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On the Need to Conduct Additional Stress Tests to Evaluate the Safety of the Hydraulic Structures Site at the Zaporizhzhia NPP

Purpose. Conducting a comprehensive analysis concerning the condition of the cooling pond dam at the Zaporizhzhia Nuclear Power Plant (NPP), which is a key component in the hydraulic structures system at this NPP, to justify further research. Additionally, identifying any extra or previously unaccounted factors that could affect the overall safety of the structure. **Methodology.** The authors performed a comprehensive review of all available engineering surveys and geotechnical research materials related to the Zaporizhzhia NPP cooling pond dam. These materials were produced by various organizations starting from the completion of the facility in 1985, with particular focus on the period 2011–2018, especially after the publication of the 2011 stress test report. Special attention was given to high-precision geodetic data on settlements and deformations of grades on the cooling pond dam. This enabled a new perspective on the findings of the engineering and geological surveys, as well as the stress tests conducted based on them. **Findings.** Based on the analysis of the dam body soil research data, previously unaddressed issues were raised and examined, including those related to the facility's operation. The need to conduct new stress tests was justified, considering the current conditions at the NPP site and its surroundings. **Practical value.** For the first time, a comprehensive analysis of the facility's condition was conducted based on accumulated geotechnical data. The stress tests performed in 2011 were found to be overly optimistic. **Originality.** The need for further research on the facility was justified, including through a program to evaluate the technical condition of the cooling pond dam using innovative methods from the Prydniprovska State Academy of Civil Engineering and Architecture.

Keywords: Zaporizhzhia NPP; cooling pond dam; alluvial sands; soil liquefaction; dynamic instability; settlement; creeping of slopes

Introduction

During the analysis of high-precision geodetic observations of the cooling pond dam settlement at Zaporizhzhia NPP, a key facility within the plant’s hydraulic structures system, as well as the results of engineering and geological surveys conducted from 2012 to 2018, it was suggested that the bearing properties of the sand foundations and the structure's body are influenced by many other factors beyond those previously identified. It was also found that earlier research and observations are clearly insufficient to determine the causes of the ongoing instability of the cooling pond dam settlement. The need to monitor this critical facility for the safe operation of the NPP arises from current regulatory requirements and departmental job descriptions for NPP hydraulic structures. Repeatedly, employees of the Prydniprovska State Academy of Civil Engineering and Architecture (now known as the Educational and Scientific Institute at the Ukrainian State University of Science and Technologies) have emphasized the need for further research on the cooling pond dam. Given its current condition and surrounding situation, the importance of this facility requires that all research focus on a dedicated section, separate from other structures at the NPP site. This article aims to justify the inadequacy and incompleteness of all previous research and to address some questions regarding po-

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tential causes of ongoing settlements of individual buildings and structures at the NPP site.

Note. The events after further complicated the situation at the site of the NPP hydraulic structures, but the analysis of their consequences is already beyond the scope of this work and is the subject of further research.

Purpose

A comprehensive analysis of the condition of the cooling pond dam at the Zaporizhzhia NPP, a key component of the hydraulic structures system at this NPP, is required to justify further research. As well as the identification of additional and previously unaccounted factors that may affect the safety of the structure as a whole.

Methodology

Physical and geographical conditions. Administratively, the study area is located in the city of Energodar, Zaporizhia region, in the western part of the NPP industrial zone, within the hydraulic structures site. Geomorphologically, the research territory lies within the first above-floodplain (sandy) left-bank Vitachiv-Bug terrace of the Dnieper River and on the left bank of the Kakhovka Reservoir. Before construction, the research area was characterized by the water area of the Kakhovka Reservoir, primarily formed by the flooded floodplain of the Konka River and partially located on the coastal terrace of the Dnieper River, with aeolian landforms. Absolute surface levels range from 18.00 m to 25.0 m, while the bottom surface of the Kakhovka Reservoir varies from 8.0 m to 9.8 m. The surface relief of the dam body is gently rolling and mainly eolian, created by wind-blown sands. In some areas, sands are stabilized by woody and herbaceous vegetation. The surface levels here range from 16.0 to 22.0 m, with the average crest level between 18.5 and 19.8 m. The main water bodies influencing the hydrogeological conditions of the research territory include*:*

– Kakhovka Reservoir;
– cooling pond.

Characteristics of hydraulic structures of the NPP. The hydraulic structures of the Zaporizhzhia NPP are a complex of engineering structures, including a cooling pond dam with blowdown structures, inlet and outlet channels, several pumping stations for various purposes, spray ponds, cooling towers, access roads, underground and overground utility networks (Fig. 1). The combined use of such hydraulic structures as a cooling pond, spray ponds, and cooling towers allows combining the maneuverability and inertia of coolers in changing weather conditions. This scheme has no analogues and, in fact, was at one time experimental, which later caused the emergence and existence of problems associated with the soils on which individual structures of this system are located, in particular, the cooling pond dam. The cooling pond is formed by fencing off a part of the water area of the Kakhovka Reservoir by means of alluviation of a sand dam, and is a water body where the effect of heated discharge waters of the NPP is closed. From the south and east, the dam adjoins the shore; from the north and west, it is washed by the waters of the Kakhovka Reservoir, which has a normal retention level at an absolute elevation of +16.0 m and a «dead» volume level of +12.0 m (according to other data – 12.7 m). The dam of the cooling pond has the shape of an irregular arc and measures 5.830 km in length (including the levee of the cargo berth). The maximum point marks of the levee ridge are 19.0…22.0 m. The width along the water's edge varies from 216 to 590 m. The dam type is an earthen alluvial dam without anti-filtration systems (devices). The dam kind is homogeneous, with freely formed slopes, a wide-profile (flattened profile). Adopted based on the technical and economic justification of the General Designer due to the need to reduce the volume of slope reinforcement. Material is fine and medium Quaternary eolian-alluvial sands of the Dnieper and Konka river valleys. The laying method is mainly alluviation by means of hydraulic mechanization under water to a depth of up to 8 m, and partly by the «dry-excavated» technique [1–3, 7, 11].

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Fig. 1. The tail-water channel from the cooling towers on the dam of the Zaporizhzhia NPP cooling pond (photo 2010)

Engineering and geological characteristics of the site. The geological structure of the area includes granites of the Archean-Proterozoic age, which form the crystalline basement of the Ukrainian Crystalline Shield (approximately at a depth of about 60 m), covered by a layer of clays of the Serogoz (former Kharkov) stage of the Paleogene, presumably lying on sandstones of the Buchak stage of the Paleogene. In the research area, clays of the Serogoz stage are greenish-gray, dense with rare inclusions of sandstone nodules, and were exposed at a depth of 33 ... 35 m. Paleogene clays underlie a layer of Quaternary eolian-alluvial sands with a thickness of about 20 m, on which the dam of the cooling pond rests. The dam was erected on fine eolian-alluvial sands using the hydraulic filling method. The dam body is non-uniform in density. In the thickness of the soils of the dam base, floodplain sandy loams are fragmentarily located, and floodplain loams are almost everywhere. The loams are dark gray, with an admixture of plant residues, soft-plastic consistency, and a thickness of 0.2 to 1.2 m. Fine alluvial sands of natural composition with a thickness of up to 14 m lie below. Alluvial sands underlie the fine sands, but of medium size.

History of the construction of the NPP cooling pond dam. Since the mid-80s, low-pressure fill dams have been widely used on cooling reservoirs of nuclear and thermal power plants and protective levees on reservoirs with beach wave-absorbing dynamic slopes. This method of wave damping in shallow water is taken from the natural analogue of sea sand beaches. Such a design of hydraulic levees from sandy or sand-gravel soils, with the laying of the upstream slope of 1:30 – 1:40 at a dam height of up to 5 m, turned out to be more economical than with the traditional laying of 1:3 – 1:5 with slope reinforcement with stone or concrete. At the same time, the increase in the volume of alluviation in terms of cost was offset by the simplification of alluviation technology, which reduced the need for fastening. A typical example of the use of hydraulic levees with a beach wave-absorbing slope was the construction of the protective levee of the Zaporizhzhia NPP on the Kakhovka Reservoir. The initial project envisaged the dumping of a stone bench

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with a volume of 1.7 million m³ into the water. The decision to replace the stone bench with sand dams with an above-water slope of 1:50 (Note: in later projects, the above-water slope was 1:40 and 1:45) and an underwater slope with location of 1:7 was made after conducting research and heated debates in the Ministry of Energy of the former USSR with the support of the Chief Engineer at the "Hydroproject" Institute T. P. Dotsenko and the Chief Hydraulic Engineer at the "Atomteploelektroproekt" Institute R. G. Minosyan. The actual savings from the implementation of this decision amounted to about $ 30 million USD. The construction of sand dams with a beach wave-absorbing slope became possible only thanks to the use of hydromechanization, a major achievement in domestic hydraulic engineering in those years [16].

Conclusions of the stress tests of the State Nuclear Regulatory Inspectorate of Ukraine for the site of hydraulic structures of the NPP in 2011. The main conclusions from the national report on the results of stress tests of the NPP site in 2011, compiled by the State Nuclear Regulatory Inspectorate of Ukraine (regarding Zaporizhzhia NPP is given in Section 3 of the report on pp. 55…58) are as follows [4].

The assessment of dam failure events was performed for the most conservative case, namely, the failure of all dams of the Dnieper cascade upstream of the Zaporizhzhia NPP, but under the condition of maintaining the operability of the dam of the Kakhovka HPP (it is located downstream of the Zaporizhzhi NPP along the Dnieper River) (Fig. 2). Based on the results of a detailed analysis, the maximum possible level in the Kakhovka Reservoir was determined to be 19.36 m, which is lower than the planned elevation of the site of the main NPP units of 22.0 m, which, in particular, is located on the indigenous bank on natural soils.

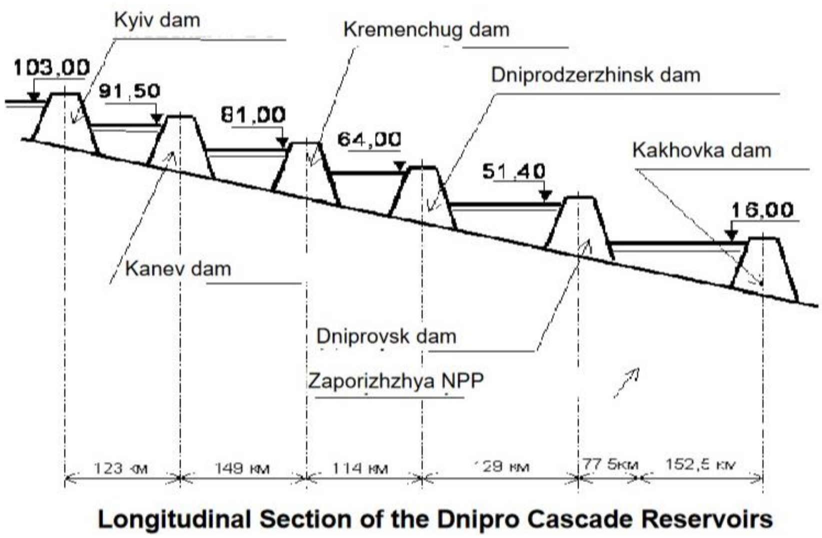

Fig. 2. Longitudinal section of the reservoirs of the Dnieper cascade of hydroelectric power plants (HPP)

The scenario for the degree of impact on the NPP site, and in particular on the cooling pond dam, was divided into several stages:

– a stable normal retention level in the cooling pond;

– overflow occurs over the top of the blowdown structure and the dam crest;

– a decrease in the level in the pond through the blowdown structure until the design level is reached;

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– a decrease in the groundwater level to natural values.

The following were established by calculations for filling and emptying the NPP cooling pond during the passage of a breakthrough wave of the upstream reservoirs of the Dnieper Cascade HPPs:

– an increase in the level in the NPP cooling pond will occur above the normal level to the 16.70 m mark;

– the time for the water level to rise in the cooling pond will be about six days;

– the additional volume of water entering the cooling pond from the Kakhovka Reservoir during the passage of the breakthrough wave will be approximately 2.0 million m^3;

– the water level in the cooling pond will decrease to the design level of 16.5 m within 29 days (43 days after the breakthrough);

– the above-mentioned fluctuations in the water level in the NPP cooling pond will not affect the safety of power units No. 1...6, since the planned elevation of the industrial site at their location is 22.0 m, which is 2.64 m higher than the calculated maximum level in the Kakhovka Reservoir during the breakthrough of the Dnieper cascade dams;

– during the overflow into the cooling pond through the dam crest, the operation of the coolers of the technical water supply of the turbine equipment may be disrupted (the cooling towers and spray pools located on the dam will not work);

– the rise and fall of the water level will occur quite slowly (the maximum daily fluctuations will be less than 1.0 m/day), which will not affect the stability of the structures located on the dam and will not cause additional deformations (the spray pools and the pumping station are protected by drainage, and the cooling towers are built on a pile foundation);

– for a northwest wind direction (during the passage of a breakthrough wave in the Kakhovka Reservoir) with a velocity of W = 17 m/s (50% probability), the calculated wave height will not exceed 0.90 m. The height of the wind surge will be about 0.02 m, the wave run-up on the slope is 0.24 m. Wave effects will cause minor reworking of the dam slope up to 10 m wide, which will practically not disrupt the design profile of the dam (width along the crest 250 ... 400 m);

– when passing the peak of the breakthrough wave, the water flow velocity in the Kakhovka Reservoir will be at least 0.82 m/s. This velocity was recognized as erosive for fine-grained sands that make up the unreinforced outer slope of the cooling pond dam. The erosion of the coastal slope of the cooling pond dam by the water flow will occur during the period when the water flow velocity exceeds 0.5 m/s. This velocity is possible for about 5 days. The washed-away soil will be deposited on the underwater part of the dam slope. According to calculations, in this case, the width of the damaged section of the dam will allegedly be less than ten meters.

In addition, as part of the «stress tests», the possibility of water loss from the NPP cooling pond, which may occur due to the destruction of the Kakhovka HPP dam after a probable seismic event, was considered. It was determined that the minimum water level in the Kakhovka Reservoir at the NPP site in the event of a dam break of the Kakhovka HPP hydroelectric complex will be 10.0 m. According to the developers of the document, due to the significant width of the enclosing dam of the cooling pond, the dam itself will not be destroyed. However, as a result of the destruction of the Kakhovka HPP dam, the NPP cooling pond water may be lost. In this case, it will also inevitably affect the operability of the system for feeding the spray pools of the technical water system of branch consumers. For this scenario of events and prevention of the impact of the consequences of accidents at hydraulic structures on the NPP structures, the following measures were planned, namely:

– a detailed analysis of the possibility of losing water from the cooling pond as a result of the destruction of the Kakhovka HPP dam;

– development of additional measures to ensure makeup of the spray pools of the technical water system of responsible consumers.

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The situation at the sites of Ukrainian NPPs and, in particular, the Zaporizhzhia NPP was also described in a number of publications that were published immediately after the publication of the stress test report [5].

Characteristics of engineering-geological surveys on the dam of the cooling pond up to 2014.

Modern geological and engineering-geological processes and phenomena. During the operation of hydraulic structures, negative man-made processes were recorded. In 1993, the slope of the bucket adjacent to pumping station No. 1 on the side of the spray ponds collapsed. In the spring of 1993, a landslide of the coastal ledge made of loose backfill sand was recorded at the dam of the cooling pond at the junction with the pumping station supplying water to the cooling towers. In both of these cases, the causes of the landslide processes were not fully clarified. The coastal slopes near pumping station No. 1 continue to be in an emergency condition to this day (2014), negative man-made processes are manifested in the form of collapse (sliding) of the coastal zone, destruction of the building's blind area, and subsidence of the concrete slope.

The following was established based on the results of the visual inspection of the cooling pond dam:

1.1 intensification in the processes of processing the shoreline of the inner slope of the dam (erosion, landslides, formation of bays), mainly in places where there is no rubble fill;

1.2 non-design man-made reservoirs (lakes) on the dam;

1.3 re-profiling of the upper part of the prism (displacement of soil masses, formation of benches) in the area between the outlet channel from the cooling towers (the highway and the shoreline);

1.4 processing of the shoreline of the outer slope of the dam (erosion of slopes, formation of beaches) in places where there is no or deformation of rubble fill;

1.5 intensification of the processes of processing the shoreline of the outer slope of the dam (formation of benches and terraces);

1.6 re-wintering of sands of the inner part of the dam in areas not fixed by grass and woody vegetation (Fig. 3, 4).

Fig. 3. Destruction of the slope fastening at the pumping station supplying water to the cooling towers (photo 2010)

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Fig. 4. Reworking of the coastal slope of the cooling pond dam from the side of the Kakhovka Reservoir (photo 2010)

Forecast of changes in engineering and geological conditions. The stability of the dam body, which is made of water-saturated loose and unconsolidated alluvial fine sands, is not guaranteed. In a water-saturated state, loose sands are dynamically (seismically) unstable and can liquefy, leading to a complete loss of bearing capacity even under minor dynamic (seismic) loads. The most significant threat to the stability of the dam body comes from seismic impacts during a design earthquake of magnitude 6. At the maximum earthquake level of 7 points, which is adopted for the territory of hydraulic structures, liquefaction of sands within the dam body becomes unavoidable.

Geodetic observations of settlements and deformations of hydraulic structures at nuclear power plants. As established during the analysis of archival documents, during wash-in, observations and control over the condition of the washed-in sands were not actually conducted. At the initial stage of constructing hydraulic structures (cooling towers No. 1 and 2, spray ponds No. 1–3, and a pumping station for feeding water to the cooling towers), zones of loose sand had already been detected in the dam body, mainly in the upper part of the geological section. During operation, the development of exogenous processes, such as the collapse of the eastern slope of pumping station No. 1 and the removal of sand into the basins and canal, was observed in certain structures. All of this necessitated additional surveys and systematic observations to develop measures for engineering protection of the structures.

Geodetic measurements were performed using a stationary system of soil grades along the dam core and coastal slopes (they were actually first initiated in 1994). The grades were initially placed along one profile, starting from the main bank up to spray pond No. 3.

High-precision geodetic observations, according to accuracy class 2, showed that between December 1997 and May 1998, the grades settled by 1 mm to 8 mm. The unevenness of settlements ranged from 6 to 12 mm. This indicates ongoing deformation of

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the earth dam. Monitoring of the soil marks on the cooling pond dam ceased in 1998. Later, around 70% of the grades were destroyed during the operation of the structure and the construction of new facilities. In 2009, after an 11-year hiatus, the soil grade network was restored. The network was expanded with new soil grades distributed throughout the entire dam body along several longitudinal and transverse profiles.

Observations in 2009–2012 revealed that deformations of the cooling pond dam continue at a rate of 2…7 mm/year. The observed settlements along the core of the cooling pond dam are less than 20% of the calculated stabilized values. Based on the results of geodetic observations, deformations of the bank slope were recorded. When comparing the geodetic surveys of 1986 and 2012, their obvious discrepancy was revealed, i.e., all signs of dam erosion were present. Thus, the process of deformation of the backfill soils and the dam body itself is in a dynamic state.

Analysis of the potential flooding risk at the Zaporizhzhia NPP industrial site. The most significant external source of flooding of the NPP site may be flooding caused by possible accidents of hydraulic structures of the Dnieper cascade of reservoirs during seismic impacts.

During a breakthrough wave passing through the Kakhovka Reservoir, water flow velocities reach peak levels, causing erosion of the cooling pond's outer slope and damaging its design profile. An increase in the Kakhovka Reservoir's volume could result in the water overflowing the dam of the cooling pond.

The following will be affected: the dam of the cooling pond with a complex of structures of the cooling system of the main turbine equipment and structures located behind the enclosing dam of the cooling pond (inside the cooling pond): spray ponds No. 1, 2; feeder channel; block pumping stations No. 1 ... 6; cooling pond blowdown facility; cooling pond make-up channel.

Conclusions based on the results of engineering and geological surveys. Based on engineering and geological surveys carried out in 1978–1983 and 2011–2012 by the NPP geological service, the following conclusions were made:

– sands that make up the dam body are characterized by a non-uniform degree of compaction and are divided into: loose and loose dynamically unstable; medium density and dense. They are also distinguished by different granulometric composition, mainly fine and less often medium-sized;

– for many areas, data on completed engineering and geological surveys at the stage of working documentation for construction are missing;

– no significant changes in the natural soils of the foundation of the structure were found;

– over the period from 1978 to 2011, a decrease in the thickness of loose sands in the dam body (core) was established, averaging 35–40%. But this is except for some areas, where an increase in the thickness of loose sands in the dam body was established, ranging from to 69%.;

– changes in the dam body indicate the process of post-compaction of the sand layer. And that the engineering and geological conditions during the survey period remain unstable (the post-compaction process is not complete), and thus the possibility of further deformations remains;

– the presence of loose sands in the dam body, especially in the first meters below the groundwater level, requires an assessment of the possibility of their liquefaction under the action of dynamic loads (earthquakes, moving vehicles, the action of filtration flows, etc.);

– according to the results of dynamic probing (2012), loose soils characterized by $Pd < 20$ kgf/cm^2 ($Pd < 2$ MPa) have a high probability of liquefaction, since these soils have virtually no consolidation cohesion.

However, despite the above, the 2014 conclusions stated that, overall, the levee is allegedly in a stable condition, even with large areas of loose variations in the sand massif. Geodetic measurements in 2012 did not record any significant deformations. The observed deformations and damages are purely local in nature and have a limited extent.

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Additionally, the recommendations provided by the NPP geologists, listed below, directly contradict the conclusions they made.

To prevent the impact of hydraulic structure accidents on the Zaporizhzhia NPP facilities and their operation, the following main measures were previously planned, but not implemented:

– additional raising of the crest of the enclosing cooling pond dam to prevent overflow from the Kakhovka Reservoir into the cooling pond when the peak of the breakthrough wave passes;

– reconstruction (building up reinforced concrete structures and upgrading hydromechanical equipment) of the blowdown structure to prevent overflow from the Kakhovka Reservoir into the pond when the peak of the breakthrough wave passes;

– fastening the outer slope of the enclosing cooling pond dam to prevent erosion of the dam when the peak of the breakthrough wave passes in the Kakhovka Reservoir.

Recommendations of the Prydniprovska State Academy of Civil Engineering and Architecture based on the results of the conducted research (2014). For further safe operation of the NPP cooling pond dam, it was necessary to carry out the following measures, namely:

– visual inspection of the technical condition of the cooling pond dam;

– instrumental inspection – planned high-altitude survey for the position of the soil grades of the cooling pond dam, carried out until the settlements are completely stabilized (noted by the authors of the article);

– conducting a set of geophysical research to determine the seismic parameters of the soils that make up the dam body and its foundation;

– measuring the transverse profiles of the dam body and the adjacent part of the reservoir bottom using ground-penetrating radar (land) and echolocation (water);

– control engineering and geological surveys to determine the dynamics in the development of technogenic processes (planned for 2018-2019);

– study of the petrographic microaggregate states of all varieties of dredged sands, as well as their research on vibrocreep.

This research could not be implemented for several reasons.

Findings

The results of the analysis of all available materials on the NPP cooling pond dam can be summarized as follows: the facility is crucial for safety and should receive primary focus. The basis for upgrading the cooling pond dam's status to a higher category, as well as the justification for further work on the facility, according to the Prydniprovska State Academy of Civil Engineering and Architecture, is the following:

1. Results of studies to assess the technical condition of the structure.

Note. Since its completion (1986), the cooling pond dam has only been studied fragmentarily as a whole.

Some of the documentation on the dam has been lost.

Unfortunately, examining individual components of the dam's structure (such as block pumping stations, cooling towers, and sluice gates) does not provide any information about their condition, given the depth of their foundations and the design features of their bases. Indirect data can be gathered from the operation of spray ponds, buried pressure pipelines, and the discharge channel from the cooling towers.

The regular monitoring observations of the groundwater level in the wells on the dam itself, given its current condition, are entirely inadequate, generally uninformative, and do not offer any insights into the processes taking place within it.

2. Repeated appeals from the relevant services of the NPP regarding the erosion of the shoreline (in particular, already at 12 sites by March 2013);

Note. The periodic visual inspections of the shoreline by the NPP hydrometallurgical shop only verify the current condition and cannot determine the internal causes that led to this. The backfilling

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of specific sections of the dam's outer and inner contours with stone and construction waste is not part of the project, does not account for the dam's overall condition, and generally provides only short-term, temporary stabilization.

3. Preliminary results from the analysis of the causes of changes in specific sections of the dam body along the length of the support profiles (based on data from the 2012 executive survey).

Note. Preliminary analysis of highly scattered data has revealed that in many areas, the lengths of the cross-sections have undergone significant changes. The reasons for this are unknown and still need to be determined.

The relief of the underwater slope of the dam from the Kakhovka Reservoir side is unknown, as it has never been studied using accepted hydrological methods.

The Prydniprovska State Academy of Civil Engineering and Architecture, based on the results of the executive survey for the cross-sections of the cooling pond dam, in particular, stated the following:

– the given comparative values, as well as the reasons for their changes, are approximate, serve mainly for the initial qualitative assessment of the intensity of geodynamic processes at the site of the NPP hydraulic structures, and need to be clarified;

– for a quantitative assessment, it is necessary to develop and implement a program to monitor the soil foundation of the dam at the NPP cooling pond. This program should include a series of geodetic observations along selected cross-sectional reference profiles of the structure, hydrological and, if needed, shallow (near-surface) engineering and geological studies, including in the water area.

– to adopt the profiles of the November 2012 geodetic survey as reference base profiles;

– the selected base profiles must be fixed on the ground in the adopted manner;

– in addition to geodetic observations along the profiles, perform similar work at selected sites located on the side of the Kakhovka Reservoir and presumably subject to the most intensive processing of the shoreline (erosion and landslides);

– hydrological research must necessarily include work on the construction of hydrological posts and line gauges, as well as mandatory depth measurements on the side of the Kakhovka Reservoir using an echo sounder or other methods.

4. Findings and conclusions from the report of American military engineers on the condition of the dams of the Dnieper cascade «ENGINEERING EVALUATION ASSESSMENT», REPORT FINAL, July 29, 2016 [13].

5. Analysis of the results of engineering surveys on the dam of the cooling pond starting from 1996, especially for the period with the nuclear power plant in 2011 to 2018.

Note. Materials from previous engineering surveys reveal some contradictions between the actual condition of the structure and the conclusions, which do not allow for a comprehensive understanding of the soils' condition. The network of exploration well profiles is quite sparse. The condition of the soils throughout the entire structure, especially within the coastal section near the Kakhovka Reservoir, remains largely unknown. This is also evidenced by geotechnical issues at the site of pumping station No. 1 and along both banks. According to survey data, loose soils are found almost everywhere, not only on the surface but also throughout the thickness of the structure itself, mainly near the groundwater level. Some of the loose soils in the dam body are even categorized into a special layer, characterized by extremely low values of physical and mechanical properties. Additionally, in some areas, loose differences have even been found beneath natural sandy soils. Presumably, the so-called «quicksand» known in local floodplains, even before construction began, is confined to these zones. Certain features of the genesis and morphology of local sands also undoubtedly influence their properties [8]. Overall, loose differences of sandy soils within the structure are particularly sensitive to any type of dynamic impacts—including seismic activity—due to their engineering and geological features, which can ultimately negatively

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affect the condition of the entire structure, given its size and location within the industrial site of the NPP.

As evidenced by the engineering survey materials from 2011–2018, the condition of the cooling pond dam was not assessed as optimistically by the authors of the reporting materials after 2012. Even then, it raised quite reasonable concerns. This is supported by numerous recommendations and the declared need for additional, highly specialized research on the soil layers. The section on recommendations regarding plans for reconstructing the entire structure deserves attention. However, the authors of the article have no information on whether these recommendations have been implemented in practice. Meanwhile, their own specialized, comprehensive research on the dam's condition, proposed by experts from Prydniprovska State Academy of Civil Engineering and Architecture, based on their assessment of the situation, was deemed unnecessary and thus not considered. Consequently, this research was not included in the 2021 tender documentation for additional dam investigation. In fact, the tender documents show that all dam research was limited to geodetic observations of settlements, performed by a third-party organization that had never previously worked at this NPP site and was unfamiliar with its specifics. *Moreover, these observations, after an initial cycle, were interrupted by the events of February 2022. (Authors' note).*

6. Results of high-precision geodetic observations of soil grades.

Note. The recorded settlement of the structure, which has a height of 10.5 to 13.6 meters, was up to 8 mm per year, and in some areas, such as around the cooling towers, much more. In other words, it significantly exceeded the maximum limits set by regulatory documents for structures of this type (no more than 2 mm per year). It indicates a lack of stabilization in the soils of the dam body, especially in many areas. Despite typical construction experience showing that stabilization of settlements in alluvial sandy soils within the Dnieper valley usually occurs within the first 2–3 years after construction, with only rare cases taking up to 10 years. The work on building the cooling pond dam was essentially completed by 1985. Therefore, it appears that the unstabilised settlements of the entire structure as a whole still continue today, and their causes remain unknown.

Geodetic observations of the dam's settlement throughout its entire service life were conducted with significant interruptions and did not provide a complete picture of its planned high-altitude position. Additionally, measuring settlement at a single point (near-surface soil grade) with a profile width of up to 500 m offers no justification for approximating the data collected along the entire profile, either in length or depth (considering the thickness and condition of the dam body's alluvial soils). Essentially, it amounts to a discrete study of the soil grade's location.

The ongoing, substantial multidirectional planned displacements of soil grades recorded during geodetic research by the Prydniprovska State Academy of Civil Engineering and Architecture suggest complex movements of soil masses, possibly influenced by fluctuations in the cooling pond and the Kakhovka reservoir, as well as the operation of cooling towers and spray ponds.

The revealed discrepancy between the current position of the majority of the requirements of individual clauses of the regulatory document SOU-N MEV 40.1–00013741–79:2012 [10].

7. Late comments on individual provisions of the 2011 stress test report by State Nuclear Regulatory Inspectorate of Ukraine by several researchers [6, 9].

Originality and Practical value

For the first time, a comprehensive analysis of the facility's condition was conducted, based both on its own research materials and on available data from third-party organizations. Given the current situation and today's realities, the need for large-scale additional research on the facility was confirmed. This includes, among other things, the Program for assessing the technical condition of the

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cooling pond dam, developed by the Prydniprovska State Academy of Civil Engineering and Architecture, utilizing its own innovative methods. Additionally, expanded research on the hydraulic structures of the NPP should become part of new stress tests of the NPP site, conducted under the auspices of the IAEA and, considering the strategic importance of the facility, must meet all the fundamental requirements of this organization [12, 14, 15, 17].

Conclusions

The conclusions based on the results of the analysis of all available materials on the dam of the cooling pond of the Zaporizhzhia NPP are as follows:

– the facility is significant for ensuring safety and should be given primary attention;

– the data for preparing the stress tests were based entirely on the materials of geotechnical research conducted, apparently, before 2000, and could not take into account further developments of the situation;

– the 2011 stress tests did not consider the condition of the soil for the structure at all, which was largely unknown in most parts of this facility before 2011. Since the main engineering and geological surveys, including the most informative dynamic probing, were conducted later and only in parts, and in many areas, especially on the side of the Kakhovka Reservoir, the condition of the soils remains unknown;

– given the condition of the soils, even a short-term increase in the level of the Kakhovka Reservoir to 19.36 m is sufficient to destroy the structure, since more than 85% of its area will be underwater, albeit possibly for a short time. Which will lead to the sloughing of the bank slopes, the destruction of the channel lining, the failure of the sluice gates, the change in the position of large-diameter pressure pipelines, the filling of spray pools, channels with sand, etc.;

– regarding the parameters of the Kakhovka Reservoir's water level increase, it is unclear which time of year the calculations refer to. The presence of a thick ice cover during winter could also alter these parameters in terms of both timing and altitude plans.

– the presence of powerful deep foundations of cooling towers and a pumping station on the dam, as well as the planning mark of the main block site located at a distance of 22.0 m from the hydraulic structures, which exceeds the flood level of 19.36 m, cannot in any way influence the development of the situation with the dam soils;

– the assessment of the structure's condition based on stress tests from 2011 appears overly optimistic due to the lowered level of the Kakhovka Reservoir. It also failed to consider the actual state of the soils, as later researchers pointed out.

– in general, the soils of the structure, due to engineering-geological and technological features, are especially sensitive to any kind of external impacts, including vibration. Which can ultimately harm the condition of the entire structure as a whole, given its dimensions and location;

– for the above reasons, any measurement of the position of the Kakhovka Reservoir mirror is undesirable due to the destruction of the hydraulic structures located above and below;

– the data from the stress tests of the NPP site from 2011 were most likely based exclusively on internal sources of information without access to the funds of closed organizations located outside the country (in particular, such as «Gidrospetsgeologiya», «Hydrogeological Expedition of the 16th District», etc.);

– all of the above, in turn, is the basis for conducting additional extended research on the hydraulic structures of the NPP;

– extended research on the hydraulic structures of the Zaporizhzhia NPP and, first of all, the dam of the cooling pond, in turn, should become part of new stress tests of the NPP site, conducted under the auspices of the IAEA.

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Про необхідність проведення додаткових стрес-тестів для оцінки безпеки гідротехнічних споруд на території Запорізької АЕС

Мета. Провести комплексний аналіз стану греблі охолоджувального басейну Запорізької атомної електростанції (АЕС), яка є ключовим компонентом системи гідротехнічних споруд на цій АЕС, для обґрунтування подальших досліджень. Крім того, виявлення будь-яких додаткових або раніше не врахованих факторів, які можуть вплинути на загальну безпеку споруди. **Методика.** Автори провели комплексний огляд усіх доступних інженерних обстежень та геотехнічних дослідницьких матеріалів, пов’язаних із греблею охолоджувального басейну Запорізької АЕС. Ці матеріали були підготовлені різними організаціями, починаючи з моменту завершення будівництва об’єкта в 1985 році, з особливим акцентом на період 2011–2018 років, особливо після публікації звіту про стрес-тести 2011 року. Особлива увага була приділена високоточним геодезичним даним про осідання та деформації укосів греблі охолоджувального басейну. Це дозволило по-новому поглянути на результати інженерно-геологічних досліджень, а також стрес-тестів, проведених на їх основі. **Результати.** На основі аналізу даних досліджень ґрунтів тіла греблі були підняті та розглянуті раніше не розглянуті питання, в тому числі ті, що стосуються експлуатації об’єкта. Була обґрунтована необхідність проведення нових стрес-тестів з урахуванням поточних умов на території АЕС та в її околицях. **Практична значимість.** Вперше було проведено комплексний аналіз стану об'єкта на основі накопичених геотехнічних даних. Стрес-тести, проведені в 2011 році, були визнані надто оптимістичними. **Наукова новизна.** Була обґрунтована необхідність подальших досліджень об’єкта, в тому числі за допомогою програми оцінки технічного стану греблі охолоджувального басейну з використанням інноваційних методів Придніпровської державної академії цивільного будівництва та архітектури.

Ключові слова: Запорізька АЕС; гребля охолоджувального басейну; алювіальні піски; розрідження ґрунту; динамічна нестабільність; осідання; повзучість схилів

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