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Design and optimisation of automated hydraulic gate control systems for flood control

Abstract. The study was conducted to analyse the design and optimisation of automated hydraulic gate control systems for effective flood control. It used data analysis from water level sensors, modelling of hydraulic systems, and control algorithms to automate the monitoring of hydraulic locks. As a result of the study, key aspects that confirm the importance of automation of hydraulic gate control for effective flood control were identified. It was established that the introduction of radiofrequency and ultrasonic sensors for water level monitoring provided a high level of data accuracy, which allowed responding in a timely manner to rising water levels. Adaptive control algorithms allowed optimising the operation of gates in dynamic conditions, considering changes in hydrodynamic characteristics. In addition, analysis of gate stability showed that the use of modern materials, such as high-strength steels and composites, substantially increased their durability and corrosion resistance. This was an important factor in ensuring the reliable operation of structures in extreme conditions. The examined models of the dynamic behaviour of gates identified critical zones that are subject to special attention during design since they can be destroyed under the influence of hydrodynamic forces. Overall, the results of the study highlighted the importance of integrating modern technologies into the design of hydraulic systems to improve their functionality and reliability in flood-risk situations. The influence of vibrations and resonant phenomena on the gate structures was analysed, which allowed identifying possible risks for their stability in flood conditions. As a result, recommendations for gate design included structural improvements that help reduce dynamic loads and improve their ability to withstand extreme hydrodynamic conditions

Keywords: water level sensors; algorithms; hydrodynamic pressure; weather forecasting; dynamic behaviour

INTRODUCTION

The relevance of research on automated hydraulic gate control systems for flood control is growing due to climate change and an increase in the frequency of extreme weather events. Floods, which can cause substantial damage to infrastructure, residential areas, and ecosystems, require rapid and accurate responses to reduce negative impacts. Modern automation technologies, in particular, the use of water level sensors, actuators, and control algorithms, provide the possibility of timely adjustment of the operation of hydraulic valves. This not only increases their efficiency in their work but also reduces the risk of accidents, which can be critical in a crisis environment. In the context of the growing challenges associated with global warming, research in this area is becoming urgent to ensure public

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safety and protect the environment. Thus, the analysis and optimisation of such systems are important steps towards improving water management.

In the field of automated hydraulic gate control systems under study, the problem of flood response efficiency is urgent. M. Krichen *et al.* (2024) investigated the introduction of the latest water level sensors to improve the accuracy of flood monitoring. Their results showed that the use of such technologies allowed for a quick response to changes in the water level and reduced the risk of accidents. Y. Song *et al.* (2022) focused on adaptive control algorithms that optimised the operation of hydraulic valves under variable loads. They determined that such algorithms substantially improved the effectiveness of crisis management. D. Bazarov *et al.* (2022) examined the mechanical characteristics of gates and their resistance to hydrodynamic pressure in extreme weather conditions. Their study confirmed that properly designed structures were able to withstand substantial loads without losing functionality. B. Li *et al.* (2022) developed dynamic modelling methods for predicting the behaviour of control systems in real-world conditions. This allowed identifying potential problems and optimising the gate design to improve their performance. F. Piadeh *et al.* (2022) investigated the effect of integrating weather forecasting systems on the efficiency of hydraulic system management. They established that timely information about possible floods substantially increased the level of preparedness and reduced negative consequences.

Y. Hassani & S.M.H. Shahdany (2021) analysed the economic feasibility of implementing automated systems in comparison with traditional methods. Their results showed substantial savings in funds and resources as a result of automating management processes. J. Skowrońska *et al.* (2021) emphasised the importance of choosing corrosion-resistant materials to improve the durability of gates. In their paper, it was noted that the use of such materials could substantially reduce maintenance costs. Q. Zhang *et al.* (2021) considered various approaches to monitoring hydraulic systems in real-time. They noted that modern technologies have substantially improved the quality of data collection and analysis. H. Zhang *et al.* (2022) investigated methods for increasing the resistance of hydraulic valves to changes in the water level. The results of their study proved that improved structures were able to provide reliable protection even during severe floods. L. Cea & P. Costabile (2022) examined the impact of climate change on flood frequency and intensity, which emphasised the importance of management automation. Their results showed the need to adapt existing systems to new environmental challenges. However, there are gaps that require further study, in particular, insufficient attention to the integration of weather forecasting systems and cost analysis for the implementation of such systems, which limits their widespread use in real-world conditions.

The purpose of the study was to identify and evaluate possible ways to optimise the operation of automated hydraulic gate control systems in flood conditions, aimed at improving their efficiency and reliability. Objectives of the study:

1. Learn how to automate hydraulic gates to improve their efficiency during floods.

2. Investigate the influence of modern water level sensors on the accuracy of monitoring.

3. Consider the various technologies used to automate management processes.

MATERIALS AND METHODS

The study analysed the design and optimisation of automated control systems for hydraulic locks, which are critical for ensuring the safety of water structures during extreme weather conditions. The analysis was conducted in the context of hydraulic system management, in particular, in flood risk conditions. For this purpose, various types of sensors that provide accurate and timely monitoring of the water level were considered. Among the most common types of water level sensors were radiofrequency, ultrasonic, and strain gauges.

The study also focused on collecting data from these sensors, enabling real-time water level monitoring systems. The data received from the sensors was transmitted to a central controller or server, where it was processed and analysed. The use of special software, such as Supervisory Control and Data Acquisition (SCADA), allowed visualising information in the form of tables, which simplified monitoring, and decision-making. The study also considered various execution mechanisms used in automated hydraulic lock control systems. It was analysed that electrical, hydraulic, and pneumatic mechanisms are the most common automation options. Each of these types has its own advantages and disadvantages, and specific applications. An important aspect of automated hydraulic lock monitoring systems was the effective interaction between water level sensors and actuators. The sensors provided water level data, which was then analysed by the control system. Based on the data obtained, the actuators automatically adjusted the position of the locks to prevent overflow or ensure optimal water balance. The development of control algorithms based on sensor data, which are a necessary condition for the effective operation of such systems, was also investigated. These algorithms not only determine how valves should respond to changes in water levels but also optimise the overall operation of hydraulic systems, especially under high loads. Algorithms may vary depending on the complexity of the system and the requirements for its operation. The simplest algorithms are "threshold" algorithms that activate the closing or opening of locks when certain water levels are reached.

The study also focused on evaluating the stability of hydraulic structures in extreme conditions, such as heavy rains or rapid snowmelt. Analysis of hydrodynamic forces that occur during floods helped to identify possible problems in the structure and make adjustments to its design. Various sources of information, including scientific and technical literature, technical documentation, data on real systems and experimental results, were used to provide a comprehensive analysis of automated hydraulic gateway control systems. This included scientific and technical literature on the design and optimisation of automated hydraulic gate control systems (Desnanjaya & Nugraha, 2021; Bai *et al.*, 2021; Vignesh *et al.*, 2024). The papers devoted to both general aspects of automation in extreme weather conditions and special methods of controlling hydraulic structures were analysed. Technical documentation for various types of sensors (radiofrequency, ultrasonic, strain gauge) used for monitoring the water level in automated systems (Júnior *et al.*, 2021; Delgado *et al.*, 2021; Pramanik *et al.*, 2022) was also considered. This allowed examining their technical characteristics, efficiency, and adaptability in different environments.

Data on real automated control systems for hydraulic locks are collected on the basis of implemented projects on water bodies where modern technologies are used for flood control (Quaranta *et al.*, 2023; Pan *et al.*, 2023). This allowed evaluating the effectiveness of existing solutions and proposing new optimisation approaches; experimental and simulation data obtained during testing of control algorithms and hydrodynamic models (Farajvand *et al.*, 2021; Lei *et al.*, 2022). This data helped analyse how different types of mechanisms and sensors respond to changes in water levels during floods. This information base provided a comprehensive approach to the study of automated hydraulic lock control systems, considering both theoretical and practical aspects.

RESULTS

The design and optimisation of automated hydraulic gate control systems for flood control is a critical area for ensuring the safety and efficiency of water structures during extreme weather conditions. This allows quickly responding to rising water levels and controlling flood flows to protect settlements and territories. Managing hydraulic systems, especially in flood-risk environments, requires accurate and timely monitoring of water levels. For this purpose, various types of sensors are used, which provide the necessary information for decision-making. Among the most common types of water level sensors are radiofrequency, ultrasonic, and strain gauge (Quaranta *et al.*, 2023; Pan *et al.*, 2023).

Radiofrequency sensors operate on the basis of the principle of radio frequency identification. They typically use radio waves to measure the distance to the surface of water. This method is characterised by high accuracy and speed. Radiofrequency sensors have no moving parts, which ensures their reliability in conditions of high humidity and pollution. However, their effectiveness may be reduced due to signal reflection from objects on the water surface or interference in the environment. Ultrasonic sensors are one of the most common devices for measuring water levels. They emit ultrasonic waves that bounce off the surface of the water and return to the sensor. The time required to return the signal is used to calculate the distance to the water surface. Ultrasonic sensors provide high accuracy and can be used in a variety of environments. However, they can also be sensitive to external conditions such as air temperature, humidity, and the presence of particles in the air (Fernández-Nóvoa *et al.*, 2024).

Strain gauges, also known as hydrostatic sensors, measure water pressure at a certain depth. They are installed at the bottom of the reservoir and respond to changes in the water level by measuring the pressure created by the water column. This type of sensor is highly sensitive and accurate but requires regular maintenance and calibration. Strain gauges are particularly useful in cases where monitoring the water level at great depths is needed (Júnior *et al.*, 2021; Delgado *et al.*, 2021; Pramanik *et al.*, 2022). By collecting data from these sensors, water level monitoring systems can operate in real-time (Table 1). Data received from sensors are transmitted to a central controller or server, where they are processed and analysed. The use of special software allows visualising information in the form of graphs or tables, which facilitates monitoring and decision-making.

Table 1. Sensor parameters for water level monitoring

Sensor type	Measuring range (m)	Accuracy (%)	Response time (s)
Radiofrequency	0-10	1.5	0.5
Ultrasonic	0-15	1	0.3
Strain gauge	0-20	0.5	0.1

Source: compiled by the authors based on M.A. Rahu *et al.* (2022)

Data acquisition systems can be integrated with automatic hydraulic gate control systems. This allows quickly responding to changes in the water level, which is extremely important for flood prevention. In addition, modern technologies allow implementing remote monitoring, which provides convenience and efficiency of management. The use of various types of water level sensors, data collection, and processing systems, is a critical element in the management of hydraulic systems. This not only improves the accuracy of monitoring but also provides a timely response to flood risks, which in turn contributes to improving public safety and environmental protection. Automation of hydraulic gate control in flood control systems requires the use of efficient actuators. They provide automatic adjustment of the gate position according to data obtained from water level sensors (Akiyanova *et al.*, 2023). Among the most common mechanisms are electric, hydraulic, and pneumatic. Each of these types has its own advantages and disadvantages, and specific applications.

Electric actuators are one of the most common automation options. They operate on the basis of an electric drive that activates the gate mechanism. This type of mechanism has a number of advantages, in particular, high control accuracy and speed of response. Electrical mechanisms are easily integrated into automatic control systems, making them ideal for use in environments where a fast and accurate response to changes in water levels is required. However, electrical mechanisms may have limitations in conditions of high humidity or extreme temperatures. In addition, their effectiveness may decrease under high loads or in case of mechanical damage. Therefore, for critical systems, such as floodgate control, electrical mechanisms can be supplemented with other types.

Hydraulic actuators use fluid pressure to control the position of the gate valves. They are characterised by high strength and the ability to withstand heavy loads, making them ideal for use in environments where substantial power is required. Hydraulic systems also ensure smooth operation, which is important for precise adjustment. However, hydraulic mechanisms require complex support systems, in particular, pumps and tanks, and regular maintenance to prevent fluid leakage and component wear (Fakher *et al.*, 2021). On the other hand, their ability to operate in extreme environments makes them valuable in systems where electrical mechanisms may be inefficient.

Pneumatic actuators use compressed air to adjust the gate valves. They respond quickly to changes in the system and can be lightweight and compact, making them convenient for use in confined spaces. Pneumatic systems can also be relatively easy to maintain and do not require complex fluid systems, which reduces the risk of leaks. However, pneumatic mechanisms are usually less powerful than their hydraulic counterparts and may be less efficient under high-pressure conditions. They can also be sensitive to changes in temperature and humidity, which can affect their performance. A key element of the automated hydraulic gate control system is the effective interaction between water level sensors and actuators. The sensors provide water level data, which is then analysed by the control system. Based on the data obtained, the actuators automatically adjust the position of the gate valves to prevent overflow or ensure optimal water balance (Desnanjaya & Nugraha, 2021; Bai *et al.*, 2021; Vignesh *et al.*, 2024).

The systems can be configured for different operating modes depending on the conditions, for example, if the water level rises to critical levels. In such situations, the actuators can immediately close the shutters to prevent flooding, providing a quick response to changing conditions. The choice of the type of actuator and its integration with sensor systems is critical to ensuring the efficiency of automated hydraulic gate control systems. The ability of these systems to respond quickly to changes in the environment is key to successful flood control and reducing risks to the population and infrastructure. Automatic hydraulic gate control is a critical aspect in flood control systems. The development of control algorithms based on sensor data is a prerequisite to ensure the effective operation of such systems (Zhang *et al.*, 2023). These algorithms not only determine how gates should respond to changes in water levels but also optimise the overall operation of hydraulic systems, especially under high load conditions.

The main purpose of control algorithms is to provide a timely and accurate response to data received from water level sensors. Algorithms may vary depending on the complexity of the system and the requirements for its operation. The simplest are "threshold-based" algorithms that activate closing or opening gates when certain water levels are reached. More complex algorithms may include control logic that considers the dynamics of water level changes, the rate of rise or fall, and forecasts based on historical data. For example, the algorithm can analyse data from multiple sensors to provide more accurate decisions about the time and magnitude of opening or closing gates. Using mathematical models, such as regression analysis or artificial intelligence-based models, can substantially improve the efficiency of decision-making. In high-load environments, such as heavy rains or floods, control systems should operate with maximum efficiency. Optimising the operation of hydraulic systems requires considering many factors, such as the flow rate, the volume of incoming water, and the state of infrastructure. Algorithms can use optimisation principles that allow achieving a balance between response speed and control accuracy. For example, if a large volume of water enters, the algorithm can increase the opening speed of the gate to avoid overflow, while controlling the likelihood of negative consequences, such as erosion or collapse of structures. For this purpose, mathematical modelling methods can be used to predict the results of actions and adapt real-time management strategies.

The variability of natural conditions, such as different rain intensities or snowmelt rates, requires flexibility in control systems. Adaptive algorithms become extremely important in this situation, as they can automatically adjust their parameters depending on changes in the environment. These algorithms can include machine learning mechanisms that allow the system to learn independently from new data. For example, if the algorithm detects that the water level is rising faster than predicted, it can adapt its response by increasing the frequency of data updates or changing thresholds to control the gate. This incre ases the flexibility of the system, reduces the risk of flooding, and prevents overloading of infrastructure elements.

Hydraulic closures are vital elements of water management systems, especially during floods. The stability of these structures in extreme conditions, such as heavy rains or rapid snowmelt, is crucial to prevent their destruction and ensure environmental safety (Zoffoli *et al.*, 2023). It is necessary to use effective methods for assessing the stability of structures and consider the influence of hydrodynamic forces to do this. Hydraulic gate stability assessment can be performed using a variety of methods, including analytical, numerical, and experimental approaches. Analytical methods are based on mathematical models that describe the behaviour of structures under the influence of loads. The main ones include calculation methods based on the theory of elasticity and fluidity, which allow estimating how gates respond to water loads. These models can help identify potential risk areas, such as local stresses or deformations. Numerical methods, in particular, finite element methods (FEM), allow for a detailed analysis of gate stability, considering complex geometric shapes and materials. Due to these methods, it is possible to visualise the distribution of stresses and deformations in the structure, which allows identifying critical zones that can be subject to destruction under the influence of hydrodynamic forces. Experimental methods, in turn, involve physical tests on gate models, which can provide valuable information about their behaviour in real-world conditions. Tests in the laboratory or in the field allow observing factors that are difficult to simulate, such as fluctuations in water levels, current velocity, or exposure to foreign objects (Farajvand *et al.*, 2021; Lei *et al.*, 2022).

Hydrodynamic forces that occur during floods are one of the main factors affecting the stability of hydraulic gates. The main components of hydrodynamic forces are hydrostatic pressure, hydrodynamic forces, and vibrations and fluctuations. Hydrostatic pressure is the pressure created by a column of water above the gate, and it increases with depth. At high water levels, the hydrostatic pressure can exceed the permissible values, which leads to deformation or even destruction of the structure. Hydrodynamic forces arise due to the movement of water, in particular, during a rapid flow or disturbance of water (waves, swirls). These forces can act on gates with different directions and values, making them difficult to estimate. They can cause additional loads on the structure, which can lead to its destruction. During floods, substantial vibrations can occur in the structure due to water disturbances. This can lead to material fatigue and reduced gate stability. It is necessary to conduct a comprehensive analysis of the effect of hydrodynamic forces to ensure the proper stability of hydraulic valves. Calculations performed using analytical and numerical methods can help identify possible problems in the design and make adjustments to its design.

Hydraulic closures are critical elements of water management systems, especially during extreme natural events such as floods (Yasmin *et al.*, 2022). The dynamic behaviour of gates during water fluctuations and load changes is an important aspect that requires detailed analysis. The examination of vibrations and dynamic loads affecting gate structures allows developing effective control methods and ensuring their stability in natural disasters. Gate fluctuations can be caused by a variety of factors, including changes in water level, flow rate, and other hydrodynamic phenomena. These fluctuations can lead to substantial dynamic loads that negatively affect the integrity of the structure. Dynamic loads on gates can be either static or dynamic (Table 2). Static loads are caused by hydrostatic water pressure, which increases with depth. Dynamic loads, in turn, occur due to the movement of water, disturbances, waves, and other factors that cause fluctuations.

Table 2. Analysis of dynamic gate loads

Operating conditions	Hydrodynamic forces (kH)	Vibrations (m/s²)	Destruction risks (%)
Normal	50	5	10
During a flood	120	15	30
Extreme conditions	200	25	50

Source: compiled by the authors based on S. Kim *et al.* (2023)

Various methods are used to examine these phenomena in detail. These include analytical models that allow determining the theoretical values of vibrations and gate loads using mathematical equations describing fluid mechanics and structural statics. Numerical methods, in particular, finite element methods (FEM), are used to model dynamic gate loads in real-world situations. These models consider all possible factors, such as pressure changes, flow rates, and vibrations. Experimental methods include physical tests on gate models under controlled conditions, which allows investigating the real dynamics of structures under the influence of various loads. Modelling the dynamic behaviour of gates during floods is an important tool for predicting their performance in extreme conditions. Modern computer programmes that use numerical modelling methods make it possible to create detailed models of hydraulic valves that reflect their behaviour during vibrations.

In the modelling process, it is important to consider hydrodynamic forces, analysing how the flow rate and water level change over time, it is possible to predict how these factors will affect the dynamics of gates. The interaction between the gate and the water environment is also important to consider, as it is necessary to understand how the gate design interacts with water, in particular, how fluid disturbances affect the stability and stability of the structure. In addition, vibrations and resonance are critical aspects, since vibrations can cause resonant phenomena that can lead to catastrophic consequences. Modelling such effects is crucial for understanding how a structure can withstand dynamic loads. Models that consider these factors allow developing strategies to improve gate stability. In particular, knowledge of dynamic behaviour can help in selecting materials, designing structures, and creating automatic control systems that respond to changes in real-time (Table 3).

Table 3. Influence of modern materials on the durability of gates

Material type	Corrosion resistance (%)	Durability (years)	Expenses (UAH/m²)
High-strength steel	85	30	800
Composite	90	25	1200
Ordinary concrete	75	15	500

Source: compiled by the authors based on M. Issaoui *et al*. (2022)

The design of hydraulic gate structures is an important component in water management systems, especially in conditions where the risk of flooding and other extreme natural phenomena is becoming increasingly relevant (Nowak *et al*., 2022). It is necessary to consider various design criteria and use modern materials and technologies that can increase their strength to ensure the reliability and efficiency of gates in such conditions. When designing hydraulic valves, it is important to follow several basic criteria. Gate structures must be designed to withstand hydrostatic and hydrodynamic loads. The maximum water pressure values that can occur during flooding, as well as possible vibrations and vibrations that can affect the stability of structures, are considered to do this. The choice of materials used in the structure should ensure their resistance to corrosion, fatigue, and other destructive processes. Modern building materials, such as high-strength steels, composites, and special concrete mixes, can provide the necessary strength and service life. In the event of changes in conditions associated with rising water levels or changes in the environment, structures must be able to adapt. This may include the modularity of the gates or the possibility of their refinement during operation. Structures must be designed with environmental impact in mind. This includes not only the selection of environmentally friendly materials but also an assessment of the impact on ecosystems and the possibility of returning to the natural environment after their operation is completed.

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DISCUSSION

In the course of the study on the design and optimisation of automated hydraulic gate control systems for flood control, it was determined that the integration of modern technologies in the management of such systems substantially increases their efficiency. The results showed that the introduction of radiofrequency and ultrasonic sensors for monitoring water levels enables a high level of data accuracy. This, in turn, allowed responding in a timely manner to changes in hydrodynamic conditions, which is critical during floods.

This problem was also investigated by J. Zaczek-Peplinska & L. Saloni (2023), where the results confirmed that the integration of modern technologies in the management of hydraulic systems, in particular, automation, has a substantial impact on the effectiveness of flood control. Automated control systems allow responding more quickly to changes in hydrological conditions, which reduces the risk of flooding and contributes to the efficient use of resources. Due to the introduction of intelligent algorithms, it is possible to anticipate potential threats and ensure the safe operation of hydraulic gates. A study by Y. Li *et al.* (2023) also showed that automation of hydraulic gate control systems during emergencies also improves the accuracy and reliability of the process. The use of modern sensors and monitoring systems allows getting real-time data on the state of water, which is critical for decision-making (Kabdoldina *et al*., 2022). This, in turn, helps to reduce the negative consequences associated with floods and ensures better management of resources in crisis situations. Notably, the automation of hydraulic system control not only increases the efficiency of emergency response but also optimises the work of personnel. Automated control systems free specialists from routine tasks, allowing them to focus on the strategic aspects of management and planning (Honcharenko *et al*., 2023). However, it is also important to consider the potential risks associated with technological failures or cyber-attacks that may threaten the security of water resources and require careful monitoring and protection.

Adaptive control algorithms have demonstrated their ability to optimise gate operation in dynamic conditions. The study showed that algorithms that consider changes in hydrodynamic characteristics can substantially improve the efficiency of automated systems. With this adaptability, the system can quickly adjust the operating mode of the gates, reducing the risk of flooding and damage. S. Cvejić *et al.* (2024) concluded that optimising the operation of hydraulic valves in response to changes in hydrodynamic characteristics is a key element in reducing the risk of flooding. Adaptive control systems that consider changes in water flows, pressure and other critical parameters allow you to adjust the position of the valves in a timely manner. This not only increases the efficiency of water disposal but also ensures the stability of the environment, reducing the possibility of environmental disasters. H. Albo-Salih & L. Mays (2021) determined that real-time hydraulic gate control using data from modern sensors and monitoring systems substantially improves flood response. Due to the analysis of input data, specialists can quickly make informed decisions about opening or closing gates, adapting their operation to changing conditions. This allows ensuring the safety of settlements and reducing the cost of flood relief, creating a more efficient water management system.

These results confirm the above study, as they demonstrate that the integration of modern technologies into the hydraulic gate control system substantially improves the response to changes in hydrodynamic characteristics. They also show that automation and the use of real-time data can reduce emergency response times, which is crucial for preventing flooding. In addition, the results point to the need for further development and improvement of technological solutions to ensure greater stability of systems in extreme weather conditions. Analysis of gate stability has shown that the use of modern materials, such as high-strength steels and composites, has a positive effect on their durability and corrosion resistance. This confirms the importance of choosing the right materials in the design of structures that must withstand extreme loads during floods (Moldabayeva *et al.*, 2021). As a result of the study, it was recommended to use materials that have high resistance to destruction, which helps to increase the reliability of structures.

The paper of J.N. Aslanov *et al.* (2022) is also notable, who emphasised that modern materials such as high-strength steels and composites play an important role in the choice of structural materials to improve the durability of hydraulic gates. The use of these materials contributes to lighter and stronger structures that can withstand substantial mechanical loads and corrosion influences. This is especially true in environments where hydraulic systems are exposed to extreme temperatures and chemical aggressors, which can reduce their efficiency and safety. In turn, H.A. Ragheb *et al.* (2021) concluded that the effectiveness of high-strength steels and composites in ensuring the reliability of structures under extreme conditions also confirms their ability to adapt to various operating scenarios. Using modern processing and manufacturing technologies leads to these materials providing a high level of resistance to mechanical damage and endurance in conditions of load fluctuations. This, in turn, increases the durability of hydraulic valves and reduces maintenance and repair costs, which is an important factor in water management systems. These data are consistent with the theses given in the previous section, as they confirm the importance of choosing modern structural materials to ensure the durability of hydraulic valves. High-strength steels and composites not only increase mechanical stability but also reduce the risk of damage under extreme conditions, increasing the overall efficiency of the system (Abdykalykov *et al.*, 2024). Therefore, investing in the latest materials can substantially reduce operating costs and improve the reliability of hydraulic structures in the long term.

The analysis of the dynamic behaviour of gates has shown that critical zones that are subject to special attention during design can undergo substantial destruction under the influence of hydrodynamic forces. The results confirmed that it is important to conduct a comprehensive assessment of such structures to identify potential problems and make adjustments during the design phase. This allows avoiding catastrophic consequences during floods and ensuring the long-term operation of the systems. S. Bhattacharjee *et al.* (2021) also conducted a study, the results of which confirmed that identifying vulnerabilities under the influence of hydrodynamic forces is crucial for developing effective risk management strategies in the design of hydraulic gates. Analysing data on loads that can occur during floods can identify potential weaknesses in structures that can lead to their destruction or inefficiency. Focusing on these vulnerabilities provides an opportunity to improve design solutions and improve the overall stability of gates. M.V. Varkey & M.P. Philbin (2022) also established that risk and problem analysis in gate design also contribute to the development of innovative technologies that can help strengthen structures. For example, the use of computer modelling and hydrodynamic calculations provides for the accurate prediction of the gates' behaviour under various loads (Momynkulov *et al.*, 2023). This, in turn, allows engineers to consider specific operating conditions and optimise structures to improve their reliability in changing conditions, in particular, during extreme weather events. Comparing the data obtained in the course of the study, it can be concluded that an integrated approach to the design of hydraulic valves is important. The results show that identifying vulnerabilities and carefully analysing risks are vital elements for ensuring the sustainability of structures during floods. This highlights the need to integrate state-of-the-art technologies, such as computer modelling, into the design process to better respond to potential threats and ensure the long-term reliability of hydraulic systems.

The study also drew attention to the influence of vibrations and resonant phenomena on gate designs. It is established that vibrations can cause resonant effects that can lead to catastrophic consequences. Knowledge of these phenomena has become the basis for developing recommendations for improving structures that help reduce dynamic loads and improve their stability. Z. Guo *et al.* (2023) concluded that the effect of dynamic loads on the stability of hydraulic gates is an important aspect that requires detailed analysis in the design of such structures. During floods, the gates are subjected to substantial vibrations that can cause resonance, leading to mechanical damage or even destruction (Homon *et al.*, 2023). Identifying these risks allows engineers to develop more reliable solutions that can withstand the extreme conditions that occur during intense hydrodynamic processes. P. Deng *et al.* (2024) state that studies analysing dynamic loads help identify critical parts of the structure that require additional reinforcement or modification. An important step is to use computer simulations to simulate the behaviour of gates under various conditions to predict potential problems. This approach provides more effective risk management, increasing the reliability of hydraulic systems and reducing the likelihood of negative consequences during emergencies.

When analysing the results of the study, it is clear that dynamic loads and fluctuations substantially affect the stability of hydraulic gates, and ignoring them can lead to serious consequences during floods. Identifying the risks associated with resonance confirms the need to implement specialised design methods that consider these factors. This requires not only the use of the latest technologies for modelling but also constant monitoring and assessment of the condition of structures to ensure their safety and efficiency in all operating conditions. Overall, the results of the study highlighted the importance of integrating modern technologies into the design of automated hydraulic gate control systems. This improves the functionality and also increases their reliability in flood-risk situations. Making changes at the design stage, based on the obtained data, contributes to the creation of more efficient and safe solutions for controlling hydraulic systems.

CONCLUSIONS

As a result of the study, the importance of automation of hydraulic gate control for effective flood control was confirmed. The introduction of radiofrequency and ultrasonic sensors for monitoring the water level provided high data accuracy, which allowed responding promptly to rising water levels. Adaptive control algorithms optimised the operation of gates in dynamic conditions, considering changes in hydrodynamic characteristics. The study showed that the use of modern materials, such as high-strength steels and composites, substantially increases the durability and resistance of structures to corrosion, which is an important factor for their reliable operation in extreme conditions. Analysis of the dynamic behaviour of the gates revealed critical zones that require special attention during design since they can be destroyed by hydrodynamic forces. The risks associated with vibrations and resonant phenomena were also identified, which confirmed the need to take these factors into account in the design process. In general, the results of the study highlighted the importance of integrating modern technologies into the design of hydraulic systems to improve their functionality and reliability in flood risk situations, which ensures more effective control of hydrological processes.

The study also established that the integration of automated control systems improved the response to changes in hydrological conditions. Automation provides fast data processing and decision-making, which is critical during floods when the situation can change in a matter of minutes. The use of adaptive algorithms allowed gates to respond more quickly to rising water levels, reducing the risk of flooding in surrounding areas. The results confirmed that automation systems improve management and contribute to public safety. Thus, the study highlighted the need to develop automated flood control systems. It is necessary to further investigate the impact of climate change on the hydrodynamic characteristics of water resources and their interaction with automated hydraulic gate control systems.

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CONFLICT OF INTEREST

None.

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Проєктування та оптимізація автоматизованих систем керування гідравлічними затворами для боротьби з паводками

Анотація. Дослідження проведено з метою аналізу проєктування та оптимізації автоматизованих систем управління гідравлічними затворами для ефективного контролю паводків. У ньому використано аналіз даних з датчиків рівня води, моделювання гідравлічних систем та алгоритми керування для автоматизації моніторингу гідравлічних шлюзів. В результаті дослідження визначено ключові аспекти, які підтверджують важливість автоматизації управління гідравлічними затворами для ефективного протипаводкового захисту. Встановлено, що впровадження радіочастотних та ультразвукових датчиків для моніторингу рівня води забезпечує високий рівень точності даних, що дозволяє своєчасно реагувати на підвищення рівня води. Адаптивні алгоритми керування дозволили оптимізувати роботу затворів у динамічних умовах, враховуючи зміни гідродинамічних характеристик. Крім того, аналіз стійкості затворів показав, що використання сучасних матеріалів, таких як високоміцні сталі та композити, суттєво підвищує їх довговічність та корозійну стійкість. Це стало важливим фактором забезпечення надійної роботи конструкцій в екстремальних умовах. Розглянуті моделі динамічної поведінки затворів дозволили виявити критичні зони, які підлягають особливій увазі під час проєктування, оскільки можуть бути зруйновані під дією гідродинамічних сил. Загалом, результати дослідження підкреслили важливість інтеграції сучасних технологій у проєктування гідравлічних систем для підвищення їх функціональності та надійності в умовах паводкового ризику. Проаналізовано вплив вібрацій та резонансних явищ на конструкції затворів, що дозволило виявити можливі ризики для їх стійкості в умовах паводків. В результаті надано рекомендації щодо проєктування затворів, які включають конструктивні вдосконалення, що сприяють зменшенню динамічних навантажень та підвищенню їхньої здатності витримувати екстремальні гідродинамічні умови

Ключові слова: датчики рівня води; алгоритми; гідродинамічний тиск; прогнозування погоди; динамічна поведінка