SAFETY CRITERIA FOR HYDRAULIC STRUCTURES

CRITERES DE LA SECURITÉ DES OUVRAGES HYDRAULIQUES

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ABSTRACT

Large Hydraulic Structures (HS) are the sources of potential dangers for the population and facilities located within their areas of influence. The international experience shows that in the event of an accident there may arise emergencies, accompanied by considerable human and large economic losses. The authors of this paper have developed "Methodological instructions on establishing safety criteria of hydraulic structures" for all types of HS. Two levels of criteria of diagnostic indicators have been considered. The first level signals the occurrence of a potentially dangerous condition and calls for the operating organisation to notify the supervision body and take prompt steps to bring the facility back to normal operating conditions. The second level, in addition to the steps taken at the first level, also involves the introduction of restrictions on the operating regime of the HS right down to the shedding of the actual loads.

The authors suggest the accident risk indicator as an index, which makes it possible to draw generalised conclusions on the safety of the HS in operation. For the automation of calculations of the composite safety indicator, procedures of safety estimation of HS in operation with the help of the generalising indicator, and the support of management decisions on HS safety improvement, the information technology for substantiation of planned preventive measures at functioning HS has been developed. The technology is intended for operation departments of economic entities, executive power and supervision bodies, responsible for the control system (monitoring) and ensuring the safety of HS. Application of the technology using data on potentially dangerous facilities of the Southern and North Caucasus Federal Districts provided to OAO "Sevkagiprovodhoz" (joint-stock company) by territorial melioration bodies and agricultural water-supply bodies of the Ministry of Agriculture of Russia, revealed the high efficiency of the information technology with respect to labour productivity and decision making quality when:

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- *budgeting the means for performing examinations and preparing safety declarations of HS;*
- *determining the priority order of funds allocation for routine repair, overhaul and reconstruction of potentially dangerous HS;*
- *substantiating requirements for the development of design and estimate documents and carrying out research on safety assessment of HS.*

Key words: *Hydraulic structures, safety criteria, diagnostic indicators, criterion values, in-situ observation*

RESUME

Les grandes Ouvrages Hydrauliques (OH) sont les sources de dangers potentiels pour la population et les installations situées dans leurs zones d'influence. L'expérience internationale montre qu'en cas d'un accident il y aura des cas d'urgence, accompagnés des grandes pertes humaines et économiques. Les auteurs de ce rapport donnent des « instructions méthodologiques sur l'élaboration des mesures de sécurité pour les ouvrages hydrauliques » pour tous types des OS. Deux niveaux de critères d'indicateurs diagnostiques ont été tenus en compte. Le premier signale l'occurrence des conditions potentielles dangereuses et exige que l'organisation d'exploitation notifie l'organisme de surveillance pour prendre les mesures nécessaires pour le fonctionnement normal des ouvrages. A part les mesures prises dans le premier critère, le deuxième critère impose des restrictions du régime d'exploitation des OS.

Les auteurs proposent les indicateurs de risque d'accident en tant qu'un index, qui permet de tirer des conclusions générales sur la sécurité des OS. La technologie d'information pour justifier les mesures préventives planifiées du fonctionnement des OS a été développée pour l'automatisation des calculs des indicateurs de sécurité, les procédures d'évaluation de sécurité des OS avec l'aide de l'indicateur généralisé. Cette technologie soutient également les décisions de la gestion pour améliorer la sécurité des OS.

La technologie est destinée aux départements d'exploitation des entités économiques, au pouvoir exécutif et aux organismes de surveillance, responsables du système de contrôle et de l'assurance de la sécurité des OS. L'application de la technologie en utilisant les données des installations potentiellement dangereuses des quartiers fédéraux du Caucase du Sud et du Nord a été fournie à OAO "Sevkagiprovodhoz" par les organismes territoriaux et les organismes d'approvisionnement en eau agricole du Ministère de l'Agriculture de la Russie. Les organismes ont indiqué la haute efficience de la technologie d'information en ce qui concerne la productivité du travail et la qualité de prise de décisions. Elle était utile pour:

- *préparer le budget pour les moyens à mettre en oeuvre et la préparation des mesures de sécurité des OS;*
- *déterminer l'ordre de priorité dans l'allocation de fonds pour divers travaux des OS;*
- *justifier les besoins du développement de conception et entreprendre les recherches sur l'évaluation de sécurité des OS.*

Mots clés: *Ouvrages hydrauliques, mesure de sécurité, indicateurs diagnostiques, valeures de critère, observation originale*

1. INTRODUCTION

Ensuring safety of hydraulic structures (HS), which is a comprehensive issue, requires the involvement of the owners and operating organisations of HS, state safety supervision bodies and expert organisations.

On the basis of generalisation of systematic research and analysis of normative documents, issued by various departments, the authors have worked out major methodical and organisational requirements with regard to safety criteria for all facilities except those in power generation and shipping industry. The requirements have been documented as "Methodological instructions on establishing safety criteria for hydraulic structures" (further referred to as Methodological Instructions). Engineering standards and recommendations for determining hydraulic structure safety criteria, tested and proven through operating experience, are incorporated in the Methodological Instructions. The Methodical Instructions give:

- the procedure of defining controlled and diagnostic indicators of a HS condition when designing the structure, commissioning it and at all stages of its operation;
- the determination of criterion values for these indicators;
- the use of qualitative characteristics as indicators of HS condition.

The Methodological Instructions also give approaches to development of forecast models applicable for the establishing of HS safety criteria. Safety levels (normal, lowered, unsatisfactory, critical) and condition indicators (fit and serviceable, serviceable, potentially dangerous, accident-prone), whose qualitative characteristic are given in the document, have been defined for HS in operation. Even one indicator, characteristic of one of the above tabulated categories, is sufficient for the attribution of the construction structure to the relevant category. In technical guidelines the maximal permissible values (MPV) of HS condition indicators are to be specified for every pressure HS; observation results obtained with control and measuring equipment and through visual evaluation should be compared with them. The list of controlled (diagnostic) HS condition indicators has been developed and is also presented in document. The indicated list is the basis for the monitoring of HS condition and may be adjusted when the facility is put onstream or commissioned. Qualitative and quantitative indicators of HS condition should be defined in guidelines for operating organisations on the basis of this list. For HS safety criteria, two value levels in the form of quantitative and qualitative indicators are fixed, on the basis of which the assessment of the state of a hydraulic structure and its operational conditions is made:

K1 - first (warning) level of controlled indicators values; when reached, the stability, mechanical and filtering strengths of the HS and its base, as well as the discharge capacity of outlet and spillway works still correspond to normal operating conditions;

K2 - second (limiting) level of controlled indicators values; when exceeded, the HS operation is inadmissible under design conditions.

Table 1. Summary of risk conditions of HS.

HS technical condition category and safety level	Qualitative assessment characteristics of the HS safety level
I – fit and serviceable condition, normal safety level	HS conforms to the design, current norms and rules, HS condition indicators do not exceed maximum permissible (criterion) values, set for the serviceable condition (K1), operation runs without violations of current legislative acts, norms or rules, priority reliability and safety measures for HS as well as orders of supervisory bodies are carried out at a stated time.
II – serviceable condition, lowered safety level	Failure to perform (shortfalls with regard to performance of) priority reliability and safety measures for HS, orders of state supervisory bodies, other violations of HS operating rules with other indicators conforming to the normal safety level of HS.
III – potentially dangerous condition, unsatisfactory safety level	Reduction of mechanical and filtration strengths of the structure elements, exceedance of maximum permissible (criterion) values, set for the serviceable condition (K1), other deviations from the design condition that may lead to the accident development.
IV – accident-prone condition, critical safety level	Dangerous processes of reduction of strength and stability of HS and their bases; HS condition indicators exceed maximum permissible (criterion) values, characteristic of the transition from 'potentially dangerous' to accident-prone condition of the structures and their bases (K2)

For Class 4 facilities and, when specifically substantiated, Class 3 facilities it is allowable to set one level of criterion values K1.

Prompt evaluation of the operating condition and safety of the HS should be carried out by way of comparison of quantitative diagnostic values K1, measured or calculated, as well as obtained via visual observation of qualitative characteristics, with their criterion values K1 and K2 or relevant qualitative characteristics with consideration of forecast changes in diagnostic indicators. The normal and lowered safety levels characterise a serviceable condition of HS, wherein the values of diagnostic indicators of HS condition do not exceed the warning level K1 ($K<K1$).

The attribution of HS condition and safety level to 'normal' or 'lowered' is done through an expert evaluation when preparing the HS safety declaration and during the State inspection. An unsatisfactory safety level corresponds to a potentially dangerous condition of HS, wherein at least one value of the diagnostic condition indicator K is such that $K1 < K < K2$. The critical HS safety level corresponds to the emergency condition of the facility, wherein at least one value of the diagnostic indicator K of HS condition exceeds the limiting level K2 ($K > K2$).

Quantitative criterion values K1 and K2 of diagnostic indicators should be established based on evaluation of reactions of the facility to the basic and special load combinations. The composition of loads in combinations and the method of determination thereof should be stipulated for a specific facility by normative documents and the design, and adjusted at the

operational stage with consideration of changing requirements of normative documents. The evaluation of the facility is done using composite indicators of the safety of the facility, including the estimation of the technical serviceability, reliability and socio-ecological factors. Such an evaluation requires monitoring data on the condition of not only individual structure elements but also of the HS as a whole. The authors suggest the use of accident risk index Ra as a composite index of the facility safety. It is determined through the amount of economic damage from possible accidents (Ye) and the safety level index Kn.

$$R_a = Ye/ Kn \quad (1)$$

The safety level index of the HS (Kn) is determined via the technical condition (Tc) and structure reliability (Ba) indicators.

$$K_n = Ba \times Tc \quad (2)$$

The integral characteristic of the technical condition of the HS (Tc) is determined by the wear of fixed assets as the relation of depreciated cost of fixed assets (Ad) to original cost (A):

$$Tc = Ad/A \quad (3)$$

The reliability indicator of the facility is computed according to the relation (4).

$$Ba = (1 – 1/N) \quad (4)$$

Where - N is the observed periodicity of emergency situations in number of years.

The evaluation of the HS condition using safety criteria does not replace the requirement of performance evaluation by the state. HS examination is to be carried out by a commission, consisting of representatives of the owner's operation department, design and/or expert organisation, territorial HS safety supervision body, no less than once every 5 years. When examining the HS, the commission, taking into account design documentation, comparing HS condition safety indicator criteria with their actual values, taking into consideration HS operating rules, the factual condition of the facility, upon reviewing and discussing the results of the examination, assesses the operating condition of the HS.

2. DETERMINATION OF CRITERION VALUES OF THE DIAGNOSTIC INDICATORS OF HS CONDITION

At the designing stage the composition and criterion values of diagnostic indicators K1 and K2 should be defined using the analysis of calculation results and experimental investigations of filtering, hydraulic and temperature regimes, the stress-strain state, strength and stability of the HS with basic and special load combinations, as well as on the basis of analysis of strength, deformation and filtration properties of materials of the facility and its base.

At the HS operating stage, criterion values K1 (and if necessary K2) of diagnostic indicators should be adjusted and supplemented using:

- in-situ data analysis results and HS operating experience;

- simulated results on the basis of statistical models, created using in-situ data;
- checking calculations according to deterministic mathematical models, "calibrated" on the basis of in-situ data, applicable to adjusted calculated design model of the HS and adjusted calculated values of property parameters of materials and base rocks, as well as parameters of basic and special load combinations.

Based on the analysis of the HS service at the operating stage, the composition and criterion values of qualitative diagnostic indicators of the HS condition K11 and K22 (similar in purpose to K1 and K2) should also be determined. For facilities, whose measured values of diagnostic indicators happen to be significantly below design values, determined at the stage of design, and in case of lack of adjusted calculations of the facility in operation, the criterion indicator values should be adopted based on forecast statistical models. In this case the said statistical models as a rule should be used within the range of loads and effects, experienced by the facility during operation.

In case of one or several diagnostic indicators exceeding criterion value K1, determined at the stage of design and adjusted through calculation at the stage of operation, as well as in case of lack of adjusted design data, it is allowable to carry out the HS behaviour forecast based on statistical models.

Diagnosis of the dangerous and unsatisfactory operating conditions of the HS should be carried out on a comprehensive basis, bringing in measurement data of all diagnostic indicators, primarily of filtering regime parameters (discharges, back pressure values, depression curve, seepage gradients) and crack formation characteristics of concrete dams, as well as using statistic forecast models and qualitative diagnostic indicators.

Criterion values of a composite indicator of the facility safety of Ra are determined at the stage of operation of the HS with account of the accident risk value, set by normative documents.

3. IN-SITU OBSERVATION REQUIREMENTS

Incorporation of requirements for the organisation of in-situ observations is necessary for providing operational and efficient monitoring of the condition of facilities with the help of diagnostic indicators and their criterion values. The measurement instrumentation in the facility should be installed so that it is possible to obtain the measured value for every criterion value of a diagnostic indicator of the HS condition.

The sensing elements should be installed primarily in those zones or points, which are most "sensitive" to the changes in the construction condition or in which as per calculation data the indicators have maximum values. Cracks and faults in rock foundations, areas of soft rock, "concrete - rock" contacts, zones adjoining rock side walls of dams, expansion and settlement joints and block joints of concrete and reinforced concrete constructions, the most stressed zones of facilities and constructions, crests and junction zones of bases and the highest areas of earth dams, zones of possible contact filtration, junction zones of concrete and earthwork structures, etc., should be regarded as such zones. Taking into account the possibility of a premature breakdown of individual sensing elements, as well as for the purpose of increasing the reliability of date from measurements in non homogeneous materials, the

sensing elements in indicated zones of facilities and their bases should be installed in sets of 2-3 pieces or the measurements should be backed up by different methods.

The measurements of controlled condition indicators of facilities must be executed by as simple and reliable a means as possible. In case of using short time lasting measurement instrumentations, a possibility of their replacement should be provided for. For the purpose of simplification of the procedure of evaluation of measured diagnostic indicators by way of comparison thereof with criterion values, the preparation of a report, containing data on measured and criterion values of diagnostic indicators of all structures of waterworks in tabular form is needed. Construction period data include:

- names of all indicators of the condition of facilities, monitored through in-situ observations;
- methods of determination of quantitative values of each indicator according to the measurement data;
- initial design values of indicators, ascertained from the design documents;
- values of indicators according to the data of measurements during significant [characteristic] operating periods of facilities;
- values of criterion indicators.

In the period of regular operation the table form is supplemented with adjusted values of diagnostic indicators as per results of measurements (the absolute value, the rate of measurements in time) and values of indicators as per the data of measurements at significant operating periods of facilities.

For increasing the facility for monitoring efficiency, the measurement periodicity should be set taking into account the following factors: importance of the facility and the cost of damage, possibility of an accident or destruction; the quality of construction and operation; the accuracy and reliability of the control system; the factual condition, unfavourable processes (or absence thereof), which may decrease the HS operational reliability and safety.

For promptness of the safety assessment of the HS operation, automated information and diagnostic system (IDS) of control and assessment of the condition of hydraulic structures should be used. For the automation of HS safety composite index calculations and support procedures for management decision on HS safety improvement, the information technology for substantiation of planned preventive measures on operating HS has been developed. Its description is given in Section 4.

The in-situ observation programme should determine the scope and order of visual observations, on the basis of which characteristics K11 and K21 of qualitative diagnostic indicators of the condition of facilities are established. Special attention should be given to the monitoring of zones of:

- changes in geological engineering conditions of the base; junctions of different facilities;
- application of concentrated static and dynamic loads;
- variable humidity and temperature conditions;
- changes in the configuration of the facility, stress concentration and distribution pattern.

4. THE PROCEDURE OF DEVELOPMENT OF HS SAFETY CRITERIA

Safety criterion of the HS are developed:

- at the stage of design – by the design organisation;
- at all stages of operation, starting from commissioning - by the HS owner or the operating organisation (using their own resources or subcontracting specialised research or design organisations).

The list and criterion values of diagnostic indicators, developed at the design stage, must be adjusted at the stage of placing the facility into operation, taking into account all additional information, obtained during the construction period, as well as with consideration of possible extension of the monitoring of the HS in operation.

Safety criteria of the HS are also to be clarified:

- in cases of changes in requirements of legislation on safety of hydraulic structures, national and other standards in effect, other norms and rules of technical regulation of HS safety;
- after performing adjustment check calculations, including seismic resistance calculations for the HS, as well as when designing the prognostic mathematical model of HS and its base;
- after performing multifactor HS research;
- on the basis of a regular or special purpose HS inspection report.

Newly developed or adjusted safety criterion should be sent for approval to the federal executive body, authorised to carry out the state supervision of hydraulic structures (hereinafter referred to as the state supervision body).

The state supervision body should be provided with a list of controlled diagnostic indicators, tabular forms with measured and criterion values of diagnostic indicators of all waterworks facility structures, measuring means location maps, the scope of visual observations, carried out at the facilities, the methods of determining values of diagnostic indicators, computed from data of measurements, and characteristics of qualitative diagnostic indicators.

Safety criteria of the HS, sent for approval to the federal supervision body, are to be signed by the design originator and design organisation if developed at the stage of design; those developed or adjusted at the stage of operation are to be signed by the owner of the HS or a person, authorised by the owner. Explanatory notes, containing the required substantiation for the selection of diagnostic indicators and calculations for determining numerical values of safety criteria, should be filed to the federal supervision body along with safety criteria.

5. INFORMATION TECHNOLOGY FOR SUBSTANTIATION OF PLANNED PREVENTIVE MEASURES AT HS IN OPERATION

A major factor in increasing the reliability of HS, having changed in the process of their operation, is such planned-preventive measures, as the repair (routine and overhaul), reconstruction, as well as flood control measures. The routine repair is the basis of normal

operation (within the limits of the design life) of facilities and equipment. Timely and quality routine repairs protect the facility and equipment from premature wear and considerably reduce overhaul expenses.

The scope of routine repairs includes: replanted (scheduled) preventive measures; extra works, [whose necessity has been] detected during operation (unforeseen works, damage repairs). The overhaul of facilities includes work, in the process of which complete or partial recovery of individual facilities or a complex of water facilities, structural elements or parts of water facilities and their equipment or the replacement of them with stronger and more cost-effective ones is done. Reconstruction is a fundamental re-equipment or rebuilding of the facility with the purpose of improvement. The planning of prevention measures (PPM) is sub classified into 'prospective', 'annual' and 'prompt'. The annual plans of overhaul and reconstruction of water facilities are drawn up in money terms and in terms of natural indicators by the organisation, whose property they are, within the general allocation, stipulated in the production activity budget of the organisation for funding these works.

The database and the computer database management system of the information technology for substantiation of planned-preventive measures for safety improvement of HS in operation make it possible to execute:

- automated formation of the list and data on potentially dangerous HS in the District and in every constituent Federation territory;
- analysis and assessment of the HS technical condition, their safety level as well as the tracking of safety declaration (with regard to the on-hand status) for these facilities;
- formation of the list of potentially dangerous HS, which are required to declare their safety, and terms for implementation of this task;
- development of the system of safety improvement measures for potentially dangerous HS, including the execution of planned-preventive works (repair, overhaul, reconstruction, flood control measures, development of design and estimate documentation for their implementation, execution of research work).

The bundled software of the technology has been tested in Southern and North Caucasus Federal Districts. In-situ studies at 19 separately located HS and at 10 facilities, comprising irrigation systems, and analysis of data from 129 operating HS have been performed for this purpose. This has made it possible to evaluate the validity of three singled out major systems of features and factors, affecting the condition of operating facilities. These include: type and class of facilities, operation conditions, ownership, operating condition, control organisation, age of facilities, territory characteristic etc. Also the high efficiency of use of the information technology has been established with regard to the increase in labour productivity and decision making quality as regards:

- the planning of financial means for the execution of examinations and development of HS safety declarations;
- the determination of the order of allocation of financial means for routine repair, overhaul and reconstruction of potentially dangerous HS;
- requirements for developing design and estimate documentation and performing research work.

The IT database has been developed on the basis of Microsoft Access DBMS. The delivery of the technology is executed on any PC storage medium (CD-ROM, etc.) and requires approximately 30 Mb storage capacity in case of an empty DBMS database. The database operation is carried out with the help of “Menu” of the main form, presented in Fig. 1.

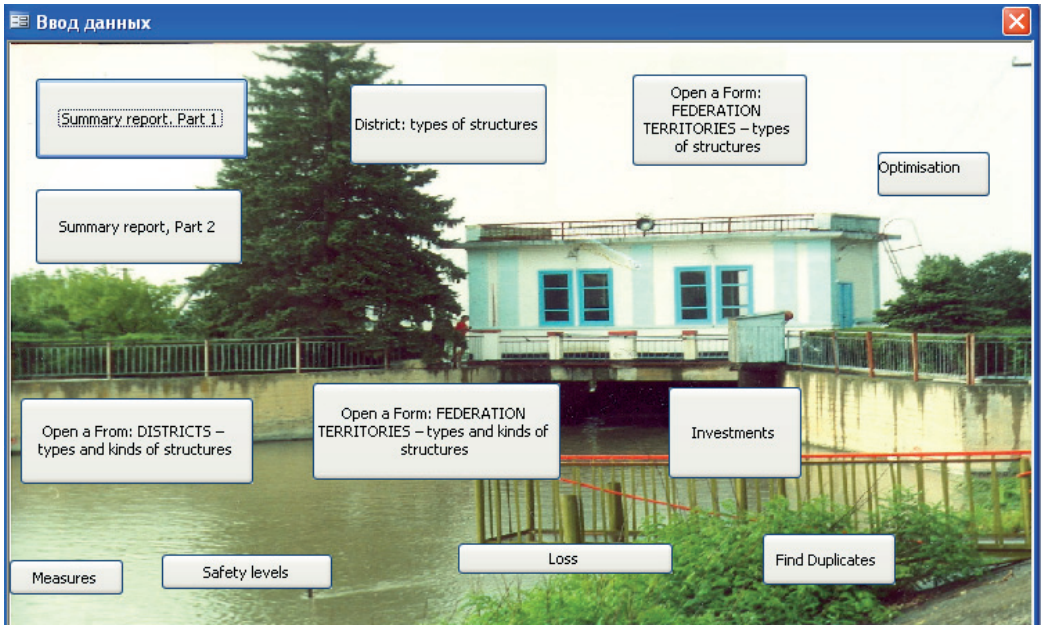

Fig. 1. The main form of the database

Le dessin. - Une principale forme de la base de données

6. RESULTS AND CONCLUSIONS

The analysis of actual application of current normative legal documents and normative technical documents regulating the relations in the field of HS safety has shown the necessity of improvement of the normative legal and normative technical documentation. The latter is linked with elimination of contradicting provisions in effective documents, removal of contradictions in provisions of normative technical documents and provisions of basic normative legal documents, addition of missing provisions, refinement of wording and development of new documents and/or parts thereof.

Improvement of the system of indicators and criteria of evaluation of the HS condition and safety level is a continuing and major task of operating organisations, supervision services, owners of facilities etc. The solution of the task to a considerable extent determines the decision-making efficiency when planning the repair measures and choosing high-priority facilities for implementation thereof. This is especially important under conditions of allocation of limited investments and is indicative of the topicality and practical importance of the performed research work.

The authors have prepared the blueprint for the Methodological instructions on establishing safety criteria of a hydraulic structure, describing fundamental methodical and organisational actions with regard to the establishing of HS safety criteria at all facilities, except for power industry and navigation facilities.

A distinctive feature of the document, determining its research novelty is:
introduction of the adjusted list of controlled indices of the HS condition and the list of fundamental technical and software tools for monitoring systems of Class 1-3 HS; the newly developed list of controlled indicators of the HS condition and the list of fundamental technical and software tools for monitoring systems of Class 4 HS, which are missing in effective documents.

The authors have developed the original criterion, which determines the general condition of the facility, and the algorithm of integral estimation of the HS safety. They make it possible to:

- detect facilities with a near-emergency status based on the index of integral estimation of safety of HS with consideration of the socio-ecological significance of the structure.
- make generalising conclusions based on monitoring results for substantiation of decisions, under conditions of limited funding, on the planning of measures to increase the operational reliability of the HS and on the choice of high-priority facilities for implementing repair measures with the purpose of decreasing ecological and economical damage.

In order to automate the process of computation of criteria and implementation of procedures of the proposed integral estimation of the HS condition, the authors have developed the database and computer database management system – an information technology tool for substantiation of planned-preventive measures to improve the safety on hydraulic structures in operation.

The software system of the technology has been tested in Southern Federal District and shown high practical efficiency as regards the increase in labour productivity and decision making quality. The results of the research are intended for an operating organisation, executive power and supervision bodies, responsible for the control (monitoring) system and ensuring the safety of hydraulic structures.

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