Review and Study on Evolution of the Cracks in Karun 4 Dam during First Impounding

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Abstract

Karun 4 dam with 230.5 m height and significant annual electricity generation is one of the most important dams under operation in Iran. The dam site with its narrow gorge and steep walls, exhibits a complicated geological conditions with a relatively large number of reverse major discontinuities and faults dipping toward downstream. First impounding of the reservoir started in March 25, 2010, where the dam was not fully completed. During the reservoir impounding, a set of cracks had been observed in the dam body, mainly adjacent to its foundation. At that time, different opinions have been raised about the origins and causes of these cracks;accordingly, disagreed statements are made for the required action and appropriate rehabilitation works.The early assessment, based on the available monitoring results and limited possible observations, has an essential role in decision making for the appropriate safety-relevant actions. Scenarios regarding to the causes like "early or rapid impounding", "insufficient arch action in the dam body", "defective dam design and inadequate bearing capacity of the abutments" and "instability or potential wedge movements in the abutments" requires that reservoir be evacuated immediately; the action which imposes serious technical and financial consequences to the project. Meanwhile, early assessment of the monitoring results provides reliable evidences for overall safety and stability of the dam and its abutments; therefore, the radical scenarios and the corresponding immediate emergency actions were abandoned.

Keywords: Karun 4, Crack, Monitoring, Early Assessment

1. INTRODUCTION

Karun 4 dam with 230.5 m height and significant annual electricity generation is one of the most important dams under operation in Iran. The dam locateson the southwest flank of the asymmetrical Sefidkuh anticline, where the relatively high tectonic pressures formed a series of reverse fractures and faults in the dam abutments.The dam laid mainly on Asmari Formation, which consist of limestone rock layers with marl / marly-limestone inter-beds [1].

First impounding of Karun 4 reservoir started in March 25, 2010, when the dam was not fully completed. During the reservoir impounding, a set of cracks had been observed in the dam body, mainly adjacent to its foundation [3] [4]. At that time, and somehow at the time being, different opinionshave been raised about the origins and causes of these cracks by different parties, and there was disagreement about compensatory measures and appropriate remedial and rehabilitation works [4]. At the time being, comprehensive investigation and exploratory works had been performed for recognizing the geometry and extension of the damages (cracks) in the dam body that provide valuable achievements for evaluation and screening of the variant causes and origins of the cracks [3].However, the early assessment, based on the monitoring results and limited possible observations, has an essential role in decision making for the appropriate safety-relevant actions. In this paper, the results of exploratory investigation of the dam cracks are explained and their role in early dam safety assessment and studying of the potential origins and causes of the cracks are discussed.

2. RESERVOIR IMPOUNDING

According to the basic design assumptions, reservoir impounding would be started after completion of the all construction works. However, due to some specific reasons, it was decided to start impounding earlier, in Farvardin 5, 1389 (March 25, 2010), when construction works of the dam and spillway were not completed yet (Figures 1&2) [3]. As shown in Figure 3,because of the low reservoir volume in the lower and intermediate heights, reservoir water rapidly growthfrom EL. 865masl up to EL. 980 in the first two month.

Figure 1.Construction progress at the start of Karun 4 reservoir impounding(March 25, 2010)

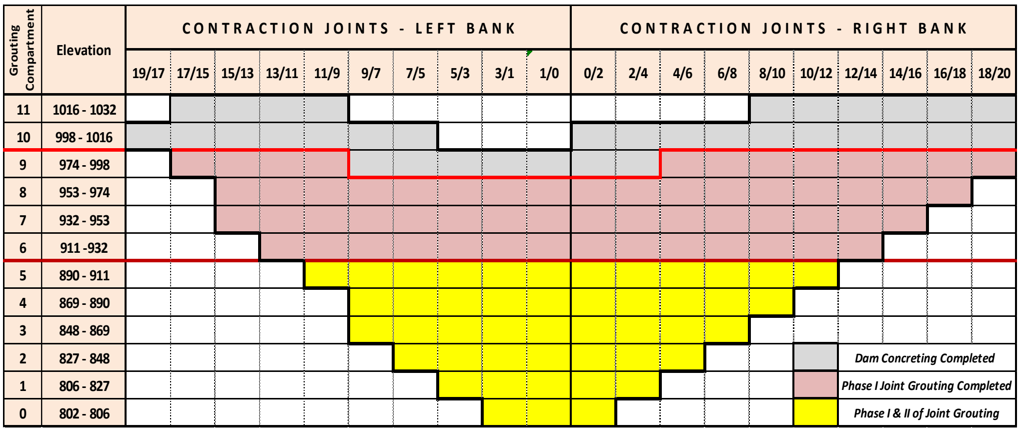


Figure 2.Status of dam concreting & contraction joint groutingat start of reservoir impounding(March 25, 2010)

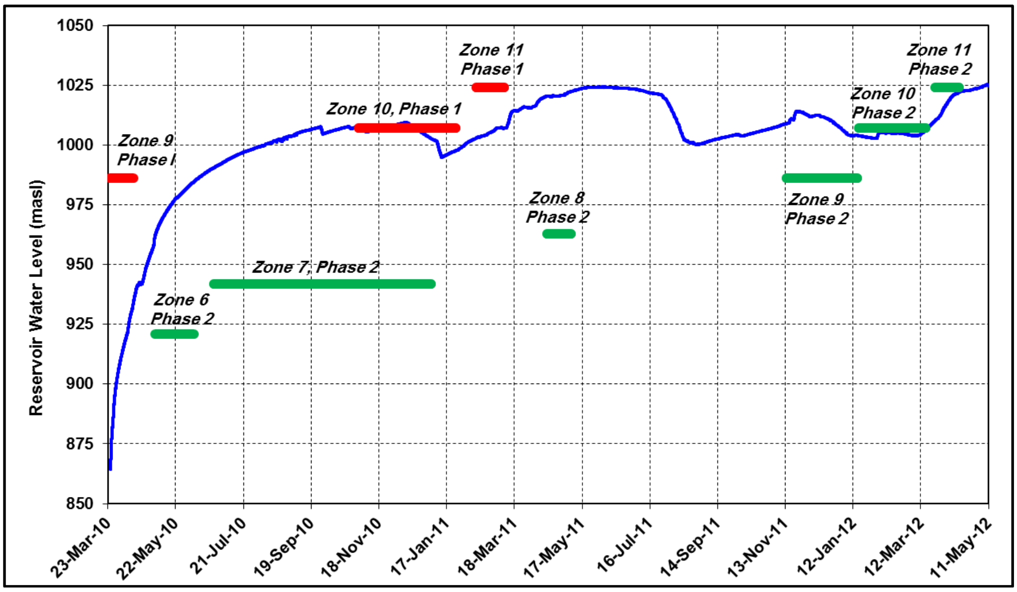


Figure 3. Karun 4 dam - Rate of the first reservoir impounding& status of contraction joint grouting

As indicated in Figures 1 & 2, concrete works of the dam blocks, and consequently, grouting of the dam contraction joints were not completed at the time of impounding (Table 1) [3].At the start of reservoir impounding, the highest dam blocks were at EL. 1031masl – close to the dam crest - and the lowest ones were at EL. 1001masl (central blocks 3 & 1).

Table 1.Dam concreting & joint groutingprogress at the start of reservoir impounding(March 25, 2010)

Dam Blocks No.		Minimum Base Elevation (masl)	Concreting Elevation (masl)	Contraction Joint Grouting EL. (masl)	
				Phase I Grouting	Phase II Grouting
Left Bank	19	1010	1016	----	----
	17	980	1022	998	----
	15	950	1031	998	----
	13	920	1025	998	----
	11	892	1031	998	911
	9	864	1025	974	911
	7	838	1019	974	911
	5	817	1010	974	911
Central Part	3	805	1004	974	911
	1	802	1001	974	911
	0	802	1010	974	911
	2	805	1016	974	911
Right Bank	4	818	1010	974	911
	6	838	1016	974	911
	8	859	1022	974	911
	10	880	1031	974	911
	12	900	1025	998	911
	14	920	1031	998	----
	16	939	1031	998	----
	18	958	1031	998	----
	20	977	1031	998	----

3. ANALYTICAL OVERVIEW ON EVOLUTION OF THE DAM CRACKS

Chronology of events and cracks (based on their observation / investigationdate) are summarizedin the following (after start of reservoir impounding in March 25, 2010):

i) April 16, 2010 (RWL: 938 masl): First subverticalcrack was observed at the interface zone of dam gallery DG7 and foundation gallery LG4 (at elevation 890masl). This crack is formed whit in the overbreak area almost along extension of the contraction joint 9-11, where terminated in the upper lift-joint (Crack 1 in Figure 4). Based on the investigation results, this crack evaluated as the minor local crack and it was treated with some traditional measures in order to control its dropping leakage [3] [4].

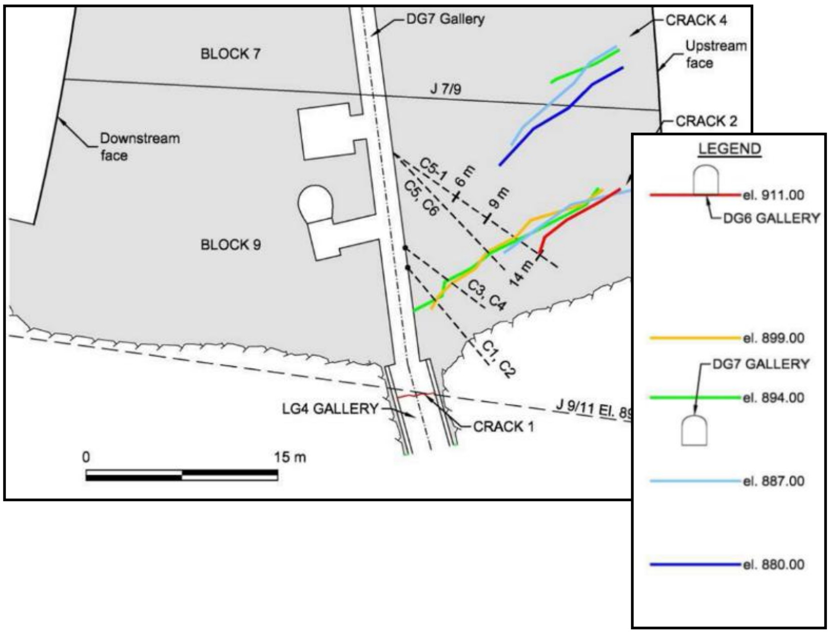
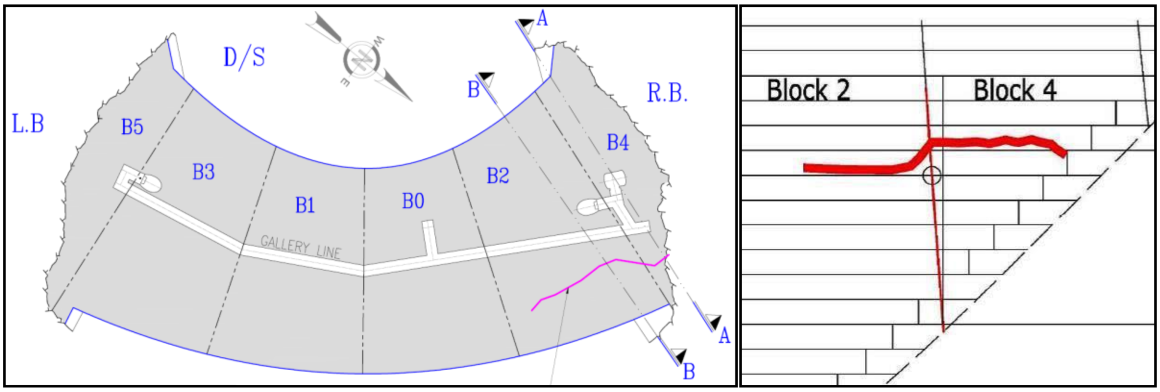
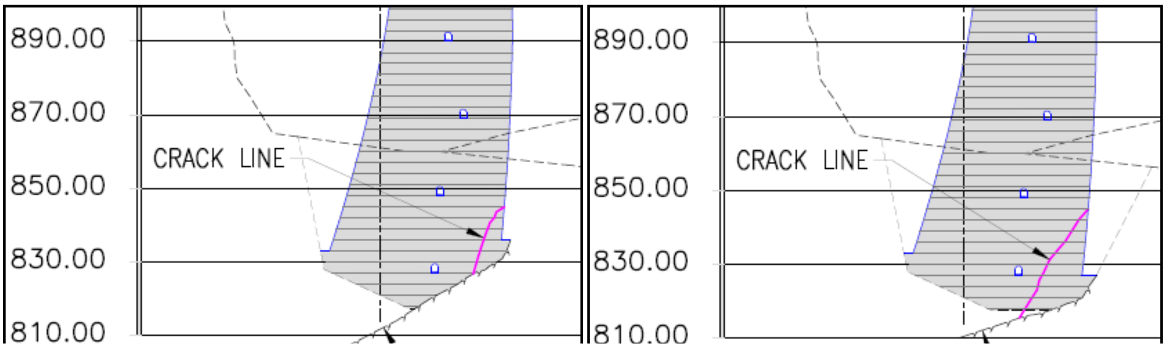


Figure 4. Close-up view of 1st & 2nd cracks in block 9 and crack in block 7 (EL. 890masl)

ii) August 23 to October 30, 2010 (RWL: 1002 to 1008 masl): Leakage from air grooves of block joint 2/4 was firstly detected in dam gallery DG9 (at EL. 848masl) and then, in dam gallery DG10 (at EL. 827masl). In the relatively short time, leakage in dam gallery DG10 (at El. 827masl) increases from 2 to 32 l/min. By grouting of the air grooves of joint 2/4 in dam gallery DG10 (in winter 2010) leads to increase of leakage in gallery DG9 from 2 to 47 l/minute. In May 2013, shortly after closing of the air outlet valves of joint 2/4 in gallery DG9, a new crack at close to the block joint 2/4,with somehow the same leakage,was formed (after this event, air outlet valves are reopened). Based on these events, the leakage from block joint 2/4 could be correlated with initiation and/or development of the cracks in dam blocks 2 and 4, which later observed by special investigation on the upstream face (Figure 5) [3].



Plan at EL. 827masl - Crack Line **Upstream View - Crack Line**



Section A-A (Block 4) **Section B-B (Block 2)**

Crack Surface: Dip: 65°-70°& Dip Direction: 200°

Figure 5-Overall geometry of the Crack(s) in blocks 2 and 4

iii) March 16 to 19, 2011 (RWL: 1014 masl): Abnormal event in a free (ungrouted) borehole in the consolidated zone of dam foundation adjacent to block 7 which equipped with a capped pipe at EL. 846masl. In that date, the borehole cap was thrown away and a considerable quantity of mud and water drained with high pressure into the dam perimeter gallery.The marly inter-beds in the left abutment shall be the only possible origin of such volume of mud.In the next day, second vertical crack was observed in the left bank in the gallery DG7(EL. 890)in dam block 9 (crack 2 in Figure 4). Two days later, a new inclined branch of the second crack (almost parallel to the dam boundary) was observed. This new branch of “Crack 2” has been the most active crack and the core of monitoring, investigation and rehabilitation works were concentrated on that.Schematic view and the investigated crack plane are indicated in Figure 6 (Crack 4 in Figure 6 is a minor crack parallel with the main crack No. 2). At the same time, electrical piezometer “EP-05-827/2U” in the adjacent area of dam foundation is showing abnormal piezometric pressures in downstream area of the grout curtain(Figure 7). The piezometer sensor locates at EL. 808masl and its borehole head is in dam block 5, gallery DG10 at EL. 827masl. As indicated in Figure 7, some hydro-jacking events occurs through a specific discontinuities when the reservoir water level (RWL) exceeded the EL. 1005m and consequently, the piezometric pressure increases with a magnified rate for RWLs higher than 1005m [2].

iv) April 10, 2011 (RWL: 1019 masl): Almost one month later of observing cracks in block 9, a similar crack was observed via dropping leakage in gallery DG9 (EL. 848masl) in block 7 (Figure 8) [3].

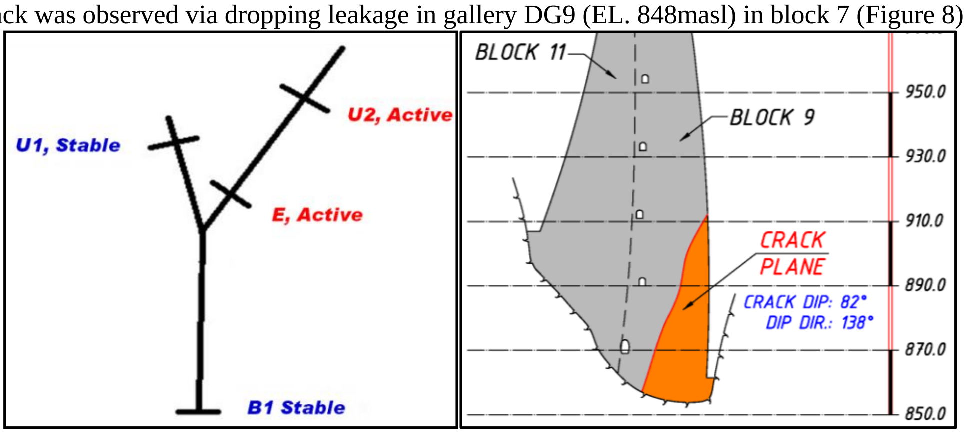


Figure 6.Crack in block 9 - Schematic view of Crack outcrop & its instruments and the investigated crack plane

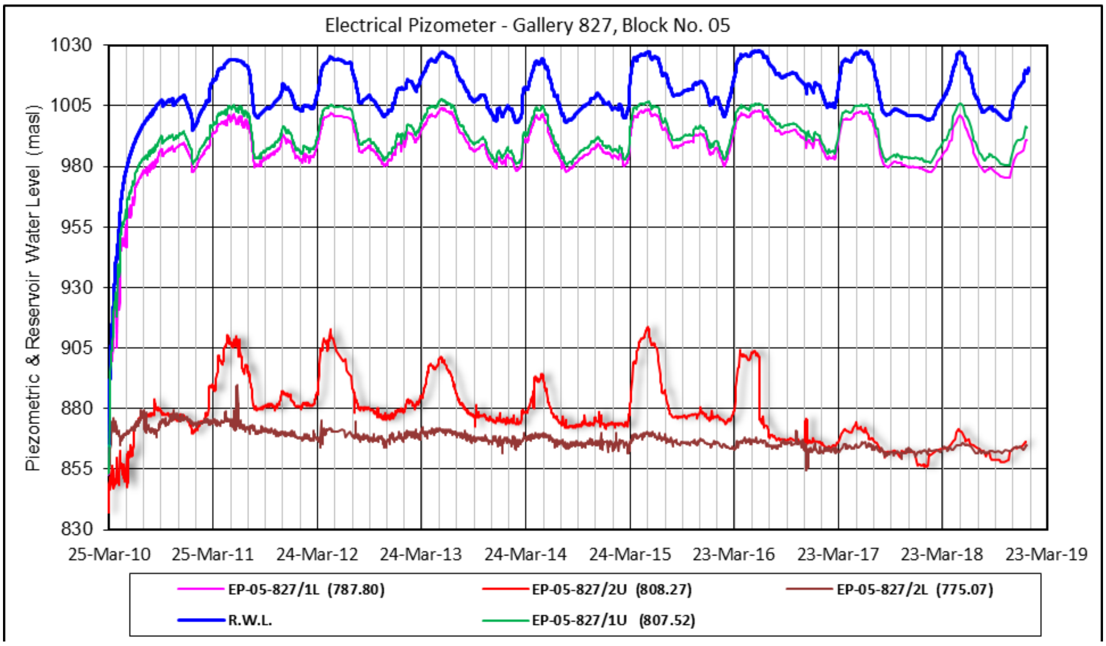


Figure 7.Abnormalreaction of piezometer EP-05-827/2U in D/S area of grout curtain (Gallery DG10, block No. 5)

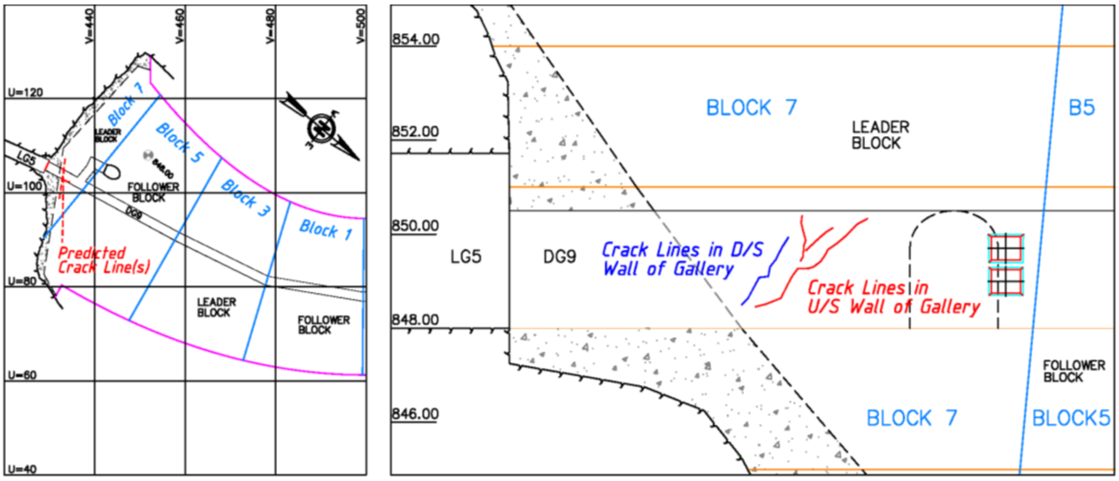


Figure 8. Crack in block 7 in gallery DG9 (at EL. 848masl) - Plan & vertical section through the gallery

Specific investigations were planed and had been performed for exploration of the cracks occurred in the dam body. In this regard, in August 13 2013, aspecial underwater video camera, which was designed for survey and inspection of the dam upstream face, indicates the outcrops of the cracks in dam blocks 9 and 7 (Figure 9) [3].Using this special device, a set of dye testswere also performed by spreading out the colored matter adjacent to the crack outcrop(s) on upstream face; the results could be summarized as follows:

- The observations proved the leakage flow from the reservoir through the crack plane. The flow intensity was clearly visible through the height of the crack outcrop; and it could certainly be said that the leaked water through the crack plane is just partially (few percent) discharged in the dam gallery. This fact indicates the direct relation and connectivity between the dam crack(s) and the adjacent foundation discontinuities (Figure 10). Studying of geological section through the dam abutments indicates the fact that a number of subvertical and inclined major joints (and secondary faults) are intersecting with the dam body adjacent to the blocks 7 and 9 (Figure 10) [3].

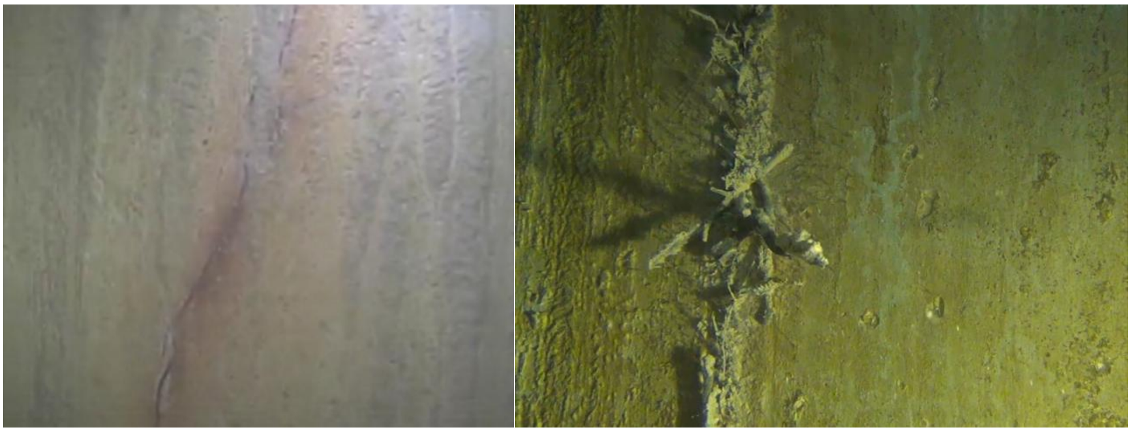


Figure 9. Cracks in blocks 7 (*left*) and 9 (*right*) – sample photos from crack outcrop in dam upstream face (2013)

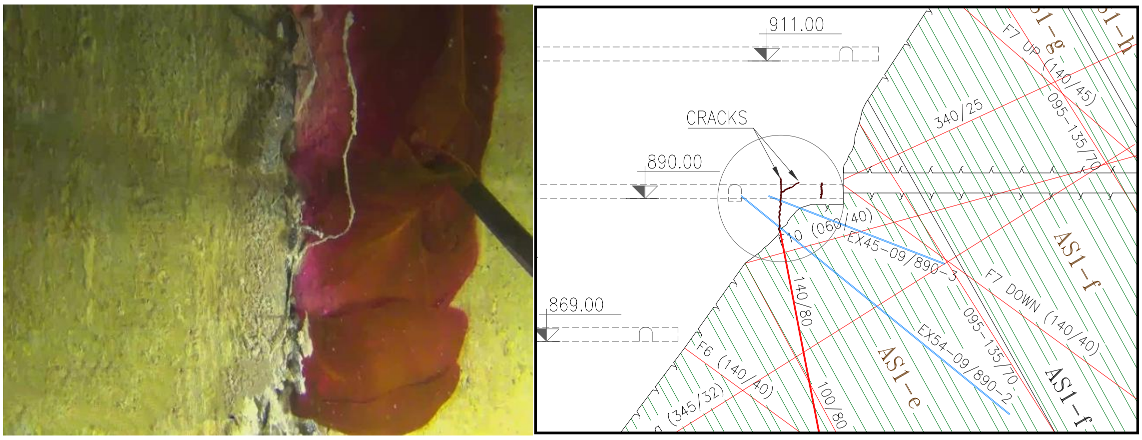


Figure 10.Dye test of the Crack in block 9 and geological section through the dam abutment close to blocks 7 & 9

- Observation of the colored materials in the leaked water to the dam gallery DG7, regardless of whether it was low, proves that the outcrops in the upstream face and inside the gallery are related to the same crack plane.

In May 2014, similar investigations were performedby the specially designed multifunction device for exploring ofpossible cracks in dam blocks 2 and 4.In these investigations, the device was equipped with driving engine and motorized cleaning brushes in order to clean the dam face and providing detail inspection of the crack outcrop. The results enlighten many facts about the crack and appearance specification of its outcrop (Figure 11). Observations showed that the crack outcrop is quasi-horizontal, starts (initiates) from the dam abutment at elevation about 845 (in right bank) and extends through dam blocks 2 and 4. Further investigations (drilled boreholes) indicate a downstream dip of 65° to 70° for the crack plane (Figure 5) [3].
Comprehensive borehole drilling program for investigating geometry of the dam cracks and was started by a professional contractor in spring 2014. Since then, many boreholes have been drilledboth for investigation purposes and for rehabilitation works (resin grouting through the crack plane). Accordingly, the detailed geometries of the dam cracks, where presented in foregoing figures, are defined.

Figure 11. Crack(s) in blocks 2 and 4 – sample photos from crack outcrop in dam upstream face(2013)

Without going through details of theinvestigation results, following outcomes could be obtained by studying the visual appearance of the crack outcrop and geometry [3]:

- Aperture of the crack outcrop in blocks 2 & 4 varies between few millimeters up to about 2cm (Figure 10). It should be noted that the wide apertures are apparent and local and the actual opening of the crack(s)based on the observations and borehole investigation results, is in order of mm. The variable and non-uniform situation of the crack outcrop does not comply with the potential "tension-crack" that could be formed in the lower parts of the dam upstream face due to hydrostatic loading.
- The presence of debris trapped inside the crack plane (both in crack in block 2 and crack in block 9) might be considered as the indication for evidence of cracking before impounding,because in case of crack initiation after impounding, such phenomenon would be very unlikely.
- From theoretical point of view, if such cracking occurs after impounding, the crack would be initiated as a "tension crack" from and normal to the dam upstream face (i.e. almost horizontal) and continued with a downward slope by the shear mechanism. This is not the case of the current crack; as indicated in vertical sections A-A & B-B in figure 5, the crack plane has a clearly sharp angle with the dam upstream face. Further analytical studies proved that the crack initiated mainly from the dam base due to behavior and high flexibility of a weak marly key-bed in the central dam foundation. Based on this scenario, the crack could be initiated before impounding; however,applying the hydrostatic pressures on the dam upstream face (after impounding) and generation of pore pressure inside the crack plane, could effectively triggered and developed the crack.

4. CONCLUSIONS

In the early stages after observation / occurrence of the above-mentioned damages in the dam body, a wide variety of reasons and causes, as the following, were raised and discussed by different parties [4]:

- Early impounding and /or rapid impounding of the reservoir
- Insufficient arch action in the dam body due to incomplete grouting of dam contraction joints at the time impounding
- Defective dam design or inadequate bearing capacity of dam body and its abutments
- Instability (and potential movement) of the critical rock wedges in the (left) abutment
- Weaknesses or defects in construction work(insufficient strength of concrete, weak foundation preparation, insufficient grouting for foundation consolidation and water tightening, …)

Appropriate action and response to each of the above scenarios would be very different. Logically, for the scenarios regarding to the causes like "early or rapid impounding", "insufficient arch action in the dam body", "defective dam design and inadequate bearing capacity of the abutments" and "instability or and potential wedge movementsin the abutments" the reservoir would be evacuated immediately and then further assessment and rehabilitation works shall be done. Obviously, this approach, if it was inevitable, imposescatastrophic and serious consequences on the project.

However, the early assessment of the monitoring results provides reliable evidences for overall safety and stability of the dam and its abutments; therefore, the radical scenarios and the corresponding immediate emergency actions were abandoned. The basic and reliable monitoring results (like pendulum measurements) and the observations and investigations results about the cracks, provides reasonable basis for the early assessment. The outstanding evidences were as follows [3]:

- Direct and inverted pendulums results, as the most reliable and simple instrument, indicate reasonable displacements in upstream-downstream direction in the dam and foundation in left, center, and right bank (Figure 12).

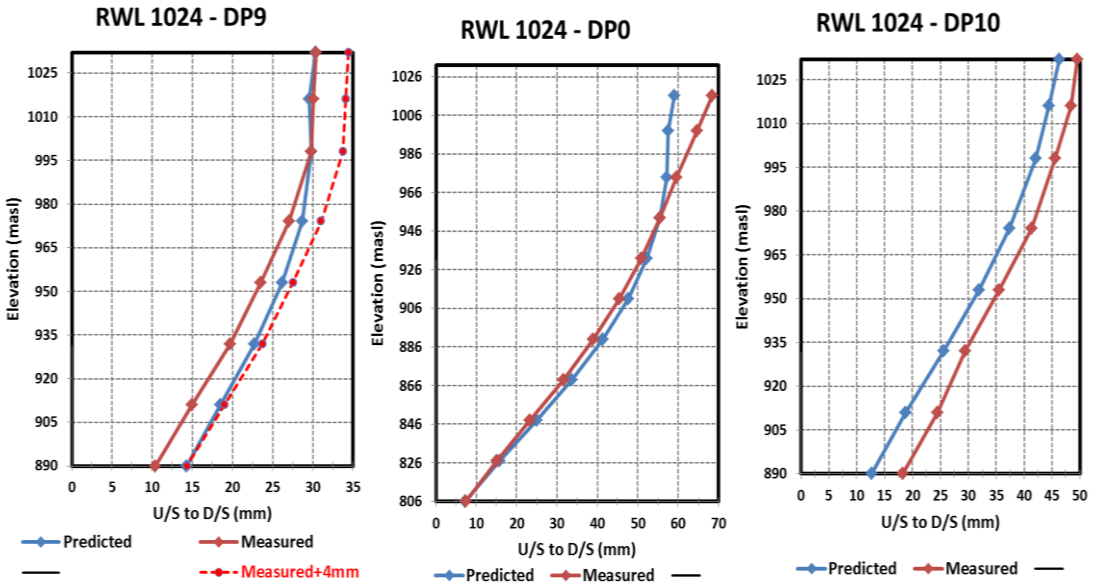


Figure 12.Measured and predicted dam and foundation displacements toward D/S – Pendulum results in May 26, 2011

- The cracks in block 9 (Figure 4) and block 7 (Figure 8) are forming between the two potential weak planes: "dam-foundation contact" and "dam vertical contraction joint". Furthermore, the crack in block 7, and some branches of crack in block 9, intersects the dam contraction joints. Logically, in case of "defective dam design", "inadequate bearing capacity of dam abutments", or "lack of proper arch behavior in the dam body (due to inadequate grouting of the dam contraction joints)", it is expected to have openings through the typical weak planes in the dam body, like vertical contraction joints and the dam-foundation contact. The crack situations in Karun 4 dam do not comply with this concept, and could be clearly concluded that all of the mentioned scenarios have no, or at least minor, role in crack formation.
- According to the initial observations, and later detail and specific investigations, it could be stated that the occurred cracks in blocks 9 & 7 are triggered and initiated by one or a set of discontinuities in the adjacent dam abutment. Same situation is more or less exists for the cracks in blocks 2& 4.
- Most likely, poor performance or inadequate design of foundation treatment has an effective role in initiation / development of the dam cracks both during dam construction and after start of reservoir impounding.

5. REFERENCES

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