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V. Y. ULIANOV^{1*}, V. V. BILYK^{2*}

^{1*}Dep. «Engineering Geology and Geotechnics», Prydniprovsk State Academy of Civil Engineering and Architecture, 24-a, Chernyshevskoho St., 49600, Dnipro, Ukraine, tel. +38 (056) 756 33 43, e-mail ulianov.vasilyi@pgasa.dp.ua, ORCID 0000-0002-9028-3408

^{2*}Laboratory of Research of Nuclear and Thermal Power Plants, Prydniprovsk State Academy of Civil Engineering and Architecture, 24-a, Chernyshevskoho St., 49600, Dnipro, Ukraine, tel. +38 (063) 247 27 42, e-mail kolemasakar@gmail.com, ORCID 0000-0002-4435-2388

Research Results for the Earth Dam Condition of Cooling Pond of the Zaporizhzhia Nuclear Power Plant

Purpose. The work is aimed to determine the real location in space and conduct possible measurement of the true geometric dimensions of the NPP cooling pond dam, especially its underwater part and to detect the additional and previously unaccounted factors that could affect these parameters, as well as the state of the entire structure in general. **Methodology.** A comprehensive analysis of all available materials about engineering surveys and geotechnical studies was carried out at the dam of the cooling pond of the Zaporizhzhia NPP. Due to this, a more comprehensive look at the results of engineering and geological surveys was obtained. **Findings.** The state of soils in the body of the earth dam can be influenced by weakened and poorly studied zones of the dam. These zones were determined based on the analysis of the soil studies data of the dam's ground. Previously uncovered issues on the operation of the facility were raised and considered. The ways and methods for additional study of the earth dam of the cooling pond were selected, the conditions for their use were substantiated. A numerical relationship between the thickness of loose soils and the amount of surface subsidence were determined for the first time. A generalized geological section of the dam body was compiled for further modeling of geotechnical processes. **Originality.** For the first time since construction, a comprehensive program was developed for assessing the technical condition of the cooling pond dam using innovative methods from the Laboratory of Research of Nuclear and Thermal Power Plants in Prydniprovsk State Academy of Civil Engineering and Architecture (PSACEA). In particular, combined hydrographic-geodetic and aerovisual methods were proposed using specially designed universal leading signs that have no analogues in world practice. **Practical value.** The application of the developed comprehensive program using innovative methods allows assessing the technical condition of the cooling pond dam of the NPP.

Keywords: Zaporizhzhia NPP; cooling pond dam; alluvial sands; soil liquefaction; dynamic instability; subsidence; slope creep

Purpose

The objectives of the research are to collect data for the development of a substantiated technical project for monitoring the soils in the body of cooling pond dam of the Zaporizhzhia NPP (ZNPP) for the entire estimated period of operation.

The purpose of the research is to determine the parameters of the actual location in space and the possible measurement of the geometric dimensions of the NPP cooling pond dam, as well as to identify additional and previously unaccounted factors that can affect these parameters, as well as the state of the entire structure as a whole.

Issue status

The results of high-precision geodetic observations, analysis of the main buildings and structures conditions on the power units of Zaporizhzhia NPP, as well as the results of engineering and geological surveys, led to the conclusion that many factors affect the bearing properties of sandy foundations.

One of the significant indicators is the morphological features of the sands of eolian-alluvial genesis. Mostly, the change in the properties of sandy soils affected the on-ground artificial structures of the site. This also applies to hydraulic structures. The main one is the cooling pond dam. This is one of the key facilities for the safe operation of nuclear power plants. There is a high necessity to monitor earth dam of the cooling pond regularly. The

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need to monitor this facility is justified by common sense and the requirements of current regulatory documents and job descriptions for operation. The importance of an additional study of the cooling pond was repeatedly reminded in their letters by the scientists of PSACEA.

The special significance of this object in its current state requires the allocation of all studies in a separate section. This section should be considered separately from other hydraulic structures of the industrial site.

The article is devoted to resolving some questions about the possible causes of subsidence of some buildings and structures on the NPP site that have not been stabilized so far.

Physical and geographical conditions.

Administratively, the work area is located in the city of Enerhodar, Zaporizhzhia region. The research area is located in the western part of the NPP industrial area within the hydraulic structures.

Geomorphologically, the territory is located on the first floodplain (sandy) left bank of the Vytachivsko-Buzka terrace of the river Dnipro and is located on the left bank of the Kakhovka reservoir.

Before the start of construction, the study area was represented by the water area of the Kakhovka reservoir, formed mainly in the floodplain of the river Konka and, partially, on the coastal terrace of the river Dnipro with eolian relief forms (the so-called «hills») and absolute surface elevations from +18.00 m to +25.0 m. Absolute elevations of the Kakhovka reservoir bottom surface vary from +8.0 m to +9.8 m. The relief of the surface of the earth dam is slightly hilly, mainly eolian, formed by the winding of sands. In some places, the sands are fixed by arboreal and herbaceous vegetation. The absolute elevation of the surface is +16.0...+22.0 m. The average elevation of the dam crest is +18.5...+19.8 m.

The main water bodies that affect the hydrogeological situation of the study area include:

- Kakhovka reservoir;
- cooling pond.

Characteristics of hydraulic structures of Zaporizhzhia NPP.

The hydraulic structures of the Zaporizhzhia NPP are a complex set of engineering structures. This complex includes a cooling pond dam with blowdown facilities, inlet and outlet channels,

pumping stations for various purposes, spray ponds, cooling towers, access roads, and underground utility networks.

The combined use of such hydraulic structures as a cooling pond, spray ponds, and cooling towers allows you to combine the maneuverability of coolers in changing weather conditions. This scheme has no analogues and, in fact, at one time was experimental. This led to the problems associated with the soils on which the individual structures of this system are located, in particular, the dam of the cooling pond.

The cooling pond of the Zaporizhzhia NPP was formed by blocking off part of the water area of the Kakhovka reservoir by the method of filling a sand dam. It is a water object where the effect of heated waste water from nuclear power plants closes.

From the south and east, the earth dam adjoins the shore. From the north and west it is washed by the waters of the Kakhovka reservoir. The normal retaining level (NRL) of the Kakhovka reservoir is +16.0 m and the dead volume level (DVL) is +12.0 m.

The cooling pond dam has an irregular arc shape and reaches a length of 5,830 km (including the cargo pier dam). The absolute marks of the dam crest are +19.0...+22.0 m. The width along the water's edge is 216...590 m.

Type of dam – soil filled without anti-filter systems (devices). It is homogeneous with freely formed slopes, wide-profile (spread profile). The dam was adopted on the basis of the Feasibility Study of the General Designer in connection with the need to reduce the amount of slope support.

Material – fine and medium Quaternary eolian-alluvial sands of the valley of the rivers Dnipro and Konka. Laying method – mainly alluvium by means of hydromechanization under water to a depth of 8 m, partially – by dry digging.

History of construction the cooling pond dam of the nuclear power plant.

Since the mid-1980s, alluvial low-pressure barrier dams have been widely used in cooling reservoirs of nuclear and thermal power plants. Such dams are also used for protective dams on reservoirs with beach dynamic wave-damping slopes. This method of damping waves in shallow water is taken from the natural analogue of sea sandy beaches.

The design of alluvial dams made of sandy or sandy-gravel soils with the laying of the upper slope 1: 30 – 1:40 with a height of dams up to 5 m turned out to be more economical than with the traditional laying 1: 3 – 1: 5 with the slope fastened with stone or concrete. The increase in the volume of alluvium in terms of cost was offset by the rejection of fastening and the simplification of the alluvium technology.

A representative example of the use of alluvial dams with a beach wave-damping slope was the construction of the enclosing dam of the Zaporizhzhia NPP on the Kakhovka reservoir.

The initial project provided the dumping of a stone banquet with a volume of 1.7 million m³ into the water. The decision to replace the rock banquet with sand dam fill with a 1:50 embankment inclination (note: in later designs the embankment inclination was 1:40 and 1:45) and the submerged slope with a 1:7 inclination was made after research and heated debate in Ministry of Energy of the USSR. The decision was supported by the chief engineer of the Hydroproject Institute T.P. Dotsenko and the chief hydraulic engineer of Atomteploelektroproekt R.G. Minosyan. The real savings from the implementation of this decision amounted to about 30 million USD [2, 6].

The construction of sand dams with a wave-resistant beach slope became possible only thanks to the use of hydromechanization technology, which in those years was a major achievement of domestic hydraulic engineering.

The site in the city Enerhodar in the Dniprodzerzhynsk Hidromekhanizatsiia construction department (currently Enerhodromekhanizatsiia OJSC in the city of Kamianske) was created in 1970 with the start of construction of the Zaporizhzhia State District Power Plant and existed until 1988. The administration itself was created in 1955 in Dniprodzerzhynsk (now Kamianske). Specialization: creation of reservoirs and construction of dams. During the construction of the ZNPP, the construction department was headed by Lotov A. A. Three dredgers of the «350-50L» series worked on the construction.

Engineering and geological characteristics of the site

The geological structure of the area is due to the participation of granites of the Archean-Proterozoic age. They form the crystalline base-

ment of the Ukrainian Crystalline Massif (approximately, at a depth of about 60 m), overlain by a layer of clays of the Sirohozkyi (former Kharkiv) Paleogene stage, which presumably lie on the sandstones of the Buchatskyi Paleogene stage.

In the studied area, the clays of layer 9 are greenish-gray, dense with rare inclusions of sandstone concretions, uncovered at a depth of 33-35 m (absolute elevation -13.0.-14.0 m). Paleogene clays underlie the Quaternary alluvial sands, about 20 m thick, on which the cooling pond dam rests.

The dam was built on fine alluvial sands by hydraulic reclamation. The body of the dam is not uniform in density. At the base of the dam sandy loams GTE-6 and dark gray loams with an admixture of plant residues of soft-plastic consistency (GTE-7) with a thickness of 0.2-1.2 m lie. Fine alluvial sands of natural composition (GTE-4) with a thickness of up to 14 m lie below. Alluvial sands of medium size (GTE-5) were uncovered at absolute elevations of -2.3...-6.0 m.

Additionally, in the thickness of alluvial soils, according to the results of late engineering surveys in certain sections of the dam, the following GTEs were identified, namely:

GTE-1A1 – sand is fine, loose, with a low degree of water saturation;

GTE-11A – fine, loose, dynamically unstable, water-saturated sand;

GTE-1A2 – fine sand, medium density, low degree of water saturation;

GTE-1A3 – sand is fine, dense, saturated with water;

GTE-1a1 – sand is medium, loose, with a low degree of water saturation;

GTE-1a2 – medium sand, medium density, low degree of water saturation.

On the sections of the dam, erected by the so-called «dry method», the following GTEs have been identified:

GTE-1B1 – bulk sand, fine, loose, wet;

GTE-1B2 – bulk sand, fine, medium density, wet.

In the thickness of natural soils GTE-4, the following sublayers are additionally identified:

GTE-4b – fine sand, medium density, water-saturated;

GTE-4v – fine, dense, water-saturated sand.

Hydrogeological conditions.

Two aquifers have been explored on the site to a depth of 60 m. The first (non-pressure) is divided into two subhorizons. The first subhorizon is confined to the thickness of alluvial soils (GTE -1A). The second subhorizon is confined to the thickness of Quaternary sands of layers 4.5 m.

The depth of the groundwater level is from 2.3 m to 4.6 m (absolute elevation +16.34...+16.92 m). The thickness of the aquifer is 16.0...20.0 m. The position of the groundwater level is determined by the normal retaining level (NRL) of the Kakhovka reservoir and cooling pond. The maximum calculated water level at 1% supply in the Kakhovka reservoir is 16.35 m. The clays of layer 9 at depths of 33.0...35.0 m (absolute elevation +13.0...+14.0 m) serve as an aquiclude. The permeability of the water-bearing strata is medium and high. The filtration coefficient of sands in layer 1A is 10 m/day, layer 4-5 is 3 m/day, layer 5 is 20.7 m/day.

For the survey period, the groundwater level was revealed at +15.6...+16.2 m (1986). The chemical composition of the water was hydrocarbonate-sulfate-calcium-sodium. The value of bicarbonate alkalinity of water was 0.61-1.4 mg/dm³, the pH value was (pH=6.5). Waters are moderately aggressive to concrete structures.

The position of the water table at the dam is affected by leakage from the discharge channel, from cooling towers and spray ponds. Outside built-up areas, the position of the groundwater table is simpler.

Methodology*Analysis of hydrogeological observations.*

According to the results of long-term observations, there is a periodic change in the chemical composition of groundwater, presumably associated with water-chemical processes in the recycling water supply system of the Zaporizhzhia NPP.

The Kakhovka reservoir and the NPP cooling pond are the basic water objects that affect the hydrological and hydrogeological conditions of the study area.

The main unfavorable technogenic factor slowing down the processes of stabilization in the ground base of the cooling pond dam, is the high level of groundwater due to the accepted general configuration of the NPP hydraulic structures. The

degree of influence of high groundwater levels together with the constant change in the chemical composition and temperature of groundwater, on these processes has yet to be assessed [3].

It is known that the stabilization of alluvial sand massifs, among other factors, also depends on the formation of silica gels around sand particles, which are usually represented by quartz and feldspars. However, this process is rather complicated and depends on the physicochemical situation in the bulk of the massif. It has been established that with aging or a decrease in pH of silicate solutions, occurs their gradual transition from a molecularly dispersed state to a colloidal one. In this process, relatively stable particles with a certain molecular weight are formed, which could exist for a long time. After the polymerization of silicic acid, a certain amount of it in molecular form remains in solution. This amount is equal to the solubility of amorphous silica.

The solubility of silica depends on the form of the solid phase. Under normal conditions, the solubility of amorphous silica is, according to various authors, from 0 to 120 mg/l. The solubility of crystalline modifications of silica is estimated at 6-22 mg/l. With an increase in the temperature and pH of the environment, the solubility of all forms of silica increases, which generally slows down the processes of stabilization of the alluvial sand massif [5, 9].

Another factor that directly affects the above processes may be the chemical contamination of groundwater and soil with oil products and synthetic surfactants. A consequence of chemical pollution is a decrease in the shear strength of dispersed soils due to the adsorption of oil products and formation of surfactants on the surface of sand grains with the formation of a hydrophilic film. The number of mechanical contacts that cause shear resistance is reduced. The degree of influence of the groundwater and high temperatures on the decrease in the strength and deformation characteristics of sands has not been quantitatively determined. This circumstance is confirmed by the belonging of dynamically unstable layers of alluvial sands to zones near the groundwater table. This is clearly manifested in almost all graphs of dynamic sounding.

To test the validity of goals for improving hydrogeological monitoring of the cooling pond dam,

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a special extended cycle of measurements of the groundwater levels, their temperature, and chemical composition was proposed.

For example, the temperature of groundwater in regime wells located outside the areas of spray pools, discharge channel and cooling towers had to be measured at 2 points: in the standard way (1 m below the groundwater level) and additionally at the bottom of the wells. Similarly, it was planned to expand the collection of water samples for chemical analysis. In addition to samplings from the wells for the first time, water sampling and temperature measurements along profiles near the coastline in the cooling pond and the Kakhovka reservoir should be carried out. However, for a number of reasons, it was not possible to implement the plan till present days.

Analysis of information from the construction period and engineering surveys during the operation of the facility.

According to the information from the design solutions, the main method of forming the dam of the NPP cooling pond sand alluvium into the water to a depth of 8 m was chosen. It is also known that, in addition to obvious advantages, the method of alluvial dams also has significant disadvantages:

- poor seismic resistance of dams due to low soil density during alluvium;
- large subsidence during seismic action and the possibility of sliding slopes;
- increased demands on the composition of quarry soil, which may not always be available;
- a large need for energy during construction of the dam (in cases where the supply of pulp occurs through pressure pipelines);
- high demands on metal (pipes, vanes and casings of pumps quickly wear out and abrade, especially in coarse sandy and gravelly soils).

The disadvantages of winter alluvium are:

- reduction (by 20-30%) of work intensity;
- freezing of above-water slopes, which makes it difficult to drain water from the alluvial structure and can cause slopes to slide in spring (especially if the dam base is waterproof);
- higher cost of work.

The fact of slope slippage during alluvium was recorded at the beginning of work on the dam, despite all the technical measures taken. As already mentioned above, the dam of the Zaporizhzhia NPP cooling pond had no analogues and was ex-

perimental in its own way. This predetermined the problems associated with its stability in the future. So, during the operation of hydraulic structures, the following negative technogenic processes were recorded at the dam site:

1993 – collapse of the bucket slope adjacent to pumping station No 1 which supplies water to the cooling towers from the side of the spray pools;

1993 – slumping of the coastal ledge, composed of loose backfill sands in the area adjacent to the building of pumping station No 1;

1993 – surfacing the section of the pressure pipeline for supplying water to the spray pools.

Engineering surveys in the bulk of loose sands revealed zones of their technogenic decompaction to a dynamically unstable state (GTE-11A). It should be especially noted that during the period of surveys at the design stage, there were not found soils in this state within this section of the industrial site. However, according to conversations with local residents, there were areas of the so-called quicksand, in which repeatedly happens loss of large domestic animals.

Perhaps, for the first time, the detailed mechanism of loose soils displacement in the dam was described in the report on soils sliding into the bowl of the onshore pumping station NS-1, which supplies water to the cooling towers. The conclusions of the report, based on field research, laboratory work and office processing, stated the following:

- sands were characterized by an inhomogeneous degree of compaction and were divided into loose and medium density sands. Moreover, loose sands prevailed with the following soil characteristics: porosity coefficient 0.72 – 0.81, conditional dynamic resistance P_d – 1-2 MPa. Sands of the loose layer GTE-1B are characterized by free immersion of the drilling tool and probe;

- in natural conditions in the area of pumping station NS-1, the slope angle of the bank slope was 11° – 19° , and in the area of the dam body in the Kakhovka reservoir, the angle of the pool flattening was 7° . It should be expected that in the future the soils in the NS-1 area would tend to take a slip angle close to 7° . Sands with such a state and properties are characterized by dynamic instability and liquefaction;

– since the necessary additional compaction of the sand mass did not occur in time, the engineering and geological conditions for the survey period remain unstable. Thus, the possibility of further deformations is preserved. This will bring the backfill into motion;

– according to measurements of the cooling pond bottom at NS-1 there is a tendency for slope soils to slide towards the intake bucket of the pumping station. Taking into account the dynamics of water during the operation of the pumping station, a constant erosion of sagging soils should be expected in the water intake bucket. This will serve as an additional factor to the further sliding of the slopes.

In 1995 vibro-mapping of soils was carried out on the territory of pumping station No. 1 for supplying water to cooling towers No. 1 – 2 and to spray pools. The study was provided by the VIOGEM Research Institute (Belgorod) to assess the vibrational influence of process equipment on backfill soils.

The aim of the work was to obtain quantitative parameters of the vibrational influence on sandy soils in various parts of the backfill zone, to establish the main dependencies of their variability, and also to create a forecast for changes in the main parameters of soil vibrations during the joint operation of pumping station units.

The results of measuring the vibration parameters of backfill soils in the area of the operating pumping unit at the cooling tower No. 2 showed that the distribution of the total velocity and range of vibration displacements has an exponentially damping character.

The frequency of ground vibrations varied from 48...50 Hz at a distance of 1.0 m from the pipeline to 35 Hz at a distance of 18 m. With the simultaneous operation of two or more pumping units, an increase in the level of total vibration oscillations by 1,6...2,0 times. With an increase in the groundwater level in the backfill zone, the highest vibration level was in the flooded soil. There is a high probability of an increase in the vibrational characteristics of the soil by a factor of 3-4 times when the radial component of the damping exponent flattens out.

Subsequently, dynamically unstable soils were found in other sections of the dam. As indicated in the reporting materials, the causes of landslide pro-

cesses and technogenic decompaction of soils have not yet been clarified. The most probable causes of technogenic sands decompaction so far have been the following:

– insufficient compaction of sandy backfill soil during construction and planning works;

– change in the properties of technogenic (bulk, alluvial) sands during additional compaction;

– influence of the hydrodynamic regime of the reservoir;

– suffusion (mechanical) removal of soil;

– influence of dynamic load from motor vehicles in conditions of unstable foundation soils. The influence of this load was especially strong during the period of existence of a permanent road to Kamenska-Dniprovska until the moment of closing the zone of hydraulic structures of the NPP.

– seismic influence on soils;

Note. A special case of the vibration-dynamic influence on the soils of the dam is the well-known military events in the spring-autumn of 2022. The consequences of this influence for the entire NPP site are yet to be studied.

In addition to the above questions, other issues related to the reasons for the lack of soil stabilization in the dam body required study. In particular, at one time, completely insufficient attention was paid to the study of the morphological characteristics of the Quaternary eolian-alluvial sands developed at the ZNPP industrial site in the upper part of the section (the so-called «hills»). These and other characteristics should be studied in accordance with the requirements of RD 34 15.073-91, since they can directly affect the stabilization of subsidence not only in hydraulic structures, but also in critical buildings and structures of the ZNPP itself [7].

As indicated in some reports, it was recognized from the results of experimental studies that the dynamic stability of sands varies depending on their structural features.

The greatest influence on the dynamic stability of sands is exerted by the bulk density, particle size, the presence of «films» on the surface, and the degree of grain roundness. Analysis of the research results and the presence of well-rounded fine-grained sands from loose to dense composition on the NPP industrial site leads to the conclusion that loose sands under dynamic loads have

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low dynamic stability, which increases with increasing density.

An increase in the number of silt-clay particles and the formation of a hydrophilic film (due to the sorption of oil products, surfactants) leads to greater decrease in the dynamic stability of sands.

In 2022, the studies to obtain numerical parameters of morphology for eolian-alluvial and alluvial sands at the Zaporizhzhia NPP site were carried out. For the first time, these studies were also carried out in a vertical section. The dependence of

the morphology index on the genesis of deposits was confirmed. To obtain numerical indicators of morphology, criteria for identifying eolian and eolian-alluvial sands in the upper part of the local geological section were proposed [8].

The summary geological section, reflecting the composition and condition of the soils in the body of the cooling pond dam, was compiled for the first time based on the materials of the surveys of 2011-2018. It is shown in Table 1.

Table 1

Geological Section and Condition of Soils in the Body of the Cooling Pond Dam of ZNPP According to the Results of Research in 2011-2018 (Generalized Data PSACEA)

Average depth interval, from. to, m	Weighted average layer thickness, m	Granulometric composition of sands	Density of sands
0.0 ... 0.82	0.82	The sands are mostly fine, low-moisture and wet	Loose build (category 1A1, 1a1). In the areas of reprofiling the upper part of the crest of the dam in the Shandor area (category 1B1)
0.82 ... 4.36	3.54	Sands are medium and fine, wet and water-saturated (below GWL)	Medium-dense build (category 1A2, 1a2). In the areas of reprofiling the upper part of the crest of the dam in the floodboard area (category 1B2)
4.36 ... 7.74	3.38	Sands are mostly fine, water-saturated (below GWL)	Loose build (category 1A1)
7.74 ... 10.07	2.33	Sands are mostly fine, water-saturated (below GWL)	Medium-dense build (category 1A2), occasionally dense (category 1A3)

It should be especially noted that the isopach maps of layers 1A1, 1a1, 1A, 1B were also compiled for the first time at PSACEA. The engineering-geological conditions, the physical and mechanical properties of the soils in the dam section are set out in the reports of Kharkiv Ehenrgoproject Institute (KhIEP), Orsk Institute of Humanities and Technology, ZNPP, PSACEA, Fundamentstroymaks LLC, GIINTIZ LLC, etc. The list of scientific and technical reports and other materials on the object of research is traditionally so great that there is no way to bring it full list of references to this article.

Analysis of soil marks subsidence. Geodetic measurements at the site of hydraulic structures were implemented using a stationary system of soil marks. The marks are located along the dam crest and bank slopes. Observations have established that subsidence of marks varied from 1 to 8 mm for the period December 1997 – May 1998. The irregularity of subsidence was 6-12 mm, which indicated the development of the deformation in the dam body. Afterwards, 70% of soil marks were destroyed during the operation of the structure, mainly while repairing the road along the top of the dam.

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In 2009, the network of soil marks was restored and supplemented both along the axis of the dam and along the transverse profiles. The number of profiles still turned out to be clearly insufficient for the analysis of deformation processes, taking into account the size and area of the object.

Geodetic observations 2009-2012 showed that the deformation of the dam body continues at a rate of 2-7 mm/year. This indicates the lack of

stabilization of the alluvial sand massif even after 25 years of operation. The stabilization of the massif in similar soil conditions should have been completed by 1996 at the latest. According to the results of measurements, for the first time a graph of the dependence between the subsidence of ground benchmarks and thickness of loose zones in the body of the dam was created (see Fig. 1).

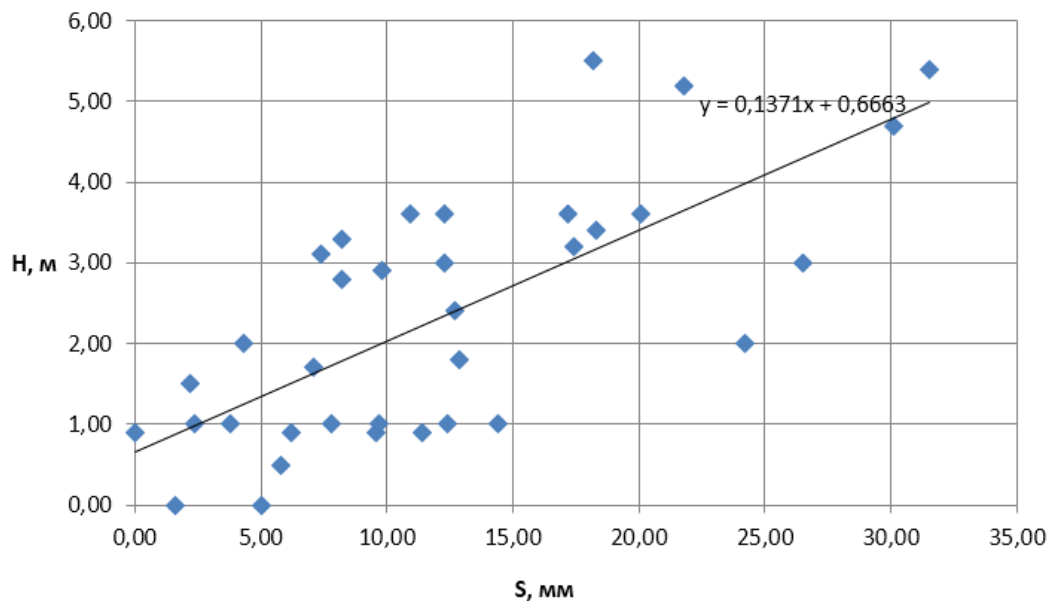


Fig. 1. Graph of the dependence between subsidences of ground benchmarks and thickness of loose zones in the body of the cooling pond dam of the Zaporizhzhia NPP

In general, it must be admitted that rare selective observations of soil marks subsidence provided in recent years cannot be considered sufficient. A radical reorganization of geodetic measurements on the cooling pond dam is required. The main proposals for the observing program will be outlined below.

Analysis of horizontal mark offsets. The results of observations of the soil marks in the new monitoring system for the period 2010–2013 are summarized in the Table. The final directions of horizontal offsets of soil marks in the body of the cooling pond dam of the Zaporizhzhia NPP are calculated.

Conclusions, based on the summary table of the final directions of soil marks horizontal offsets in the body of the NPP cooling pond dam for the period from 2010 to 2013:

– surface marks may not reflect the state of the soils in the dam body. These marks are fixed only

in the upper layer of soil, represented by sands of medium density. Loose varieties, located in the middle part of the section, are not observed;

– soil marks of the new monitoring system reflect only the movement of the upper layer of sands, mainly of medium density;

– mainly, the new soil marks are installed along the axis of the dam. Thus, soils of the dam core made in the early stages of construction are mainly observed. This part of the dam has almost stabilized subsidence values;

– analysis of the soil marks offsets shows that the offsets are mainly directed towards the cooling pond and the Kakhovka reservoir;

– the most stable soil positions are in the area where soil marks with circular offsets located;

– there are offsets of soil marks towards permanent water bodies;

– the dependence between the thickness of alluvial soils and the value of horizontal offsets of

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soil marks in contrast to their subsidence is not traced;

- the most stable section of the dam body is in the western part, most of which was built by the so-called «dry digging method»;

- displacements of the upper layer of soils are most noticeable in the central and eastern parts of the dam, especially in the area of cooling towers and spray pools;

- some of the soil marks moved to the Kakhovka reservoir. This can be explained by the extreme lack of observation points on the coastal sections on the outer part of the dam body.

Similar approaches are widely used in the world practice of hydraulic engineering [12, 14–16].

Findings

Reasons to continue monitoring on the dam of the cooling pond of Zaporizhzhia NPP.

The bases for further work on the dam of the cooling pond of Zaporizhzhia NPP are as follows:

- results of work on the assessment of the technical condition of the structure;

- repeated appeals of the relevant services due to erosion in certain sections of the cooling pond dam from the side of the Kakhovka reservoir. The works to strengthen the coastline are performed regularly;

- preliminary results of the reasons for changing the lengths of the support profiles in certain sections of the dam body;

- the new methods and technical instrument for performing a qualitative survey of such structures and ensuring safe operation;

- requirements of SNiP 2.06.05-84 and SNiP 2.02.02-85;

- large-scale construction of various facilities on the dam is planned. This will lead to changes in the vertical position of individual sections;

- the dam of the cooling pond is located on the outer perimeter of the NPP industrial site. The outer perimeter is subject to the maximum influence during any natural and technogenic changes in the Kakhovka reservoir surface [11, 13];

- disturbance of the sod cover and woody vegetation, which fix the moving alluvial sands, due to the large-scale construction of various facilities on the dam;

- analysis of the results of engineering surveys on the dam of the cooling pond since 1996;

- subsidence of the structure 2-8 mm/year and more, exceeding the limit according to the requirements of regulatory documents, indicating the absence of soil stabilization in the dam body;

- analysis of the results of high-precision geodetic observations of PSACEA, incl. significant multidirectional horizontal displacements of soil marks recorded in the course of geodetic surveys;

- vibration-dynamic impact on the soils of the dam at the time of military events in the spring-autumn of 2022. The consequences of these events for the entire industrial site of the nuclear power plant must be studied [17, 18];

- non-compliance of the current situation with most of the requirements of individual clauses of the regulatory document SOU-N MEV 40.1-00013741-79:2012 [10].

Planned measures. It is planned to use a complex of geodetic, hydrological and aerovisual methods to solve different tasks. If necessary, a complex of shallow (near-surface) geotechnical studies.

This project is fundamentally different from all the work previously carried out at the facility. The first priority under this project is the installation of special aerovisual leading signs-benchmarks on selected transverse profiles. The design of aerovisual guiding signs was developed by PSACEA specifically for work on the ZNPP dam and has no analogues. The installation of signs precedes the entire complex of works on the dam. These signs will be used for performing a complex of geodetic, hydrological and aerovisual works. Before the installation of signs or simultaneously with it, conventional high-precision geodetic observations will be carried out on a network of soil marks.

The choice of locations for installation of signs should be made only after the completion of special reconnaissance activities on the ground, together with a comprehensive analysis of all available technical information on the dam. The final configuration, dimensions and location of benchmarks for geodetic, hydrological and aerovisual observations at the dam will be selected based on the results of reconnaissance work on the ground and analysis of information.

A serious factor that for decades hindered the high-quality geodetic observations at the ZNPP industrial site and at the location of hydraulic structures is the clearly insufficient number of depth benchmarks. Moreover, at the site of hydrau-

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lic structures (GTS), there were no deep benchmarks from the very beginning. This led to significant inconvenience and costs in observations.

The most acceptable option is to place one or several clusters of deep benchmarks directly on the territory of hydraulic structures section of the ZNPP. Based on the convenience of access and high-quality observations, the benchmark clusters should be placed outside the strict security perimeter of ZNPP.

It is very difficult to comply with all the requirements of SOU-N MEV 40.1-00013741-79:2012 and other regulatory documents due to the layout scheme of the ZNPP hydraulic structures. The most acceptable areas for the location of deep benchmarks clusters within the hydraulic structures section are located on the dam and near it, on the bedrock bank.

It is proposed to take the profiles of the geodetic survey measured in November 2012 as reference base profiles. The selected base profiles must be fixed in place in an accepted way.

In addition to geodetic observations along the profiles, it is necessary to perform similar work on selected sites, on the side of the Kakhovka reservoir. This side is presumably influenced by the most intense deformations of the coastline (erosion and landslide).

Hydrological studies must necessarily include work on the construction of hydrological posts and alignments, as well as observations on them. It is obligatory to carry out depth measurements along the side of the Kakhovka reservoir and the cooling pond with an echo sounder or by other means along the newly equipped profiles.

It is reasonable to provide the aerovisual surveys by unmanned aerial vehicles (UAVs) on the entire area of the cooling pond dam. Research should be carried out using special aerovisual benchmarks. The design of these benchmarks was developed for this object in the science research laboratory PSACEA. For high-quality research, first of all it is necessary to install aerovisual benchmarks on the dam according to the proposals of PSACEA. The installation must be coordinated with the ZNPP administration, taking into account the specifics of the facility.

In technical terms, the process of aeronautical monitoring using UAV consists of three stages:

- preparatory stage,
- shooting,
- post-processing of the received data.

At the preparatory stage, the coordinates of reference points (numbered aerovisual benchmarks – leading signs) are determined. During the installation, the benchmarks must be additionally equipped with geodetic centers, colored and numbered for their reliable recognition on aerial photos.

At the stage of surveying, the UAV moves in tacks along the profiles. The overlap of images should be 60-80%. The survey provides with the obligatory capture of the coastline of the dam, both from the side of the cooling pond and from the side of the Kakhovka reservoir. In order to avoid the loss of the device, moving it away from the shore and working above the water area is not recommended.

The choice of the flight profile in the area of the cooling towers is made taking into account the general weather conditions (including the actual wind direction). The flight altitude to ensure the required accuracy is no more than 100 m. In accordance with the requirements of Geodetic, Cartographic Instructions, Norms and Regulations (GCINR) -02-036-02, to obtain topographic maps at a scale of 1:2000, a photo base with a resolution of 15 cm/pixel is required. The error in determining the coordinates at each point is no higher than 60 cm [4, 1]. Such a resolution is easily provided when shooting with modern civilian UAVs such as DJI Phantom Pro or their analogues.

The binding of the required accuracy is achieved by high-precision geodetic measurements of the coordinates of aerovisual benchmark centers. To determine the coordinates, it is recommended to use high-precision GNSS receivers. It is proposed to use the existing TNT-TPI network as base stations. It is also allowed to use the geodetic network built on the fundamental geodetic benchmarks of the Zaporizhzhia NPP.

At the stage of post-processing, the aerial photographs are combined into a single orthomosaic using Agisoft PhotoScan or similar software. Aerial photography of the site will be considered completed if its area is covered by continuous routes and successfully assembled into a single orthomosaic.

Originality and practical value

For the first time since construction, a comprehensive program has been developed for assessing the technical condition of the cooling pond dam using innovative methods of PSACEA. In particular, a monitoring system based on combined hydrographic, geodetic and aerovisual methods is proposed. The technique is proposed to be implemented using specially designed leading signs, which have no analogues in world practice.

Carrying out such studies, in the light of recent war events at the ZNPP industrial site, seems to be absolutely necessary and urgent.

For the first time, the numerical dependence between the thickness of loose soils and the magnitude of subsidence of the surface has been determined. The possible contours of weakened zones in the body of the dam are determined. A generalized geological section of the dam body was compiled for further perspective modeling of geotechnical processes.

Conclusions

The analysis of materials from studies of soils in the body of the dam made it possible to identify possible weakened and understudied zones. These zones can directly affect the state of the dam. Previously uncovered issues on the operation of the facility are raised and considered in this article.

A special case of the vibration-dynamic impact on the soils of the dam is the well-known military events of spring-autumn 2022. The consequences

of these events for the entire industrial site of the nuclear power plant have yet to be studied.

The measures for further study of the state of the earth dam of the cooling pond were selected and the conditions for their use were substantiated. For the first time since construction, a comprehensive program for assessing the technical condition of the cooling pond dam has been developed using the innovative methods of PSACEA. Also, for the first time, the numerical dependence between the thickness of loose soils and the magnitude of subsidence of the surface was determined. A generalized geological section of the dam body was compiled for further modeling of geotechnical processes.

The analysis of the soil conditions of the object is also quite consistent with previous studies on obtaining numerical parameters of morphology for eolian-alluvial and alluvial sands in the vertical section. The dependence of the morphology index on the genesis of deposits was also confirmed.

Criteria for identifying eolian and eolian-alluvial sands in the upper part of the local geological section were proposed. This will explain the reasons for the long-term unstabilized settlement of individual buildings and structures of the ZNPP.

The results of the conducted research can be applied to calculate the indicators of sandy soils in the foundations of buildings and structures. They can be used in the calculations of hydraulic structures of energy facilities – cooling ponds of nuclear power plants, thermal power plants, various dams, soil approaches to transport facilities, etc.

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В. Ю. УЛЬЯНОВ^{1*}, В. В. БЛИК^{2*}

^{1*}Каф. «Інженерна геологія і геотехніка», ДВНЗ «Придніпровська державна академія будівництва та архітектури», вул. Чернишевського, 24-а, Дніпро, Україна, 49600, тел. +38 (056) 756 33 43, ел. пошта uluanovvu@gmail.com, ORCID 0000-0002-9028-3408

^{2*}Лабораторія досліджень атомних і теплових електростанцій, ДВНЗ «Придніпровська державна академія будівництва та архітектури», вул. Чернишевського, 24-а, Дніпро, Україна, 49600, тел. +38 (063) 247 27 42, ел. пошта kolemasakar@gmail.com, ORCID 0000-0002-4435-2388

Результати дослідження стану ґрунтової дамби ставка-охолоджувача Запорізької атомної електростанції

Мета. У роботі передбачено визначити реальне розташування в просторі, провести можливе вимірювання справжніх геометричних розмірів дамби водойми-охолоджувача АЕС, особливо її підводної частини, та виявити додаткові і раніше не враховані фактори, які можуть вплинути на ці параметри, а також на стан конструкції в цілому. **Методика.** На дамбі ставка-охолоджувача Запорізької АЕС проведено комплексний аналіз усіх наявних матеріалів про інженерні вишукування та геотехнічні дослідження, завдяки чому отримано більш повне уявлення про результати інженерно-геологічних вишукувань. **Результати.** На стан ґрунтів у тілі ґрунтової дамби можуть впливати ослаблені та маловивчені зони. Ці зони визначено на основі аналізу даних досліджень ґрунтів дамби. Порушено та розглянуто раніше висвітлені питання щодо функціонування об'єкту. Запропоновано шляхи та методи додаткового дослідження ґрунтової дамби ставка-охолоджувача, обґрунтовано умови їх використання. Уперше встановлено чисельну залежність між товщиною насипних ґрунтів і величиною поверхневого осідання. Для подальшого моделювання геотехнічних процесів складено

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узагальнений геологічний розріз тіла дамби. **Наукова новизна.** Уперше з моменту будівництва розроблено комплексну програму оцінки технічного стану дамби водойми-охолоджувача за інноваційними методами Лабораторії досліджень атомних і теплових електростанцій ДВНЗ «Придніпровська державна академія будівництва та архітектури» (ПДАБА). Зокрема, запропоновано комбіновані гідрографічно-геодезичні та аерофотограмметричні методи з використанням спеціально розроблених універсальних провідних знаків, які не мають аналогів у світовій практиці. **Практична значимість.** Застосування розробленої комплексної програми з використанням інноваційних методів дозволяє проводити оцінку технічного стану дамби ставка-охолоджувача АЕС.

Ключові слова: Запорізька АЕС; дамба ставка-охолоджувача; алювіальні піски; розрідження ґрунту; динамічна нестабільність; осідання; повзучість схилу

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