CRACK FORMATION PROCESS IN ARCH DAM FOUNDATION

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This report presents theoretical solution and analysis of stress state and correspondingly seepage process in arch dam tectonic foundation. Such as demonstrative object is represented Enguri HPP arch dam.

Foundation of Enguri HPP dam (height of 271.5 m) has complex geological structure. The bedrock consists of carbonate rock strata of Lower Cretaceous stage, represented by non-uniform, strongly fissured limestone and dolomite. The rock massif is layered with clayey marl at every 40-50 m of depth, with the thickness of the layers ranging from 3-10 cm to 50 cm. This rock actually screens the seepage flow and strengthens the anisotropy of the foundation. There is a 120m-deep grout curtain and drainage arranged on the entire perimeter of the gorge, which play a role in the seepage regime in the dam foundation.

In the dam operation period, the seepage pressure significantly increased behind the grout curtain in the central section, and the pressure dynamics can be tracked back as follows: the first peak occurred in 1989, followed by a certain drop, and then a rise again. Therefore the area was assessed as an anomalous one. Since 1999 to date, when the cracks started to fill with mud, the seepage pressure behind the grout curtain has restored to normal regime parameters.

According to general evaluation, processes ongoing behind the grout curtain are linked to the existence of tensile stresses in the tectonic foundation of the dam, potentially followed by opening of the cracks, damaging of the curtain, and then mud filling of the cracks.

In 2006-2007, grout curtain and drainage rehabilitation works were conducted in the frame of a rehabilitation program, which resulted in reduction of seepage discharge in the dam galleries.

This study aimed to evaluate the anomalous seepage and its causes in the central part of the dam foundation. For this purpose, the study consisted of:

- *Analysis of foundation's static stress state and current seepage processes, taking into account the grout curtain behavior, both independently, and together with the drainage, during reservoir filling/emptying (as part of unsteady regime);*
- *Evaluation of crack development in view of decreased pressures and friction resulting from the crack mud filling process).*

The static and seepage analyses have been conducted using a 3D Finite Element Model of the dam-foundation, whereas crack development was evaluated using 2D models based on fracture mechanics approaches. This report presents some results of the study.

Introduction and Background

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1. Geological Structure and Seepage Characteristics of the Dam Foundation

The dam foundation has rather complex geological structure (fig. 1.1, 1.2). There are anticline strata in the central part of the foundation that consist of least permeable soils. A low-permeability breccia stratum located 150m upstream from the dam continues along the existing layers in the foundation, and spreads for 200 meters from the dam base. Thus, the seepage flow sharply narrows at the lower border of the grout curtain, resulting in additional flooding of the rock massif located in front of the curtain, which causes increased readings in piezometers located there. There are tectonic faults in the base that are filled with clayey material and screen back the seepage flow, which explains the difference in readings between piezometers located at some distance from each other.

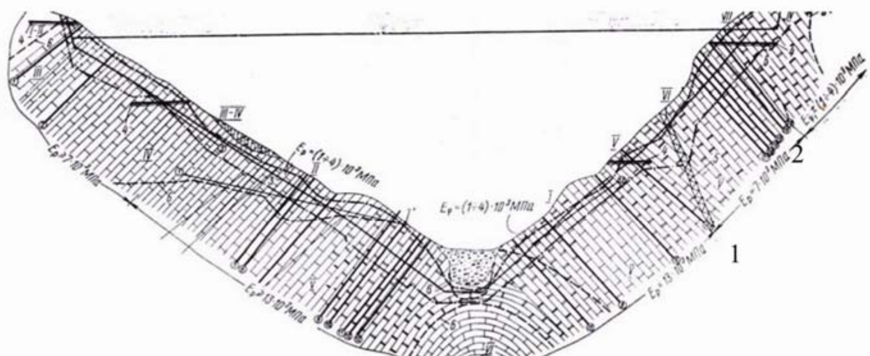

fig. 1.1 geological cross section.
1-major geological fracture; 2- geological cracks.

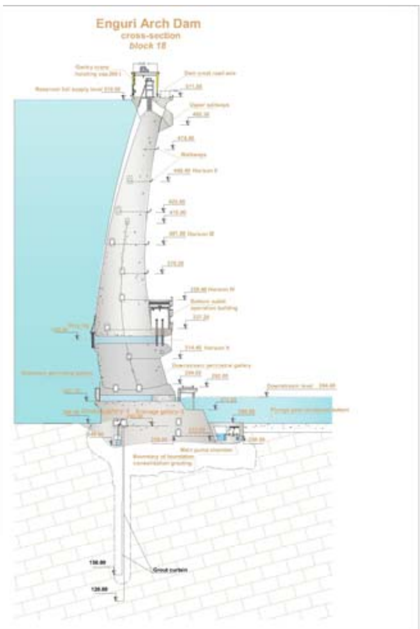

figure. 1.2 Dam central section

A comparatively comprehensive analysis of the seepage regime in the dam foundation is possible using measured heads (pressures) in piezometers and seepage discharge measured in grouting adits and galleries. Most of the piezometers are situated in grouting adits, and are mainly located in pairs: in front of and behind the grout curtain.

Monitoring in the foundation after reservoir filling showed progressing chemical and mechanical suffosion (piping). The overall background mineralization of the seepage flow dropped from 1.28 to 0.18 g/l over the monitoring period (1989-1991). Chemical composition of the seepage water is getting similar to that of surface water, which confirms that filling material of seepage paths and cracks existing in the foundation rock is washed out. In the same time, pH increased from 8 to 9.5-11, which generally indicates that concrete leaching is going on [1].

In the period of first reservoir filling (since 1986) when the water level in the reservoir reached 460 meters, there were spasmodic rises of pressures (heads) behind the grout curtain, a trend occurring with increasing frequency compared to previous years (fig. 2). In 1989-1990 (NOL=510 m), monitored pressures in piezometers located in that zone constituted about 80-90 per cent of pressures at the dam, which indicated that the grout curtain was damaged.

2. Dam Foundation Analysis Models

This study reflects only processes going on in foundation in the dam centerline section. The crack development and current seepage analysis was conducted using a 2D model taking into consideration results of 3D stressed state model of the dam-foundation based on static-seepage diagram.

With respect to crack development in the foundation, there is a suggestion that when the reservoir is being emptied, the cracks filled with water under the dam pressure face behave under compressive stress and therefore close. At that moment the pressure in the cracks increases compared to that in the surrounding rock, which causes the crack to widen and develop. It is rather difficult to confirm this suggestion using an empirical model. This study demonstrates a crack development model that shows that in the operation period edges of tensile cracks under the

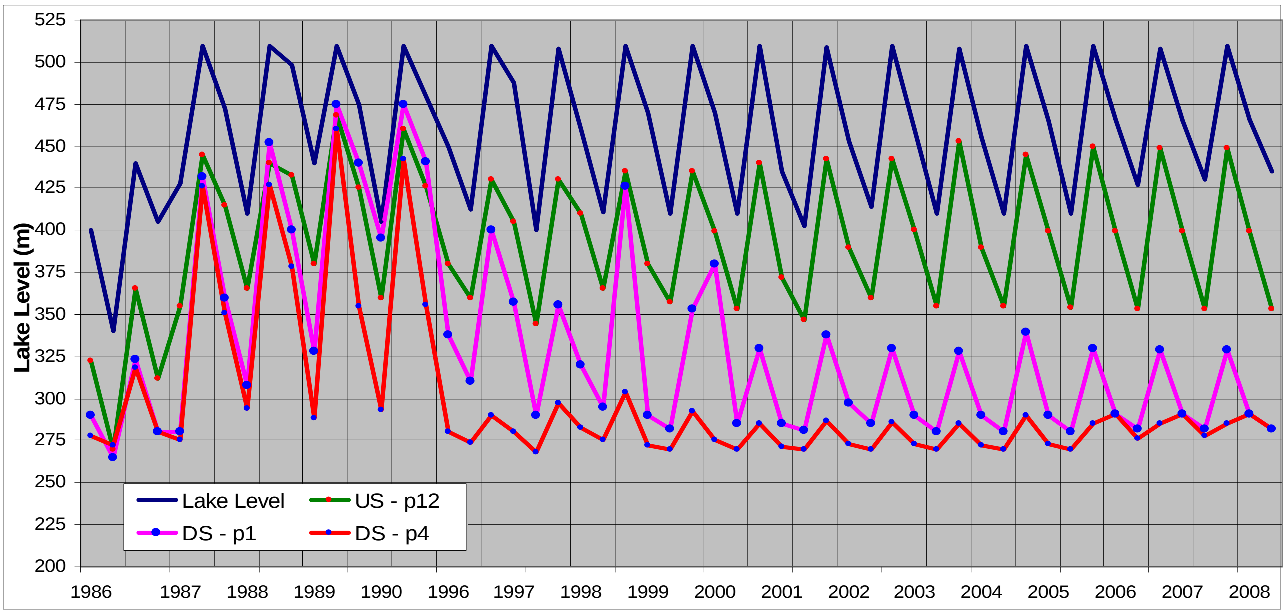

Figure 2. Piezometer pressure distribution:
p1, p4 - behind the grout curtain; p12 - before the grout curtain

pressure dam face are filled and then covered by clayey mud. This increases hydrostatic pressure on the crack surface and decreases friction. When the reservoir is full, the increased pressured inside the crack fosters further cracking, and when the water is at the lowest level, cracks that are subject to compressive stresses (because of low friction on the surface) may also develop further. The fact that the cracks get filled with mud is also reflected in the piezometer readings (Figure 2).

The crack analysis was conducted using fracture mechanics approaches. The crack depth was conditioned by the fact that under the influence of operational loads the value of the normal stress intensity at the end of the crack equaled zero.

The foundation seepage analysis for reservoir drawdown/filling was conducted for nonstationary regime. The foundation FEM reflected main defined seepage factors, including existing non-uniform structure of rock in the depth of the massif, the grout curtain, the screening tectonic faults, and the drainage.

The calculations were made under operation loads (dead load, hydrostatic seepage pressures), in the range between the highest and lowest water levels in the reservoir (510-410 meters).

3. Crack Development Analysis in the Dam Foundation

3.1 Crack Development during First Reservoir Filling

Generally, seepage causes loading of the foundation and crack edges, which is reflected in formula: $p = (1-\alpha_2)\gamma h$ (where α_2 is coefficient of effective backpressure area; γ -is water density, h- is water head pressure). Analysis of sediment close to the dam shows that the sediment mainly consists of mud

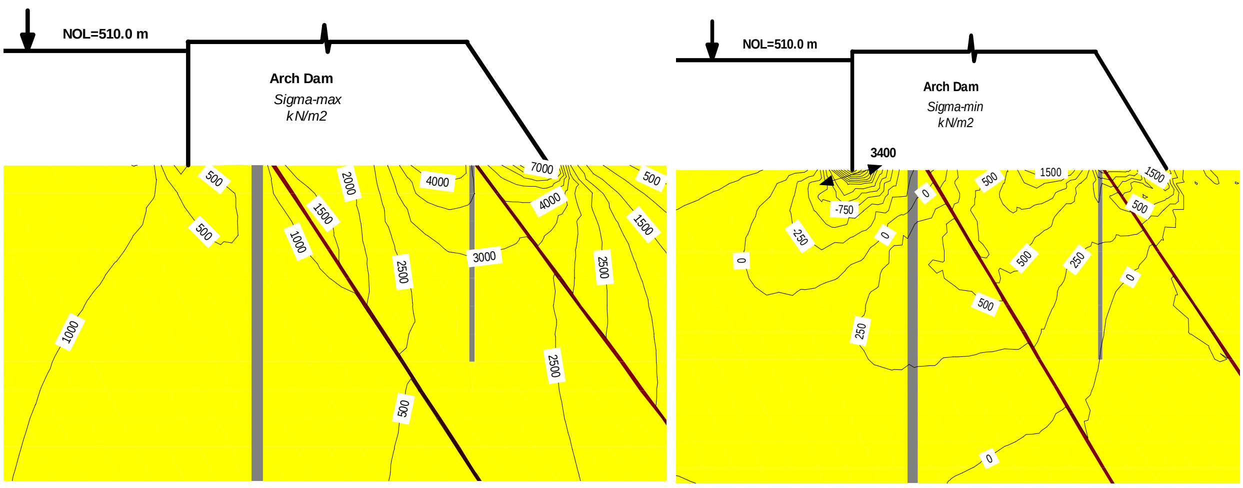

Figure 3. Main stress distribution in foundation of dam central cantilever (according to 3D model).

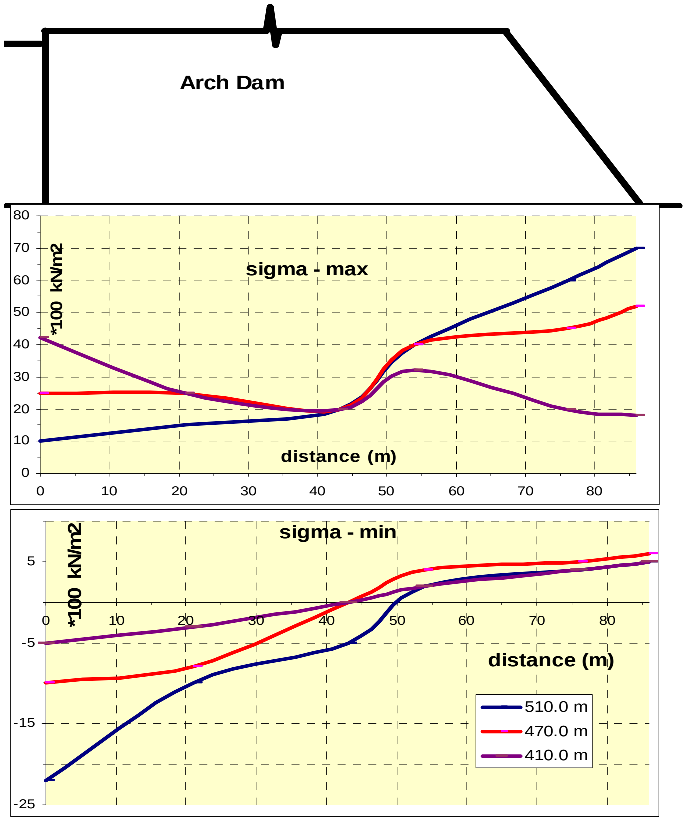

Figure 4. Main stress distribution in dam-foundation contact

sediment particles and causes covering of crack surface, thus decreasing permeability of the cracks α_2 and respectively increasing hydrostatic pressure on crack edges. Piezometer readings confirm that mud filling of cracks is really going on. Crack analysis was conducted in view of the foundation geology (blocks and tectonic faults).

Calculation outcomes are as follows:

- According to the 3D dam-foundation model, there is a wide range of main stresses in the central cantilever section (Figure 4). Tensile stresses penetrate deep into the foundation (Figure 3);
- At the water level of 450 m in the reservoir, opening of the dam-foundation contact zone was registered under the pressure face. In the same time the grout curtain was still strong enough (according to pizometer readings, Figure 2).
- The depth of crack (0-1) reached 7.5 m and its orientation almost followed the dip of strata (figure 9).

3.2 Crack Development during Reservoir Drawdown Low level.

The inclined crack located under the pressure face of the dam (0-1) is subject to high compressive stress during reservoir drawdown (Figure 6), so that the crack shear resistance needs to be investigated. According to Griffith criteria modified by McClintock and Walsh, the critical stress (Figure 5), is defined as follows [2,3]:

$$\sigma_{1,cr} = \frac{-4T + \sigma_2(\sqrt{(1+\mu^2)} + \mu)}{\sqrt{(1+\mu^2)} - \mu}$$

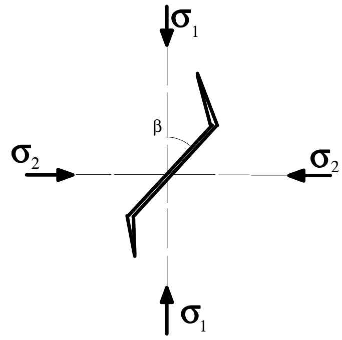

Figure 5. shear crack development scheme

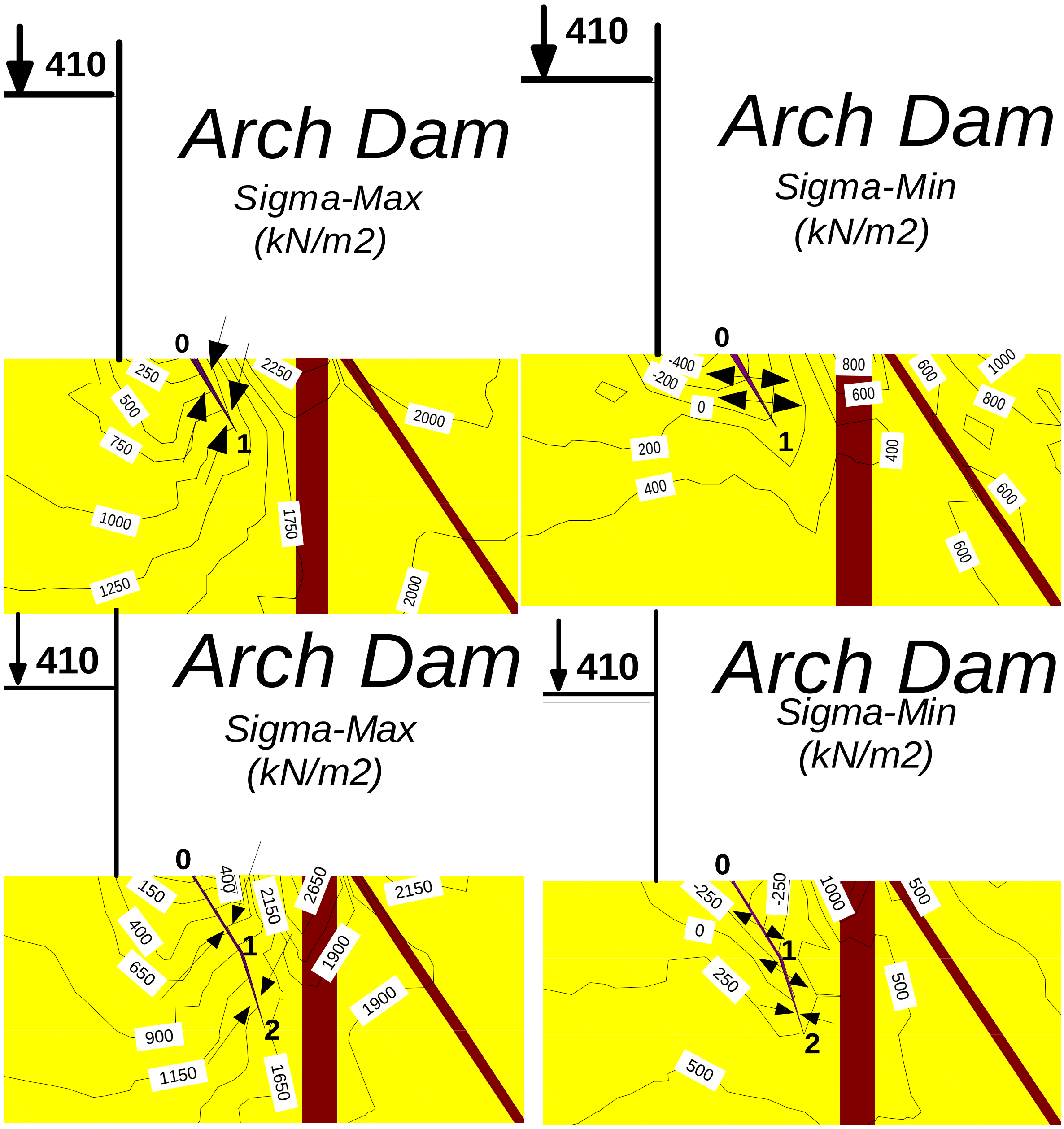

Figure 6. Crack development dynamics in the dam foundation (under compressive stress) during reservoir low level.

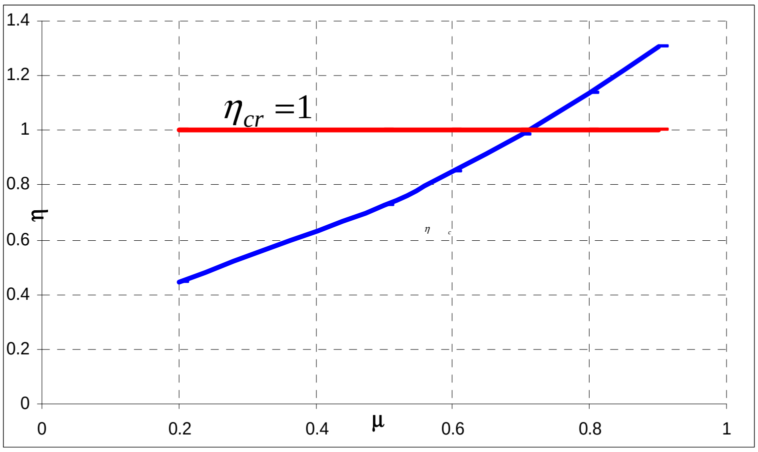

Figure 7. Shear crack stability to different surface frictions

where T - is ultimate tensile strength; σ_2 - is the minimum compressive stress; μ - is cohesion factor in the shear zone.

Cracks can be evaluated using safety factor:

$$\eta = \frac{\sigma_{1,cr}}{\sigma_{1,c}}$$

where $\sigma_{1,c}$ is the calculated value of the maximum compressive stress. If $\eta \succ 1$, the shear crack retains its stability, but at $\eta \le 1$ it starts developing.

Sources [2] and [5] show that the friction factor for concrete and rock ranges within $\mu = 0.6 \div 0.9$. During the mud-filling process the friction decreases on the 0-1 crack surface compared to normal friction conditions. Because of lack of clarity in this respect, the calculations have been made for the range of $\mu = 0.2 \div 0.9$.

The calculations show that in the interval of $\mu = 0.2 \div 0.8$ the safety factor for the 0-1 crack is exhausted (Figure 7). A new crack 1-2 developed almost vertically to the length of 3 meters (Figure 6).

3.3 Crack Development in the Foundation during Subsequent Reservoir Filling

During subsequent reservoir filling, the crack became longer compared to the previous time (0-1-2), and the surfaces were partly covered with mud (as confirmed by peizometer data), which respectively caused decrease of α_2 (Figure 8).

According to standards, the recommended value of α_2 for rock massif is $\alpha_2 \approx 0.5$. Because of unclear α_2 related to the mud-filling process, a range of $0 \prec \alpha_2 \prec 0.5$ was considered for the crack analysis. In the same time, the hydrostatic pressure on the crack edges may double.

The calculations show that crack started to develop at $\alpha_2 = 0.1 \div 0.2$. The crack actually damaged the grout curtain. The overall length of the 0-1-2-3-4 crack was 12 meters (Figure 9).

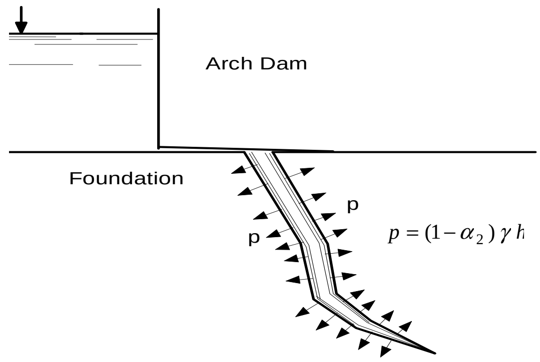

Figure 8. Crack modeling during mud filling

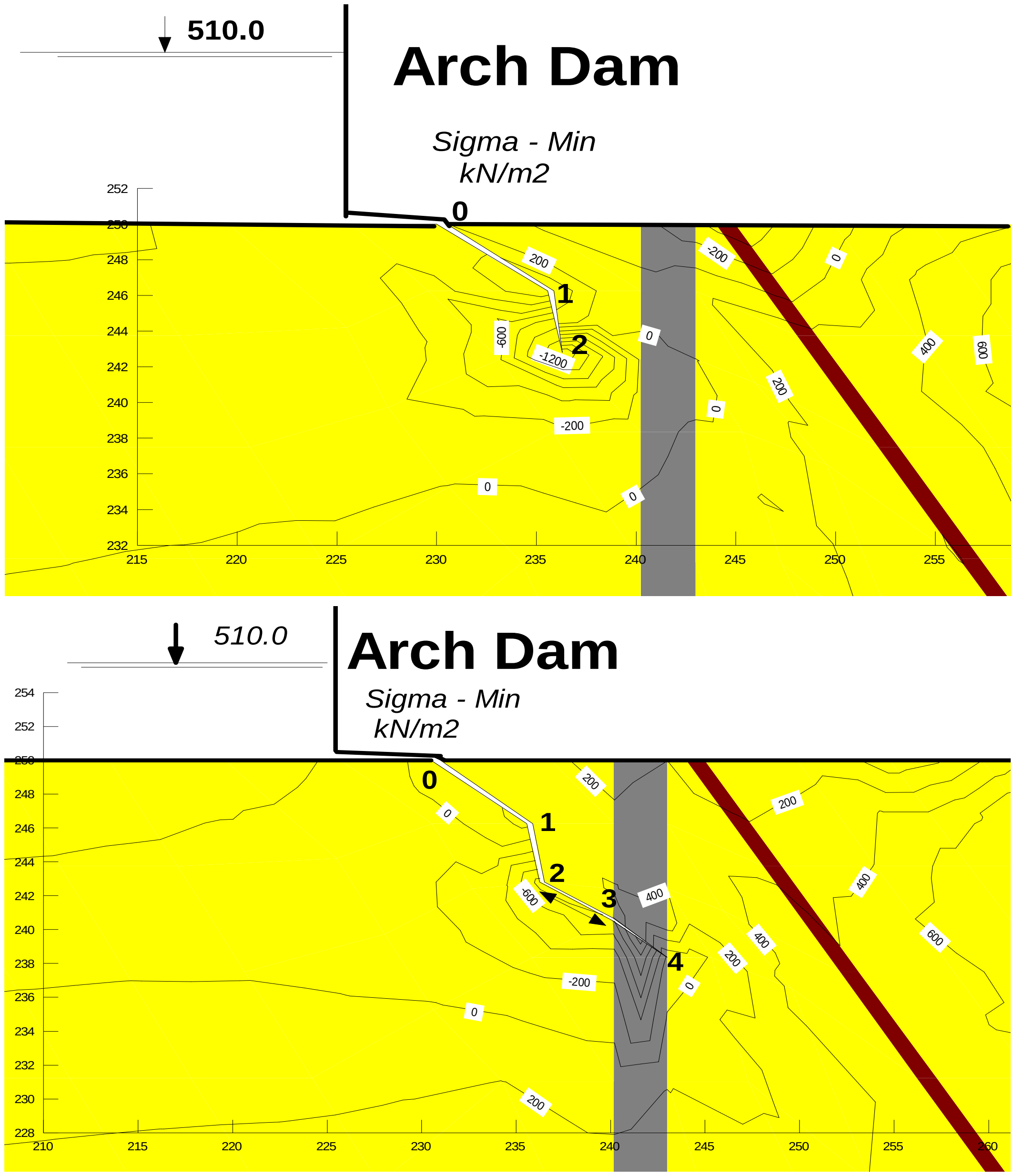

Figure 9. Crack development dynamics in the dam foundation during Subsequent Reservoir Filling 0-1 – tensile developed during first filling of the reservoir (NOL=510 m); 1-2 – shear crack developed during drawdown (MinOL=410 m); 2-3-4 – tensile crack developed during re-filling (NOL=510 m)

4. Seepage Regime in the Dam Foundation

4.1 Pressures in cases of Normal and Damaged Curtain

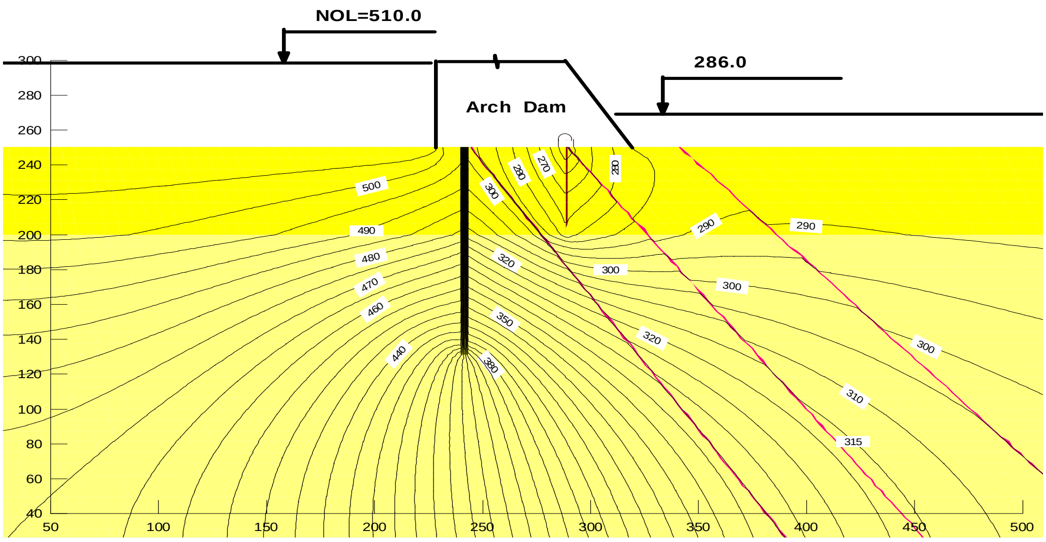

Figure 10. Pressure distribution in the dam foundation with the intact grout curtain and drainage in place

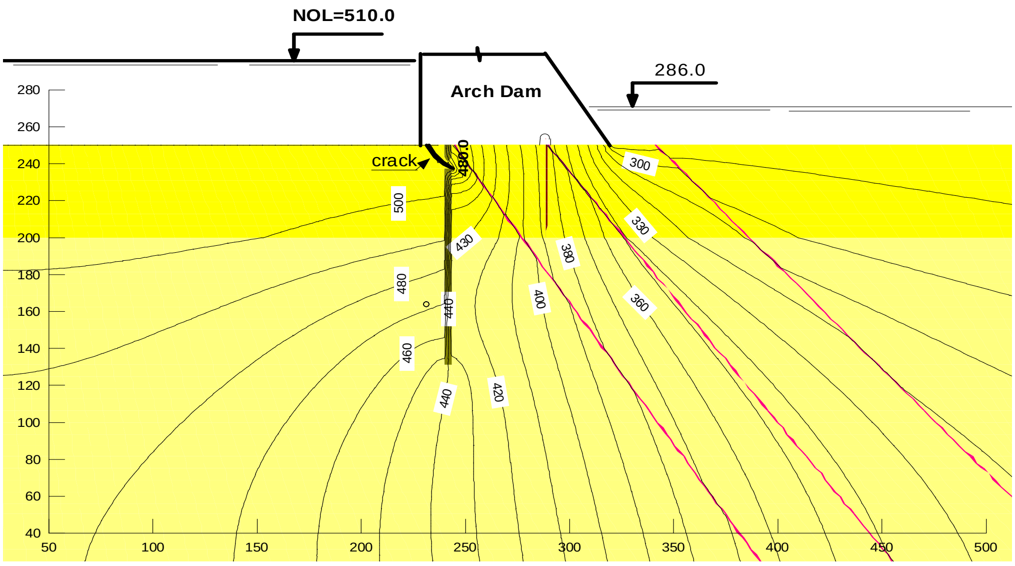

Figure 11. Pressure distribution in the dam foundation with the damaged grout curtain and drainage

In view of the foundation geology, also behavior of the grout curtain and drainage, the obtained pressure distribution (Figure 10) well corresponds to measurements made in peizometers. Dam foundation non-uniformity, in particular, screening tectonic faults, have a significant impact of the seepage regime. Under the influence of drainage, pressure in the area in front of it decreased by up to 20 per cent (Figure 12). After the contract crack of 0-1-2-3-4 in the foundation damaged the grout curtain, the seepage regime sharply changed (Figure 11), which also corresponds to results of piezometer measurements.

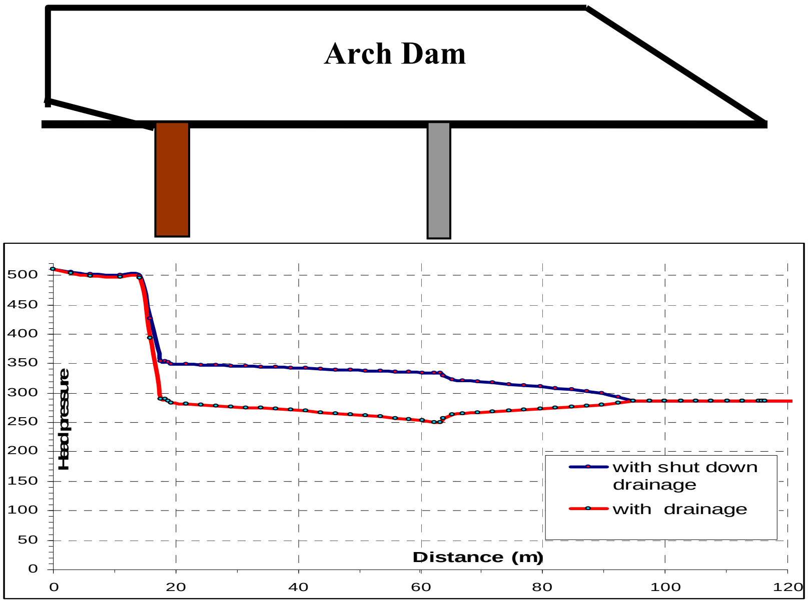

Figure 12. Pressure (head) distribution in the dam-foundation contact

Conclusions

- **The damage of the dam-foundation contact and the grout curtain of the Enguri HPP dam (detected in 1987) was caused by joint dam-foundation behavior under static influence of operational loads. Development of cracks and associated damage of the curtain is indentified on different dams, so the issue is pressing indeed. The presented analysis model could be used as a general methodology for different dams.**

- **Mud-filling of cracks results in increased hydrostatic pressure and decreased friction on the crack surface. Thus until the mud-filling process was completed, high compressive and tensile stresses occurred at high and low water levels in the reservoir, which fostered further crack development. Crack modeling in the mud-filling process was based on fracture mechanics. The model was used to understand the dynamics of crack development and current seepage processes in the Enguri dam foundation during reservoir filling and emptying. The model was used to analyze opening of the dam-foundation contact and damaging of the grout curtain.**

- **The foundation anisotropy, especially the geological cracks (filled with clay), has a significant impact on seepage processes and crack development:**
  - **Cracks screen back the seepage flow, respectively distributing pressures, and thus increasing the pressures – a fact that has been taken into consideration when analyzing piezometer data.**
  - **Structural orthotropy of rock mass has increased tensile and shear crack development during reservoir filling/emptying.**

- **During rapid filling (under the influence of non-stationary seepage regime), there is an additional load on the foundation surface, which fosters contact opening under the pressure face of the dam.**
  During drawdown, the flow in the upper layer of the foundation (about 6m) moves backwards: from the foundation to the reservoir, which creates conditions for contact and crack washing.

- **In 1997, the cracks started to fill with mud, which then became irrevocable. Rehabilitation (2006-2007) of the grout curtain minimized seepage in the foundation. At present the seepage regime in the foundation is stabilized.**

REFERENCES

1. **Bronstain V.I. State of the arch dam and foundation of the Inguri hydroelectric station. Hydrotecnical Construction. Vol.28. #2.1994. pp.77 – 84.**
2. **Zertsalov M.G. Engineer model deformation and destruction of rock and concrete under comprecive stress. Hydrotecnical Construction. #4.1990. pp 33-37.**
3. **McClintock F. A.,Walsh J B., Friction on Griffith cracks in rock under pressure. Proc. 5th Congress on Aplied Mechanics, Bereley, pp.1015-1021, 1962.**
4. **Jeger C. Rock mercanics and engineering. Cambrige at the university press**
5. **Coulson J.H. Shear strength of flat surfacesbin rock. The 13 Simposium on Rock Mechanicks. ASCE. Illinois, pp. 77-105. 1972.**
6. **KalabegiShvili M. The analysis of parameters defining Inguri waterpower plant water-storage reservoir impoundment. Hydro 2007. New approaches for a new era. 2007, Granada, Spain.**

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- **JACOBS Ltd (London), (IDCDP project, 2003-2004) – expertise high-head ears and rock-fill dams: Sioni, Algeti, Zonkari.**
- **ISTC (2002-2005) – new design of high-pressure prestressed reinforced frame;**
- **Rehabilitation of Enguri HPP pressure tunnel (2005), Ortachala HPP and Shaori HPP dams (Georgia, 2005-2006);**
- **In association with designing company Kocks Consult GmbH, Consulting Engineers - Gori and Ricoti highway tunnels (2007- 2010) in Georgia**
- **Zinvali HPP – rehabilitation of spillway dam (2010).**

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