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DEVELOPING MEASURES FOR ENSURING THE RELIABILITY AND SAFETY OF HYDRAULIC STRUCTURES: A CASE STUDY OF THE "BESHARIQ" WATER KNOT)

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Abstract: Under the influence of the vortex zone formed at the confluence of two channels, sediments intensively settle. Taking these sediments into account, the hydraulic and geometric parameters of the flow are determined. The analytical solution shows that at the confluence of flows, where the secondary channel (Channel 2) joins the main channel (Channel 3), the streamlines bend and contract. This leads to the emergence of a transverse flow. As the flow impacts the left bank of the main channel (Channel 3) and moves toward the right bank, a vortex flow is generated. The resulting vortex flow causes sediment accumulation on the right bank at the inlet section, while the remaining sediments are transported at high velocity in the contraction zone. The high velocity in the contraction section may lead to erosion of the left bank of the main channel (Channel 3). The solution to this issue is explored by varying the angle of channel confluence. During the solution process, the velocity distribution in the channels, as well as the shape and dimensions of the vortex zone, are determined analytically.

Keywords: flow confluence, cavitation, vortex zone, velocity, flow velocity, reflection, complex potential, confluence angle.

Introduction. In the modern world, the sustainable development of economic sectors and the safety of the population heavily depend on the effective operation of water management complexes. Hydraulic structures (HS) are complex engineering facilities that perform strategic tasks such as managing large water resources, power generation, irrigation, and flood control. In the context of global climate change, destabilization of hydrological regimes, and increasing anthropogenic pressure, evaluating the reliability and ensuring the safety of hydraulic structures has become more critical than ever.

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The safety of hydraulic structures refers to the ability of the facility to ensure the protection of human life, health, and legal interests, while safeguarding the environment and economic objects from emergencies. Any accident or malfunction at a major water node can lead to massive economic damage, environmental catastrophe, and loss of human life. Therefore, establishing safety criteria during operation, continuously monitoring their technical condition, and forecasting potential accident scenarios are among the most crucial tasks in water management engineering.

The "Beshariq" water node, located in the Fergana Valley region, plays a vital role in regional agriculture and water supply. Due to its long-term operation and the specific natural and climatic conditions of the region, its technical condition requires systematic and regular analysis. Global experience and statistical data show that over 60% of accidents in earth dams occur due to overtopping of the dam crest and mechanical or chemical suffosion (seepage failures). Hydrological regimes of rivers are shifting, with sudden increases or decreases in water inflows reaching 30–40% globally. Given these hydrological hazards and high seismic activity (earthquakes of magnitude 7 and above), developing scientifically justified measures to increase the reliability of the "Beshariq" water node is highly relevant.

Method. The general principles of reliability theory and methods for evaluating technical systems have been widely studied by numerous domestic and foreign scientists. However, due to the unique characteristics of hydraulic structures—such as their continuous operation over long periods and direct interaction with the natural environment (water, soil, climate, seismicity)—the direct application of general reliability theory is insufficient. Existing scientific literature often evaluates the reliability of separate elements (e.g., gates or concrete sections individually) rather than analyzing the entire water node as a single, complex system that integrates natural and anthropogenic factors. Furthermore, there is a lack of localized studies adapted specifically to the geological and hydrological conditions of the Fergana Valley.

The main objective of this research is to comprehensively assess the factors influencing the operational reliability and safety of the "Beshariq" water node, and to develop a set of scientific and technical measures to guarantee its secure operation.

To achieve this objective, the following tasks have been defined:

Conduct a systematic analysis of existing regulatory, legal, and technical framework requirements for the safety of hydraulic structures;

Classify and evaluate the natural (hydrological, seismic, engineering-geological, climatic) and anthropogenic factors affecting the reliability of the "Beshariq" water node;

Study the development risks of seepage and suffosion processes in the earth dam, and analyze the discharging capacity of water outlet structures;

Model reliability theory states (operable, inoperable, and functioning conditions) across the structural elements of the water node system (intake structure node, settling basin, main canal, etc.);

Formulate practical recommendations to minimize the risk of emergencies and optimize the technical monitoring system at the water node.

The most critical characteristics of a system are its **operable (faultless), inoperable (faulty),** and **functional** states.

When calculating system reliability, an **element** is considered an independent component that possesses an overall reliability indicator. At this stage of the calculations, the reliability of the individual element is assumed to be a known value. Here, as in most literature on reliability theory, the concept of an element is adopted conditionally. For instance, when analyzing the reliability of the **Beshariq water node**, the entire headworks unit, the settling basin, or the main canal can be defined as an element. Conversely, when analyzing the reliability of the headworks unit itself, its constituent structures are treated as elements, and during the analysis of a specific structure, its individual components are considered elements.

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Operable (Faultless) State – A state in which the system fulfills all requirements under standard conditions for all its primary and secondary elements over a given period.

Inoperable (Faulty) State – A state in which the system fails to meet at least one of the operational requirements specified for its primary or secondary elements within a given period. A fault implies the inability of the system to perform its intended functions based on the parameters specified in the technical documentation.

Functional Capacity (Workability) – A state in which the system meets all established requirements at a given moment only in terms of its primary parameters, which characterize the normal execution of designated functions. The operable state inherently encompasses functional capacity.

Defect (Secondary Fault) – A deterioration of the normal state of an item that does not affect (hinder or prevent) the execution of its primary function.

Failure – In reliability theory, this refers to the occurrence of an impermissible limiting state, during which the system partially or completely loses its functional capacity. Failures can vary and may occur during the commissioning period, suddenly, or due to wear and tear.

The primary indicators of system durability are its technical resource and service life.

Technical Resource – The cumulative operating time of a system during its exploitation period up to its breakdown or another limiting state. Essentially, the technical resource represents the actual operating hours of the system throughout its entire service period.

Service Life – The calendar duration of the exploitation period up to a breakdown or another limiting state. The service life of a system is determined based on its purpose, regulatory documents, and other reference data.

Initial Non-failure (Incorruptibility) refers to the system's capacity to avoid impermissible limiting deformations at the beginning of its operating period, during construction, or during testing. This value characterizes the strength, stability, and sudden failure probability of various hydraulic structure elements and designs at the start of their construction and exploitation phases. The required initial non-failure state is ensured by selecting an appropriate margin or safety factor.

Beyond those discussed, several other concepts exist in reliability theory. One of the most effective means of increasing reliability is the introduction of **redundancy.**

Redundancy – A method of increasing object reliability through additional resources or capabilities. It is implemented by activating a designated reserve (either in parallel or after the failure of the primary system) provided during the design or operation of the structure.

There are two methods of redundancy: **global** (redundancy of the entire system) and **individual** (redundancy applied only to specific elements). Redundant elements and systems can be engaged throughout the entire exploitation period or exclusively when the primary components fail. In terms of structural coverage, redundancy is classified into system, group, and element redundancy; in terms of activation, it is divided into continuous and standby (interchangeable) types.

A **reliability criterion** is a dimension or indicator used to evaluate the reliability of various elements and systems. A **reliability characteristic**, on the other hand, is the quantitative value or magnitude of the reliability criterion for a specific system element.

The primary reliability criteria are divided into two main groups: those characterizing the reliability of **non-repairable elements** and those characterizing repairable elements.

Non-repairable Elements (Systems) – Components that cannot be repaired or restored during the execution of their designated functions.

Repairable Elements (Systems) – Components that allow for restoration and repair while performing their designated functions.

Let us first examine the reliability criteria for non-repairable elements.

Development of the "Fault Tree" for the "Beshariq" Water Node

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Evaluating the reliability of irrigation systems is carried out based on the reliability theory of highly complex systems. This, in turn, is implemented by assessing parametric reliability through the construction of "Fault Trees" using the theory of stochastic (random) processes.

Based on systematic field observations and statistical analysis conducted at the "Beshariq" water node, the following fault tree models were developed:

"Fault Tree" for the water intake structures (Table 1).

Table 1. Logical structure of the fault tree for the water intake structure

Failure Code (ID)	**System / Element Level**	**Failure (Risk) Description**	**Logical Connection (Gate)**
G-0	**Top Event**	**Functional failure of the water intake structure (Inability to divert water)**	**"OR" Level**
A-1	1st-level branch	Hydraulic and operational factors	Connects to G-0 via "OR"
A-1.1	Primary element	Severe siltation and sedimentation of the approach channel	Component of A-1
A-1.2	Primary element	Water level dropping below the design minimum indicator	Component of A-1
A-1.3	Primary element	Total blockage of trash racks by floating debris or ice	Component of A-1
B-1	1st-level branch	Technical and mechanical malfunctions	Connects to G-0 via "OR"
B-1.1	Primary element	Mechanical jamming or corrosion of control gates	Component of B-1
B-1.2	Primary element	Failure of lifting mechanisms (hoists, gears, cables)	Component of B-1
B-1.3	Primary element	Power outage or failure in the main electrical supply line	Component of B-1
C-1	1st-level branch	Structural and engineering-geological degradation	Connects to G-0 via "OR"
C-1.1	Primary element	Piping or cavity formation beneath foundation (suffosion)	Component of C-1
C-1.2	Primary element	Critical cracks in concrete structures due to seismic loads	Component of C-1

When the structure is equipped with a **SCADA** system, all regulators are outfitted with position sensors, as well as upstream and downstream water level sensors.

In automatic mode, the system:

Maintains the regulators according to the designated water horizon level;

Displays all data received from the sensors on mnemonic diagrams;

Provides emergency protection (gate jamming, exceeding maximum levels, power outages, unauthorized opening of electrical panels, etc.).

To control the structure within the SCADA system, the following components are required:

Computers;

Programmable logic controllers (PLCs);

Input and output (I/O) modules;

Water level sensors and gate position sensors;

Data transmission systems.

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For water level monitoring, Prosonic FMU230E (4-20 mA) ultrasonic sensors (Figures 1 and 2) are utilized. Any potential errors in the device are corrected using an integrated temperature sensor. The instruction manual for the device is provided along with the equipment.

Figure 1. Water level sensor.

Figure 2. Installation of the water level sensor.

Result. In the comprehensive assessment of the technical condition and safety of the structures at the "Besharik" hydrosystem, the factors affecting its safety were evaluated. Furthermore, the overall safety of the structures was assessed, alongside preparations for localizing and mitigating the consequences of potential emergency situations at the "Besharik" hydrosystem.

In assessing the impacts on the safety of the "Besharik" hydrosystem, the following aspects were analyzed:

Changes in maximum water discharges resulting from updates in regulatory standards and modifications in the analyzed historical time series (periods);

Re-determination of the structural classification based on the assessment of the hydraulic structure's (HTS) risk category;

Clarification of the physical-mechanical and filtration properties of the soils in the dam body and its foundation, incorporating regulatory changes and monitoring data collected during the construction and operational phases;

Evaluation of the operational performance of mechanical and electrical equipment;

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Assessment of potential accident scenarios likely to occur under current operational conditions, including the evaluation of post-accident structural conditions after restoration works are completed;

Analysis and development of relevant recommendations regarding the preparedness for localizing and eliminating the consequences of emergency situations at the "Besharik" hydrosystem within this chapter.

Conclusion

Safety Definition: Hydraulic structure safety is defined as its ability to protect human life, health, legal interests, the environment, and economic assets.

Risk Factors: The reliability of hydraulic structures (HTS) depends on three main groups of factors: natural, anthropogenic, and resource-use limiting constraints.

Natural Threats: Key natural hazards include changing river hydrological regimes, seismic activities (shocks of 7+ magnitude), geotechnical foundations, and harsh climate impacts.

Failure Vectors: Statistics show that 60% of earth dam failures result from overtopping due to inadequate spillway capacity, while another 60% of dam incidents are triggered by mechanical piping (internal erosion).

Secondary Hazards: Siltation, dynamic seismic loads (accounting for 4% of earth structure accidents), concrete cracking, wave action, and chemical corrosion heavily degrade structural safety.

System States: Operational reliability is strictly classified into healthy state (normal operation), faulty state (failure to meet any technical criteria), and functional capability.

Mitigation Priority: Preventing catastrophic failures at the Besharik hydrosystem requires continuous monitoring, timely repair of anti-seepage/drainage devices, and routine maintenance of mechanical equipment and gates.

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