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ANALYSIS OF EXPERIMENTAL STUDIES ON METHODS FOR PROTECTING POPULATIONS AND TERRITORIES FROM HYDRODYNAMIC ACCIDENTS

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Abstract. This article presents an analysis of experimental studies aimed at reducing potential damage to the population and territories resulting from hydrodynamic accidents. The main parameters of the flood wave generated by accidents involving dams, reservoirs, and other hydraulic structures are investigated, including water flow velocity and depth, propagation time, and the affected area. The study also examines the assessment of the effectiveness of protective measures through physical modeling of hydrodynamic accidents under laboratory conditions. Based on the research findings, proposals have been developed for the early identification of hazardous areas, population evacuation, the placement of engineering protective structures, and the improvement of emergency warning systems.
Keywords: hydrodynamic accident, reservoir, dam, flood wave, experimental study, physical modeling, hazardous area, evacuation, population protection, engineering protection.

Introduction. Ensuring the safe operation of large reservoirs, dams, and other hydraulic structures is currently one of the key areas within the system for protecting the population and territories from emergencies. Accidents that may occur at hydraulic structures can result in the uncontrolled release of large volumes of water within a short period of time, posing a serious threat to populated areas, industrial facilities, transport infrastructure, and engineering utilities.

The Law of the Republic of Uzbekistan “On the Safety of Hydraulic Structures” places particular emphasis on ensuring the safety of hydraulic structures, monitoring their technical condition, and preventing the risk of accidents [1]. In addition, a number of organizational and legal measures are being implemented in the country to develop the water management system and improve the safe operation of water facilities and hydraulic structures [6–8].

A distinctive feature of hydrodynamic accidents is their extremely rapid development and the spread of hazardous factors over large areas. In particular, the parameters of a flood wave generated by the complete or partial failure of a dam or dike determine the scale of accident consequences. The main hazard indicators include water flow velocity, water depth, propagation velocity of the wave front, and duration of flooding.

Therefore, experimental investigation of the development patterns of hydrodynamic accidents, assessment of flooding processes, identification of hazardous zones, and improvement of methods for the timely protection of the population are among the most relevant scientific issues. In assessing the safety of hydraulic structures, it is essential to conduct a comprehensive analysis of their structural characteristics, operating conditions, and potential accident scenarios [3, 5].

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The main risk factors leading to hydrodynamic accidents, the processes associated with their development, and the corresponding countermeasures are presented in Table 1.

Table 1

Main Risk Factors of Hydrodynamic Accidents and Corresponding Countermeasures

No.	Risk factor	Process leading to an accident	Main countermeasure
1	Extreme precipitation	Excessive filling of the reservoir	Hydrological forecasting
2	Defect in the spillway system	Overtopping of the dam	Regular technical inspection
3	Seepage	Internal erosion	Piezometric monitoring
4	Cracks	Water penetration into the structure	Deformation monitoring
5	Foundation settlement	Redistribution of stresses within the structure	Geodetic monitoring
6	Geological instability	Landslide or foundation failure	Geological monitoring
7	Earthquake	Dynamic deformation	Seismic assessment
8	Human factor	Improper operation or management	Automation and operational regulations
9	Deterioration	Reduced reliability of materials and equipment	Reconstruction
10	Delayed information	Late detection of hazardous conditions	Real-time monitoring

The main objective of the research is to analyze experimental studies conducted on methods for protecting the population and territories from hydrodynamic accidents and, based on their results, to develop scientific approaches aimed at improving protective measures.

To achieve this objective, the following tasks were defined:

to analyze the factors contributing to the occurrence of hydrodynamic accidents;

to study the formation of flood waves resulting from the failure of dams and dikes;

to evaluate the results of experimental studies conducted using laboratory experiments and modeling;

to determine the influence of flood-wave parameters on the level of hazard;

to analyze existing methods for protecting the population and territories;

to assess the effectiveness of monitoring, forecasting, and early-warning systems.

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Theoretical analysis, laboratory experiments, mathematical modeling, and computational experiments play an important role in the investigation of hydrodynamic accidents. The integration of these methods makes it possible to conduct a comprehensive assessment of accident risks when evaluating the condition and ensuring the safety of hydraulic structures [3, 5].

Experimental studies employ scaled models of hydraulic structures or their individual components. In such models, dam-breach parameters are varied and the characteristics of the resulting water flow are observed. In particular, parameters such as water level, flow velocity, flood depth, and wave propagation time are measured.

In assessing hydrodynamic processes, the variation of water level as a function of time and distance can generally be expressed as follows:

$$H = f(t, x)$$

where:

H – water level or flood depth;

t – time;

x – wave propagation distance.

The propagation of a flood wave is influenced by the size of the breach in the structure, the volume of water in the reservoir, the water level, the terrain, and the characteristics of the ground surface. These factors must be taken into account in the design and operation of hydraulic structures [5].

Experimental studies demonstrate that an increase in the size of a dam breach results in an increase in water discharge and flow energy. Consequently, the hazardous area expands and the time required for the flood wave to reach populated areas decreases.

When a hydrodynamic accident occurs, the main hazardous factors affecting the population and territories include:

high-speed propagation of the flood wave;

rapid inundation of the territory;

dynamic impact of water flow on buildings and structures;

failure of transport and engineering utility systems;

limited opportunities for evacuating the population to safe areas;

occurrence of secondary emergencies.

Experimental studies have established that the degree of damage caused by water flow is closely related to its velocity and depth. As the flow velocity increases, its dynamic impact on buildings, engineering structures, and other facilities also increases.

The dynamic pressure of water flow can generally be expressed by the following formula:

$$Pd = \rho V^2 / 2$$

where:

P_d – dynamic pressure of the flow;

ρ – density of water;

V – water flow velocity.

This relationship demonstrates that an increase in water flow velocity significantly intensifies its dynamic impact. Therefore, flow velocity is regarded as an important parameter in hydrodynamic risk assessment.

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The results of the experimental studies conducted and analyzed demonstrate the importance of several key factors in assessing the consequences of hydrodynamic accidents.

The first factor is the dam-breach parameters. An increase in breach width and depth increases water discharge and leads to more rapid formation of the flood wave.

The second factor is the volume of water upstream of the hydraulic structure. The greater the volume of water, the larger the potentially inundated area resulting from an accident.

The third factor is the terrain. In flat areas, a flood wave may propagate over considerable distances. In areas with steeper slopes, however, the probability of increased water-flow velocity and stronger dynamic impacts becomes higher.

The fourth important factor is the proximity of populated areas to the hydraulic structure. Since the arrival time of a flood wave is shorter in areas located close to the structure, early-warning and evacuation systems are of critical importance. From this perspective, advance assessment of accident risks and the development of population protection plans are essential [1, 3].

Based on experimental studies, flood-risk areas can conventionally be divided into three zones.

Table 2

Zoning of Areas According to Flood Risk

Zone	Main characteristic	Protective measure
High-risk zone	Flooding may occur rapidly and with high intensity	Immediate warning and rapid evacuation
Medium-risk zone	The time to flooding is relatively longer	Phased evacuation and preparedness measures
Low-risk zone	The impact of flooding is relatively limited	Monitoring and public warning

This approach makes it possible to plan protective measures according to the actual level of risk in a particular area.

Based on the analysis of experimental studies, measures for protection against hydrodynamic accidents can be divided into the following main areas.

Regular monitoring of the technical condition of hydraulic structures is essential for the early detection of accident risks. During monitoring, water level, pressure, structural deformation, seepage or moisture conditions, and other technical parameters are controlled.

Technical monitoring and regular assessment of the condition of hydraulic structures constitute important components of the applicable safety requirements [1, 7]. The use of modern digital sensors makes it possible to receive and analyze data in real time.

Based on experimental data and mathematical models, potential scenarios for accident development can be assessed in advance. This makes it possible to identify hazardous areas and develop population protection plans beforehand.

The application of forecasting and modern management methods is one of the important areas in the development and management of the water management system [6, 8].

Rapid and accurate communication of hazard information to the population is one of the fundamental conditions for ensuring public safety. For this purpose, the integrated use of sirens, mobile communications, notification systems, and other information channels is advisable.

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The effectiveness of early-warning systems primarily depends on the timely detection of hazardous processes and rapid processing of monitoring data. Therefore, the development of real-time monitoring and automated information-exchange systems is of particular importance.

The arrival time of a flood wave determined through experimental studies represents essential baseline information for the development of evacuation plans. Safe evacuation routes, assembly points, and procedures for movement should be determined in advance for each hazardous area.

When planning measures for the protection of the population under hydrodynamic hazard conditions, the specific characteristics of the territory, the probability of flooding, and potential accident-development scenarios must be taken into account [3, 4].

In areas with a high risk of flooding, protective dikes, water-diversion structures, and other engineering solutions may be used. The effectiveness of such measures should be evaluated through experimental and computational studies.

In the design and operation of hydraulic structures, the reliability of structural solutions, resistance to water flow, and operating conditions are of significant importance [5].

Today, digital technologies are becoming increasingly important in preventing hydrodynamic accidents and mitigating their consequences. Geographic information systems (GIS), remote sensing, automated monitoring sensors, and mathematical modeling tools make it possible to comprehensively assess hazardous processes.

The analyzed experimental studies demonstrate that mitigation of the consequences of hydrodynamic accidents cannot be limited to a single protection method. An effective protection system should be developed through the integration of technical monitoring, mathematical forecasting, hazardous-area assessment, rapid public warning, and evacuation measures.

Based on the research results, it is advisable to take dynamic parameters into account alongside static data when assessing hydrodynamic risk. In particular, information on the real-time movement of flood waves, changes in water levels, and flow velocity improves the effectiveness of the decision-making process.

Furthermore, integrating the results of experimental modeling with digital models makes it possible to assess various hydrodynamic accident scenarios and develop appropriate protective measures for each territory.

Conclusions and Recommendations

Based on the analysis of experimental studies on methods for protecting the population and territories from hydrodynamic accidents, the following conclusions were reached:

The scale of the consequences of hydrodynamic accidents is directly dependent on the parameters of dam or dike failure, water volume, terrain characteristics, and flood-wave parameters.

Experimental studies have demonstrated that flood depth, flow velocity, and wave propagation time are the main indicators for assessing the level of hazard.

Zoning hazardous areas on the basis of predicted flood-wave parameters makes it possible to plan targeted measures for protecting the population.

Automated monitoring of hydraulic structures plays an important role in the early detection of accident risks and mitigation of adverse consequences [1, 7].

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Integrating the results of experimental studies with mathematical and digital modeling makes it possible to assess hydrodynamic accident-development scenarios with a high degree of accuracy.

The integrated application of technical, organizational, and digital solutions in ensuring the safety of hydraulic structures is an essential prerequisite for reducing accident risks and limiting their consequences [1, 6–8].

Consequently, the integration of experimental research, mathematical modeling, real-time monitoring, and operational management systems into a unified information and decision-support platform can be regarded as a promising scientific and practical direction for improving the system of protecting the population and territories from hydrodynamic accidents.

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