Issues of Enguri Arch Dam Bottom Outlet Structure

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Abstract

Enguri HPP high-pressure outlet is equipped with service and maintenance gates, which are installed in cantilever part of the arch dam (downstream). With the view of ensuring the protection of the chamber casing from the velocity flow influence (cavity resistance) and reduces the dynamic loads on the arch dam the maintenance gates designed with accompanying ring. During operation bottom outlet, due to disruption of water tightness of maintenance gate chamber casing and leakage developed in the concrete, the steel plate of the casing of service gate chamber was disconnected from the reinforced concrete diaphragm and was deformed in direction of the gate. This hampered the gate operation, also caused the redistribution of loads and worsened the strength conditions of the cantilever.
This report includes some results of dam cantilever strength analysis during operation (chambers service gates water tightness loss).

Keywords: high-pressure bottom outlet, sealing, water tightness, cracking, strength margin.

Introduction

Enguri HPP high-pressure outlet (Fig. 1,2) is unique in the world by both its structure and parameters, which had been designed as follows:

- 7 outlets (4 were considered for water discharge, 3 – for pumped-storage power station) are located on the same elevation;
- diameter of each outlet is 5.0 m;
- at 181m head the design capacity of each outlet is 750 m3/s.

The high-pressure outlet includes: the maintenance stoplog (with embedded details); 8.2/5m diameter transition section; steel pressure pipeline; themaintenance gates with accompanying rings (dimensions 11355 x 6200mm); service gates; chambers of the maintenance and service gates (Fig. 3). The maintenance and service gates are installed in the special chambers in the cantilever part of the dam (Kochanov, 1981).

The function of the maintenance gates is to dewater the chambers during maintenance or failure of the service gates. The gate closes the pipeline and is under 40 mN load at 181m head. The casing of the gates is made of 30-40 mm steel sheets, which transfer the loads from the gate to the cantilever and provide protection of concrete from leakage and velocity flow influence.

During lowering of the maintenance gate, the accompanying ring goes down in the lower part of the chamber (7.6m depth) and the upper part of the gate closes the pipeline.

When raised, the accompanying ring of the gate is positioned on the outlet opening. Thus, by using the accompanying ring (D=5.04m), the circular section of the flow keeps its constancy.

Figure1. *Enguri HPP arch dam*

Figure 2. *Enguri HPP high-pressure bottom outlet*

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The accompanying ring fully ensures protection of the chamber casing from the cavitations and reduces the dynamic loads on the arch dam.

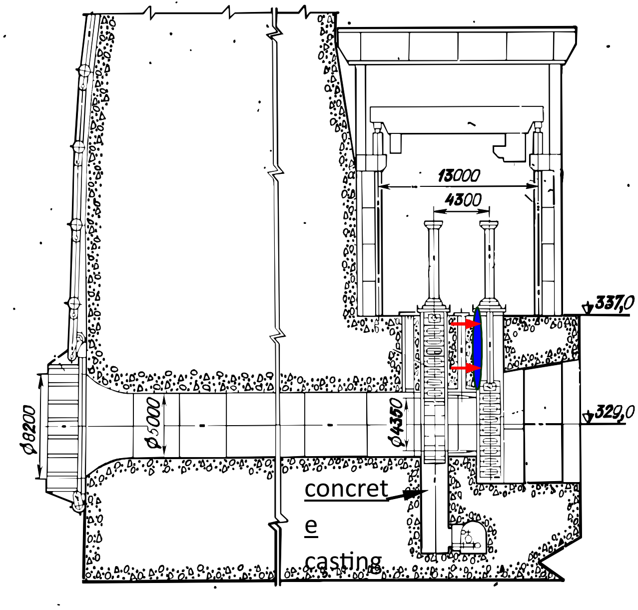


Figure 3. *Longitudinal profile along the outlet axis*

The design considered two-side tightness of the accompanying ring. Only upper sealing operates in the condition of closed gate.
Unfortunately, distortions from the design dimensions of the casing of the maintenance gates was made during concreting and installation of high-pressure outlets. Due to the above mentioned, the sealing from the downstream could not be installed. Therefore, when the service gate is in closed position, the chamber of the maintenance gate is permanently under pressure and 210 mN load is applied on the cantilever part, whereas the design allows such load only for 40 minutes. During such periods the loads on the dam cantilever are increased twice. During operation the upstream polyethylene seals have been damaged almost on all pipelines.

Restoration of design parameters of the gate requires the full modification (decreasing of thickness etc.) of the gate, which is almost impossible. The special diaphragm was installed in the outflow part of the outlet, which decreased the water flow (to 465 m3/s), flow velocity and risk of cavitations in the body of the maintenance gate. As a result of these arrangements, existence of the accompanying ring became unnecessary.

The decision to modify N.17 outlet was made in 1989. These modifications included cutting of accompanying ring of the maintenance gate and concreting lower part of the chamber. As a result of these modifications, the load on the cantilever was reduced to 1.35 mN.

Research Methodology

Dam cantilever stress state analysis

This report includes some results of dam cantilever calculations and strength analysis:

- during normal operating conditions (gate seals are working properly);
- during abnormal operating conditions (assessment of crack resistance of the structure when pressure is applied on the maintenance and service gate bodies);
- during later stage of operation with crack and seepage pressure in the reinforced structure of the cantilever.

The failure and abnormal operation conditions of N17 outlet necessitated an assessment of stressed condition and strength margin of the cantilever. For this purpose the structure was calculated within the 3D model of elasticity theory, using the isoperimetric elements (fig. 4) (Bathe, 1976).

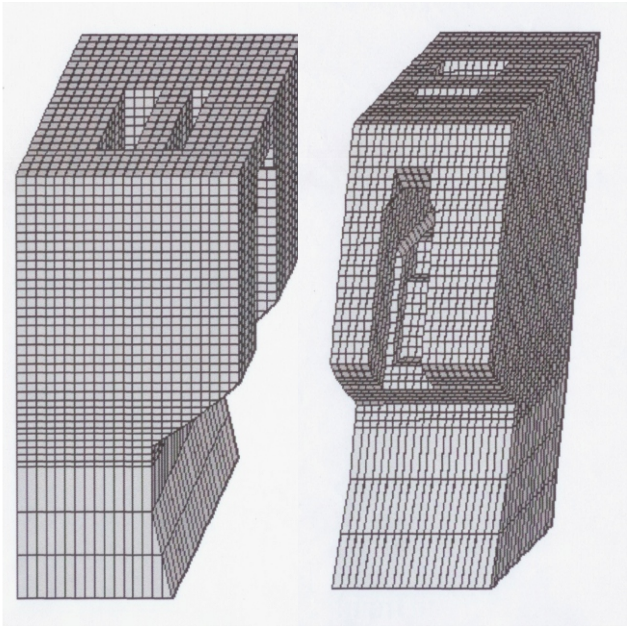


Figure 4 *Calculation scheme of cantilever part of*N17outletThe main bearing steel bars of the cantilever was considered according to the specific parameters (elasticity modulus and stress):

$$\begin{cases} E_{Rs} = E_{R0} \dfrac{S_{R0}}{S_{cs}} \\ \sigma_R = \sigma_{RS} \dfrac{S_{cs}}{S_{R0}} \end{cases}$$

where$_{0R}E$,$_{Rs}E$; $_{0R}S$,$_{cs}S$; $_{R}\sigma$, $_{RS}\sigma$ are initial and specific values of the elasticity modulus, cross section and stress respectively.

Crack resistance analysis

The assessment of crack resistance of the reinforced concrete structure was made with the following condition (Berezinski and Banthia, 2002):

$$n_c\sigma_c \otimes [R_c]$$

where $_{c}n$ is factor of overlapping of loads, $_{c}\sigma$- stress in the concrete, $][_{c}R$ - normative tension strength of concrete; $][_{c}R$=2600 kN/m2 .

Cracking assessment was carried out by using the theory of fracture mechanics.
Limiting state of crack occurs when performed the condition (Hilton, 1973) :

$$K_I \quad K_{IC}$$

where KI, KIC are design and critical values of stress intensity factors respectively.

Failure analysis of the chamber N17 outlet service gate

The water loss was 25m3/s during operation (in 2006, at 500m reservoir level) due to damaged sealing along the most part of the perimeter from upstream face of the maintenance gate. After lowering the service gate (with temporary rubber sealing), the water loss was reduced to 3 m3/s. In this moment failure occurred - suddenly water flow increased with accompanying strong noise.
Inspection of the service gate chamber revealed (Fig. 5) that:

- the steel plate of the chamber was disconnected from the reinforced concrete and bent by 4.5cm ;
- 2 steel installation plates, which were installed in 1989 during concreting of the bottom part of the chamber were removed from the upstream face of the maintenance gate chamber, and steel surface on the sealing side was very cavitated;
- the rubber sealing of the service gate was also broken (this increased the water flow).

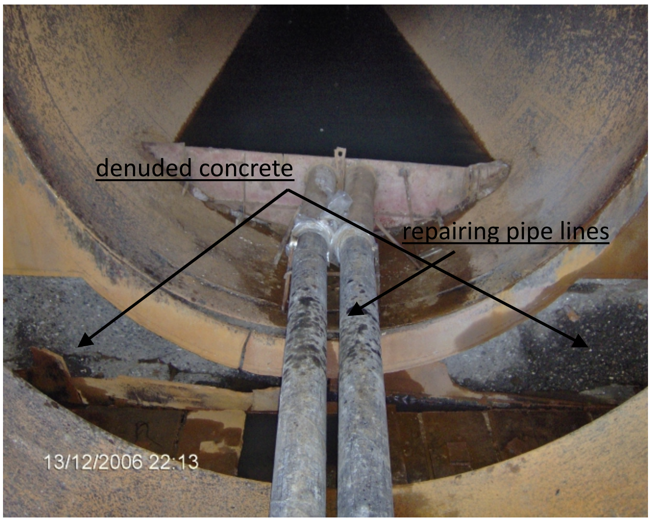


Figure 5. *The damaged casing of the chamber ofNo.17 outlet maintenance gate*

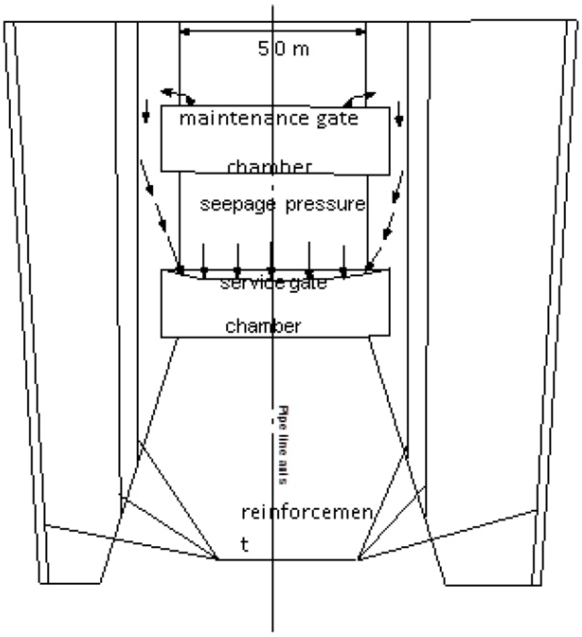


Figure 6*Bottom outlet section*

Therefore, the analysis of the inspection results has shown that due to high turbulence of the flow in the maintenance gate chamber, the plates had been broken, which caused disruption of the chamber water tightness and reinforced concrete structure of the cantilever appeared under pressure. The pressure was applied on the service gate chamber, on the chamber casing and concrete contact or through the cracks in the concrete (Fig.6). Finally, the ribbed steel plate was disconnected from the reinforced concrete diaphragm, bent and remained fixed only on perimeter (Fig. 2, 7).

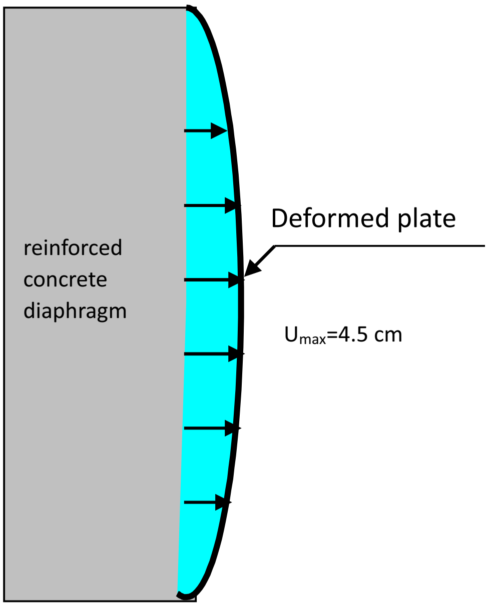


Figure 7.*Separation of the metal plate on concrete diaphragm under the influence of seepage pressure*

The theoretical calculations of the chamber plates (considering initial 4.5cm value of plate bending) have shown that at 500m reservoir level (H=170m) the load on the steel plate reached 630mN critical value, and the tension stresses of the reinforced diaphragm and plate contact reached 4.5 x 105 kN/m2 which exceeds the failure limit of the steel. Finally, in the steel plate calculating stresses (by von Mises) at maximum level (510m, H=181m) reached 5604 kN/m2 (Fig. 8).

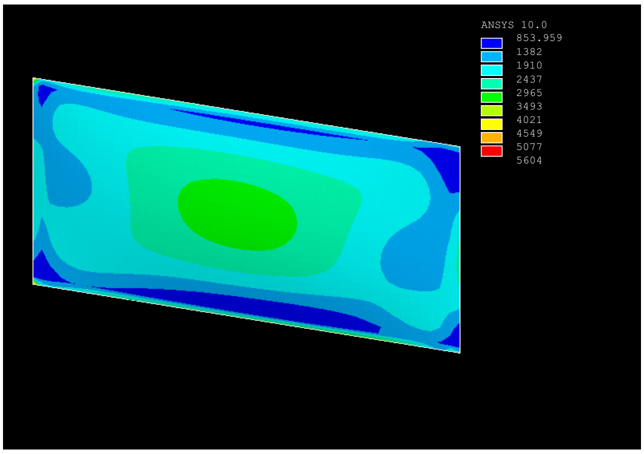


Figure 8 **Stress-strain state (by von Mises stress) of the steel plate (service gate chamber).**

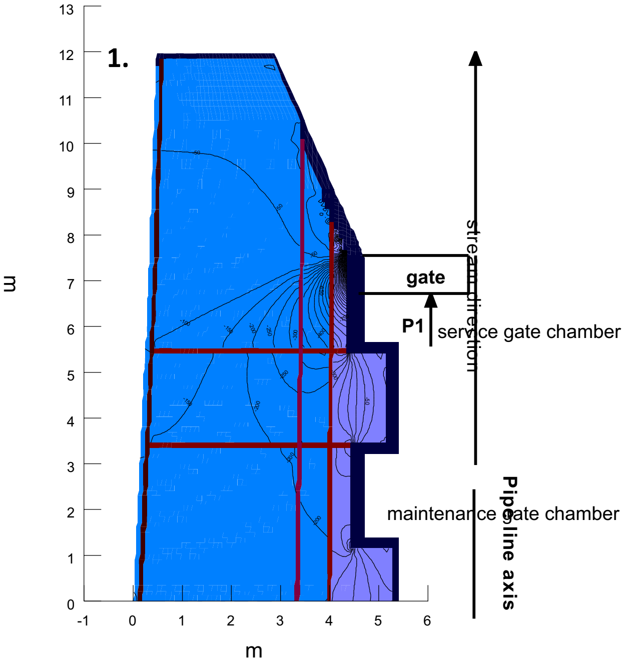
Assessment of crack resistance

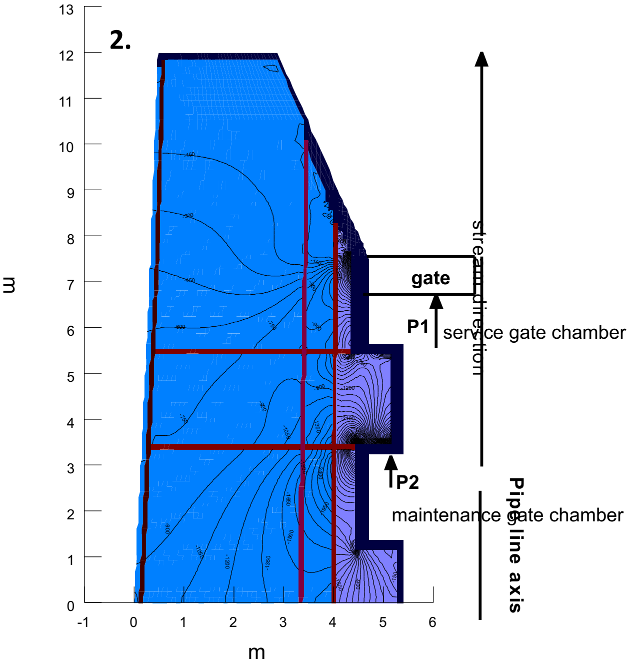
The strength analysis of the cantilever was made for different operation modes, including recent failure case with broken water tightness of steel casing of the maintenance gate chamber and with seepage pressure (H=181m) in the cracks of the concrete. Therefore, the calculation cases are (fig.13:

1. The service gate is closed and all seals work properly (normal operation). During this period only loads (P1=355.2mN) acting on the gate are transmitted to the service gate chamber;
2. The service gate is closed and sealing of the maintenance gate chamber is broken. During this period the additional load P2 = 1744.8 mN, along with load P1=355.2 mN, is transmitted to the maintenance gate chamber;
3. The service gate is closed, the chamber water tightness is disrupted and the pressure is applied on the service gate chamber, which causes failure of the casing steel plate. In this case on the chamber casing is applied one more additional P3 load (corresponding to area of disconnected plate), which at maximum water head equals P3=651.6 mN. In this moment the diaphragm between the maintenance and service gates is partially unloaded. Thus, loads P1 and P3 are applied on the service gate casing.

The results for calculation cases are the following (fig. 9, 10, 11, 12 4.1.1, 4.1.2, 4.1.3, 4.1.4):

1. In normal operating conditions the maximum tension stress in concrete does not exceed 500 kN/m2;





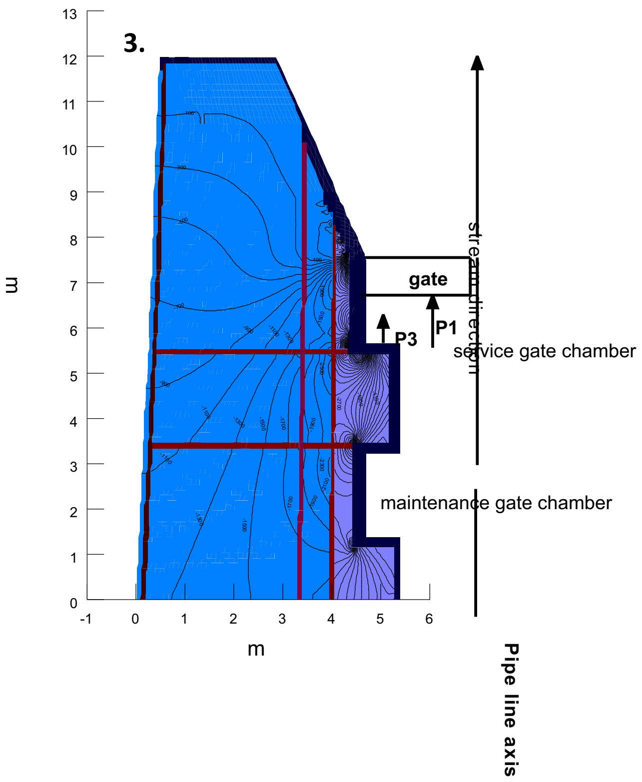
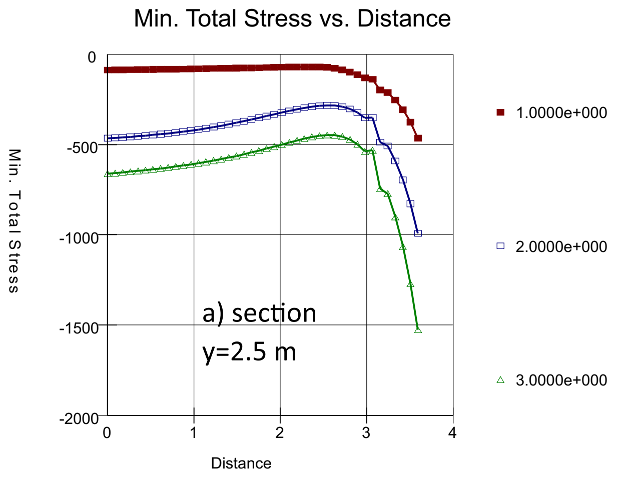
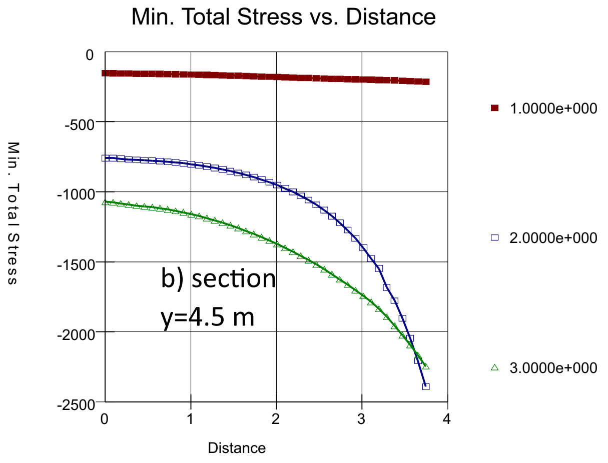


Figure 9: Tension stresses in cantilever structure (on pipeline axis) with consideration of reinforcement 1., 2., 3. calculation cases





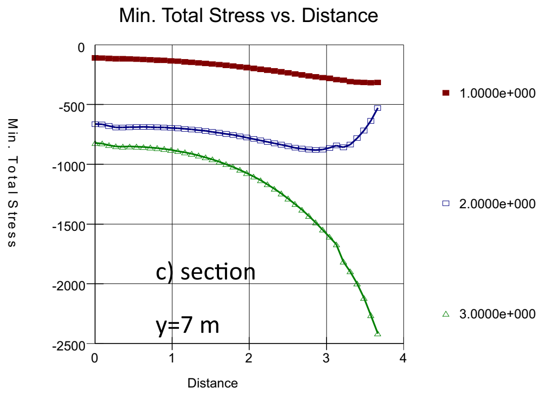


Fig. 10 a), b), c) Tension stresses in cantilever sections for 1., 2., 3. calculation cases.

1. In the condition of pressure influence on the maintenance gate chamber the maximum tension stress is 2400 kN/m2;
2. In the condition of pressure influence on the service gate chamber from the concrete side the tension stresses are 2450 kN/m2 due to increase of stress concentration;

- the maximum stress in the main reinforcement does not exceed 2.1 x 104 kN/m2 (Fig. 12).

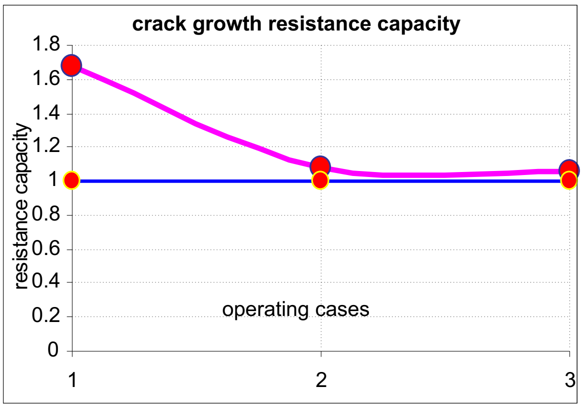


Figure 11 ***Crack resistance margins for different calculation cases***

Thus, in 2 and 3 calculation cases the strength margin was considerably reduced (fig. 9) in comparison with normal operating conditions, which makes practical grounds for crack development not permitted by the design. It has to be mentioned that in case of crack development in the concrete of the cantilever structure, the loads are transmitted to the reinforcement, which has high strength margins. However, the risk of developing the pressure in the cracks of the concrete, which increases the loads on the structure, is increased in case of break of gate chamber water tightness.

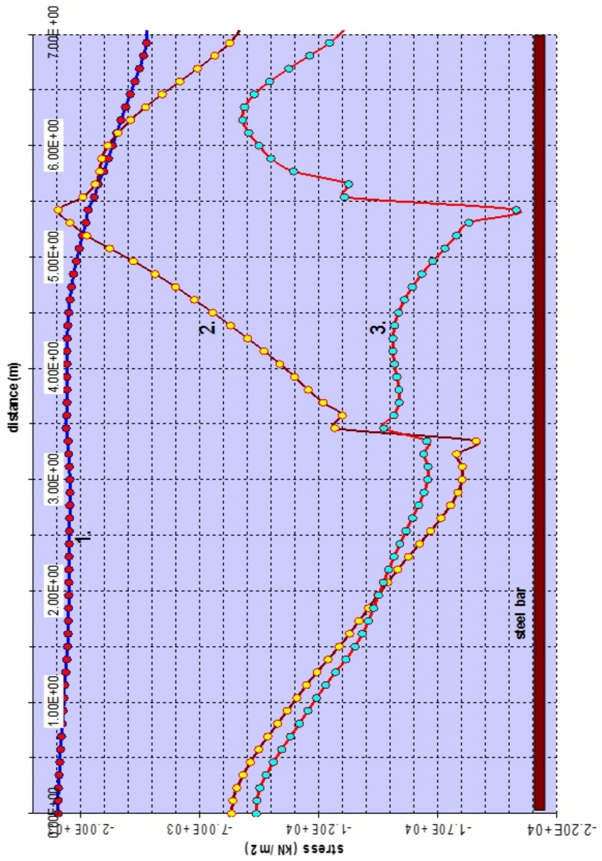


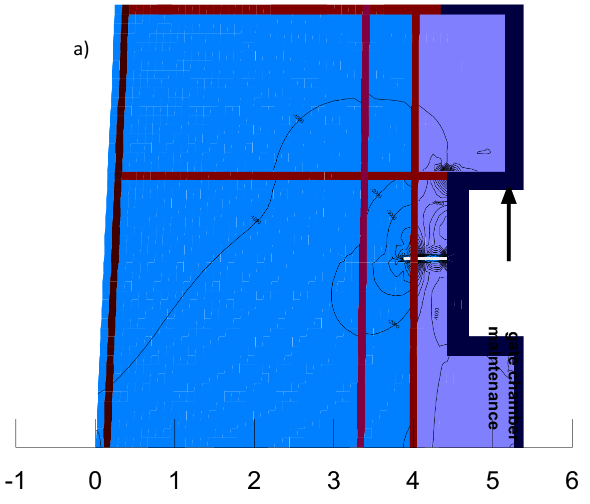
Figure 12. ***Tension stresses in main reinforcement for 1., 2., 3. calculation cases***

Cantilever strength assessment in case of pressure development in the cracks

The assessment of the strength margin of the cantilever was made for the case that can take place after rehabilitation, namely:

- the lower part of the chamber is concreted, the service gate is closed and water tightness of chamber is disrupted;

- there is a crack (with hydrostatic pressure) perpendicular to cantilever reinforcement (crack resistance of concrete is broken).



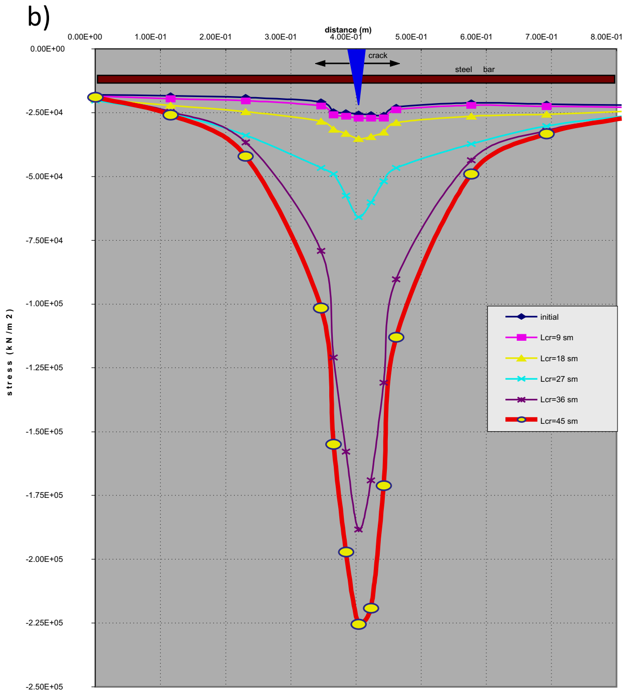


Fig. 13 Tension stresses propagation in the vicinity of cracks: a) in the cantilever structure with critical length (Lcr=45cm) crack; b) in the main reinforcement with gradual increase of crack length.

On the basis of fracture mechanics it was defined thatwhen operation loads are applied, the condition for crack development KI > KIC (where KI, KIC are design and critical values of stress intensity factors respectively) is fulfilled in the crack existing in the concrete. Thus, in case of crack development in cantilever structure, the strength depends only on the bearing capacity of steel reinforcement.

The iterations have been carried out, which considered the crack with increased length ($cmL5=\Delta$). It was defined that the crack with Lcr=45cm is critical and at this time the tension stresses reach the design tension strength of steel][$_R R$=2.7 x105 kN/m2 (fig. 4.2.1).

Conclusions

- During concreting and installation of the arch dam high-pressure bottom outlet, the actual dimensions of the maintenance gates chambers were distorted from the design dimensions. Due to the mentioned issue, the sealing has not been installed in downstream. As a result, when the service gate is closed, the 210mN load is constantly applied on the dam cantilever, while design allows such load only for 40 minutes. For this reason, the loads applied on the dam cantilever are increased almost twice.

Due to improperly implemented (in 1989) installation works of No.17 maintenance gate chamber and high turbulence in the chamber, the installation plates were disconnected and water tightness of the chamber was disrupted. As a

- result of influence of seepage pressure (developed in the concrete) on the chamber of the service gate, the chamber plate was disconnected from the reinforced concrete diaphragm and bent, thus hampered the gate operation. The above mentioned also indicates the existence of various cracks in the concrete. At this time stresses are redistributed – reinforced concrete diaphragm is partially unloaded and the loads on the service gate chamber are increased.

- Breaking of normal operating conditions of the cantilever is caused by development of high pressure on the chambers of the maintenance and service gates, which considerably increases tension stresses in the cantilever and disrupts the crack resistance of the cantilever concrete.
- In the later stage of operation, in case of breaking of water tightness of the maintenance gate chamber casing, the influence of seepage pressure (which was actually revealed) in the cracks of the structure considerably increases the loads on the cantilever. According to the calculation results, the strength margin of the reinforcement bars is exhausted in case of development of 45 cm pressure crack in cross direction of the cantilever, which makes real risk of structure failure. It has to be mentioned that during reservoir operation the cantilever is also influenced by the vibration.

Considering the inspection results and inability to install the seal between the maintenance gates and chambers, it is necessary to concrete the lower parts of the chambers of the remaining outlets in order to ensure safety of the dam. In

- addition, the water tightness of the chamber should be ensured.
- For comprehensive study of the problem it is necessary to measure the vibration parameters, calculate the frequencies of the cantilever shaking during operation period and assess the cantilever stability, which represents the next stage of the study.

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