Engineering substantiation of the need to strengthen the operated concrete hydraulic structures

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Abstract. The issue of strengthening the concrete high-pressure hydraulic structures in operation is considered.

Introduction
Much attention is paid to the issues of ensuring the hydraulic structures safety in the Russian Federation and in the world. Federal Law of 27.07.2010 No. 225-FL “On Compulsory Insurance of Civil Liability of the Dangerous Facility Owner for Damage resulting from an Accident at a Dangerous Facility”, all the hydraulic structures listed in the Russian Register of Hydraulic Structures are classified as dangerous. Special requirements are legally enshrined at all stages of the life cycle for hydraulic structures of I and II classes, classified in accordance with the Article 48.1 of the Urban Planning Code of the Russian Federation as particularly dangerous, technically complex and unique (for structures with a height of more than 100 meters). When designing, it is necessary to undergo a state examination of design documentation and engineering survey results (Article 49 of the Russian Federation Town Planning Code), with simultaneous scientific and technical support and independent design control carried out by an organization other than the one having developed the project (Interstate Standard for the reliability of building structures and foundations (GOST 27751-2014) p. 10.5, 12.4); during the construction - regular state construction supervision carried out by the authorized federal executive body of the Russian Federation; during the operation - the annual control and surveillance activities, and for the hydraulic structures of class I the regime of continuous state supervision (Decree of the Russian Federation Government dated 05.05.2012 No. 455 "On the regime of constant state supervision at hazardous production facilities and hydraulic structures".

Methods of research
For facilities which violation or interruption of their functioning may lead to a decrease in the life safety of the population, Federal Law dated 21.12.1994 No. 68 "On the Protection of the Population and Territories from Natural and Technogenic Emergencies" defines a separate category - a critically important object. Such facilities, which obviously include all the hydraulic structures of classes I and II, as well as the individual hydraulic structures of class III, also have special requirements for anti-terrorist protection.
– The above-mentioned requirements are primarily associated with serious risks of irreversible consequences for various sectors of the economy in the event of an emergency. An accident at a
hydraulic structure related to a breakthrough of a pressure front can lead to harm to the life and health of citizens, public and private property, as well as to a significant decrease in the life safety of the population.

- It should be taken into account that during the life cycle of a hydraulic structure, several stages are distinguished:
  - the process of improving the technical properties and increasing the strength characteristics of concrete due to the ongoing cement hydration while reducing resistance against the external factors’ negative effects background;
  - upon reaching the equilibrium, in the future there is a process of significant deterioration of the individual concrete zones’ state with a significant area and local decrease in concrete resistance.

The most urgent circumstance leading to a change in the static hydraulic structure work is the non-monolithicity of the dam’s pressure profile associated with crack formation in the construction and operational periods. The various configurations cracks presence on the pressure side, together with the long life of the structure, negatively affects the stress-strain state of the dam-base system and can lead to the pressure front breakthrough with irreparable damage to human life and health, the environment and physical objects, located in the downstream.

The main reasons leading to the hydraulic structures concrete structures destruction be attributed to the unsatisfactory quality of the engineering surveys complex (engineering-geodetic, engineering-geological (hydrogeological), engineering-hydrological), errors in the design and calculation of strength and stability (wrong choice of type constructions, materials for concrete, its class and brand), as well as deviations from the project and defects in the work performance.

As a rule, the aforementioned shortcomings manifest themselves in the first stages of the construction and reservoir filling or in the first years of the hydraulic system operation. As an example, we consider the destruction of the arch-gravity dam of St. Francis (59 meters height). Built in 1927 for the purpose of water supply, the St. Francis Dam collapsed after filling the reservoir for 1 year and claimed the lives of 600 people.

According to the accident investigation’s results, the presence of an inactive fault that was not taken into account at the dam base, which was set in motion due to the intensive filtration processes, was established.

The Malpasse arched dam 59 meters high, built in 1959 in France for irrigation purposes, was also destroyed during the first reservoir filling. As in the first case, the cause of the accident was the flaws in the base soil properties study, which led to uneven sediments of the dam, the appearance of through cracks and the formation of a breakthrough wave subsequently. As a result of the hydrodynamic accident, 423 people died.

An example of an accident caused by unaccounted for external influences is the accident at the Vajont Dam. The arched concrete dam, 261.6 meters high, was built in Italy in 1961. In 1963, a mountain massif collapsed in the reservoir, as a result of which the displaced volume of water poured over the structure with partial destruction of the dam crest and claimed the lives of 2 to 3 thousand people, according to various estimates.

Despite the emergence of modern mathematical methods for calculating the stress-strain state of engineering structures, newly designed and the constructed structures, as practice shows, are also at a certain risk of an emergency (pre-emergency) condition due to possible flaws (errors) during engineering surveys, design, and implementation of construction works.

Discussion
The problems of predicted the crack formation (non-monolithicity) in dams (in contrast to the above examples of the occurrence of emergency defects) were considered in various theoretical and practical (related to field observations) works. In the practice of design and construction of hydraulic structures the following features can be distinguished:

- temperature cracking associated with laying a large volume of concrete in concrete blocks and failure to take measures to reduce the cement hydration heat;
disclosure of intercolumn joints due to low-quality cementation;
- cracking under the action of external loads during the reservoir filling and the hydraulic structure operation;
- concrete destruction due to the chemical reactivity of the aggregate;
- opening the contact zone of the dam-base system.

Figure 1. The main types of cracks. 1 - the contact “concrete-rock” disclosure, 2 - operational cracks, 3 – the horizontal construction joints’ disclosure, 4 – the inter-column joints’ disclosure.

Despite the adoption of a set of preventive measures (reducing the cement hydration, heat limiting the volume of concrete blocks, excluding zones with tensile stresses), it is not possible to prevent (minimize) the cracks appearance in concrete during construction and subsequent operation. As an example, we turn to the field observations on individual large concrete dams [1].

Table 1. The number of cracks in high-pressure concrete dams

| The construction name                        | Maximum height, m | Number of cracks (visual examination) |
|----------------------------------------------|-------------------|---------------------------------------|
| Arch-gravity dam on the Yenisei River         | 242               | 5851                                  |
| Gravity dam on the Angara River               | 125               | 3763                                  |
| Gravity spillway dam on the Angara River      | 105               | 1524                                  |
| Gravity dam on the Yenisei River              | 128               | 1289                                  |
| Arched Dam on the Sulak River                 | 232.5             | 956                                   |
| Arch Dam on the Inguri River                  | 271.5             | 827                                   |
| Massive buttress dam on the Zeya River        | 115.5             | 500                                   |

Despite the fact that the cracks presence in pressure structures at the initial stage does not always indicate an unsatisfactory state of the stress-strain state of the dam, it should be taken into account that during the operation, the cyclic loads associated with changes in the outside temperature, partial reservoir discharge (filling) lead to increase the width of the cracks opening with the growth of their geometric dimensions. In some cases, these circumstances can lead to a total change in the deformed state and redistribution of volumetric stresses in the body of the concrete dam and lead to irreversible consequences.

The crack systems appearance urgency problem in pressure concrete hydraulic structures (including as a result of seismic effects) is also confirmed by the information regularly published by the US Committee for Large Dams (USCOLD) [2, 3, 4].

The scientific works analysis showed that there are a number of theoretical technical solutions for reinforcing concrete dams at present, which can conditionally be divided into structural and technological. Structural solutions include a change in the transverse profile of the dam (Figure 2),
arrangement of notch seams (Figure 3), compression of the upper face by the prestressed anchors, extension of the crest mark, etc. [5, 6, 7, 8, 9, 10]. Technological solutions include regulating the temperature regime of the structure (including regulating the closure temperature for arched type dams), as well as comprehensive optimization of the building cycle, taking into account the optimal combination of the construction and loading sequences [11, 12].

![Figure 2. A constructive solution to optimize the arch dam.](image)

1 - existing arched dam, 2 - buttresses.

![Figure 3. The device of the seam in the rocky base.](image)

1 - existing concrete dam (gravity, arched, etc.), 2 - notch seam.

There are also some examples of strengthening (repairing) the damaged dams [13]. The 200 m high Cologne arched dam, was built in Austria from 1971 to 1979. During the period of the second stage of filling the reservoir, due to an increase in compressive stresses, the damage requiring restoration work was recorded on the lower face (Figure 4).
The additional drainage device and the damaged surface cementation, proposed in the first stage, did not solve the problem of cracking. To eliminate the defects, it was necessary to carry out some capital measures with strengthening the dam. The engineering team proposed four options for optimizing the design (Figure 2).

After the feasibility studies, a persistent concrete prism was installed in the structure downstream (option 4), which made it possible to redistribute the forces arising on the lower edge of the arch dam from hydrostatic loading and prevent the crack systems’ re-emergence.
The Fontana Gravity Dam 150 m high, was built in the USA between 1942 and 1944. For the first time, the damage on the lower edge was recorded in 1949. Studies have shown that a system of cracks was formed due to the thermal expansion of the concrete mixture during the construction, as well as the alkaline aggregate reaction, accompanied by an increase in concrete volume with the development of additional stresses.

As a solution for dam optimization, compression of the transverse profile by prestressed anchors was taken (Figure 3). A similar solution was used to compress the Koyna gravity dam (India) and the Xinfeng Jiang buttress dam (China), which were damaged by the earthquake.

It should be noted that the anchoring of existing structures with compression of the required area can be very effective, especially from the point of view of the possibility of regulating the stress-strain state during operation.

![Figure 6. The solutions for anchoring the Fontana gravity dam. 1 - inspection gallery, 2 - existing crack, 3 - anchor rods.](image)

As follows from the above examples, the proposed options for strengthening exploited concrete dams are feasible only if the technical feasibility of full (partial) operation of the reservoir in the upper pool for the possibility of construction and installation works.

**Summary**

Based on the foregoing, taking into account the annual increase in the risk of an emergency (due to the long-term operation of facilities), as well as in connection with existing regulatory legal acts regulating the need for reconstruction of hydraulic structures related to the changes in external factors, the following conclusions can be made:

1. The need for the development and numerical analysis of solutions for strengthening exploited concrete dams was confirmed, which may be due to the following circumstances:
   - errors (deficiencies) arising on one of the life cycles of the hydraulic structure existence - the design implementation estimates (including engineering surveys), design, calculation of strength and stability, construction and installation works;
   - long-term operation in the cyclic mode of the main loads (hydrostatic pressure, temperature effect), negatively affecting the strength characteristics of concrete structures of the hydraulic structures;

2. The relevance of the operated concrete dams strengthening the structures issue, including the arched ones, which are technically and technologically complex spatial structures, the most susceptible...
to changes in external influences, is substantiated.

3. The need for the constructive and technological solutions’ development for optimizing the stress-strain state of the exploited concrete dams as well as for conducting the numerical studies of the reinforcement solutions effectiveness for individual types has been proved.

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