Evaluation and Optimization of the Instruments Installed on the Crack in Dam Block No. 9 - Karun 4 Dam & HPP Project

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Abstract
Instrumentation systems shall be designed for monitoring the particular data representing indexes for safety assessment of the proposed structure both in the design stage and during operation, where required. The index parameters usually defined based on the design and analyses results and the proposed performance. In this regard, each instrument should have a specific objective considering the measurement requirements.Furthermore, while insufficient instruments may results in loss of part of the index data, excessive number of instruments shall provide a mass of data that could result in ambiguity by itself. Sometimes, in ambiguous and emergency situations, extra instruments might be necessary for clarifications (evaluation of well performance of the previous instruments and safety insurance), however, it is necessary to re-evaluate and optimize the instruments periodically. In this paper, results of the studies on evaluation and optimization of the instruments installed for monitoring of the crack movements in the Karun 4 dam (in the dam block No. 9) are presented and discussed. At the early stages after observation of the crack, due to some uncertainties and ambiguities in the crack behavior, more than 9 instrument were installed on the crack outcrops in a limited space. Certainly, such a high density of the instruments is not logical for a long-time monitoring. Therefore, based on the re-evaluation of the installed instruments, the three representative instruments were kept and the other ones are removed.
Keywords: Instrumentation, Optimization, Karun 4, Crack.

1. INTRODUCTION

Instrumentation systemsare basicallydesigned for monitoring the particular data representing indexes for safety assessment of the proposed structure. The index parameters shall be defined based on the design and analyses results. After project implementation, during operation, new instruments might also be neededfor monitoring the damages occurred, and/or to evaluate the effectiveness of the rehabilitation works.Each instrument in the instrumentation system shall be designed and provided for a specific objective; considering themeasuring environment, appropriate instrument type, reasonable data redundancy, and optimum number of the instruments.Wrong type of instrument may not provide proper results; furthermore, while insufficient instruments may results in loss of part of the index data, excessive number of instruments shall provide a mass of data that may hide the valuable results. Therefore, it is important to balance the density of instruments based on the design requirements and hazard assessment.

In this respect, the studies were performed for optimizing the instrumentation system in Karun 4 dam for the crack occurred in dam block 9, are discussed in this paper [3].

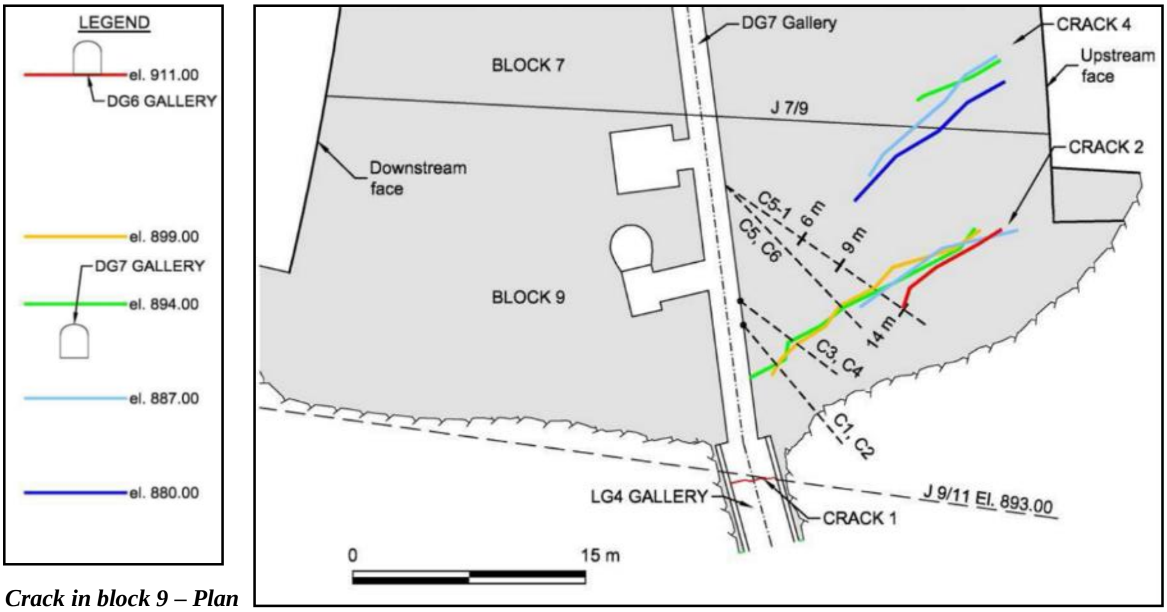
2. OBSERVATIONS OF THE CRACK IN KARUN 4 DAM BLOCK NO. 9

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 locates on 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]. During the first reservoir impounding (started in March 25, 2010)a set of cracks had been observed/occurred in the dam body; the most important one is the crack occurred in the dam block 9 [4]. Special exploratory investigations were performed to define the crack geometry and its development in the dam body;accordingly, the crack extension was defined with a proper

precision
(Figure 1) [4]. As indicated in Figure 1, the crack outcrop is visible in upstream wall and partially in roof and bench of the dam gallery DG7 at elevation 890 masl.

Different scenarios had been raised for the origin and/or the main cause(s) of the crack and a relatively large number and various types of instruments had been installed on the crack outcrop (in the dam gallery DG7) and through the crack plane in order to monitor and assess the crack behavior. As the result, significant amounts of data were obtained, which in some cases are apparentlycontradicted with each other [2].

It is worth noting that a minor crack was occurred early after impounding, almost at the extension of the dam contraction joint 9/11, which was terminated just above the gallery DG7, at elevation 893 masl. This crack is of minor importance and repaired by local sealing materials (Figure 1) [4].The main crack in dam bock 9 has two outcrop lines in upstream wall of the DG7 gallery, named as “U1” & “U2” by their observation time (Figure 1). Despite the early observation of “U1”, this branch of the crack outcrop is partially extends in the gallery upstream wall and exhibits limited response during the monitoring [3].



Crack in block 9 – Plan

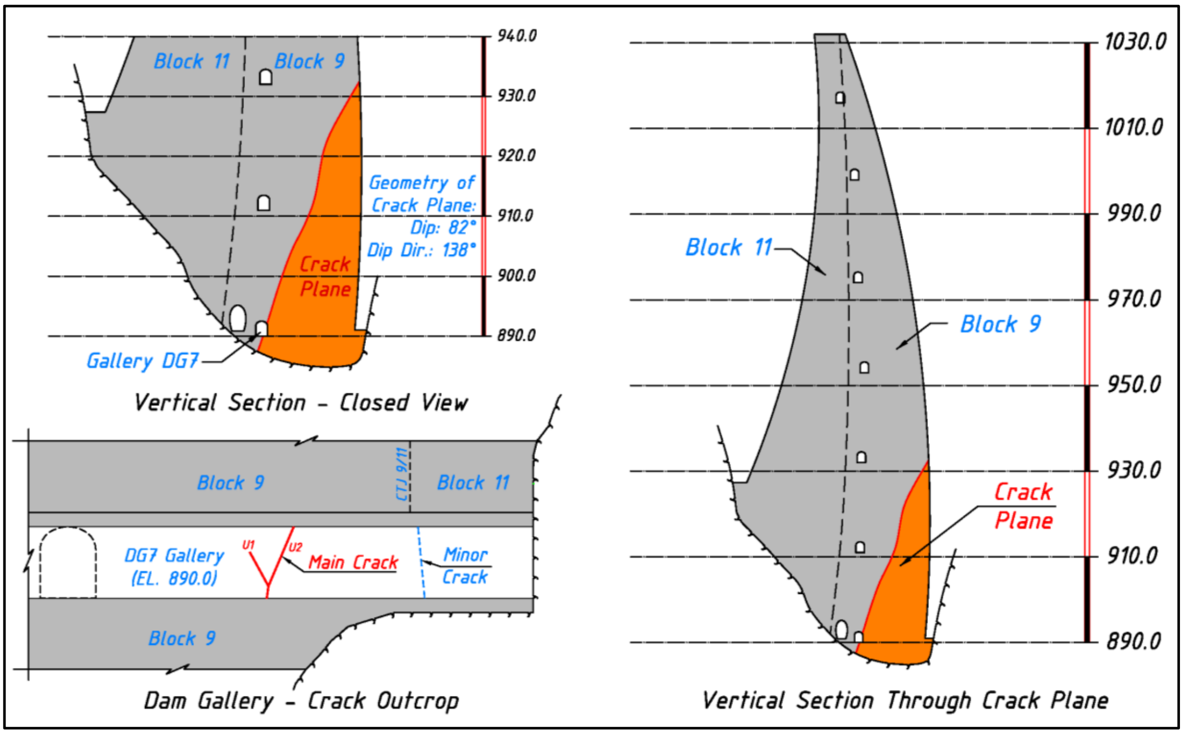


Figure 1. Crack in block 9 – Plan (top), Crack outcrop and vertical section through crack plane (down)

The next and main branch of the crack outcrop line, “U2”, was observed in less than two days after “U1”. This outcrop line extends in all whole height of the upstream wall and partially in the bench and roof of the DG7 gallery. Most of the further monitoring activities and assessment studies had been performed on this branch of the crack outcrop [2] [4].

3. INSTRUMENTATION OF THE MAIN CRACK IN DAM BLOCK NO. 9

Considering the importance and effectiveness of the behavior of this crack in assessing the overall safety and stability of the dam body, a large number of instruments had been installed in early stages after crack observation until the comprehensive rehabilitation works. The instruments were installed on the crack outcrop and through a number of the exploratory boreholes drilled for investigating the geometry and extension of the crack plane [3] [4].

At the early time after the crack observation, there were many uncertainties and ambiguities about the extent of crack development and its behavior. Furthermore, due to the continuation of the construction works, the installed instruments were subjected to possible damages and shocks (and/or malfunctioning) due to the presence of traffic in the dam galleries, as well as the ambient factors (temperature changes, etc.). Therefore, a number of similar or identical instruments were installed to clarify and/or explain some doubtful monitoring results. After a while, a large number of the instruments are installed for monitoring the crack behavior as indicated in Figure 2 and listed by their installation date in Table 1, and plenty of the measured data had been generated by them [3].

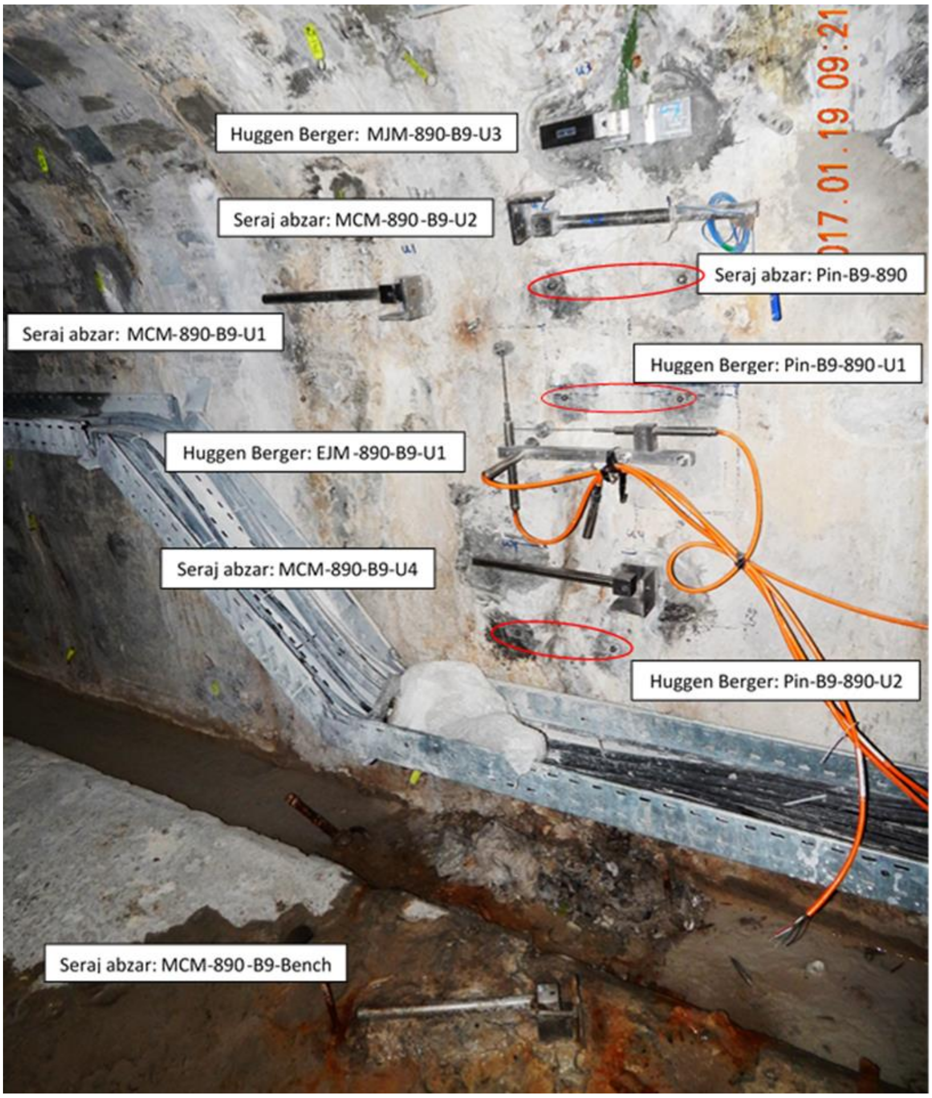


Figure 2. Instruments installed on the crack outcrop (1st& 2nd branches, left & right) - Gallery DG7, block No. 9

Table 1. Instruments installed for monitoring of crack in block No. 9

No.	Instrument Type	Supplier	Code	Location	Installation Time	Monitoring Objective
1	MechanicalCrack meter	S.A.[1]	MCM-890-B9-U1	1stBr., U/S Wall	March 16, 2011	▪ Crack Movements ▪ Evaluation of Rehabilitation Works ▪ Crack Development toward Downstream
2	MechanicalCrack meter	S.A.	MCM-890-B9-U2	2ndBr., U/S Wall	May 28, 2011	
3	MechanicalCrack meter	S.A.	MCM-890-B9-B	Gallery Bench	Oct. 23, 2011	
4	ElectricalJointmet er	H.B.[2]	EJM-890-B9-U1[3]	2ndBr., U/S Wall	June 13, 2012	▪ Crack Movements ▪ Automatic Reading
5	Extensometer	S.A.	EX6-B9-C3	Exp. Boreholes	Feb. 27, 2013	▪ Crack Movements ▪ Evaluation of Rehabilitation Works ▪ Interaction of 1st& 2nd Branches of the Crack
6	Deformeter Pins	H.B.	PIN-B9-890-U1	2ndBr., U/S Wall	Oct. 24, 2013	
7	Mech.Jointmeter	H.B.	MJM-890-B9-U3	2ndBr., U/S Wall	Nov. 8, 2013	
8	Deformeter Pins	S.A.	PIN-B9-890	2ndBr., U/S Wall	Nov. 19, 2013	
9	Extensometer	S.A.	EX14-B9-C5-1	Exp. Boreholes	Feb. 8, 2014	
10	Extensometer	S.A.	EX23-B9-19	Exp. Boreholes	Oct. 25, 2014	
11	Extensometer	S.A.	EX22-B9-20	Exp. Boreholes	Oct. 28, 2014	
12	Extensometer	S.A.	EX14-B9-C10	Exp. Boreholes	Feb. 13, 2015	
13	Deformeter Pins	H.B.	PIN-B9-890-U2	U/S (Lower Part)	Jan. 27, 2016	
14	Mech.Crackmeter	S.A.	MCM-890-B9-U4	U/S (Lower Part)	Jan. 27, 2016	
15	Extensometer	S.A.	EX-B9-M02	Exp. Boreholes	Sep. 9, 2018	
16	Extensometer	S.A.	EX-B9-M13	Exp. Boreholes	Sep. 9, 2018	

[1] S.A. stands for SerajAbzar, [2] H.B. stands for Huggen Burger
[3] Due to systematic error in readings of this instrument at early period, the readings from Jan. 27, 2016 are considered.

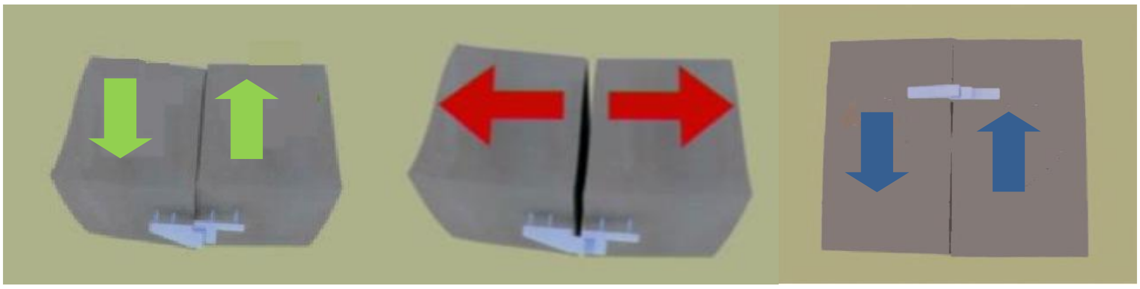
4. ASSESSMENT OF THE OBJECTIVES& NECESSITY OF THE INSTRUMENTS INSTALLED ON THE CRACK OUTCROP IN DAM GALLERY DG7

Regarding the mentioned situation, due to the specific installation details and the measuring methods, interpretation of the measured displacement components in some cases was not easily possible;and sometimes, the obtained data of similar instruments were apparently at odds with each other. Therefore, in order to re-organizing and optimization of these instruments, a specific study had been performed for studying the obtained dataand evaluation of the various instruments installed on the crack outcrop. Accordingly, main objectives of theinstruments used for monitoring of the crack are classified as follows:

- Monitoring the crack movements including opening, tangential (lateral) and offset movements
- Investigating the crack development, mainly toward downstream
- Clarification of the previously installed instrument
- Interaction of 1st& 2ndbranches of the crack
- Evaluation and control of the rehabilitation works

Keeping the above-mentioned objectives, with attention to the updated knowledge about the crack, necessity and effectiveness of the instruments are studied and finalized as discussed in the following.

To have a closer view and to evaluate the crack-meters &jointmeters results, the local coordinate system used for measuring the crack movements is presented in Figure 3 [2]; note that the reference for the positive movements in “X” and “Z” directions is the index jaw of the instrument.



Positive Movement in “X-dir” Positive Movement in “Y-dir” Positive Movement in “Z-dir”

Figure 3. Local coordinate system defined for jointmeter and crack-meter measurements

a) Mechanical Crack-meter “MCM-890-B9-B”, Installed on the Crack Outcrop at the Gallery Bench:

This crack-meter, according to its installed position, was completely exposed to traffic inside the gallery, therefore, the risk of collision with the instrument and causing shock to the measured result is high. The measurement results of this instrument are indicated in Figure 4. According to the obtained results, there was some stepwise increase in “Y” component and two sharp and concurrent shocks in the “X” and “Z” components of the measurements. Logically, such high and sharp movements (with a magnitude of about 1.0 mm) shouldbe along with the appearance changes in the crack outcrop; furthermore, similar (not the same) shocks expected to be seen in the other instrument. Inspections of the crack outcrop and review of the other instrument measurements did not support such a high shocking movements. The trend of the following measurements shows almost no sensible movement [3]. Finally, it was decided to remove this instrument because of its high-risk installation location and the potential for unreliable performance [3].

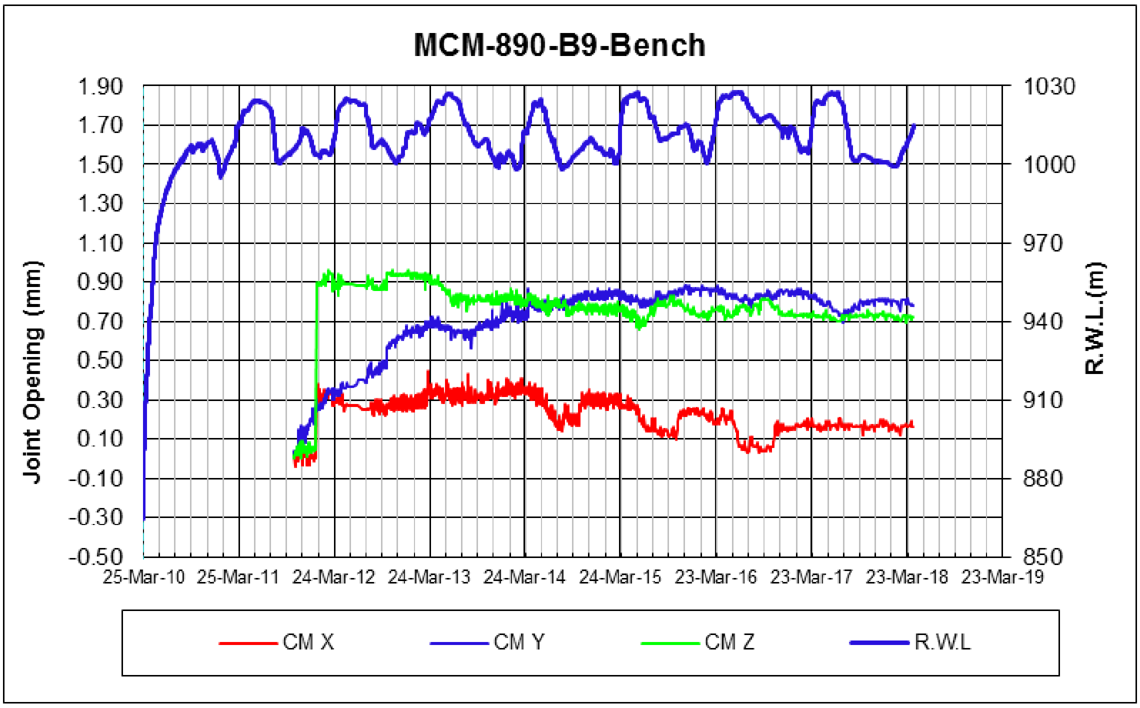


Figure 4. Results of the crack-meter "MCM-890-B9-B" installed on the crack outcrop in DG7 gallery bench

b)Crack- &Jointmeters Installed on the Crack Outcrop through the Gallery Upstream Wall:

As indicated in Figure 2, crack-meters and jointmeters installed on the 1st and 2nd branches of crack outcrop on DG7 upstream wall, are almost parallel together. Therefore, related components of the measured movements could be compared to each other, after unification of the instrument local coordinate systems. Regarding the different installation times of the instruments on 2nd branch of the crack outcrop, for better understanding and comparability of the measured results, instrument measurements are superimposed to related measurement values of the oldest instrument (MCM-890-B9-U2), as the index baselines. The comparative graphs of movement components in "X", "Y" and "Z" directions are plotted in Figure5 [3]. In this Figure, the periods of first and second stage of "resin grouting" through the crack plane are also indicated (Grouting of the crack plane by appropriate resin materials was intended as the primary rehabilitation treatment which could dry out the crack surface and make it more stable by providing a reasonable bonding between the crack faces).

According to the graphs presented in Figure 5, jointmeters "MCM-890-B9-U1" and "MCM-890-B9-U2", the two early installed instruments on the 1st and 2nd branches of the crack outcrop, exhibits fully different movement values and trends of the crack plane."MCM-890-B9-U1" indicates moderate and soft movements in all directions; the only potential movement of the crack plane is some "offset" type displacement (in "X" direction) by magnitude of about 0.2 mm. In the contrary, "MCM-890-B9-U2" represents very sharp and rough movements through the crack plane in all directions. According to the obtained results, there would be gradual opening through the crack plan up to a magnitude of more than 1.3 mm, and sharp and stepwise slipping and offsetting movements through the crack plane.

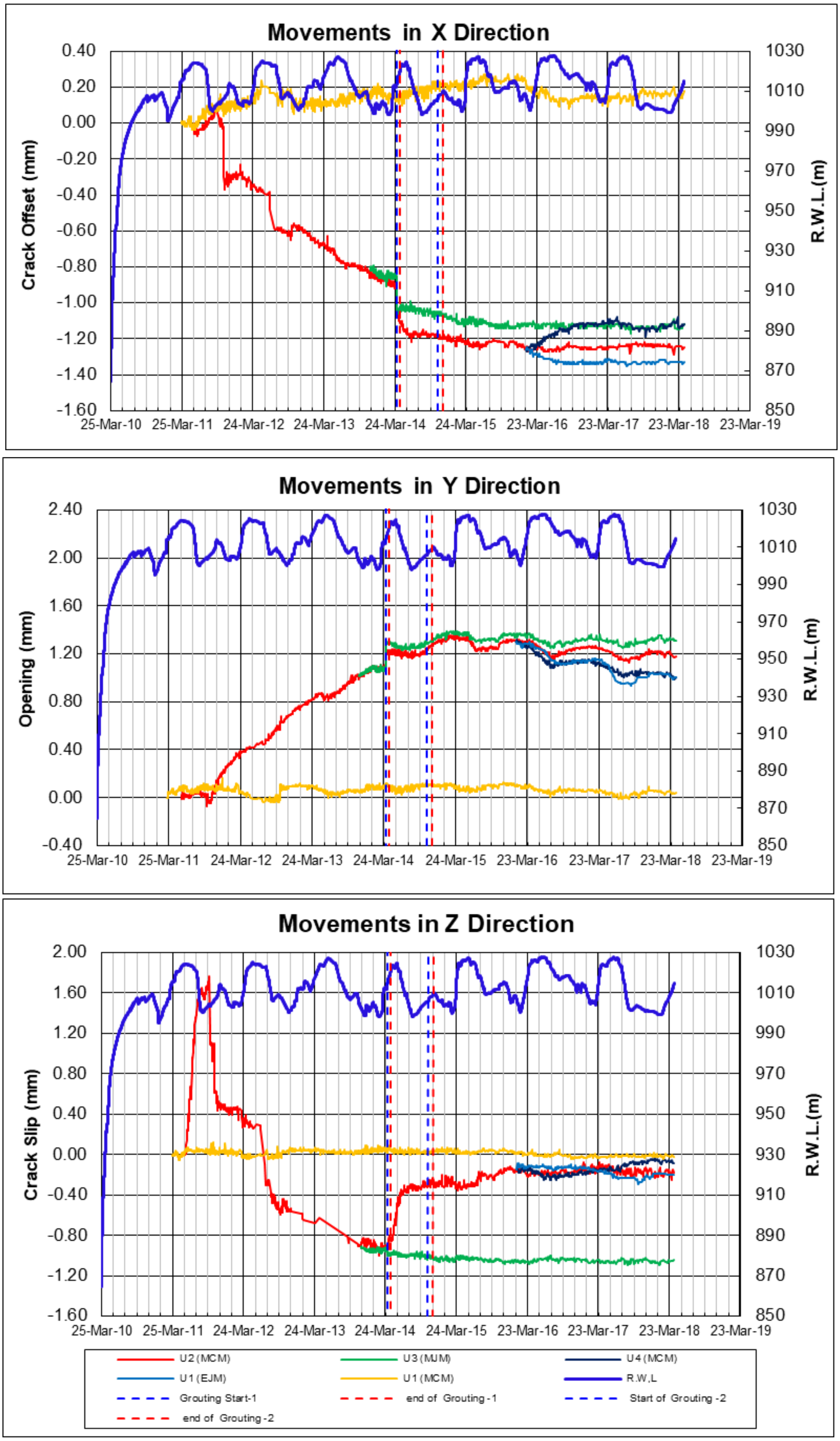


Figure 5. Results of the crack-meters and jointmeters installed on the crack outcrop in DG7 gallery U/S wall

It was quite strange that vertical slipping movement more than +1.6 mm was depicted by this instrument and after a while, this slipping movement trend is reversed and its magnitude reduced to about -1.0 mm. These abnormal and doubtful movements were not justified by visual inspection and appearance of the crack [3] [4]. These rough and ambiguous measuring results would imagine thepossibilities of "malfunctioning of the instrument (due to damages, potential hitting, etc.)" and/or possible active movements of the second branch of the crack outcrop.To clarify this, a number of new instruments were installed on the 2nd branch of the crack outcrop for verification of the measurements given by "MCM-890-B9-U2" and investigating the potential movements of the crack plane. The results obtained by the new installed instruments were not follow the sharp variations indicated by "MCM-890-B9-U2"; this is more clear by comparing the movement lines of the "MJM-890-B9-U3" and "MCM-890-B9-U2" for movements in "X" and "Z" directions. The interesting event is that by resin grouting of the crack plane, the rough variations in the measured movements by "MCM-890-B9-U2" were removed and trends of the results become more or less similar to the results obtained by "MCM-890-B9-U1". It is worth noting that resin grouting of the crack plane was not sensible effect on the trends of displacement lines resulted by "MCM-890-B9-U1". Following two hypotheses could explain these results:

- Full effectiveness of the rehabilitation works (resin grouting through the crack plane) on stability of the crack, or
- Side effect of the resin grouting on fixing the potential defects of the "MCM-890-B9-U2".

As it is explained, visual inspections and other facts, like the seepage discharges through the crack plane, were not support the sharp and rough movements of the crack showed by "MCM-890-B9-U2". Furthermore, results of the "MCM-890-B9-U1"do not support "Full Effectiveness" of rehabilitation works (resin grouting through the crack plane) on stability of the crack; because there was no sensible changes on its measured movement trends before and after resin grouting.

Disregarding the level of validity of each of the above scenarios, the results of all of the crack-meters and jointmeters installed on the crack outcrop in DG7 upstream wall are more or less the same (Figure 5). Therefore, it was decided to [3]:

- Keep the MCM-890-B9-U2 as the representative mechanical crack-meter on the crack outcrop,
- Keep the EJM-890-B9-U1 as the representative electrical jointmeter on the crack outcrop, which provides the possibility of automatic data acquisition in the ADAS system, and
- Remove the other crack-meters and jointmeters.

c)Deformeter Pins Installed on the Crack Outcrop through the Gallery Upstream Wall:

As indicated in Figure 2 and Table 1, three sets of two-point pin were installed on 2nd branch of the crack outcrop in DG7 gallery upstream wall. Measurement results of these pins are comparable with the opening or "Y" component measurement of the 3D crack-meters and jointmeters. Therefore, in order to evaluate the results obtained from these instruments, comparative graphs of pin measurements and the measurements of "MCM-890-B9-U2" in "Y" direction are plotted in Figure 6.

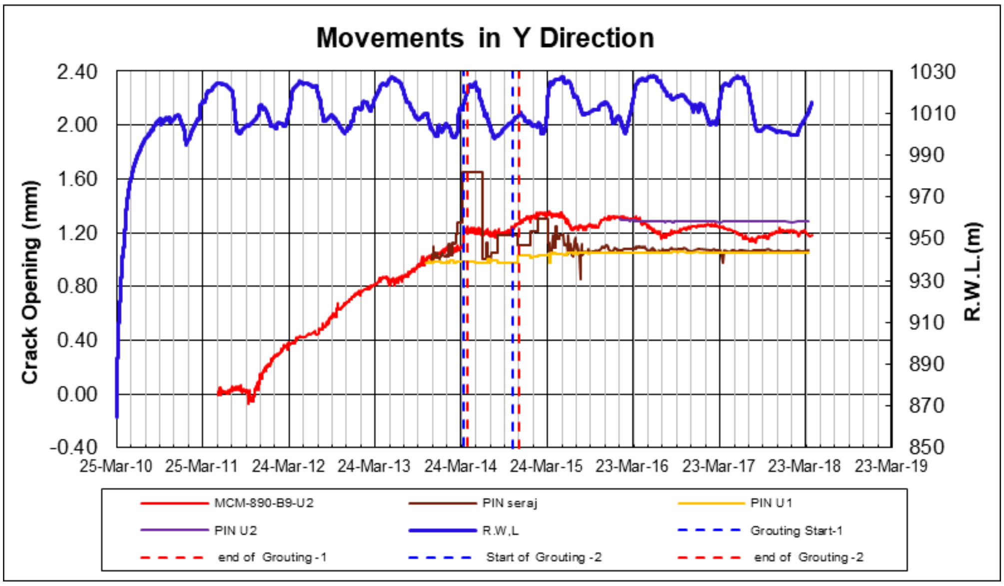


Figure 6. Results of the two-point pins compared with "MCM-890-B9-U2" in "Y" direction (DG7 gallery U/S wall)

As indicated in this Figure, the measurement results of the pins are not representing similar trends of crack opening; moreover, they do not conform to the results of the crack-meter “MCM-890-B9-U2”. This somehow might be due to relatively high sensitivity of the reading process of the pins. Anyway, it was decided to remove or stop readings of these instruments [3].

5. CONCLUSIONS

As discussed in this paper, it is essential to define specific objective(s) of each instrument in the instrumentation system and to balance the reasonable density of instruments based on the monitoring requirements and hazard assessment. Sometimes, in ambiguous and/or emergency situations, extra instruments might be necessary for clarifications (evaluation of well performance of the previous instruments and safety insurance), however, it is necessary to re-evaluate and optimize the instruments to avoid providing mass data, which could result in ambiguity by itself.

In this paper, results of the experiences in instrumentation of the main crack in the dam block 9 are reviewed and discussed. Accordingly, among the 9 instruments installed on the crack outcrop in gallery DG7, 6 instrument were removed (Figure 7). It is worth noting that the main objective of the installed extensometers (indicated in Table 1) was controlling the grouting process of resin materials through the crack plane; however, some of these extensometers are reading as the permanent instruments.

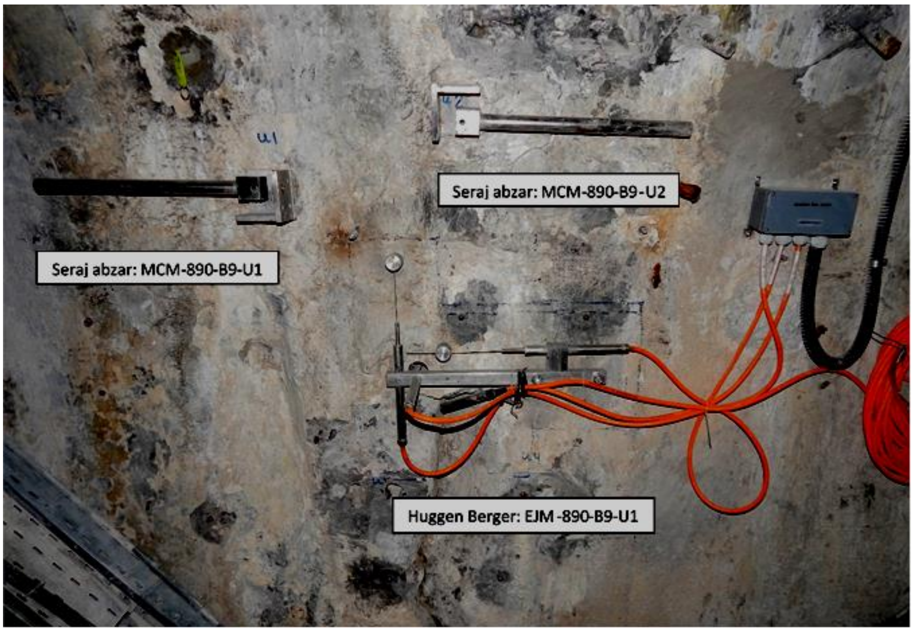


Figure 7. View of the Crack instrumentation after removal of the unnecessary instruments (DG7 gallery U/S wall)

6. REFERENCES

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