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ASSESSMENT OF THE TECHNICAL CONDITION OF THE KRASNOPAVLIVSK RESERVOIR EARTH DAM

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Abstract. *Dams and weirs of the reservoirs are objects of increased man-made hazard, which is due to the high probability of catastrophic flooding of territories and destruction as a result of their breakthroughs. The probability of technogenic accidents at reservoirs increases not only with exceeding the design operating lifespan, but also as a result of hostilities and climate changes, which lead to changes in the hydrological regime of surface and groundwater. According to the conducted research, it has been found out that monolithic reinforced concrete supports of the upper slopes of dams are particularly susceptible to destruction. This is primarily due to the destruction of temperature-deformation and structural joints of fastening structures, as well as the manifestation of chemical and mechanical suffosion. As a result, cavities form in the base of the earth dam body deck, which leads to subsidence and destruction of the deck, a decrease in the stability of the upper slope, and the manifestation of filtration processes. In order to assess the technical condition of the structural elements of the earth dam of the Krasnopavlivsk reservoir and determine the potential reserve of its operation, field surveys were conducted, which allowed assessing the stability of both the fastening structures and the earth dam body. The reservoir was put into operation in 1984 as a component of the hydroelectric facility of Dnipro–Donbas canal. It ensures the uninterrupted operation of the canal, and in case of emergencies it is used as a freshwater reservoir for water supply. The reservoir dam is made of soil. The upper slope is secured in the lower part with a stone cape, and in the upper part with monolithic reinforced concrete slabs. The bottom slope is secured with a layer of soil with grass seeding. To discharge the filtration water and drain it into an open drainage collector, tubular drainage and discharge wells are arranged. The dam's load characteristics are typical for the most reservoir dams in Ukraine. During the surveys, a set of diagnostic methods was used, including non-destructive examinations of the concrete cover of the upper slope reinforcement and assessment of its strength using a Schmidt hammer, georadar studies to determine cavities in the thickness of the underlying layer of the soil dam base under the concrete cover using a VIY5 600 georadar, as well as geodetic methods for measuring the geometric parameters of facilities' structures and the consequences of the destruction of structural elements. According to the research materials, violations of the geometric parameters of the dam were noted, as well as the presence of deformation processes in the form of the subsidence of the dam crest in places where anomalous phenomena occurred. The effect of the destruction of the concrete cover on the stability of the earth dam, the manifestation of the activation of filtration processes accompanied by increased suffosion of the underlying layer of the base of the reinforcement, were noted.*

Keywords: *reinforced concrete reinforcement, earth dam, depression curve, surveys, non-destructive testing methods, suffosion, technical condition*

Relevance of research. Reservoirs play a key role in the systems of water supply, energetics, and irrigation in Ukraine.

The hydraulic facilities of reservoirs built during the 60s and 70s years of XX century require radical restoration and technical re-equipment. Among the hydraulic facilities, earth dams have a special place, as they are the most affected by wave and mechanical loads. According to previous studies, monolithic reinforced concrete supports of the upper slopes of dams are particularly susceptible to destruction.

This is primarily due to the destruction of temperature-deformation and structural joints of the fastening structures, as well as the manifestation of chemical and mechanical suffosion, which is accompanied by the formation of cavities in the base of the deck of the earth dam body, leads to the subsidence and destruction of the deck, a decrease in the stability of the upper slope, and the manifestation of filtration processes.

The determination and assessment of the technical condition of facilities, the determination of a potential reserve for their operation, is possible by conducting field surveys, which make it possible to fully assess the stability of both the supporting structures and the earth dam.

During the assessment of earth dams' technical conditions, the following are the subjects of inspection: structures for fastening the upper and lower slopes; the condition of monitoring wells for determining the filtration regime of the facility; facilities of the drainage system; the body of the earth dam.

To conduct field surveys of the technical condition of earth dam facilities, the earth dam of the Krasnopavlivsk reservoir was chosen as the base object, which is typical in terms of loads for almost the most reservoir dams.

Analysis of recent research. There are 1054 reservoirs and 49444 ponds, with a total area of 2891 km^2 [1, 2], a complex of water protection dams with a length of 3,8 thousand km, 1,2 thousand km of banks reinforcement, and over 600 pumping and compressor stations for pumping excess water that are operated in Ukraine [3]. Dams and weirs of the reservoirs are the objects of increased man-made hazard, which is due to the high probability of catastrophic flooding of territories and destruction as a result of their breakthroughs. The probability of man-made accidents at reservoirs increases not only with exceeding the design operating lifespan, but also with the consequences of hostilities, and climate changes. The latter leads to the changes in the hydrological regime of surface and groundwater. For these reasons, in Ukraine, special attention is paid to ensuring the reliability and safety of hydraulic facilities' operation, both in terms of improving the legislative regulation of the rules for their safe operation [4, 5], monitoring the hydrological regime of rivers and reservoirs, and the technical condition of facilities, determining the criteria for their stability and safety, increasing work efficiency, improving the technical base and methods of surveys, determining the causes of emergency situations, modeling and forecasting negative consequences as a result of emergency situations during the destruction of dams, levees, gates, landslide processes, etc. [6, 7]. A significant number of recent scientific studies are devoted to the current problems of assessing the technical condition and forecasting possible negative consequences of the operation of individual reservoirs, including the Krasnopavlivsk reservoir [3, 8–10]. In [10], a program for assessing the consequences of a hydrodynamic accident, developed on the example of the Krasnopavlivsk reservoir is presented.

The aim of research. Assessment of the technical condition of the structural elements of the earth dam of the Krasnopavlivsk reservoir.

Research methodology. The research was carried out in accordance with the "Methodology for conducting field surveys of earth dams and protective dams of water management purposes" developed at the Institute [11].

During the assessment of the technical condition of the earth dam of the hydroelectric facility, the following were subjects of survey: the dam body; fastening of the upper slope at levels from 106,5 to 112,0 m; fastening of the lower slope; filtration regime of the facility.

A set of diagnostic methods was used, which included:

– visual inspections of the object (photos of damages);

– non-destructive surveys of the concrete covering of the upper slope reinforcement (using a Schmidt hammer);

– georadar studies to determine cavities under concrete pavement (VIY5 600 georadar);

– instrumental measurements of geometric parameters of facilities and the consequences of destruction of structural elements (level, measuring tape, gap gauge, etc.).

The position of the depression curve was determined based on the results of groundwater level monitoring in observation wells located on the downstream slope of the dam.

Research results and their discussion. *The Krasnopavlivsk reservoir* is located in the Lozovsky district of the Kharkiv region and is an important component of the water supply system of the Donbas and the Kharkiv regions. The situational plan and general view of the Krasnopavlivsk reservoir are shown in Fig. 1. The reservoir was put into operation in 1984 as a component of the Dnipro–Donbas canal. The total volume of the reservoir is 410 million m^3, the useful volume is 380 million m^3, the length of the coastline is 127,4 km, and the greatest width is 2,48 km.

a b c

a – situational plan; b – panoramic view; c- dam crest

Fig. 1. Krasnopavlivsk reservoir

The mirror area at normal supported level (NSL) is 34 km^2, and the catchment area is 35 km^2. The reservoir is of a canal type, located in the valley of the Popilnya river. To accumulate the water coming from the Kamyansk reservoir, an earth dam of 2,2 km long and 35 m high was built in the area of the Krasnopavlivka settlement. The hydroelectric facility includes: an earth dam and a water outlet (bottom, tubular). The reservoir is characterized by seasonal flow regulation. The reservoir ensures uninterrupted operation of the canal, in the case of an accident, it is also used as a freshwater reservoir for water supply to Kharkiv, Lozova, and Pervomayisk [12].

Krasnopavlivsk Reservoir Dam. The dam is made of soil, homogeneous loam, classified as CC2. The base of the dam's canal section is made of silty loam, which is why the dam has a flattened profile.

To improve the conditions for the consolidation of the foundation soils and the drainage of the dam body, a sand cushion 0,5 m thick is provided under its bottom wedge on the left and right bank sections, and up to 1,0 m thick on the canal section of the dam.

Dam's parameters are as follows: total length – 2200 m; width along the crest – 12 m; maximum height – 35 m; crest mark – 123,5 m; maximum design level (MDL) in the upper reaches – 120,0 m; maximum reservoir filling volume – 410 million m$^{3;}$ top slope 1:3, bottom slope 1:7. A highway runs along the crest of the dam.

The upper slope up to the 100,0 m mark is secured with a stone cap D=150–250 mm, higher (to the dam crest) – with monolithic reinforced concrete slabs with a thickness from 20 cm up to 25 cm. The lower slope is secured with a layer of soil with grass seeding.

Under the lower slope of the dam, there is a tubular drainage designed to discharge filtration waters and drain them into an open drainage collector.

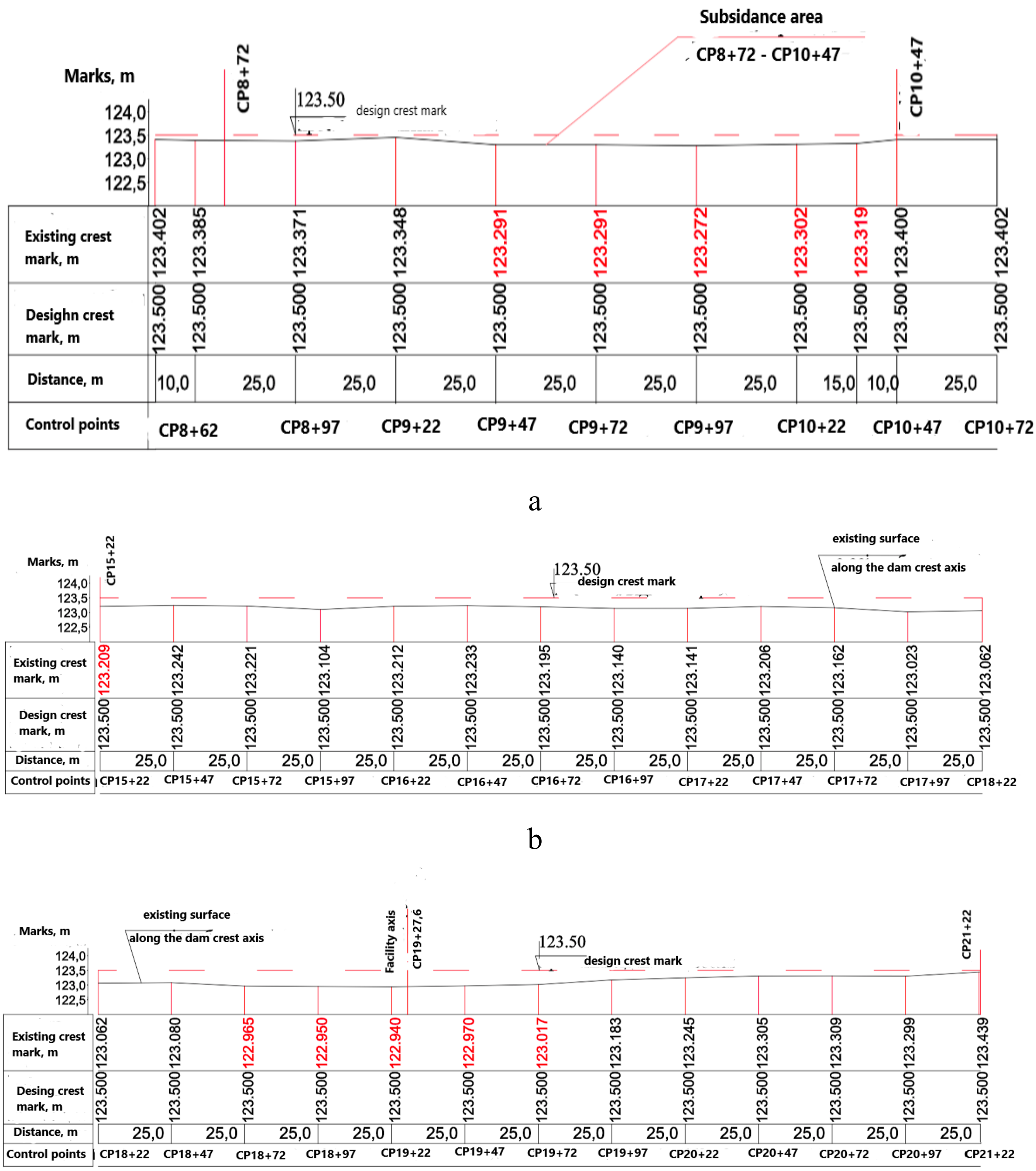
In the downstream part of the dam, unloading wells and closed drainage of the right slope of the dam are provided.

The above-mentioned engineering solutions aimed to ensure the reliability of the hydropower facilities were adopted after the tests with static and dynamic loads, especially wave loads and the tests of the impact of changes in the level regime.

Considering that the main damages of dam structures are associated with changes in the loads on the dam, including changes in the level regime of filling the reservoir and its operation, predicting the technical condition of structures is directly related to the results of monitoring and the need of conducting field surveys.

Field surveys of the dam's geometric parameters. During of the deformation processes survey of the earth dam body, subsidence along the crest was recorded. The condition of the upper slope fastening was determined by the presence of subsidence of the reinforced concrete fastening; the condition of temperature and deformation joints, the presence of cracks as a result of the destruction of the cladding, areas of destruction of the reinforced concrete fastening, the detection of cavities under the cladding as a result of chemical and mechanical suffosion and, as a result, the removal of soil particles from under its base were recorded. The results of instrumental surveys were presented in a form of a table according to the Methodology for conducting field surveys of earth dams and protective dams for water management purposes.

To assess the deformation processes occurring in the dam body, a geodetic survey was performed. According to the survey results, the subsidence of the dam crest ranged from 35 cm (CP8+22–CP11+97) to 64 cm (CP15+22–CP 21+22) (Fig. 2).



c

a – CP8+72 – CP10+47; b – CP15+22 – CP18+22; c – CP18+22 – CP21+22

Fig. 2. Longitudinal profiles along the axis of the dam crest in areas of subsidence

Thus, the selection of these plots for further survey is related to the nature and magnitude of subsidence, which became the basis for further research in terms of geophysical diagnostics of the technical condition of the upper slope at elevations 106,5–112,0 m at the indicated plots. The layout of the cross-section bases during the diagnostics of the earth dam body along with the results of visual inspection and vibroacoustic diagnostics on CP8-CP8+50 are shown in Fig. 3, 4. In Fig. 4, the area of cavity formation under the concrete coating is marked in red.

Geophysical studies to determine anomalous processes along the underlying layer of the earth dam's concrete foundation were performed using the VIY5 600 Georadar instrument at CP8-CP8+50. The probing depth can reach up to 3,5 meters.

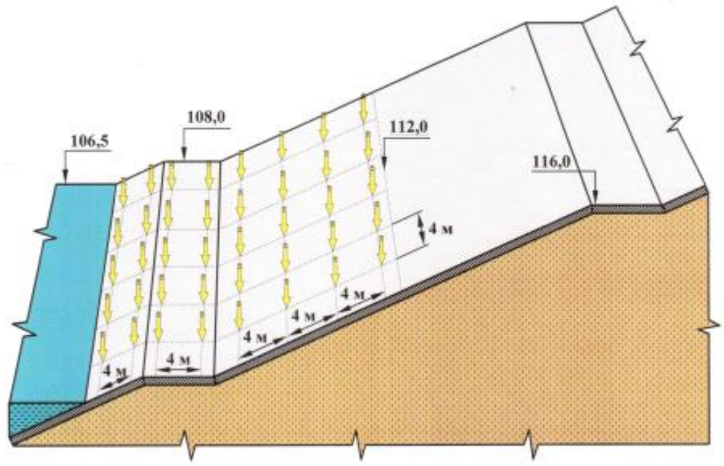


Fig. 3. Layout of cross-section bases during diagnostics of the earth dam body

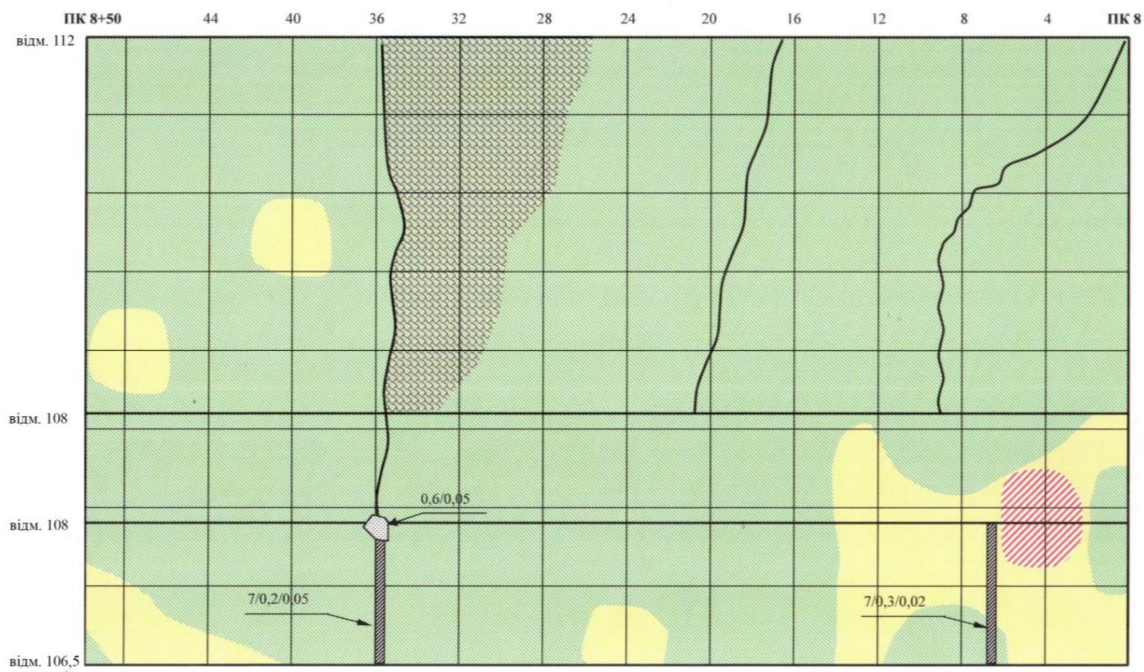


Fig. 4. Results of visual inspection and vibroacoustic diagnostics on CP8-CP8+50

The formation of voids under the concrete facing of the upper slope is due to the manifestation of suffosion processes of removal of the underlying sand layer as a result of overmoistening due to the pressure filtration through deformation-temperature joints and cracks in monolithic concrete.

Based on the materials of the conducted surveys, the areas and volumes of voids under the concrete covering of the upper slope at the elevations of 106.5–112.0 m of the CP8-CP10 section, and the category of destruction were determined (Table 1).

The area of destruction according to the above-mentioned criteria is on average: "low" – 80,85 %; "medium" – 16,28 %; "high" – 11,5 %.

Taking into account the significant size of the object (the dam length is 2200 m), the study of the technical condition of the upper slope reinforcement at the marks 106,5–112,0 m was carried out according to the following program: visual inspections of the dam's technical condition; assessment of the condition of local areas of destruction of the upper slope reinforcement; detailed assessment of the condition of the temperature and deformation (structural) joints; assessment of the condition of the concrete covering of the reinforcement.

1. Volumes of voids under the concrete pavement at the plot CP8-CP10

Plots	Area, m^2			Voids volume, m^3			Total volume, m^3
	Destruction category			Destruction category			
	Low	Medium	High	Low	Medium	High	
CP8-CP8+50	89,0	9,9	1,1	2,8	1,6	0,7	5,1
CP8+50-CP9	81,5	15,7	2,8	2,6	2,5	1,8	6,9
CP9-CP9+50	70,0	23,6	6,4	2,2	3,8	4,1	10,1
CP9 +50-CP10	82,9	15,9	1,2	2,7	2,5	0,8	6,0

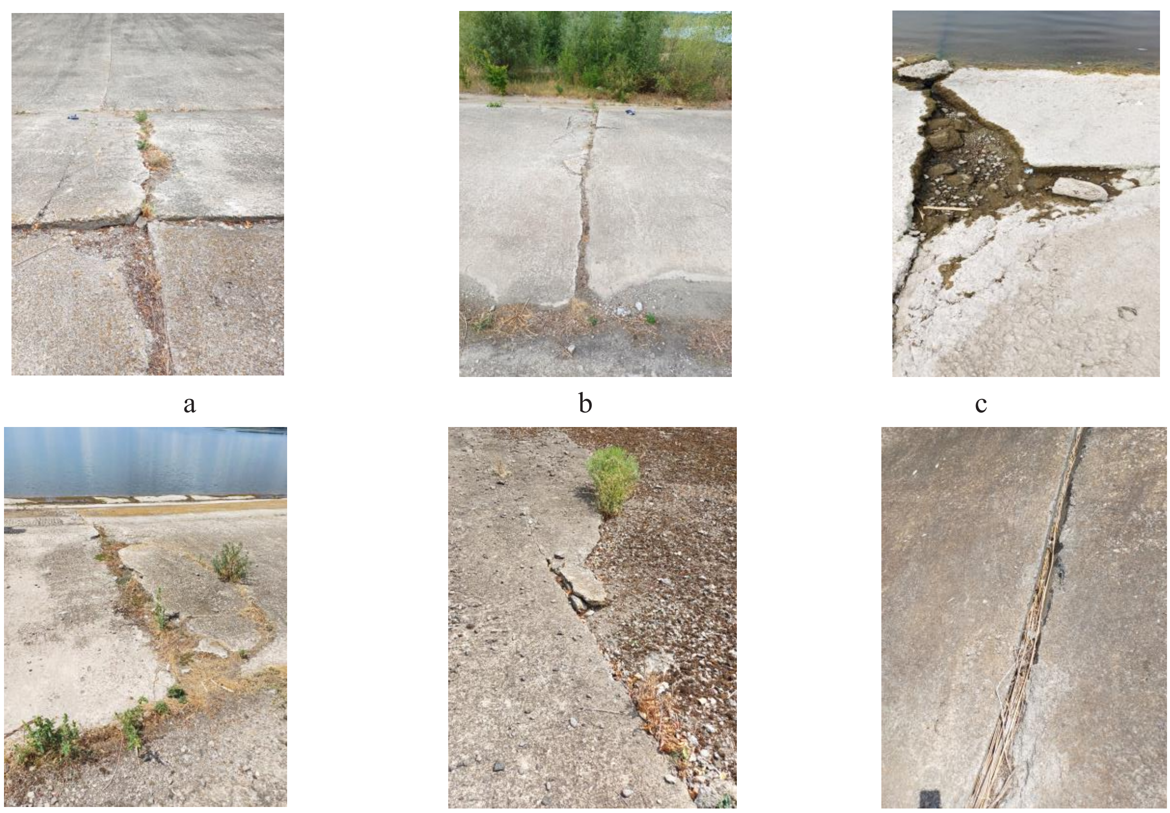
Diagnostics of reinforced concrete facilities by a non-destructive method using mechanical devices was used to determine the actual grade of concrete in order to establish its compliance with design solutions. The work on determining the concrete grade was carried out in accordance with the current regulatory and methodological provisions [13–15].

The concrete grade was determined by a non-destructive method using a Schmidt reference hammer. The Schmidt hammer works on the principle of elastic rebound, which measures the impact impulse generated in concrete under an applied load. This method is borrowed from the practice of measuring the strength of metals.

Based on the research results, the concrete grade of individual elements of the hydraulic facilities of the Krasnopavlivsk reservoir was determined.

The strength of the concrete fastening of the upper slope of the dam at the control points CP8+22–CP11+97 and CP15+22–CP21+22, according to the results of the research, is as follows: in line 1 – 42,36 MPa; in line 2 – 44,28 MPa (the concrete strength of 38,54 MPa corresponds to class C25/30).

In accordance with the survey program, documentary confirmation of the detected damage to the concrete pavement was carried out by visual inspection with photo fixation and instrumental measurements (Fig. 5).



a b c

d e j

a – local destruction of expansion joints; b – formation of cracks; c – local spalling of concrete; d – destruction of structural joints; e – corrosion of the concrete surface; f – decompression of temperature-deformation joints

Fig. 5. Detected damage to the concrete covering of the upper slope of the dam

The results of the survey of the technical condition of the monolithic concrete reinforcement of the upper slope of the Krasnopavlivska dam in the zone of marks from 106,5 to 112,0 m are given in Table 2.

The presented research results provided an opportunity to assess the technical condition of monolithic concrete reinforcement and outline technical measures to eliminate the damage.

The filtration strength of the dam body was assessed based on research materials during the filtration processes observation. Special attention was paid to the position of the depression curve; the shore connections of the earth dam and the concrete part of the hydroelectric facilities; concentrated filtration in the form of fistulas, boils, springs; the presence of filtration from the base in the low part.

Based on the position of the depression curve, calculations on the filtration strength of the dam body based on pressure gradients were made.

The calculation of the effective (actual) average head gradient $J_{est.m}$ was performed using the formula [16]:

$$J_{est.m} = H/L,$$

where H is the calculated pressure difference between the upper and lower parts; L is the length between calculation points A and B according to the calculation scheme for the average head gradient (Fig. 6).

2. Destruction of monolithic concrete reinforcement of the upper slope of the Krasnopavlivska dam

№№	Survey plot		2024			
			Cracks		Seams	
	From CP	To CP	Quantity, pcs.	Total length, m	Destroyed, pcs.	Total length, m
1	2	3	7	8,0	9	10,0
2	4	6	3	72,0	2	64,0
3	6	7	2	70,8	3	112,0
4	7	8	2	47,8	2	70,0
5	8	9	2	43,0	1	32,0
6	9	10	2	59,0	2	64,0
7	10	11	1	32,0	6	192,0
8	11	12	5	110,0	2	71,0
9	12	15	2	41,0	2	64,0
10	15	17	3	90,0	–	–
11	17	18	1	27,0	–	–
12	18	19	1	27,0	1	16,0
13	19	20		–	4	55,0
14	20	22				
Total				627,6		750,0

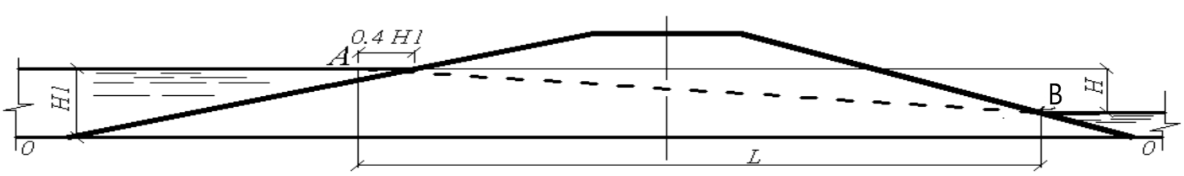


Fig. 6. Scheme for calculating the average head gradient $J_{est.m}$

The filtration strength of the earth dam was determined by calculating the average head gradient $J_{est.m}$ on three transverse lines at CP14+63; CP15+56; CP16+70.

The calculation of the theoretical depression curve was performed taking into account the mark of the lower part at the drainage gallery, which corresponds to 90,60–90,70 m [17]. As an example, Figure 7 shows the calculation diagram of the position of the depression curve along the line1 (CP14+63).

The results of calculations of the theoretical head gradient $J_{est.m}$ along the lines 1-3 are given in Table 3.

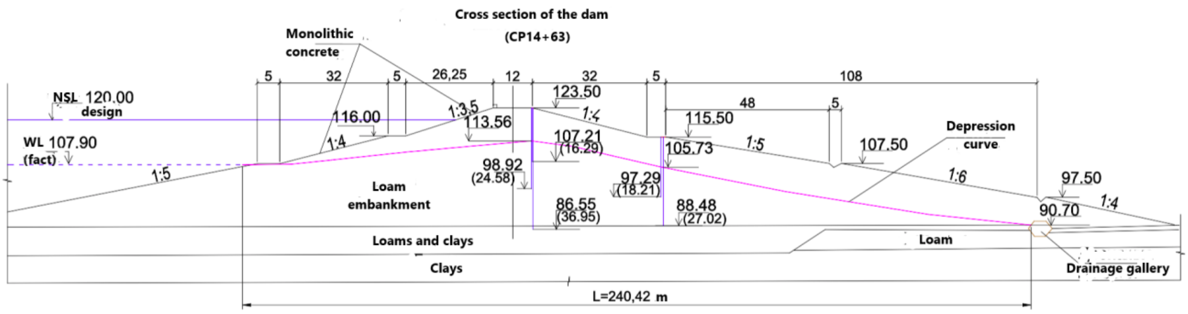


Fig. 7. Calculation scheme for determining the average pressure gradient

3. Results of the theoretical head gradient $J_{est.m}$ calculation of Krasnopavlivska earth dam

Line number	Control point	Water level in the reservoir	Average head gradient of the dam body $J_{est.m}$		Dam body soil
			theoretical	critical [6]	
Line 1	CP 14+63	107,90	0,076	1,5 – 4,0	Loam
Line 2	CP 15+56	107,90	0,07	1,5 – 4,0	Loam
Line 3	CP 16+70	107,90	0,072	1,5 – 4,0	Loam

As can be seen from Table 3, the head gradient of the earth dam as of September 8, 2024 is from 0,076 (line 1) to 0,07 (line 2) – which is significantly less than critical and indicates a safe filtration mode of the dam.

Based on the position of the depression curve, calculations of the actual pressure gradient were performed.

Since the depression curve has a positive and negative slope, calculations of the actual head gradient were performed for two components of the depression curve position (Table 4).

Table 4 presents the results of calculations on the actual position of the depression curve with positive and negative slopes.

4. Results of calculation of the actual head gradient $J_{est.m}$ of the Krasnopavlivska earth dam

Line number	Control point	Water level in the reservoir	*Average head gradient of the dam body $J_{est.m}$*			Dam body soil
			actual		critical [6]	
			with positive slope	with negative slope		
Line 1	CP 14+63	107,90	0,10	0,06	1,5–4,0	Loam
Line 2	CP 15+56	107,90	0,15	0,04	1,5–4,0	Loam
Line 3	CP 16+70	107,90	0,13	0,04	1,5–4,0	Loam

As can be seen from Table 4, the values of the head gradients of the earth dam for both positive and negative slopes of the depression curve indicate a safe filtration regime of the dam.

Conclusions

1. By instrumental studies we have determined the presence of the subsidence of the crest of the earth dam in two sections – CP8+22–CP11+97 and CP15+22–CP21+22, respectively, by 0,35 m and 0,64 m, which indicates a violation of the stability of the dam in these sections.

2. Typical destructions of reinforced concrete covering are the destruction of temperature-deformation joints as a result of a failure of wooden fillings; the presence of transverse and longitudinal cracks in the reinforced concrete covering as a result of a decrease in the stability of the fastening base, which is caused by the development of filtration processes (mechanical suffosion) and the removal of particles from the sand cushion (h = 0,35 m); the corrosion and local destruction of concrete.

3. The crack openings, the size of which reaches up to 3,0 cm, are due to the presence of deformation processes of the base of the underlying layer of concrete reinforcement, as a result of which cracks form in the concrete coating down to a depth of up to 25 cm.

4. The effect of the destruction of the concrete cover on the stability of the earth dam, the activation of filtration processes accompanied by increased suffosion of the underlying layer of the base of the reinforcement, were noted.

5. The filtration strength of the earth dam has been established, which is confirmed by theoretical calculations of the head gradient, ranging from 0,07 to 0,076, and the actual one from 0,04 to 0,15, which is significantly less than the critical one (1,5–4,0).

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ОЦІНКА ТЕХНІЧНОГО СТАНУ ҐРУНТОВОЇ ГРЕБЛІ КРАСНОПАВЛІВСЬКОГО ВОДОСХОВИЩА

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Анотація. *Греблі і дамби водосховищ відносяться до об'єктів підвищеної техногенної небезпеки, що зумовлено високою ймовірністю катастрофічного затоплення територій і руйнувань в результаті їх проривів. Ймовірність техногенних аварій на водосховищах зростає не лише із перевищенням проектних термінів експлуатації, але і внаслідок бойових дій та кліматичних змін, що призводять до зміни гідрологічного режиму поверхневих і підземних вод. За даними виконаних досліджень встановлено, що особливо піддаються руйнуванню монолітні залізобетонні кріплення верхових укосів гребель. Це, у першу чергу, пов'язано з руйнуванням температурно-деформаційних та конструктивних швів конструкцій кріплення, а також проявом хімічної та механічної суфозії. В результаті відбувається формуванням порожнин в основі кріплення тіла грунтової греблі, що призводить до просідання та руйнування кріплення, зменшення стійкості верхового укосу та проявлення фільтраційних процесів. З метою оцінки технічного стану конструктивних елементів грунтової греблі Краснопавлівського водосховища і встановлення потенційного резерву її експлуатації були проведені натурні обстеження, що дозволили оцінити стійкість як конструкцій кріплення, так і тіла грунтової греблі. Водосховище введене в експлуатацію у 1984 р, як складова частина гідровузла каналу Дніпро–Донбас. Воно забезпечує безперебійну роботу каналу, а у випадку аварійних ситуацій використовується як резервуар прісної води для водопостачання. Гребля водосховища грунтова. Верховий укіс у нижній частині закріплений кам'яним накидом, у верхній – монолітними залізобетонними плитами. Низовий укіс закріплений шаром ґрунту із посівом трав. Для розвантаження фільтраційних вод та відведення їх у відкритий дренажний колектор влаштовано трубчатий* *дренаж та розвантажувальні свердловини. Гребля в частині навантажень є характерною для більшості гребель водосховищ України. В ході виконання досліджень було використано комплекс діагностичних методів визначення , що включали неруйнівні обстеження бетонного покриття кріплення верхового укосу і оцінку його міцності із застосуванням молотка Шмідта, георадарні дослідження з визначення порожнин у товщі підстилаючого шару основи ґрунтової греблі під бетонним покриттям з використанням георадара VIY5 600, а також геодезичні методи вимірювання геометричних параметрів конструкцій споруд та наслідків руйнування конструктивних елементів. За матеріалами досліджень відмічено порушення геометричних параметрів греблі, наявність деформаційних процесів в частині просідання гребеня греблі в місцях проходження аномальних явищ. Відмічено вплив руйнування бетонного покриття на стійкість ґрунтової греблі, проявлення активізації фільтраційних процесів із супроводженням підвищеної суфозії підстилаючого шару основи кріплення.*

Ключові слова: *залізобетонне кріплення, земляна гребля, крива депресії, натурні дослідження, неруйнівні методи контролю, суфозія, технічний стан*