, 9) and IV – IV (wells Nos. 4, 5, 6) are shown in Figure 4.

The position of the ground horizon initial level in the base of the bund wall according to the calculated sections of the modeled areas is determined by the results of measurements in piezometers and according to the geophysical studies data. According to measurements in piezometers, located within the detailing area, the ground water table in the base of a dam is located at a depth from 6.61 to 8.20 m, and this corresponds to its position by absolute elevations 54.90 – 55.42 m.

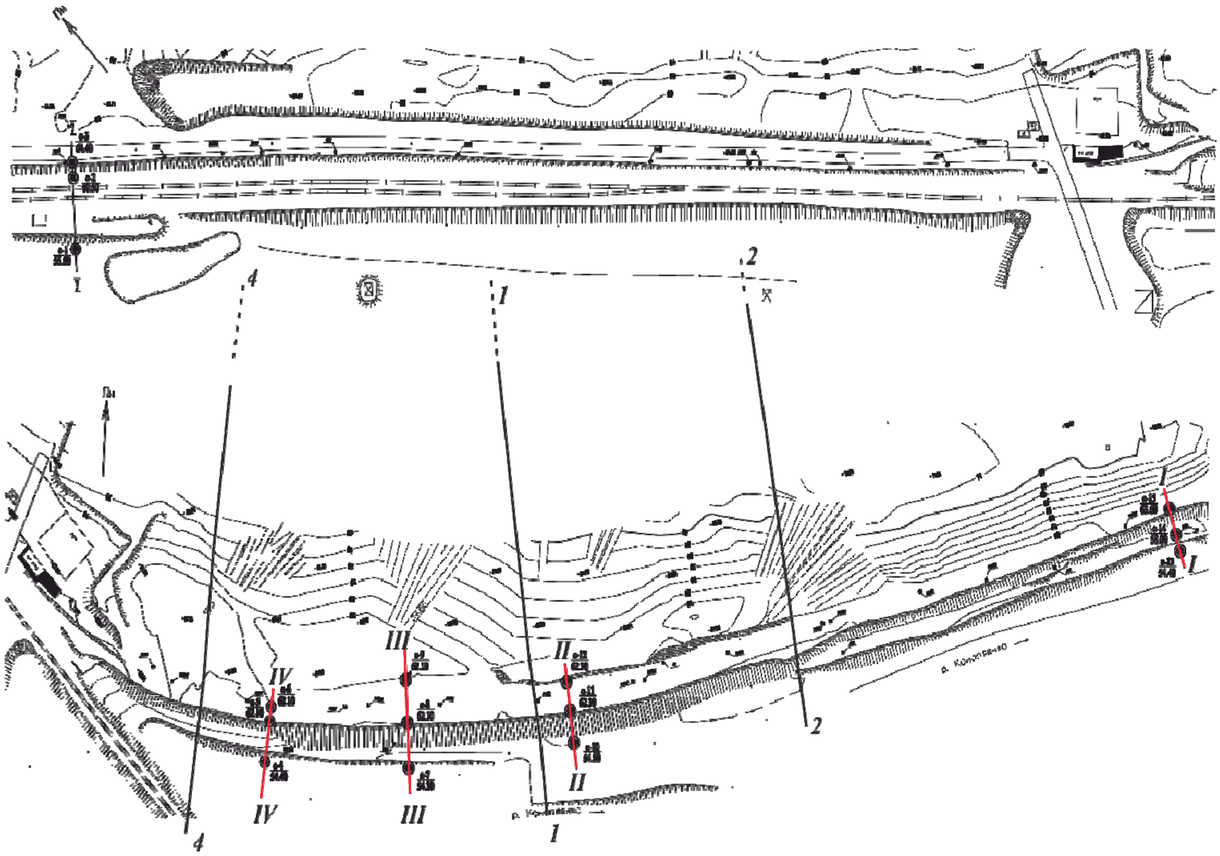

Figure 4. The layout of prospecting profiles and calculated sections in the detailing area of the tailing dump bund wall

When determining the thickness of the water-logged zone above the ground water table, the results of laboratory determination of the humidity degree of soils in the range of tested intervals were used. According to these data, the thickness of the water-logged zone for the calculated sections is 2.6 m (section I – I, well 15), 3.8 m (section II – II, well 11), respectively, 2.3 m (section III – III, well 8), 3.0 m (section IV – IV, well 5).

The calculated values of the stability factors, determined from the modeling data, with account of occurrence in a dam section above the water level of soils with a high degree of humidity close to their total water saturation ($S_r > 0.8$), are given in Table 3.

According to the presented data, a dam area located in section II – II is characterized by the minimum stability margin. And this, with an average dam height of 7.5 m and its bottom slope horizontal equivalent 1:1.8, is due to controlling influence on its state of the water-logged soils interval with a thickness up to 3.8 m, located above the ground water table in the base of a dam (Figure 5).

3. CONCLUSION

The performed calculations of the hydro and geomechanical stability of the bund wall of the Dniprovsk tailing dump have shown that the stress-strain state of its elements is determined by the geometric dimensions of a dam, the slopes horizontal equivalent within the bounds of the modeled sections, by position of the ground water initial level and by the distribution of deformation and strength characteristics of the rock material in the section of the bund wall.

Based on the results of the calculations, it was found out, that on an equal height of the bund wall within the bounds of assessed areas, the areas with insignificant angles of bottom slopes horizontal equivalent from 1:3.4 to 1:2.0 are characterized by greater stability margin, and their resistance to shear deformation factor is comparable to the strength of alluvial sands shear in the base of a dam.

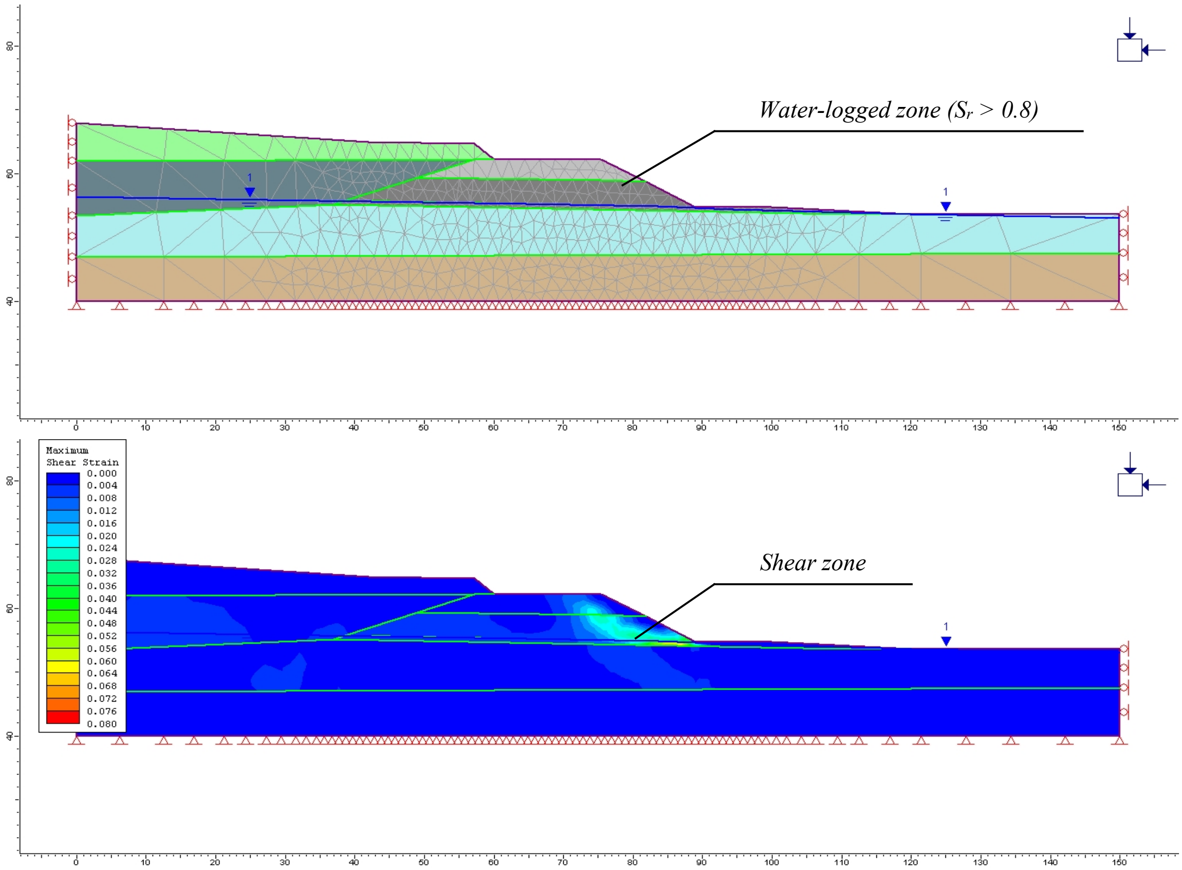

Figure 5. Calculation scheme and the nature of shear deformation of the bund wall bottom slope, section II – II – stability margin factor C_S = 1.59

With an increase in the angle of horizontal equivalent to 1: 1.3, the shear deformation factor occurs directly in a body of the dam, with maximum values concentration within the bounds of bottom slope areas. Under these conditions, an influence grows on their stability of a possible rise in the ground water table and related decrease in the deformation and strength characteristics of the rock material, which builds up a bund wall body.

According to the performed assessments, a dam area is characterized by the minimum stability margin (C_S = 1.59), within the bounds of which the occurrence of water-logged soils interval (S_r > 0.8) with a thickness up to 3.8 m, located above the ground water table. In these conditions, the engineering measures directed at the ensuring the hydro and geomechanical stability of the bund wall elements should provide their protection from additional watering by way of the tailing dam damp-proofing and implementation of surficial water removal.

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ОЦІНКА ГІДРОГЕОМЕХАНІЧНОЇ СТІЙКОСТІ НИЗОВОГО УКОСУ ОГОРОДЖУВАЛЬНОЇ ДАМБИ ХВОСТОСХОВИЩА "ДНІПРОВСЬКЕ"

В. Тимощук, В. Тішков, Ю. Сорока

Мета. Оцінка стійкості огороджувальних елементів гідротехнічної споруди в умовах порушеного експлуатацією хвостосховища гідродинамічного режиму на підставі уточнених даних про геомаханічний стан і фізико-механічні властивості матеріалу огороджувальної дамби та ґрунтової основи.

Методика. Для оцінки гідрогеомеханічної стійкості огороджувальних елементів хвостосховища (дамби обвалування) використано математичне моделювання методом кінцевих елементів за допомогою програмного пакету Phase 2 v.8.0, що враховує вплив сил гідростатичного зважування й гідродинамічного тиску, а також нестабілізованого стану водонасичених порід у тілі огороджувальної дамби.

Результати. За результатами виконаних оцінок встановлено запас геомеханічної стійкості огороджувальних елементів хвостосховища "Дніпровське". Виявлено, що при рівній висоті огороджувальної дамби великим запасом стійкості характеризуються ділянки з малими кутами закладення низових укосів, а їх опір розвитку зсувних деформацій можна порівняти з опором зрушення алювіальних пісків у основі дамби, при цьому, запас стійкості пов'язаний з визначальним впливом на стан огороджувальної дамби водонасичених ґрунтів, розташованих вище рівня ґрунтових вод у тілі дамби.

Наукова новизна. Встановлено вплив на гідрогеомеханічний стан огороджувальних елементів гідротехнічної споруди наявності в межах огороджувальної дамби хвостосховища інтервалів змінно водонасиченого породного матеріалу, розташованого вище фіксованого положення рівня ґрунтових вод.

Практична значимість. Результати моделювання гідрогеомеханіческого стану дамби хвостосховища, що враховують багатофакторну обумовленість гідродинамічних і деформаційних процесів у тілі огороджуючих елементів, складають основу для обґрунтування комплексу інженерних заходів, спрямованих на забезпечення подальшої безпечної експлуатації гідротехнічної споруди.

Ключові слова: *технічна споруда, огороджуюча дамба, геомеханічна стійкість, чисельне моделювання, запас стійкості*

ОЦЕНКА ГИДРОГЕОМЕХАНИЧЕСКОЙ УСТОЙЧИВОСТИ НИЗОВОГО ОТКОСА ОГРАЖДАЮЩЕЙ ДАМБЫ ХВОСТОХРАНИЛИЩА "ДНЕПРОВСКОЕ"

В. Тимощук, В. Тишков, Ю. Сорока

Цель. Оценка устойчивости ограждающих элементов гидротехнического сооружения в условиях нарушенного эксплуатацией хвостохранилища гидродинамического режима на основании уточненных данных о геомеханическом состоянии и физико-механических свойствах материала ограждающей дамбы и грунтового основания.

Методика. Для оценки гидрогеомеханической устойчивости ограждающих элементов хвостохранилища (дамбы обвалования) использовано математическое моделирование методом конечных элементов с помощью программного пакета Phase 2 v.8.0, учитывающее влияние сил гидростатического взвешивания и гидродинамического давления, а также нестабилизированного состояния водонасыщенных пород в теле ограждающей дамбы.

Результаты. По результатам выполненных оценок установлен запас геомеханической устойчивости ограждающих элементов хвостохранилища "Днепровское". Выявлено, что при равной высоте ограждающей дамбы большим запасом устойчивости характеризуются участки с малыми углами заложения низовых откосов, а их сопротивление развитию сдвиговых деформаций сопоставимо с сопротивлением сдвигу аллювиальных песков в основании дамбы, при этом, запас устойчивости связан с определяющим влиянием на состояние ограждающей дамбы водонасыщенных грунтов, расположенных выше уровня грунтовых воды в теле дамбы.

Научная новизна. Установлено влияние на гидрогеомеханическое состояние ограждающих элементов гидротехнического сооружения наличия в пределах ограждающей дамбы хвостохранилища интервалов переменно водонасыщенного породного материала, расположенного выше фиксируемого положения уровня грунтовых вод.

Практическая значимость. Результаты моделирования гидрогеомеханического состояния дамбы хвостохранилища, учитывающие многофакторную обусловленность гидродинамических и деформационных процессов в теле ограждающих элементов, составляют основу для обоснования комплекса инженерных мероприятий, направленных на обеспечение дальнейшей безопасной эксплуатации гидротехнического сооружения.

Ключевые слова: *техническое сооружение, ограждающая дамба, геомеханическая устойчивость, численное моделирование, запас устойчивости*

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