Rationale for engineering activities to prevent and reduce adverse impact of accidents at low-head hydraulic structures

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Abstract. The paper considers the safety of operating hydraulic structures for reclamation. Such research is imperative today due to the high risk of accidents at such structures. Meeting the technical, economic, environmental, and aesthetic requirements to hydraulic structures is absolutely necessary; otherwise, significant damages may ensue. Hydraulic structures (HS) are operated in two ways of organizing the maintenance and repairs: periodic inspections to check the condition of HS elements and find whether repairs are necessary; and carrying out pre-scheduled repairs and adjustments. Analysis of the two methods reveals that scheduled preventive repairs can ensure the fail-safe and reliable operation of hydraulic structures, and are therefore fundamental to proper operation.

1. Introduction

According to the Water Strategy of the Russian Agroindustrial Complex (AIC) for until 2020, the “strategic goal of advancements in the AIC waterworks is to ensure the safety of hydraulic structures, protect the people and infrastructures from floods and sundry water-related damages by solving the socio-economic problems in a balanced manner as well as by preserving a favorable environment and natural resources.” [1].

Empirical data suggest that socially oriented advancements in the reclamation and water industry of the AIC are impossible without proper control over the safety of hydraulic structures (“the HS”) and adjacent areas [2,3].

Any HS operation must be aimed at environmentally friendly use of natural resources. The urgent issues of today comprise the environmental issues of using the reclaimed land, of laying the foundations for environmentally sustainable production and consumption models [4]. A flexible reclamation strategy will enable further advancements of the existing HS, which will prevent all the processes, parameters, and geoeconomic limitations from causing the emergence of any unacceptable condition (or fault) in any element or in the entire system, thus effectively preventing any adverse environmental impacts over the entire service life of such structures [5].

The main problem of operating a HS, including low-head HS, consists in ensuring reliable and safe operation. The accident rates are higher for low-head HS than for high- or mid-head ones due to inadequate maintenance, lack of maintenance staff, lack of funding and assets for keeping such structures in a fail-safe condition, and, sometimes, due to loss of owner and(or) operator [6,7].
2. Methods

According to Rostekhnadzor, most (95) of the HS belong to the water industry, while 96.3% of the HS are low-head HS as of 2014. According to SP 58.13330.2012 *Hydraulic Structures. General Provisions*, a low-head HS is a Class IV HS with a water head of up to 15 m and a reservoir volume of up to 50 mln m³ [8].

HS technical condition is evaluated by operational inspections, surveys, and finding the actual operating performance (“the OP”). Comparing the actual operating performance against the standard reveals the physical deterioration and technical reliability of structures [9,10]. If the actual OP and accident risks are not within acceptable limits, the risk of accident is increased. Further operation of such structures “as designed” is not permissible; instead, the operator should switch to safer parameters.

Below is the list of the monitored technological and technical HS indicators [11]:

- technical indicators: reliability (a combined fail-safety, durability, and maintainability score), strength, sustainability, etc.;
- structural indicators: structure type, the design and condition of inlets, outlets, and waterways;
- technical and economic indicators.

OP is what provides the interconnection and continuity of design, erection, and operation. This means that the standard OP values are fundamental to all stages: the construction, design, and operation of structures (“the MR”) [12].

Figure 1 presents the structural diagram of safe and reliable HS operation.

![Figure 1. Diagram of reclamation HS operations.](image)

The main goal of operating a low-head hydraulic structure is to optimize its operation, ensure healthy condition and appropriate safety over the entire standard service life (life cycle) [13].

Low-head HS repairs and maintenance shall address the following:

- restore or improve the technical condition;
- maintain elements or structures as a whole;
- repair elements or structures as a whole;
- manage the MR system.

Maintenance must include measures to keep structural elements and structures in a healthy condition, to eliminate the identified minor defects and malfunctions. HS maintenance must be tailored to the operating specifications (per GOST 2.601) and meet the technical condition and safety requirements per national standards.

GOST 18322-78 classifies repairs into following categories: current repairs; overhauls; emergency repairs.
Current repairs of hydraulic structures are aimed at eliminating minor defects and malfunctions. These are taken regularly throughout the year and usually do not cause any downtime. Total current repair costs must not exceed 20% of the initial book value of the repaired facility.

Overhauls involve complete or partial restoration of an HS, which has its structural elements and parts replaced with stronger or more cost-effective counterparts. Total overhaul costs must not exceed 50% of the initial book value of the repaired facility. Exceeding that threshold means the facility is eligible for total renovation or retrofitting. Emergency-related damage must be prioritized. For overhauls, preliminary drafting of design estimates is a must. Empirical data suggest it is only scheduled preventive repairs can ensure efficient HS operation.

This research into HS operation experience complements GOST-standardized quantitative reliability indicators with hydraulic and strength characteristics of structures, meeting which results in fail-safe and reliable operation, see Table 1 below.

The hydraulic indicators are taken from scientific and engineering literature as well as from the RosNIIPM studies [10].

| Standardized indicators | Reliability threshold | Hydraulic efficiency threshold |
|-------------------------|-----------------------|-------------------------------|
| Fail-safe operation probability | $P = 1 - e^{-\lambda t} \geq 0.97$ | In terms of sustaining the hydraulic variation: $\phi(Z) = z - z_c \leq 0$ |
| Availability factor | $K_a = \frac{T_s}{T_n + T_r} \geq 0.95$ | In terms of throughput: $\phi(Q) = Q - Q_c \to 0$ |
| Cost-effectiveness | $K_c = \frac{C_{nc}}{C_{nc} + C_r} \geq 0.85$ | In terms of complying with the required “flooded” afterbay parameters: $\phi(h^+) = h^+ - h_n < 0$ |
| Maintainability factor | $K_m = \frac{C_c}{C_s} \leq 0.5 - 0.8$ | In terms of the fail-safe operation probability: $\phi(P) = P - P_m > 0$ |
| Durability | The service life of the primary hydraulic structure elements and that of the whole structure depends on the class | By the filtering deformation of the subsoils: $l_{sr} = \frac{l}{m}$ |

HS operations are carried out in two fundamentally different ways of organizing maintenance and repair.

The first way involves periodic inspections to identify the technical condition of HS elements and whether they need any repairs [11]. In this case, the scope and deadlines for repair operations can be determined by inspecting the structural elements of engineering systems.

The second method is recommended by FSSE RosNIIPM; it implies pre-scheduled repairs and adjustments to prevent the failure of structural elements and engineering systems. This is referred to as scheduled preventive repairs. The very name conveys the intent: scheduled, because all the activities are pre-scheduled; preventive, because all the activities are intended to prevent premature deterioration of HS elements.

The periodicity of current repairs, overhauls, and adjustments depends on the service life [13,14].

An HS can be considered a system of individual structures, engineering devices, and machineries, each of which has its own service life $T_s$. 
The averaged element-specific service life can be found by the formula:

$$\bar{T}_i = \frac{\sum_{i=1}^{m} x_i m_i}{m}$$

(1)

where $i=1,2,\ldots,m$; $\bar{T}_i$ is the averaged service life of the element; $x_i$ are the survey-registered possible service lives of the HS element; $m_i$ is the number of elements that have that specific service life; $m$ is the total number of surveyed elements [14].

To find the numerical values of the possible events, introduce the concept of statistical probability. If there has been conducted a series of $K$ surveys, each of which may have registered the event $A$, i.e. detecting a faulty element, or no such event, then the statistical probability (rate) of this event in this survey series is the ratio of the number of surveys $m_i$, where the event $A$ has been detected, to the total number of surveyed elements.

$$p_i = \frac{m_i}{m}$$

(2)

where $p_i$ is the statistical probability of this event.

Substituting $m_i/m$ with $p_i$ to get:

$$\bar{T}_s = \sum_{i=1}^{m} x_i p_i$$

(3)

However, comprehending all possible service lives of an element requires more than knowing the mean service life. When finding the element-specific time between repairs, the deviation of a specific service life from the mean is the variance $D_x$ found by the formula:

$$D_x = \sum_{i=1}^{m} (x_i - \bar{T}_i)^2 p_i$$

(4)

The variance has the dimension of the squared service life. To characterize the service life scattering, use a value of the service life dimension. To that end, extract the square root of variance. The resultant value is the mean squared deviation (or standard deviation) of service life:

$$\sigma_x = \sqrt{D_x}$$

(5)

where $\sigma_x$ is the standard deviation of service life.

3. Results

As noted above, the HS element service life is a random value, which, given a sufficiently large number of observations, does not significantly affect the mean. Random deviations from the mean, which are inevitable in any specific survey, will mutually offset, or level each other [15].

To find the possible limits of deviations of element-specific service lives from the mean system-wide service life, use the Chebyshev inequality, in which any specific service life will deviate from the mean within some practical limits, outside of which the failure of that specific element is unlikely. The practical assumption is that the specific service life of a building element cannot exceed $\bar{T}_i \pm 3\sigma_x$.

Analysis of the random variables reveals that the distribution of their specific values follows certain patterns [16]. The random variable distribution law is this value as a function of its occurrence probability. For HS element service life, the closest law is the normal distribution. Note that the more surveys, the closer is the distribution to being normal. Analysis of the density of normal service life distribution has the three following features:

- the less is the deviation of a specific service life from the mean, the likelier is its occurrence; greater deviations reduce the occurrence probability;
• deviations of the same absolute magnitude but opposite in sign have the same probability; the probability of deviating to the right of the mean equals the probability of deviating to the left of the mean;
• service life deviations have a practical limit; deviations exceeding that limit are unlikely.

The conclusion is that preventing an HS element failure requires scheduled preventive repairs at a time that the failure probability begins to rise:

\[ T_{re} \geq T_x - 3\sigma_x, \]

where \( T_{re} \) is the HS element service life between repairs.

Repairing before or after that specific timepoint is impractical. In the former case, repairing means under-utilization of the HS element resource; in the latter case, the structure will run unsafely, which is not acceptable [17].

Therefore, it is a system of scheduled preventive repairs that must be fundamental to adequate HS operation [18]. Repairs are scheduled depending on the durability of the element that features the least time between repairs; each scheduled repair of that element will involve repairing other elements that have approached their scheduled repair time [19,20]. Thus, each scheduled repair of a building implies repairing a set of elements, each time different.

4. Conclusions
The paper dwells upon the basic methods of operating a low-head hydraulic structure in such a way to optimize its operation, ensure healthy condition and appropriate safety over the entire standard service life (life cycle). Analysis of results shows that fail-safe reliable operation of hydraulic structures requires pre-scheduled repairs and adjustments.

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