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APPLICATION OF A LOGICAL-PROBABILISTIC METHOD OF FAILURE AND FAULT TREES FOR PREDICTING EMERGENCY SITUATIONS AT PRESSURE HYDRAULIC FACILITIES (THE CASE OF KAKHOVKA HYDROELECTRIC COMPLEX)

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The problem of forecasting emergency situations at hydraulic facilities of a hydroelectric complex, forming its pressure waterfront, based on the application of a logical-probabilistic approach is considered.

The relevance of the studies and their practical significance are determined by the need to assess the compliance of the safety of hydraulic facilities with international safety standards and current national legislation. Therefore, the reports on the environmental impact assessment of hydraulic facilities should present the results of assessing the additional risk of emergency situations at the hydroelectric complex. This assessment, in turn, requires an analysis of the probability of accidents at the hydroelectric complex before and after new construction.

In the present study, using the example of the Kakhovka hydroelectric complex (Ukraine), the systemic nature of possible causes of accidents at pressure hydraulic facilities as part of hydroelectric complexes is found. An accident at a hydroelectric complex is considered as a complex natural and man-made event, which can be associated with various natural and man-made factors. The total (generalized) probability of an accident at the hydroelectric complex is estimated by the logical-probabilistic method of failure and fault trees based on a deductive approach.

The upper limit estimates of the probability of accidents at individual hydraulic facilities of the hydroelectric complex and the generalized estimate of the probability of an accident at the hydroelectric complex as a whole are calculated. It is found that the probability of an accident depending on the hydraulic facility of the hydroelectric complex can vary. In the case of the Kakhovka hydroelectric complex, it varies from $2.1\cdot10^{-6}$, year^{-1}, at the run-of-river earth dam, to $5.6\cdot10^{-6}$, year^{-1}, at the spillway dam. The total probability of an accident at the hydroelectric complex is $2.35\cdot10^{-5}$ emergency events per year. However, these estimates do not exceed the permissible value of $5\cdot10^{-5}$, year^{-1}, which is regulated for hydraulic facilities of the corresponding consequence class. Thus, it is concluded that the current reliability and safety of the hydraulic facilities of the Kakhovka hydroelectric complex can be recognized as sufficient

Keywords: Kakhovka hydroelectric complex, pressure hydraulic facilities, environmental impact assessment, accident scenario, technological safety

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1. Introduction

The Kakhovka hydroelectric complex on the Dnieper River is one of the largest hydroelectric complexes in Ukraine. Hydraulic facilities of the hydroelectric complex are located in the lower reaches of the Dnieper River, 5 km from the city of Nova Kakhovka, Kherson region [1]. This is the last sixth step of the Dnieper River system of hydroelectric power plants (HPP).

Construction work at the Kakhovka hydroelectric complex began in the spring of 1952; the hydraulic facilities were put into permanent operation in 1959. In the summer of 1955, the filling of the Kakhovka Reservoir was started, which is now the largest in Ukraine – 18.19 km^3 with normal water level (NWL) and the second largest water surface area (2,155 km^2) after the Kremenchuk Reservoir.

The Kakhovka hydroelectric complex has many purposes. It is used in hydropower, water transport, irrigation, municipal and service water supply, recreation, fisheries. Strategic road and railway bridges also pass through the hydraulic facilities of the hydroelectric complex [1].

The Kakhovka hydroelectric complex includes seven pressure hydraulic facilities, forming a pressure waterfront with a total length of 3.8 km. Starting from the right bank, these are:

1) a run-of-river earth dam with a length of 1206.0 m and a maximum height of 30.0 m;

2) the HPP structures with a total length of 212.0 m, combined with bottom spillways, where there are six vertical hydraulic units with a total capacity of 334.8 MW;

3) a concrete gravity spillway dam with a total length of 412.0 m and a height of 35.0 m from the foundation to the top of the division wall, with 28 spillways;

4) an earth dam between the HPP structures and the lock with a length of 188.0 m and a maximum height of 22.0 m;

5) a single-lift lock;

6) left-bank floodplain earth dam with has a length of 500.0 m and a maximum height of 19.85 m;

7) left-bank above floodplain earth dam with a length of 1275.0 m and a maximum height of 12.85 m.

According to the current building codes (DBN V.2.4–3: 2010 [2]), the pressure hydraulic facilities of the Kakhovka hydroelectric complex belong to the highest consequence class – CC3. To substantiate compliance of reliability and safety of hydraulic facilities of this class with current standards [2], along with traditional calculations within the deterministic approach, it is allowed to evaluate them on the basis of a probabilistic approach. As for the pressure hydraulic facilities of the Kakhovka hydroelectric complex, the relevance of research to predict the probability of accidents at them is determined not only by the high liability of hydraulic facilities for consequences. Currently, it has been decided to start work on substantiating the expansion of the Kakhovka hydroelectric complex by constructing another hydraulic facility – the building of the Kakhovka HPP-2. This construction is envisaged by the Hydropower Development Program for the period up to 2026 [3] as one of the promising areas for the development of the Dnieper River system of HPP [4]. In accordance with the Law of Ukraine "On Environmental Impact Assessment" [5], Ukrhydroenerho PJSC submitted the relevant information to the Unified Register for Environmental Impact Assessment (EIA) [6]. According to the Law [5], a number of probabilistic forecasts must be presented in the EIA report. Accidents at pressure hydraulic facilities are among the most significant factors of the likely negative impact on the environment from the Kakhovka hydroelectric complex. The construction of the Kakhovka HPP-2 can affect the situation with emergencies at the hydroelectric complex, as it is expected to be carried out within the existing hydraulic facilities [3, 6]. In order to comply with the requirements of the Law [5] and identify the "vulnerability of the project to emergency risks", it is important to assess the additional risk of an accident at the hydroelectric complex associated with new construction. In turn, this requires assessing the probability of an accident at existing hydraulic facilities of the hydroelectric complex.

It should be noted that the hydraulic facilities built in Ukraine do not differ from the hydraulic facilities built and operated in the world [7]. Therefore, the proposed approaches can be applied to any hydraulic facilities, regardless of geographical location and size. At the same time, the choice of the Kakhovka hydroelectric complex as the subject of study was made not by chance, since in this case the pressure waterfront is simultaneously formed by several hydraulic facilities of different types and purposes, each of which can be considered as a unique facility.

The absence of serious accidents at the hydroelectric complexes of Ukraine, especially at large ones, including pressure hydraulic facilities of the Kakhovka hydroelectric complex, should not reassure Ukrainian scientists, engineers, and officials. The problem of the safety of hydraulic facilities as a part of hydroelectric complexes exists irrespective of whether there were accidents at them in the past or not. Over time, due to the aging of hydraulic facilities built in the last century and the increasing number of new hydraulic facilities, the problem of accidents at hydroelectric complexes will not disappear. Practice shows that accidents may occur at hydraulic facilities that have not occurred before and to which the engineering community may be unprepared [8]. Thus, the issue of predicting hypothetical accidents at pressure hydraulic facilities of hydroelectric complexes is relevant regardless of the state (serviceable or faulty) they are now in and how they are operated.

2. Literature review and problem statement

Pressure hydraulic facilities of hydroelectric complexes are among the most common engineering facilities among complex, major, and unique engineering systems. In many cases, they are both critical infrastructure facilities [9–11] and potentially hazardous facilities [10, 12]. At the same time, studies concerning both critical infrastructure [9–11] and the affiliation of pressure hydraulic facilities to potentially dangerous facilities usually ignore the factor of their interaction within the hydroelectric complex as a system.

Thus, without the functioning of various pressure hydraulic facilities as critical energy, water, and transport infrastructure facilities, it is impossible to imagine the functioning of the national economy and livelihoods of the population.

At the same time, according to item 13 "Methods of identification of potentially dangerous facilities" [12], pressure hydraulic facilities in Ukraine belong to potentially dangerous facilities. They can cause accidents and emergencies that threaten human life and health, property, and the environment. Particularly dangerous emergency events are hydrodynamic accidents, which involve the uncontrolled spread of large volumes of water over a long distance at high speeds. Such accidents occur during the destruction (breakthroughs of the pressure waterfront) of dams, gates, depressurization of HPP pressure paths and can lead to extremely severe economic, environmental, and social consequences.

In the history of hydraulic construction, there were a significant number of accidents at pressure hydraulic facilities, including catastrophic accidents with numerous victims. The most famous examples:

– destruction of the 62.6 m high St. Francis Dam in the United States in 1928 with the death of more than 400 people;

– destruction of the 66 m high Malpasset Dam in France in 1959 with the death of 421 people;

– catastrophic accident at the reservoir of the 262 m high Vajont Dam in Italy in 1963 with the death of more than 2,600 people;

– destruction of the 26 m high Machchhu Dam II in India in 1979 with the death of more than 2,000 people [7].

Among the recent catastrophic accidents at pressure hydraulic facilities, the accident at the Sayano-Shushenskaya HPP in Russia in 2009 with the death of 75 people should be noted [8].

An important requirement for pressure hydraulic facilities, in comparison with other facilities subject to the Law of Ukraine "On High Safety Facilities" [13], is to ensure the continuity of their operation even in cases of emergency situations. In the event of an emergency, pressure hydraulic facilities cannot always be urgently (automatically) put out of operation, immediately deactivating them. In many cases, pressure hydraulic facilities (especially dams, spillways) play the role of the last reserve to prevent a man-made catastrophe in emergency operation usually by emergency operation of the reservoir. In this case, the emergency operation of the reservoir can also lead to catastrophic consequences, including the destruction of hydraulic facilities with a breakthrough of the pressure waterfront [14, 15].

Catastrophic accidents at pressure hydraulic facilities have occurred in the past and cannot be completely avoided in the future, despite the current trend towards a gradual decrease in the probability of such accidents [16, 17]. No country or facility is safe from accidents at pressure hydraulic facilities. It should be borne in mind that hydraulic facilities wear out and age. As the scale of natural resource use in the river valleys and the development of riverine areas increase over time, we should expect an increase in catastrophic accidents at pressure hydraulic facilities. This is due to the population growth in accident impact areas of hydraulic facilities, development of socio-economic infrastructure, etc.

The literature [7, 8, 10, 33] provides examples of studies based on the application of probabilistic methods to analyse and evaluate the reliability and safety of complex man-made facilities. In particular, [7, 8] indicate the importance of the scenario approach in assessing the safety of hydraulic facilities and [10] indicates the need to take into account their interaction as part of hydroelectric complexes. In [14, 15], various problems of reliability and safety of hydraulic facilities are formulated within the framework of the probabilistic approach with the analysis of the factors determining the reliability and safety of hydraulic facilities of different type and purpose. In [16, 17], the results of statistical analysis of the accident rate of hydraulic facilities depending on their type are given. Fundamental solutions concerning the methods of parametric reliability theory for various types of facilities and structures are given in [18, 19], methods of system (statistical) reliability theory – in [20]. The need to combine methods of parametric and system reliability theories in assessing the reliability of machines, structures, facilities is stated in [21, 22].

In [14, 23–25], attention is focused on taking into account uncertainty and risk when assessing the reliability and safety of technical facilities and systems, including hydraulic facilities [14, 24, 25]. Methods of probabilistic analysis of strength and stability of ground hydraulic facilities are described in [26]. Features of application of statistical estimates of accident rate of hydraulic facilities when assessing their reliability are analysed in [27]. In [28], hydraulic factors that can determine the state of hydraulic facilities during operation are analysed. Among the fundamental works on equipment reliability and development of the probabilistic approach, we can also highlight the work [29]. Some practical aspects of reliability assessment of building structures by probabilistic methods are described in [30], structurally complex systems – in [31]. The importance of taking into account the seismic factor in assessing the reliability of hydraulic facilities, in particular the Kakhovka hydroelectric complex, is substantiated in [32], hydrological – in [33]. However, as the analysis of the causes of accidents at hydroelectric complexes and conditions of their development shows, they are systemic in nature, can be determined by an extremely large number of different natural and man-made factors. The interaction of various hydraulic facilities and equipment at the system level should also be taken into account. This interaction, despite the similarity of facilities, their structural elements, etc., is implemented according to stochastic laws and occurs in various forms and under various scenarios. This requires structuring the problem, applying different methods and approaches at different stages of research.

Given that predicting an accident at a hydroelectric complex is a "poorly structured" system problem, burdened by various uncertainties (stochastic and epistemological, structural and parametric, etc.) [7, 10, 14], its solution, in the absence of a significant statistical sample, is a complex and unsolved task. The reason for this is, in particular, that the classical deterministic (dynamic) approach is extremely difficult to apply to the forecasting of accidents at hydraulic facilities. This is due to the fact that this approach is aimed at an unambiguous prediction of future states of the research subject, depending on its initial state. In this case, a strict (functional or logical) causal relationship is assumed to exist between the cause event and the consequence event [7].

An alternative to the deterministic (dynamic) approach in forecasting is the probabilistic approach, which allows finding a probabilistic relationship between the cause event and the consequence event. According to this approach, the same cause event can correspond to different consequence events with different probabilities. In this case, all or part of the parameters that describe the behaviour of the research subject, factors, conditions, and circumstances that determine its behaviour are considered probabilistic, stochastic, the values of which are implemented randomly.

As is known, the most important sign of the randomness of physical phenomena and processes that determine the behaviour of any hydraulic facility as a system is the absence of signs of their finite dimension. It should be borne in mind that the full formalization of most factors of accidents at hydraulic facilities is possible only at the level of assumption events. Therefore, the probabilistic approach, based on the partial determinacy of phenomena and processes occurring at hydraulic facilities and in the environment, can be considered as a more adequate approach to predicting accidents at them. Thus, it can be confidently stated that the probabilistic approach can significantly simplify the structuring of the problem of predicting accidents both at a single hydraulic facility and at the hydroelectric complex in general, provides the possibility of synthesizing the obtained estimates by probability. This approach allows the use of various methods and models: mathematical statistics and probability theory, stochastic dynamics, reliability theory, and risk theory.

These can be logical and probabilistic methods of analysing the reliability and safety of structurally complex systems, and methods of randomization of tested models and design schemes of facilities, their structures and foundations.

3. The aim and objectives of the study

The aim of the study is to predict emergency situations at the existing pressure hydraulic facilities of the Kakhovka hydroelectric complex in the context of analysing the possibility of safe implementation of construction plans of another pressure hydraulic facility – Kakhovka HPP-2.

To achieve the aim, the following objectives were set:

– to propose a method of forecasting accidents at the hydroelectric complex, which allows taking into account their complex systemic nature, formed under the influence of various natural and man-made factors;

– to determine the compliance of the upper limit estimate of the probability of an accident at the Kakhovka hydroelectric complex as a whole and at each of its pressure hydraulic facilities with the norms regulated by the current legislation;

– to assess the possibility of expanding the composition of pressure hydraulic facilities of the hydroelectric complex by constructing the Kakhovka HPP-2 within the existing pressure waterfront.

4. Research materials and methods

4. 1. Some fundamental remarks and accepted hypotheses

The selection and substantiation of hypothetical (probable) forms of accidents at pressure hydraulic facilities of the hydroelectric complex were carried out taking into account their specific features and according to the general recommendations of the International Commission on Large Dams (ICOLD) [24, 25]. Based on the results of deductive analysis (decomposition) of accident forms, probabilistic models of failures and faults of hydraulic facilities, their structures, foundations, elements, devices, and equipment were selected. Accident statistics were also used to estimate the probabilities of individual emergency events [16–27]. In all cases, the hypothesis of independence and compatibility of the accepted forms of accidents was accepted.

When estimating the probabilities of violation of the stability and strength of pressure hydraulic facilities of the hydroelectric complex, a mathematical apparatus of random variables and their functions was used (the time factor was not explicitly taken into account). At the same time, the results of calculations of hydraulic facilities were randomized by the method of limit states, regulated by the current design standards. This has significantly simplified the task of estimating the probabilities of elementary emergency events that can initiate emergency processes at hydraulic facilities.

At all stages of probabilistic forecasting of emergency events and states, in accordance with the axioms of probability theory, complete groups of events were formed by factors that determine the operating conditions of hydraulic facilities. These groups of state events include combinations of loads, hazards, impacts, failures, faults, and violations, etc. The probabilities of state events were determined from the assumption that the development of the corresponding emergency scenario at the hydraulic facility occurs in the case of exceeding some generalized force impact at a given combination of loads for a given period of time.

Heuristic approaches were used in the decomposition of complex emergency events and identification of causal relationships between cause events and consequence events, along with formal methods of system analysis, models of mathematical reliability theory [14, 19]. The analysis was carried out taking into account the experience of investigating the causes of accidents that occurred at hydraulic facilities [7, 8, 14, 16, 17, 24–26].

At the same time, expert estimates of probabilities for assumption events were used only for the emergency events, the probabilities of which could not be determined by analytical or logical methods of mathematical reliability theory, probability theory, and mathematical logic.

The Bernoulli-Laplace principle was used to take into account several independent, incompatible scenarios of emergency events at hydraulic facilities, each of which can lead to a hypothetical form of an accident at a hydraulic facility or a hydroelectric complex as a whole. According to this principle (the principle of insufficient reasons), all potential scenarios in such a group of events were accepted as equally plausible hypotheses. This principle was applied only in the absence of data that would reliably remove the uncertainty about the probability of each of these scenarios in the group of emergency events.

If among the possible emergency events at the hydraulic facility there is a common cause (e. g., flood, earthquake, etc.) the "common cause" principle will be used. According to this principle, the generalized unconditional probability of an accident, taking into account all such events, cannot exceed the probability of the corresponding common cause. At the same time, it was assumed that as a result of multiple emergency events and states at the hydraulic facility or hydroelectric complex in general, which arise due to a common cause, several independent forms of accidents can be initiated simultaneously. All these forms of accidents are combined into one generalized accident scenario due to the implementation of the corresponding "common cause" [8, 14].

This approach allows obtaining effective upper limit (sup) estimates of probabilities of emergency consequence events which cannot be exceeded, at each stage of probability calculations and aggregation of emergency events by probability. In particular, when generalizing alternative incompatible scenarios of accidents, indirectly, emergency events and states having a common cause and leading to the same consequence event can be taken into account. This eliminates the risk of underestimating those events and states, the significance of which may be underestimated when assessing the probability of accidents.

In the probabilistic modelling of the parameters determining the state of pressure hydraulic facilities, their structures and foundations, data on standard (50 % availability) and calculated (95 % availability) values of their quantitative characteristics were used. The hypothesis of a normal law of distribution of these characteristics as random variables was accepted. Stochastic variability of characteristics was taken at the level of maximum allowable values (with a risk margin), determined taking into account the experience of design, construction, and operation of hydraulic facilities of different types and on different foundations. Relevant data are given in [14, 26].

4. 2. Fundamental principles of the failure and fault tree method

The probability of an accident at the pressure hydraulic facilities of the Kakhovka hydroelectric complex was estimated by the failure and fault tree method. This method allows implementing the scenario approach [7], taking into account a variety of factors and parameters that determine the state of hydraulic facilities during operation [14], revealing uncertainties and analysing risks [23, 26]. The computational model of this method is a circuit-free tree graph, the vertex of which is some resulting emergency consequence event; the set of elements – defined counted set of certain cause events of the emergency consequence event, and the set of correspondences – relations between them.

The construction of the failure and fault tree diagram is based on deductive logic, taking into account the possible causes of some resulting emergency assumption event. When modelling, special structural elements such as event symbols and operator symbols (or logical operators) are used [7, 14]. The event symbols display various events, which, depending on their hierarchy, causal relations, etc., determine the occurrence and course of an accident at a hydraulic facility. Logical operators display the logic of causal relationships between different emergency events and calculate the probabilities of consequence events. The following logical operators were used:

– "OR" – in cases where the consequence event may occur as a result of any of the cause events included in the logical operator; the "OR" operator corresponds to the logical operation "disjunction";

– "AND" – in cases where the consequence event occurs with the simultaneous implementation of all incoming cause events; corresponds to the logical operation "conjunction";

– "XOR" – in cases where the consequence event may occur as a result of any of the incoming incompatible cause events; corresponds to the logical operation "exclusive disjunction";

– "PROHIBITION" – to simulate the situation when the consequence event is associated with some additional state in the implementation of the input cause event; wherein this state event blocks (prohibits) the occurrence of the consequence event, thus reducing its probability; corresponds to the logical operation "implication";

– "PARTIAL PROHIBITION" – in cases where the consequence event is associated with some additional state when it is possible to implement two incoming incompatible cause events; the corresponding state event blocks the occurrence of the consequence event, reducing its probability, only when one of the cause events occurs;

– "M of N", which combines n cause events and a consequence event that occurs when at least m cause events occur.

Table 1 below gives the formulas for calculating the probabilities of emergency consequence events depending on the actions of logical operators.

Table 1

Formulas for calculating the probabilities of consequence events of the failure and fault tree

Operator	Formulas for estimating the probabilities of consequence events A
"OR"	$P(A)=1-\prod_{i=1}^{n}\left(1-P(B_i)\right),$ (1) n – total number of the i-th random independent cause events B_i
"XOR"	$P(A)=\sum_{i=1}^{n}P(B_i),$ (2) n – total number of the i-th incompatible cause events B_i
"AND"	$P(A)=\prod_{i=1}^{n}P(B_i),$ (3) n – total number of the i-th random independent cause events B_i
"PROHIBITION"	$P(A)=P(B)\cdot P(C)$ (4)
"PARTIAL PROHIBITION"	$P(A)=P(B_1)\cdot P(C_1)+P(B_2)\cdot\left(1-P(C_1)\right)$ (5)
"M of N"	$P(A)=P(A)_m+P(A)_{m+1}+\ldots+P(A)_n,$ (6) where the probabilities $P(A)_m$, $P(A)_{m+1}$, $P(A)_n$, for $P(B_i)=P(B)$, $i=\overline{1,n}$, $m<n$: $P(A)_m=\left(1-\left(1-P(B)\right)^n\right)\cdot\left(1-\left(1-P(B)\right)^{n-1}\right)\cdot\ldots\cdot\left(1-\left(1-P(B)\right)^{n-m+1}\right);$ $P(A)_{m+1}=P(A)_m\cdot\left(1-\left(1-P(B)\right)^{n-m}\right);$ ……; $P(A)_n=P(B)^n.$ (7)
In formulas (1)–(7), probabilities: $P(B_i)$ – the i-th event at the input (cause event); $P(C)$ – state event C; $P(A)$ – consequence event A	

For the convenience of checking the failure and fault tree diagram, conducting intermediate calculations, etc., some fragments of it were built, covering part of the problem situation. To avoid the excessive complexity of the failure and fault tree, the system integration approach (aggregation) was also used. Simple emergency events and states were purposefully integrated into more general events and states, which were later considered basic (initial). The principle of the least interaction in the system was used, according to which the basic emergency events were selected among stochastically independent events.

4. 3. The solution of the problem, results and their analysis

Eight hypothetical emergency events at the Kakhovka hydroelectric complex were considered:

A_1 – reservoir overflow;

A_2 – accident at the run-of-river earth dam;

A_3 – accident at the spillway dam;

A_4 – accident within HPP structures;

A_5 – accident at the lock;

A_6 – accident at the earth dam between HPP structures and the lock;

A_7 – accident at the floodplain earth dam;

A_8 – accident at the above floodplain earth dam.

The failure and fault tree diagram used in predicting the accident at the pressure hydraulic facilities of the Kakhovka hydroelectric complex and estimating its probability is presented in separate fragments in Fig. 1–7. Fig. 1 below shows its peak events, detailing the accident at the lock (emergency event A_5).

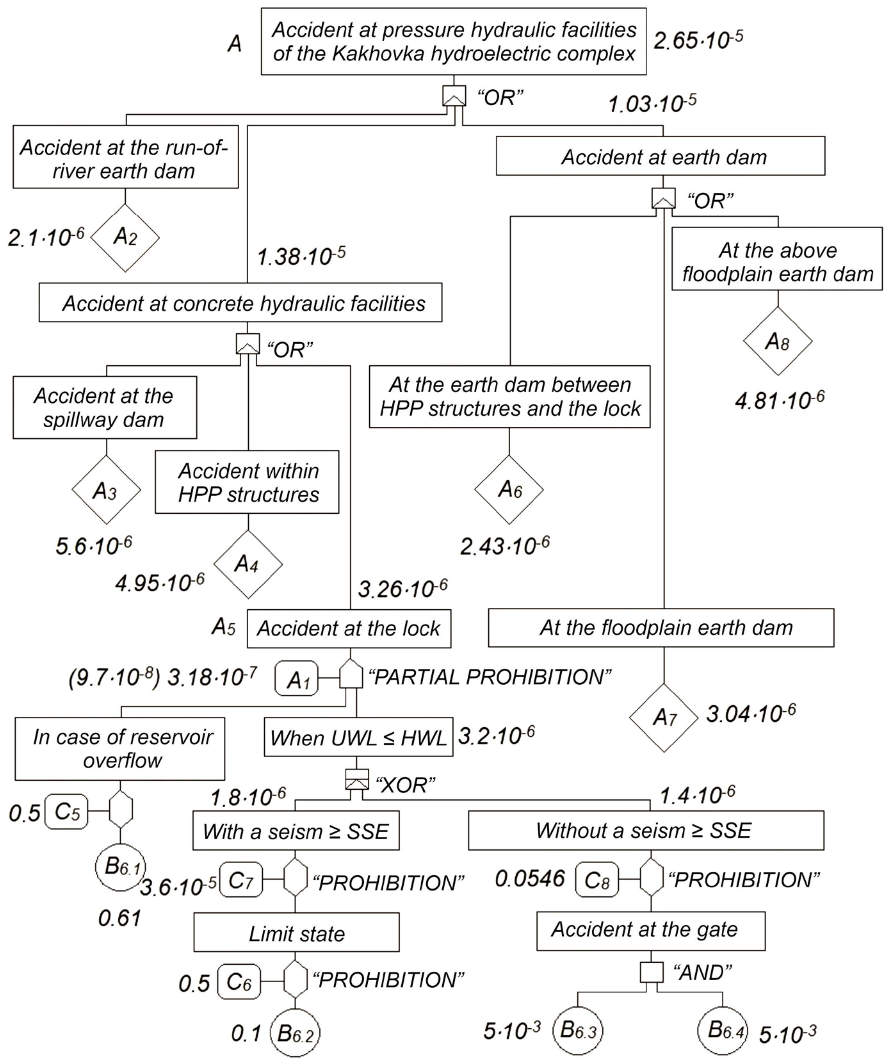

Fig. 1. Failure and fault tree for estimating the probability of an accident at the pressure hydraulic facilities of the Kakhovka hydroelectric complex (continuation of the diagram in Fig. 2–7)

Thus, the emergency event A_5 in Fig. 1 is investigated to the level of elementary basic events, the probabilities of which can be determined by methods of parametric and statistical reliability theories.

4. 3. 1. Probability of overflow of the Kakhovka reservoir

A fragment of the failure and fault tree diagram for assessing the probability of overflow of the Kakhovka reservoir (event A_1) is shown in Fig. 2. Table 2 presents the situations in which the emergency event A_1 was predicted and their estimated probabilities. The maximum water flow rate of the Dnieper River in the water site of the Kakhovka hydroelectric complex in the relevant situations and probabilities of exceeding this rate are given in Table 3.

The probability of mechanical equipment failure at the spillway facilities of the hydroelectric complex (spillway dam, HPP structures) was estimated by the formula [14]:

$$P(t+t_r)=1-\exp\{-\lambda\cdot t\cdot\exp(-\mu\cdot t_r)\}, \quad (8)$$

where λ is the failure rate of the facility before the first failure; μ is the repair rate; t_r is the additional time to repair the facility.

Table 2

Situations in which the overflow of the Kakhovka Reservoir was predicted and their probabilities

Situation	Description	Probability, year^{-1}
C_1	Maximum water flow rate of the Dnieper river exceeds 23,200 m^3/s, $Q_{max}\geq Q_{0.01\%}$	10^{-4}
C_2	Maximum water flow rate of the Dnieper river exceeds 21,400 m^3/s but does not exceed 13,260 m^3/s, $Q_{0.014\%}\leq Q_{max}<Q_{0.01\%}$	$4\cdot10^{-5}$
C_3	Maximum water flow rate of the Dnieper river exceeds 20,740 m^3/s but does not exceed 21,400 m^3/s, $Q_{0.016\%}\leq Q_{max}<Q_{0.014\%}$	$2\cdot10^{-5}$
C_4	Maximum water flow rate of the Dnieper river exceeds 20,080 m^3/s but does not exceed 20,740 m^3/s, $Q_{0.018\%}\leq Q_{max}<Q_{0.016\%}$	$2\cdot10^{-5}$

Basic emergency events in which the overflow of the Kakhovka reservoir was predicted and their probabilities are given in Table 4.

Table 3

Probabilities P of exceeding maximum water flow rates Q_{max} of the Dnieper River

P, %	0.01	0.014	0.016	0.018	0.1	1	5	10
Q_{max}, m^3/s	23,200	21,400	20,740	20,080	14,000	9,800	8,000	7,000

The failure rate of the "gate-lifting mechanism" system was taken according to statistical data (for example, [14]): for the "service gate – gantry crane" system at the spillway facilities of the hydroelectric complex λ=2·10^{-3}, year^{-1}; for the "guard gate –bridge crane" system at the HPP λ=10^{-3}, year^{-1}. With a risk margin for all cases of flooding at the hydroelectric complex, the additional time to repair the "gate-lifting mechanism" systems was taken equal to t_r=0. The service life of mechanical equipment for the spillway facilities of the hydroelectric complex, during which at least one operation is expected, was taken equal to 10 years, t=10 years; for the HPP t=1 year.

Table 4

Basic emergency events in which the overflow of the Kakhovka Reservoir was predicted and their probabilities

Event	Description	Probability
$B_{1.1.1}$, ..., $B_{1.1.28}$	Failure of the mechanical equipment of the spillway leading to the impossibility of lifting service gates in case situation C_1	$2 \cdot 10^{-2}$
$B_{1.2.1}$, ..., $B_{1.2.28}$	Failure of the mechanical equipment of the spillway leading to the impossibility of lifting service gates in case situation C_2	$2 \cdot 10^{-2}$
$B_{1.3.1}$, ..., $B_{1.3.28}$	Failure of the mechanical equipment of the spillway leading to the impossibility of lifting service gates in case situation C_3	$2 \cdot 10^{-2}$
$B_{1.4.1}$, ..., $B_{1.4.28}$	Failure of the mechanical equipment of the spillway leading to the impossibility of lifting service gates in case situation C_4	$2 \cdot 10^{-2}$
$B_{2.1.1}$, ..., $B_{2.1.6}$	Failure of the mechanical equipment of the HPP leading to the impossibility of lifting guard gates in case of situation C_1	10^{-3}
$B_{2.2.1}$, ..., $B_{2.2.6}$	Failure of the mechanical equipment of the HPP leading to the impossibility of lifting guard gates in case of situation C_2	10^{-3}
$B_{2.3.1}$, ..., $B_{2.3.6}$	Failure of the mechanical equipment of the HPP leading to the impossibility of lifting guard gates in case of situation C_3	10^{-3}
$B_{2.4.1}$, ..., $B_{2.4.6}$	Failure of the mechanical equipment of the HPP leading to the impossibility of lifting guard gates in case of situation C_4	10^{-3}

4. 3. 2. Taking into account the survivability of hydraulic facilities in emergency situations

When simulating emergency situations at the hydroelectric complex, in particular in case of the reservoir overflow, the survivability of hydraulic facilities was taken into account depending on their type under emergency overloads (survivability coefficients in [16]).

Conditional probabilities of emergency events at pressure hydraulic facilities were estimated as the addition of survivability coefficient k_v to unit.

For earthen hydraulic facilities, k_v=0.63 and, accordingly, the conditional probability of an accident will be 0.37. For concrete hydraulic facilities (spillway dam, HPP structures, lock), the survivability coefficient is k_v=0.39. The conditional probability of an accident will be 0.61 [16].

Among the state events under which the pressure hydraulic facilities of the Kakhovka hydroelectric complex can lose survivability, the following situations were also considered (Table 5):

– for earthen hydraulic facilities – the effect of wind waves, 50 % probability of exceeding (state event C_5);

– for concrete hydraulic facilities – the effect of ice load, 50 % probability of exceeding (state event C_6).

Table 5

Situations in which the loss of survivability of pressure hydraulic facilities of the Kakhovka hydroelectric complex was predicted and their probabilities

Situation	Description	Probability, year^{-1}
C_5	Effect of wind waves, 50 % probability of exceeding	0.5
C_6	Effect of ice load, 50 % probability of exceeding	0.5

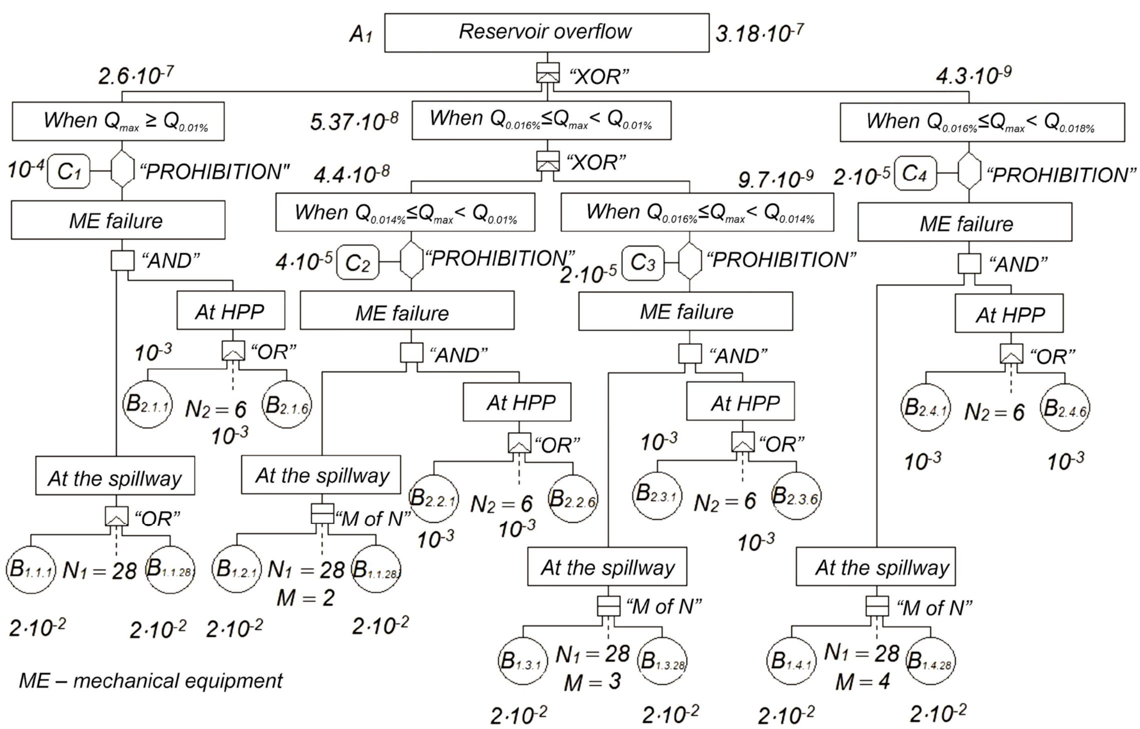

Fig. 2. Fragment of the failure and fault tree diagram for estimating the probability of reservoir overflow of the Kakhovka hydroelectric complex

So, we can conclude that the values of the probabilities of state events C_5, C_6 were taken in accordance with the requirements of current design standards for pressure hydraulic facilities [2].

4. 3. 3. Taking into account the seismic factor

According to the new seismic zoning plans (ZSR-2004 plans [22]), the location of the hydraulic facilities of the Kakhovka hydroelectric complex is referred to the zone of possible earthquakes with the following seismic intensity (in points of the MSK-64 scale):

– 6 – for medium soils with a frequency of once in 1,000 years (ZSR -2004-B plan) or annual probability of exceeding the corresponding seismic event of 10^{-3}, year^{-1};

– 7 – for medium soils with a frequency of once in 5,000 years (ZSR-2004-C plan) or annual probability of exceeding the corresponding seismic event of $2{\cdot}10^{-4}$, year^{-1}. The provision (probability of exceeding) of acceleration a_{max}=0.1 g (for example, [32]) in an earthquake with an intensity of 7 points is 80 %. The provision of the same acceleration in an earthquake with an intensity of 6 points will be 25 %.

For earthquakes with an intensity of 7 points on the MSK-64 scale, the probability $P(I_7)$ was taken equal to the probability of exceeding the corresponding seismic event with a seismic intensity of 7 points: $P(I_7)=2{\cdot}10^{-4}$, year^{-1}. Then for earthquakes with an intensity of 6 points, taking into account the condition of forming a complete group of events, $P(I_6)=8{\cdot}10^{-4}$, year^{-1}.

The total probability that the seismic acceleration of 0.1 g exceeds the safe shutdown earthquake (SSE) taking into account seismic events with a seismic intensity of 6 and 7 points at the site of the hydraulic facilities of the Kakhovka hydroelectric complex will be:

$$P\left(a_{\max} \geq 0{,}1g\right) = \sum_{k=6,7} P\left(a_{\max} \geq 0{,}1g \mid I_k\right) \cdot P\left(I_k\right), \quad (9)$$

where $P(a_{max}{\geq}0.1g|I_k)$ is the probability of exceeding the seismic acceleration $a_{max}=0.1{\cdot}g$ in case of an earthquake with an intensity of k points; g is the acceleration of free fall; $P(I_k)$ is the annual probability of a seismic event with the seismic intensity of k points. We have $P(a_{max}{\geq}0.1g)=3.6{\cdot}10^{-4}$, year^{-1}.

We assume that the upper limit estimate of the probability of the limit state of the first group associated with the violation of the overall strength or stability of the hydraulic structure in SSE, taking into account the load combination factor γ_{lc}=0.9 [2], (with a risk margin) is equal to 0.1.

Calculations of seismic loads for hydraulic facilities are usually carried out at upper water levels close to the normal water level (NWL). Exceeding the NWL for CC-3 class hydraulic facilities (top of surcharge storage) during the designated service life of 100 years is expected no more than once in 10 years (for a flood with the probability of exceeding 0.1 %). Hence, the total probability of exceeding the combined emergency loads under seismic impacts (state event C_7) will be: $P(C_7)=3.6{\cdot}10^{-5}$, year^{-1}.

To determine the annual probability of the state event (situation) C_8, a complete group was formed consisting of event C_8 and events A_1 and C_7.

It was assumed that during the service life of the hydraulic facility T_p=100 years, the total probability of one of the events A_1, C_7 will be:

$$P\left(A_1, C_7, T_p\right) = 1 - \left[1 - P\left(A_1\right) - P\left(C_7\right)\right]^{T_p}. \quad (10)$$

The total probability of the state event C_8 for T_p=100 years will be:

$$P\left(C_8, T_p\right) = 1 - P\left(C_1, T_p\right). \quad (11)$$

The annual probability of the state event C_8, which complements events A_1 and C_7:

$$P\left(C_8\right) = 1 - \left[1 - P\left(C_8, T_p\right)\right]^{\frac{1}{T_p}}. \quad (12)$$

The results of estimating the probabilities of state events (situations) C_7, C_8, related to the seismic factor, are given in Table 6.

Table 6

Situations related to taking into account the seismic factor in which accidents at the pressure hydraulic facilities of the Kakhovka hydroelectric complex were predicted and their probabilities (HWL – highest water level/top of surcharge storage)

Situation	Description	Probability, year^{-1}
C_7	Load with UWL≤HWL and with earthquake intensity ≥ SSE, where HWL – highest water level (top of surcharge storage)	$3.6{\cdot}10^{-5}$
C_8	Load with UWL≤HWL and without earthquake intensity ≥SSE	0.0546

Given the calculated values, the expected service life T_p=100 years was taken in accordance with the requirements of the current design standards [2] as for CC-3 class hydraulic facilities.

4. 3. 4. Forecasting accidents at hydraulic facilities of the hydroelectric complex

Table 7 below shows the basic events at the run-of-river earth dam with which the accident at this facility was predicted and their probabilities. Table 8 shows the situations in which accidents related to the violation of the overall stability and strength of the hydraulic facilities of the Kakhovka hydroelectric complex were predicted and their probabilities. At the same time, UWL≤HWL and seismic impacts with intensity ≥SSE were not considered.

To determine the annual probability of situation (state event) C_{10}, a complete group was formed consisting of events C_9 and C_{10}, where C_9 is the estimated flood with the 0.1 % probability of exceeding.

With the estimated service life of the hydraulic facility T_p=100 years, the total probability of the event C_9 will be:

$$P\left(C_9, T_p\right) = 1 - \left[1 - P\left(C_9\right)\right]^{T_p}. \quad (13)$$

Taking into account the condition of forming a complete group of events, the total probability of the state event C_9 for T_p=100 years will be:

$$P\left(C_{10}, T_p\right) = 1 - P\left(C_9, T_p\right). \quad (14)$$

Giving that, the annual probability of the state event C_{10}, which complements the event C_9, will be:

$$P\left(C_{10}\right) = 1 - \left[1 - P\left(C_9, T_p\right)\right]^{\frac{1}{T_p}}. \quad (15)$$

Fragments of the failure and fault tree for estimating the probability of an accident at the pressure facilities of the hydroelectric complex are shown in Fig. 3–8.

Basic emergency events at the pressure hydraulic facilities of the Kakhovka hydroelectric complex and their probabilities are given in Tables 9–14.

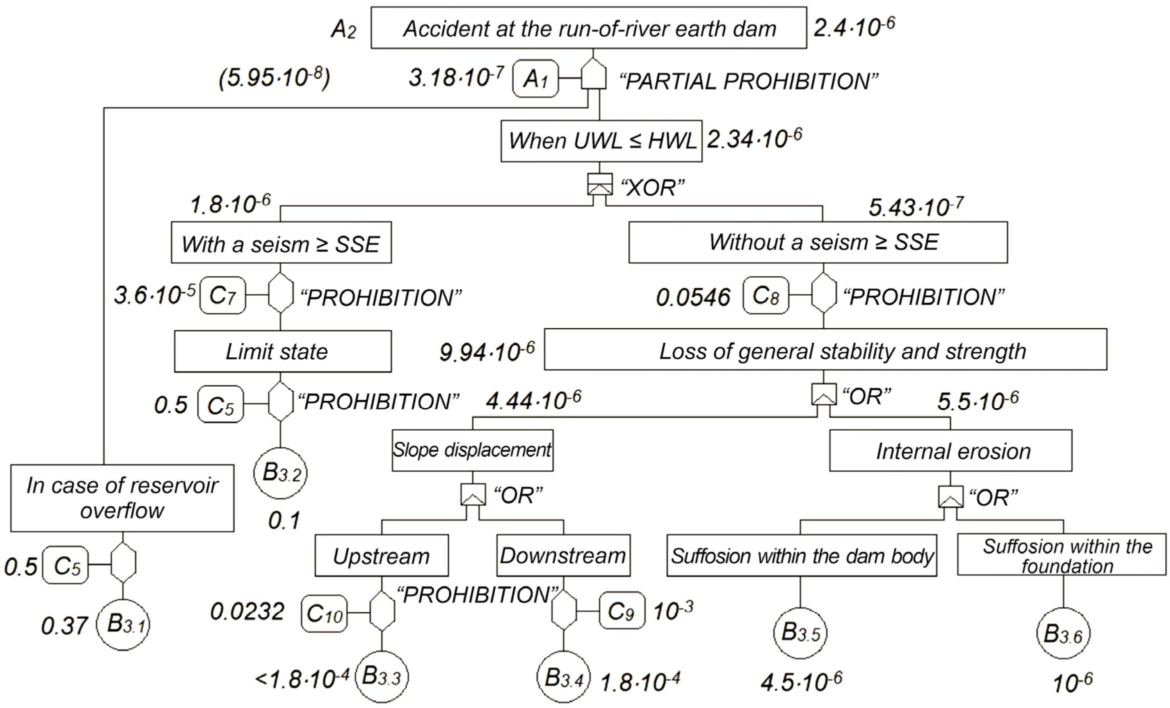

Fig. 3. Fragment of the failure and fault tree for estimating the probability of an accident at the run-of-river earth dam

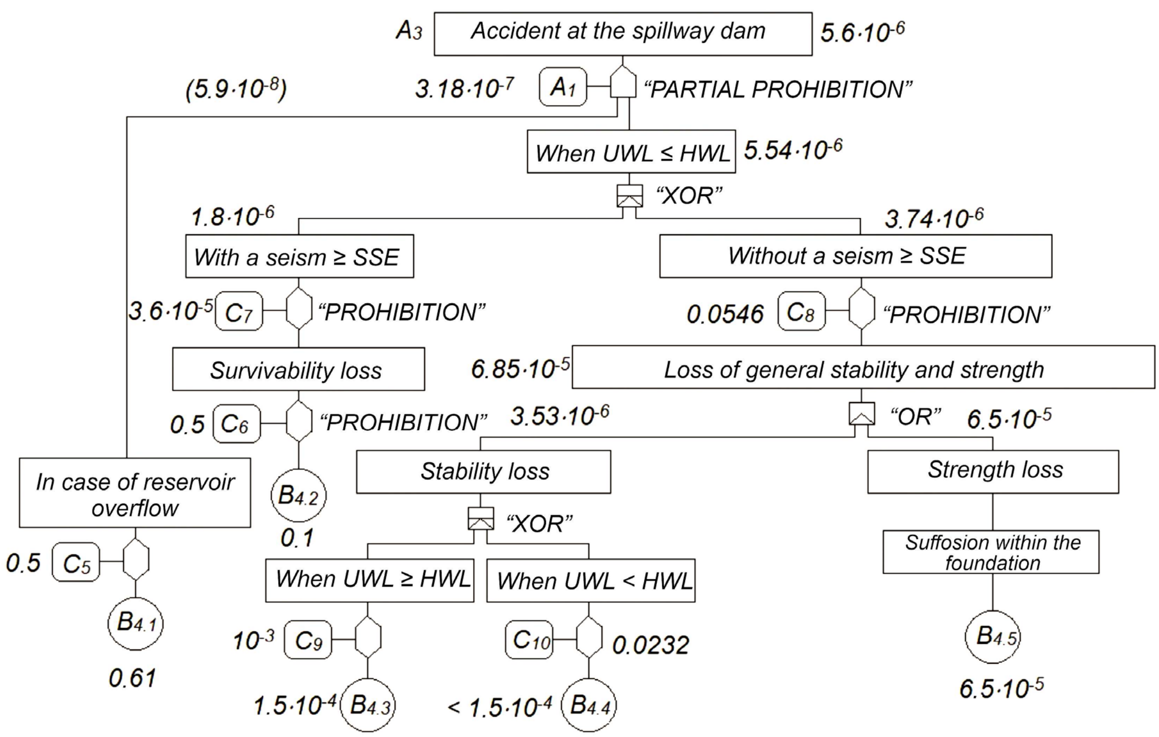

Fig. 4. Fragment of the failure and fault tree for estimating the probability of an accident at the spillway dam

Table 7

Basic emergency events at the run-of-river earth dam of the hydroelectric complex and their probabilities

Event	Description	Probability
$B_{3.1}$	Loss of survivability of the run-of-river earth dam structure	0.37
$B_{3.2}$	Limit state of the run-of-river earth dam structure under seismic effects with intensity ≥ SSE	0.1
$B_{3.3}$	Displacement of the upstream slope of the run-of-river earth dam	$<1.8\cdot10^{-4}$
$B_{3.4}$	Displacement of the downstream slope of the run-of-river earth dam	$1.8\cdot10^{-4}$
$B_{3.5}$	Suffosion within the body of the run-of-river earth dam	$4.5\cdot10^{-6}$
$B_{3.6}$	Suffosion within the foundation of the run-of-river earth dam	10^{-6}

Table 8

Situations in which accidents related to the violation of the overall stability and strength of the hydraulic facilities of the Kakhovka hydroelectric complex with UWL≤HWL and without seismic effects≥SSE were predicted and their probability

Situation	Description	Probability, year^{-1}
C_9	Projected flood with 0.1 % of probability of exceeding	10^{-3}
C_{10}	Water levels in the reservoir≤NWL	0.0232

Table 9

Basic emergency events at the spillway dam and their probabilities

Event	Description	Probability
$B_{4.1}$	Loss of survivability of the concrete spill-way dam structure	0.61
$B_{4.2}$	Limit state of the spillway dam structure under seismic effects≥SSE	0.1
$B_{4.3}$	Loss of stability of the concrete spillway dam with UWL≥NWL	$1.5\cdot10^{-4}$
$B_{4.4}$	Loss of stability of the concrete spillway dam with UWL≤NWL	$<1.5\cdot10^{-4}$
$B_{4.5}$	Loss of filtration strength of the spillway dam foundation	$6.5\cdot10^{-5}$

Table 10

Basic emergency events within HPP structures and their probabilities

Event	Description	Probabil-ity
$B_{5.1}$	Loss of survivability of HPP structures	0.61
$B_{5.2}$	Limit state of HPP structures under seismic effects with intensity≥SSE	0.1
$B_{5.3}$	Loss of stability of HPP structures for UWL≥NWL	$1.1\cdot10^{-4}$
$B_{5.4}$	Loss of stability of HPP structures for UWL≤NWL	$<1.5\cdot10^{-4}$
$B_{5.5}$	Loss of seepage strength of the HPP foun-dation	$6.5\cdot10^{-5}$

Table 11

Basic accidents at the lock and their probabilities

Event	Description	Probability
$B_{6.1}$	Loss of survivability of the lock structure under reservoir overflow	0.61
$B_{6.2}$	Limit state of the lock structure under seismic effects with intensity ≥SSE	0.1
$B_{6.3}$	Destruction of the upper gate of the lock	$5\cdot10^{-3}$
$B_{6.4}$	Destruction of the lower gate of the lock	$5\cdot10^{-3}$

Table 12

Basic accidents at the earth dam between the HPP structures and the lock and their probabilities

Event	Description	Probability
$B_{7.1}$	Loss of survivability of the earth dam structure	0.37
$B_{7.2}$	Limit state of the earth dam structure under seismic effects with intensity≥SSE	0.1
$B_{7.3}$	Displacement of the upstream slope of the earth dam	$<1.8\cdot10^{-4}$
$B_{7.4}$	Displacement of the downstream slope of the earth dam	$1.8\cdot10^{-4}$
$B_{7.5}$	Suffosion within the body of the earth dam	$4.5\cdot10^{-6}$
$B_{7.6}$	Suffosion within the foundation of the earth dam	10^{-6}

Table 13

Basic emergency events at the floodplain earth dam and their probabilities

Event	Description	Probability
$B_{8.1}$	Loss of survivability of the floodplain earth dam structure	0.37
$B_{8.2}$	Limit state of the floodplain earth dam structure under seismic effects with intensity≥SSE	0.1
$B_{8.3}$	Displacement of the upstream slope of the floodplain earth dam	$<7.9\cdot10^{-4}$
$B_{8.4}$	Displacement of the downstream slope of the floodplain earth dam	$7.9\cdot10^{-4}$
$B_{8.5}$	Suffosion within the body of the flood-plain earth dam	$1.55\cdot10^{-6}$
$B_{8.6}$	Suffosion within the foundation of the floodplain earth dam	$1.02\cdot10^{-6}$

Table 14

Basic emergency events at the above floodplain earth dam and their probabilities

Event	Description	Probability
$B_{9.1}$	Loss of survivability of the above flood-plain earth dam structure	0.37
$B_{9.2}$	Limit state of the above floodplain earth dam structure under seismic effects≥SSE	0.1
$B_{9.3}$	Displacement of the upstream slope of the above floodplain earth dam	$<2.13\cdot10^{-3}$
$B_{9.4}$	Displacement of the downstream slope of the above floodplain earth dam	$2.13\cdot10^{-3}$
$B_{9.5}$	Suffosion within the body of the above floodplain earth dam	$1.55\cdot10^{-6}$
$B_{9.6}$	Suffosion within the foundation of the above floodplain earth dam	$1.02\cdot10^{-6}$

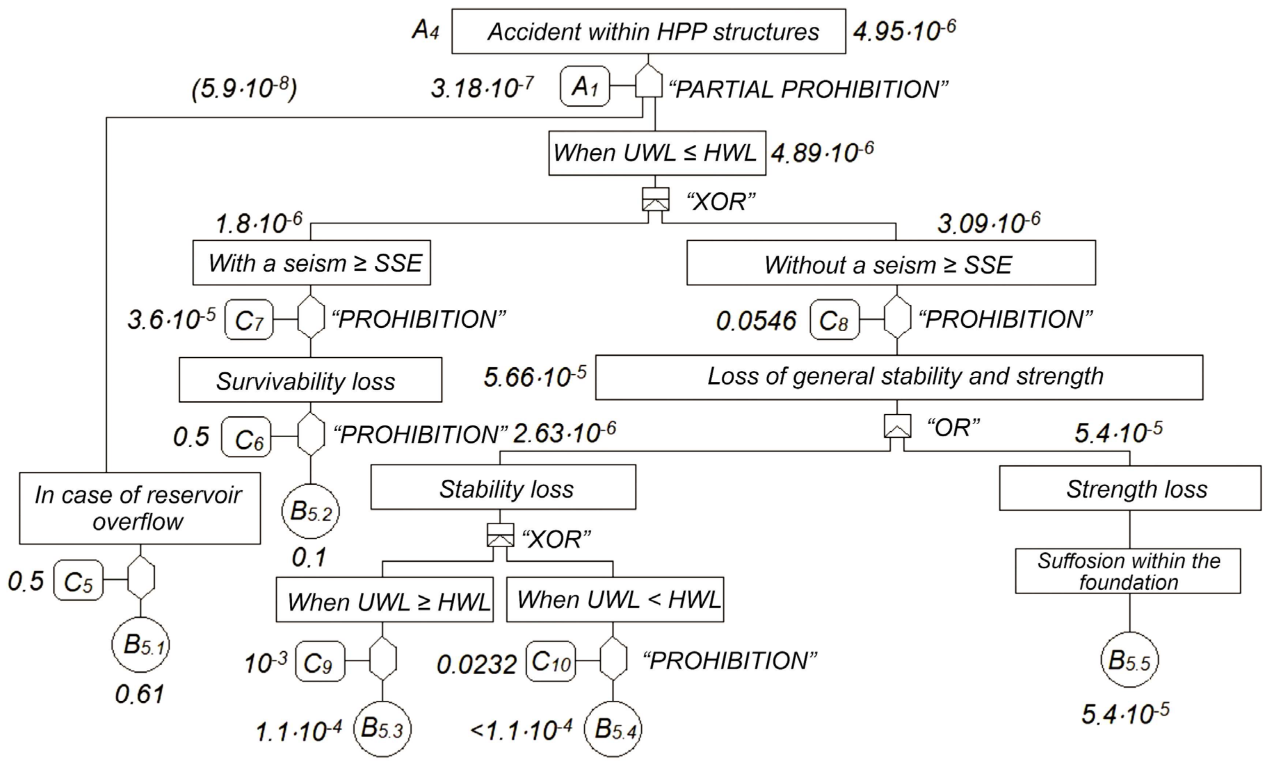

Fig. 5. Fragment of the failure and fault tree for estimating the probability of an accident within the HPP structures

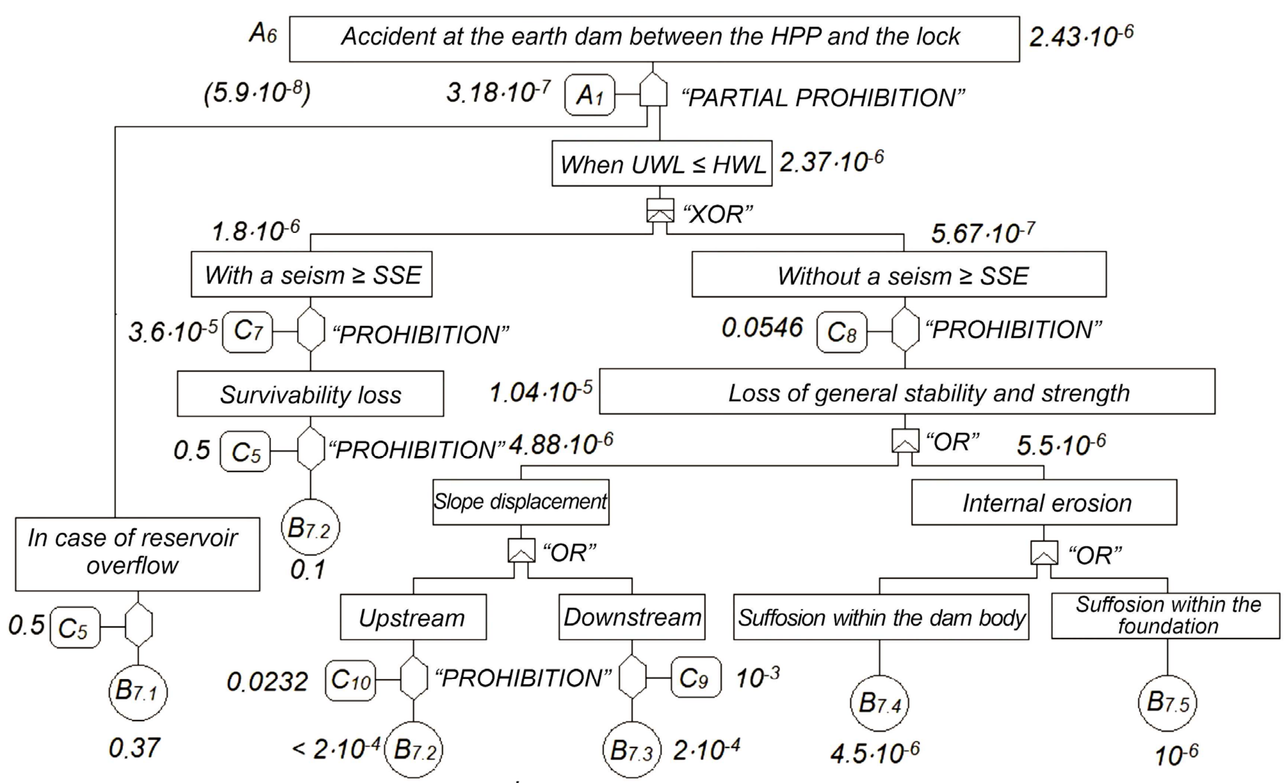

Fig. 6. Fragment of the failure and fault tree for estimating the probability of an accident at the dam between HPP structures and the lock

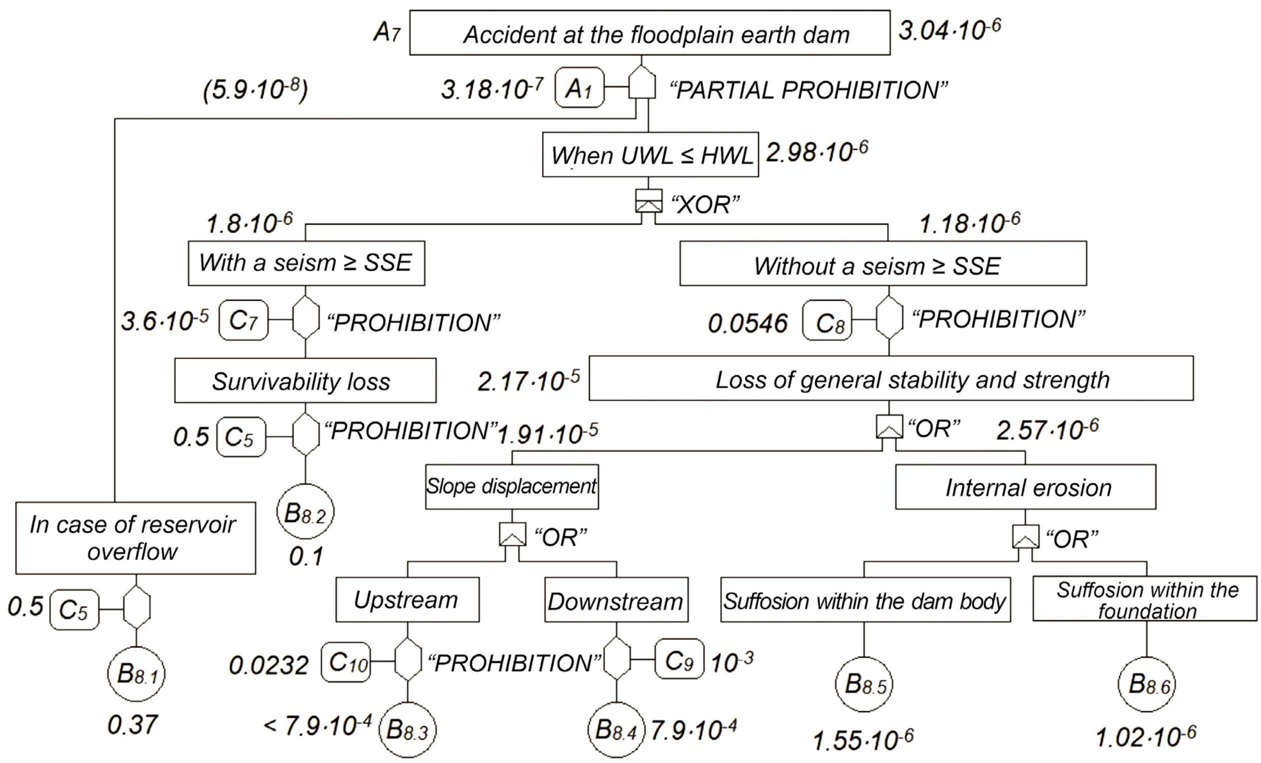

Fig. 7. Fragment of the failure and fault tree for estimating the probability of an accident at the floodplain earth dam

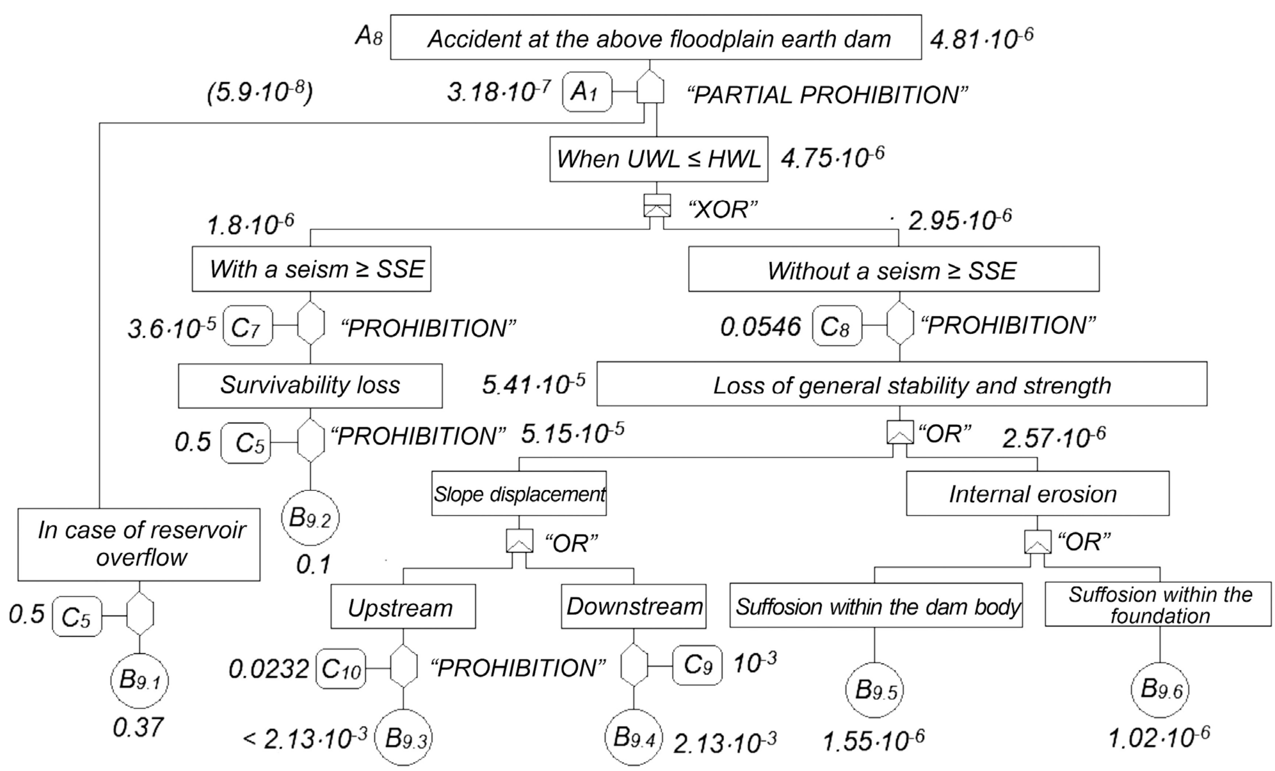

Fig. 8. Fragment of the failure and fault tree for estimating the probability of an accident at the above floodplain earth dam

The results of forecasting accidents at the pressure hydraulic facilities of the Kakhovka hydroelectric complex with the estimation of their probabilities are presented on the diagrams of the failure and fault tree (Fig. 1–8) and are summarized below in Table 15. It was found that the upper limit estimate of the probability of an accident at the pressure hydraulic facilities of the hydroelectric complex, summarized by its various forms, scenarios and structures, does not exceed $2.65 \cdot 10^{-5}$, year^{-1}.

5. Checking the reliability of the pressure hydraulic facilities of the Kakhovka hydroelectric complex in the context of the possibility of constructing the Kakhovka HPP-2

The purpose of checking the reliability of the existing pressure hydraulic facilities of the Kakhovka hydroelectric complex within the probabilistic approach was to determine the possibility of expanding the hydroelectric complex by constructing the Kakhovka HPP-2. The probabilistic approach allows estimating the reliability of both individual hydraulic facilities of the hydroelectric complex and the hydroelectric complex as a whole as a complex system. In addition, the probabilistic approach allows identifying the reliability reserves of the hydroelectric complex that cannot be done using the traditional approach.

The existing pressure hydraulic facilities of the Kakhovka hydroelectric complex were checked for reliability by comparing the estimated values of accident probabilities with their permissible values. Since the pressure hydraulic facilities of the Kakhovka hydroelectric complex belong to the CC-3 consequence class, according to [2] the allowable probability of an accident at these facilities is $[P(A)]=5\cdot10^{-5}$, year^{-1}. The results of checking the reliability of the hydraulic facilities of the Kakhovka hydroelectric complex by the criterion of not exceeding the allowable probability of an accident are given in Table 15.

Table 15

Results of estimating the probabilities of accidents at the pressure hydraulic facilities of the Kakhovka hydroelectric complex with checking their reliability

Hydraulic facility	Estimated value of accident probability $P(A)$, year^{-1}	Permissible value of accident probability $[P(A)]$, year^{-1}	Conclusion on reliability
Run-of-river earth dam	$2.1\cdot10^{-6}$	$5\cdot10^{-5}$	reliable
Spillway dam	$5.6\cdot10^{-6}$	$5\cdot10^{-5}$	reliable
HPP structures	$4.95\cdot10^{-6}$	$5\cdot10^{-5}$	reliable
Lock	$3.26\cdot10^{-6}$	$5\cdot10^{-5}$	reliable
Earth dam between the HPP structures and the lock	$2.43\cdot10^{-6}$	$5\cdot10^{-5}$	reliable
Floodplain earth dam	$3.04\cdot10^{-6}$	$5\cdot10^{-5}$	reliable
Above floodplain earth dam	$4.81\cdot10^{-6}$	$5\cdot10^{-5}$	reliable
Pressure waterfront of the Kakhovka hydroelectric complex as a whole	$2.65\cdot10^{-5}$	$5\cdot10^{-5}$	reliable

It was found that the probabilities of accidents at each of the pressure hydraulic facilities of the hydroelectric complex generalized by different events, as well as the generalized probability of an accident at the hydroelectric complex as a whole, do not exceed the permissible values. At the same time, there is almost a double margin of reliability of the hydroelectric complex, which is likely to be $2.35\cdot10^{-5}$ emergency events per year. Therefore, we can conclude that the pressure hydraulic facilities of the Kakhovka hydroelectric complex are sufficiently reliable, which allows expanding it by constructing another hydroelectric power plant.

6. Discussion of the results of forecasting accidents at the existing hydraulic facilities of the Kakhovka hydroelectric complex

As a result of studies, it was found that the probability of an accident depending on the hydraulic facility of the hydroelectric complex varies from $2.1\cdot10^{-6}$, year $^{-1}$, at the run-of-river earth dam, to $5.6\cdot10^{-6}$, year^{-1}, at the spillway dam. Differences in the values of accident probabilities at different hydraulic facilities of the hydroelectric complex are primarily explained by the functional and structural features of individual facilities. Higher probabilities of accidents at floodplain and above floodplain earth dams in comparison with the run-of-river earth dam can also be explained by the peculiarities of their foundations. Note that the different probabilities of accidents at different hydraulic facilities of the hydroelectric complex indicate their difference in reliability. It would be impossible to detect this within the traditional deterministic approach.

The obtained estimates of the probabilities of accidents at the pressure hydraulic facilities of the Kakhovka hydroelectric complex are the maximum limit estimates (sup). Their excess under the accepted operating modes of hydraulic facilities is currently not expected. This means that the placement of another pressure hydraulic facility as part of the Kakhovka hydroelectric complex is possible. However, when choosing the option of placing a new hydroelectric power plant (Kakhovka HPP-2) within the existing pressure hydraulic facilities, the greater reliability of the run-of-river earth dam should be taken into account. The decision to place a new hydroelectric power plant within the spillway can be considered the least reliable option.

The proposed failure and fault tree can be used to refine the obtained estimates of the probability of accidents at the hydraulic facilities of the Kakhovka hydroelectric complex, taking into account the placement of the hydraulic facility of a new hydroelectric power plant. Thus, an additional accident scenario should be provided in the form of the corresponding branch of the general failure and fault tree. In turn, some fragments of the model of the proposed failure and fault tree can be used in assessing the probability of accidents at hydraulic facilities of other hydroelectric complexes.

Predicting an accident at a hydroelectric complex is a complex "poorly structured" system problem, burdened by various uncertainties – stochastic and epistemological, structural and parametric, etc. The proposed method of forecasting accidents at the hydroelectric complex allows structuring the problem, taking into account the systemic nature of hypothetical accidents at the hydroelectric complex and the impact of various natural and man-made factors on the accident rate of facilities. This takes into account the interaction of different hydraulic facilities in the hydroelectric complex, the role of equipment at the system level. Within the framework of the proposed model, as new information arrives, it is allowed to constantly clarify the probabilities of basic events that can initiate emergency processes and state events under which emergency processes occur.

One of the limitations of the study is the lack of explicit consideration of the aging factor of hydraulic facilities. The existing hydraulic facilities of the hydroelectric complex have been in operation for more than 60 years. This was one of the reasons for estimating the maximum limits (sup) of the probabilities of accidents at the hydraulic facility. With more detailed studies, it is possible to specify the obtained estimates of probabilities of accidents at pressure hydraulic facilities of the hydroelectric complex towards their reduction. In the future, when predicting the probability of an accident at a hydroelectric complex, taking into account the construction of another facility (Kakhovka HPP-2), this shortcoming can be taken into account and eliminated.

The proposed approach offers significant prospects for substantiating and making informed decisions on the reliability and safety of both existing hydraulic facilities and those to be rehabilitated. At the same time, when assessing the impact on the environment, it is possible to justify the feasibility of such decisions taking risks into account. Within the framework of such studies, it is possible to put into practice the concept of practically achievable minimum risk, according to which efforts to reduce the probability of an accident at a hydroelectric complex and increase its reliability and safety can be reconciled with real economic opportunities. Such problems are rather complex intelligent problems, solving which should involve data and knowledge from various subject areas. To some extent, this may deter such research in practice.

7. Conclusions

1. It is shown that forecasting an accident at a hydroelectric complex is a complex "poorly structured" system problem, burdened with various uncertainties – stochastic and epistemological, structural and parametric, etc. The logical-probabilistic method of failure and fault trees is proposed and used. This method allows taking into account the systemic nature of hypothetical accidents at the hydroelectric complex, the impact of various natural and man-made factors on the accident rate of facilities, the interaction of different hydraulic facilities and equipment at the system level.

2. Forecasting of accidents at the pressure hydraulic facilities of the Kakhovka hydroelectric complex on the basis of the probabilistic approach is made. It is found that the probabilities of accidents at each of the pressure hydraulic facilities generalized by different emergency events, as well as the generalized assessment of the probability of an accident at the hydroelectric complex as a whole ($2.35\cdot10^{-5}$, year^{-1}), do not exceed the permissible values regulated by the current standards ($5\cdot10^{-5}$, year^{-1}).

3. The obtained indicators show the possibility of expanding the composition of pressure hydraulic facilities of the hydroelectric complex by constructing the Kakhovka HPP-2 within the existing facilities. In particular, the safest option for placing a new hydraulic facility as part of the existing pressure waterfront can be considered its placement within the run-of-river earth dam. The probability of an accident at this dam is currently the lowest and is $2.1\cdot10^{-6}$, year^{-1} (about 9 % of the probability of an accident at the hydroelectric complex as a whole). The results of forecasting accidents at pressure hydraulic facilities of the Kakhovka hydroelectric complex can be used in the analysis and assessment of the risk of accidents at the hydroelectric complex, taking into account both the probabilities of relevant emergency events and their consequences. This will contribute to a better understanding of the issues of ensuring the proper reliability and safety of the hydroelectric complex as a national critical infrastructure and a potentially hazardous facility, in particular in the context of its expansion through the construction of a new hydropower plant.

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