Sensitivity of the Monitoring Results and their Interpretation to Minor Imprecision in Instrument As-Built Drawings (Case Study of Karun 4 Dam)

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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 locates in southwest of Iran on the Karun River, about 200 meters upstream of the Monj tributary confluence. The dam and its foundation equipped with almost comprehensive instruments, mainly by 5 sets of direct and inverted pendulums in the left, central and right bank. Despite the reliability and simplicity of the pendulums, their measurement results indicate ambiguous lateral displacements in the dam body. Pendulums are usually the most reliable instruments and theirmeasurement results are of particular interest in interpretation and evaluation of the dam behavior.Therefore, specific studies were performed to investigate the reason and origin of such ambiguous results. In this study, two scenarios were considered for interpretation of these abnormal results; 1) presence of one or more sub-horizontal cracks and/or possible sheared lift joints through the dam blocks, and 2) possible defect and/or malfunctioning of the instrument. Finally, it was find out that “minor deviations” in set plates azimuths in the pendulum measuring stations is the main reason of the abnormal monitoring results. By modification of the measurement processing, logical displacement curves were obtained.

Keywords: Karun 4 Dam, Pendulum, Set Plate, Azimuth, Monitoring.

1. INTRODUCTION

Karun 4 dam with 230.5 m height is the highest dam under operation in Iran with the main purpose of power generation.The dam site locates in southwest of Iran on the Karun River, just at the upstream end of the Karun 3 reservoir, and around 200 meters upstream of Monjtributary confluence with Karun River. From geological point of view, 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].

Karun 4 reservoir impounding started in Farvardin 5, 1389 (March 25, 2010) when construction works of the dam and spillway were not fully completed (Figure 1) [4].According to the design documents, the dam and its foundation equipped with almost comprehensive instruments, mainly by 5 sets of direct and inverted pendulums in blocks 17 & 9 in left bank, block 0 in center, and blocks 10 & 20 in the right bank (Figure 2) [1]. Pendulums are the most reliable and simple instruments and their measurement results are of particular interest in interpretation and assessment of the dam behavior. Therefore, in order to monitor the dam displacements, direct pendulums installed temporarily following the construction situation in the related dam blocks. By completion of the dam blocks, these instruments were reinstalled on its designed position (with hanging points in the dam crest).

Because of malfunctioning of the invert pendulum IP17 at early stages after start of impounding, this pendulum reinstalled on its upper 1/3 depth and its remaining defective parts replaced by two direct pendulums DP17-1 & DP17-2, as shown in Figure 2. This rehabilitation and replacement works lasted almost until the end of the first reservoir impounding; therefore, representative pendulums for evaluation of the dam behavior are “IP10 & DP10” in the right, “IP0, DP0-2 & DP01” in the center, and “IP9 & DP9” in the left.

2. SPECIFICATIONS OF THE PENDULUM SET-PLATES AND THE PROCESSED RESULTS

According to the design assumptions of Karun 4 dam, measurement plates (set plates) in all pendulum reading-stations are aligned parallel and perpendicular to the dam reference plane. On the other word, all measurements would be made in parallel with the local coordinate axes "X" and "Y" [1]. Therefore, no translation matrix shall be used for coordinating of the measured displacements both in reading stations of one pendulum or in different. Furthermore, by this design approach, the results of the analysis shall be directly comparable to the pendulum measurements and the risk of errors in coordination processing of the measurements and / or the designed allowable limits would be minimized. In Karun 4 project, final setting of the pendulum set-plates had been done simultaneously and the plates were fixed by second stage concrete. Relying on the precise construction method of the pendulum set plates, "as-built" drawings of the pendulum measuring chambers and set plates were not prepared accurately.

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

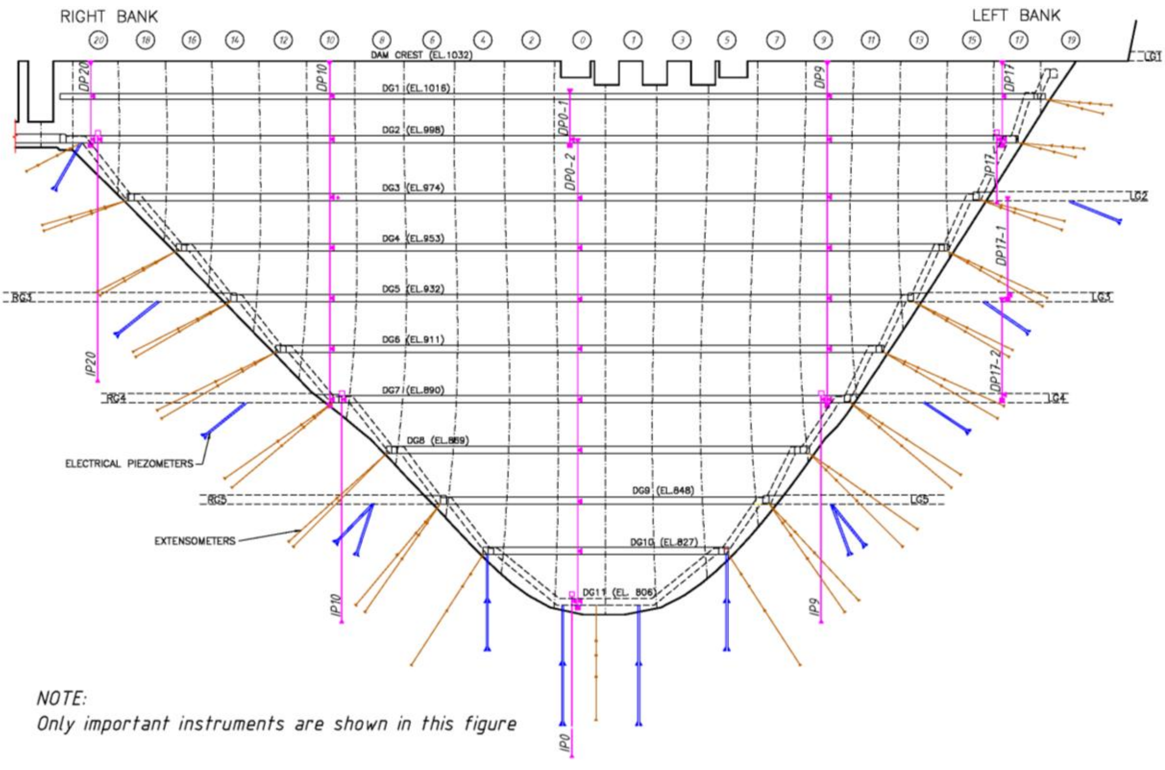


Figure 2.Main instrumentation of the Karun 4 dam and its foundation (dam D/S profile)

By growing up of reservoir water level during the first impounding, a series of abnormal lateral (left to right) displacements were resulted in some pendulum measuring stations, especially in pendulums in central block "0" and block "10" in right bank [2] [4]. The related predicted and measured "left to right" displacement lines are presented in Figures 3 to 5 corresponding to reservoir water levels (RWLs) 980, 1005 & 1016 masl, respectively. The "zigzag" or "broken" displacement lines, which somewhere intersect the predicted displacement lines, could not be explained by the elastic deformation of the continuum dam body; considering that the dam body is relatively rigid against lateral displacements. These abnormal pendulum results had been remained during operation for about 5 years.

Specific studies were performed to investigate the reason and/or origin of such abnormal displacement results. In these studies, the two following main scenarios were proposed [3]:

- Due to the relatively rigid behavior of the dam body, such a sharp variations in displacement lines would not be explained by elastic deformations, therefore, a possible scenario could be the presence of one or more sub-horizontal cracks and/or possible sheared lift joints in the dam blocks where the abnormal lateral displacements are measured. These sheared cracks and/or lift joints logically should be connected to the slide sub-horizontal discontinuities in the abutments, which imposed the displacement (sliding) to the potential cracks in the dam.
- The second scenario is based on possible error(s)in installation of the measurement set plates, because as the state of the practice, even in precise construction conditions, minor deviations in installations of the pendulum measuring set plates from the designed directions (local coordinate axes) might be possible.

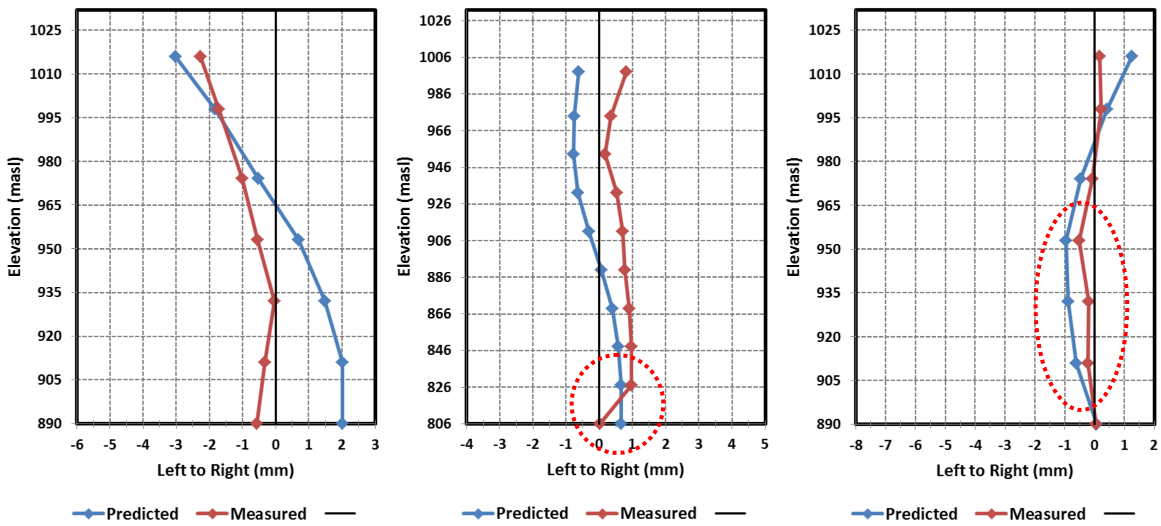


Figure 3. Abnormalities in pendulum results in block 9 (left), block 0 (center) & block 10 (right) – RWL 980masl

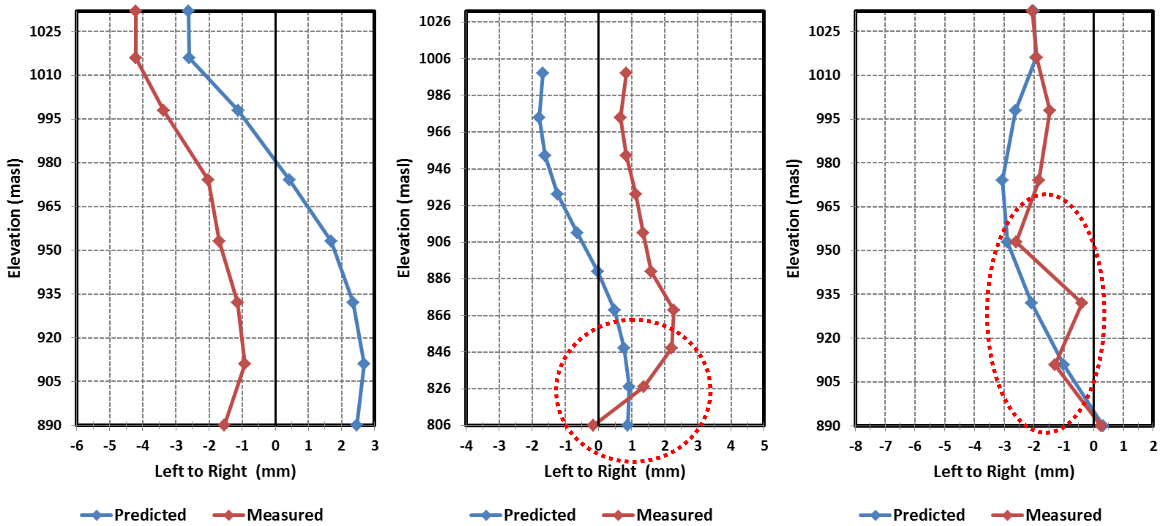


Figure 4. Abnormalities in pendulum results in block 9 (left), block 0 (center) & block 10 (right) – RWL 1005masl

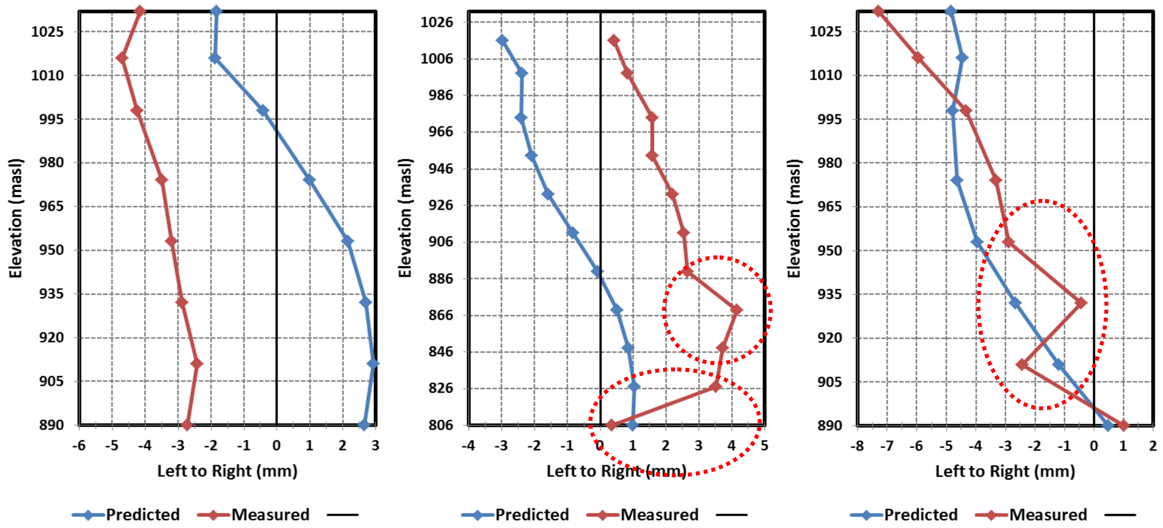


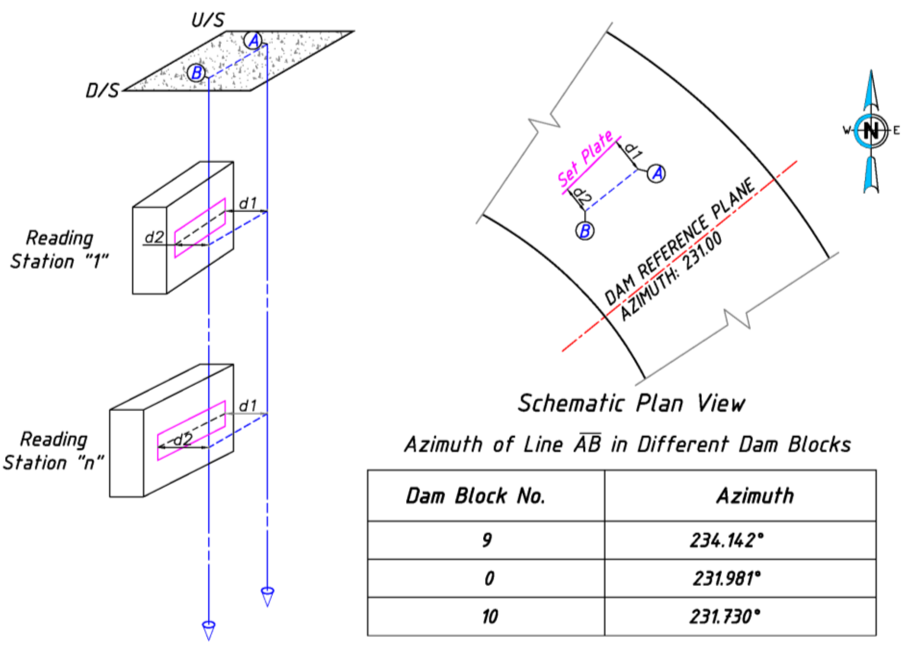
Figure 5. Abnormalities in pendulum results in block 9 (left), block 0 (center) & block 10 (right) – RWL 1016masl

2.1. Assessment of Scenario 1(Presence of Sub-horizontal Cracks in the Dam)

In the first scenario, because the proposed “shear-type” displacement(s) are detected by the pendulums, the possible shear displacements would be observed as one or a number of “offset(s)” through the pendulum wells between the related measuring stations. In order to clarify this, specific investigations were performed using detailed “borehole camera-check” through the pendulum wells. The observed results do not show any offset-type displacement through the pendulum wells. Therefore, this scenario was abandoned [3].

2.2. Assessment of Scenario 2(Deviation of Pendulum Set Plate)

Specific evaluation method was designed and implemented for surveying and verification of the set-plate azimuths in pendulum measuring stations. For this purpose, the pendulum wire was set aside, and two temporary wires were hanged up from the top. These two wires are located in a way that they are readable by cardioscope in all measuring stations. The azimuth of the connected line between twowires was defined accurately using the existing benchmarks. Afterwards, by reading the relative distances of the wires and the set plate in each reading station, the azimuth of the set plate was determined (Figure 6).



Dam Block No.	Azimuth
9	234.142°
0	231.981°
10	231.730°

Figure 6.Schematic explanation of method used for surveying of set-plate azimuths in pendulum readingstations

The obtained results are presented in Table 1; accordingly, the average deviation in set plate azimuths is about 2.7 degrees, with the maximum values of 4.5° in block 9, 5.1° in block 0, and 6.4° in block 10. Despite these minor deviations in the pendulum set plates, sensitivity analysis of the displacement vector indicates that the lateral component of displacement is highly sensitive to minor variation of the set plate azimuth. As indicated in Figure 7, 5°-rotation in set plate azimuth could introduce 87% error in the lateral displacement component. This effect magnifies by increasing the displacement component in U/S-D/S direction.

Table 1.Results of determining the pendulum set plates azimuths – deviations from the design assumption

Pendulum	Station Elevation	Design Azimuth	U/S Point on Set Plate		D/S Point on Set Plate		Set Plate Azimuth	Deviation in Azimuth (°)
			X	Y	X	Y		
DP9	1016.0	231.00°	449958.043	3496086.480	449957.945	3496086.403	231.916	0.916
	998.0		449958.040	3496086.483	449957.940	3496086.410	233.891	2.891
	974.0		449958.071	3496086.441	449957.972	3496086.365	232.611	1.611
	953.0		449958.072	3496086.440	449957.970	3496086.368	234.754	3.754
	932.0		449958.072	3496086.440	449957.972	3496086.365	233.453	2.453
	911.0		449958.071	3496086.441	449957.969	3496086.369	234.778	3.778
	890.0		449958.073	3496086.438	449957.971	3496086.367	235.498	4.498
IP9	890.0		449974.168	3496009.533	449973.945	3496009.326	235.433	4.433
DP0-1	998.0	231.00°	449916.515	3496169.742	449916.261	3496169.516	228.298	-2.702
DP0-2	974.0		449921.541	3496173.993	449921.427	3496173.912	234.651	3.651
	953.0		449921.537	3496173.998	449921.429	3496173.910	231.151	0.151
	932.0		449921.540	3496173.995	449921.430	3496173.908	231.633	0.633
	911.0		449921.538	3496173.997	449921.431	3496173.908	230.388	-0.612
	890.0		449921.536	3496173.999	449921.431	3496173.907	228.970	-2.030
	869.0		449921.540	3496173.995	449921.431	3496173.907	231.058	0.058
	848.0		449921.536	3496174.000	449921.429	3496173.910	229.758	-1.242
	827.0		449921.538	3496173.997	449921.432	3496173.906	229.206	-1.794
	806.0		449921.535	3496174.001	449921.434	3496173.903	225.871	-5.129
IP0	806.0		449920.698	3496172.772	449920.452	3496172.574	231.223	0.223
DP10	1016.0	231.00°	449837.198	3496220.223	449837.102	3496220.158	235.848	4.848
	998.0		449837.201	3496220.218	449837.106	3496220.154	235.650	4.650
	974.0		449837.200	3496220.220	449837.110	3496220.149	231.614	0.614
	953.0		449837.199	3496220.220	449837.110	3496220.149	231.617	0.617
	932.0		449837.197	3496220.223	449837.107	3496220.153	231.990	0.990
	911.0		449837.193	3496220.228	449837.112	3496220.146	224.618	-6.382
	890.0		449837.195	3496220.226	449837.106	3496220.154	231.069	0.069
IP10	890.0		449835.994	3496219.564	449835.747	3496219.376	232.685	1.685

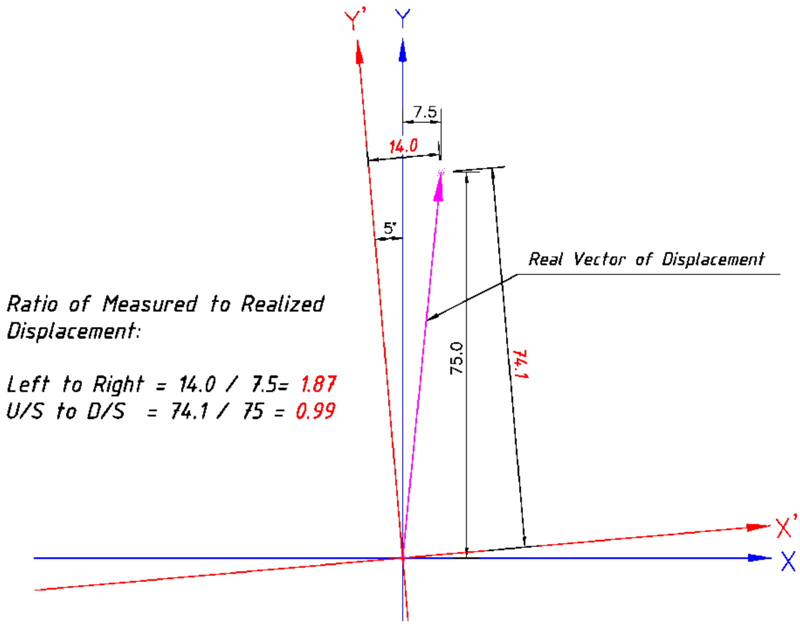


Figure 7.Sensitivity of the lateral displacement component to minor deviation in set plate azimuth

Modified pendulum results by applying the related transfer matrix for each reading station are presented in Table 2 and Figure 8. As indicated, the lateral displacement lines are fully changed and the broken and sharp variations are almost disappeared.The other important issue is changing the tendency of lateral displacement in block “0” (central block) towardthe left bank, as expected due to the dam geometrical specification.

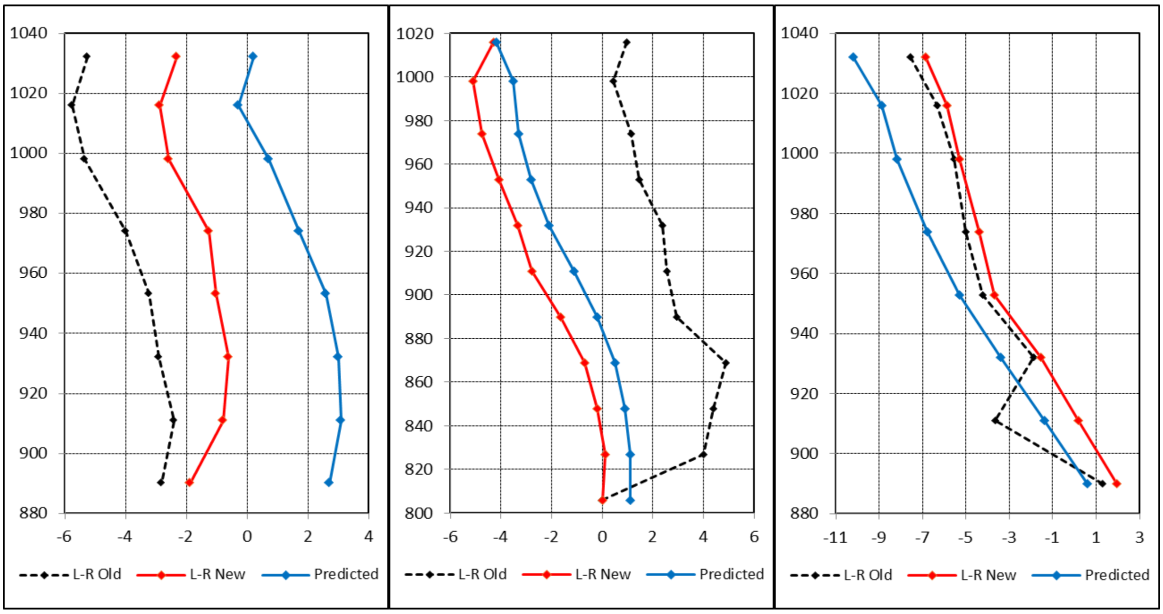


Figure 8.Old & New (modified) pendulum results in left to right direction – Pendulums 9, 0 & 10 - RWL 1026m

Table 2. Pendulum readings before and after applying corrections on the set plates deviation – RWL 1026masl

Pendulum	Station Elevation	U/S to D/S Movement				Left to Right Movement			
		Old	*Modified*	*Variation (mm, %)*		*Old*	*Modified*	*Variation (mm, %)*	
DP9	1032.0	37.04	*37.33*	0.29	*0.8%*	-5.24	*-2.33*	2.91	*-124.6%*
	1016.0	34.99	*35.29*	0.30	*0.9%*	-5.74	*-2.87*	2.87	*-100.3%*
	998.0	33.69	*33.99*	0.30	*0.9%*	-5.33	*-2.59*	2.74	*-105.6%*
	974.0	30.09	*30.35*	0.26	*0.9%*	-3.98	*-1.27*	2.71	*-213.7%*
	953.0	26.50	*26.69*	0.19	*0.7%*	-3.23	*-1.02*	2.21	*-217.5%*
	932.0	22.32	*22.53*	0.21	*0.9%*	-2.89	*-0.62*	2.27	*-369.8%*
	911.0	17.35	*17.50*	0.15	*0.9%*	-2.40	*-0.80*	1.60	*-201.3%*
	890.0	12.11	*12.29*	0.18	*1.5%*	-2.81	*-1.87*	0.94	*-50.6%*
DP0-1	1016.0	77.47	*77.23*	-0.24	*-0.3%*	0.98	*-4.29*	-5.27	*122.8%*
DP0-2	998.0	71.89	*71.68*	-0.21	*-0.3%*	0.43	*-5.1*	-5.53	*108.4%*
	974.0	66.39	*66.15*	-0.24	*-0.4%*	1.13	*-4.75*	-5.88	*123.8%*
	953.0	62.26	*62.05*	-0.21	*-0.3%*	1.48	*-4.08*	-5.56	*136.3%*
	932.0	57.65	*57.42*	-0.23	*-0.4%*	2.37	*-3.32*	-5.69	*171.4%*
	911.0	51.73	*51.55*	-0.18	*-0.4%*	2.54	*-2.78*	-5.32	*191.4%*
	890.0	45.18	*45.08*	-0.10	*-0.2%*	2.95	*-1.64*	-4.59	*279.9%*
	869.0	37.19	*36.98*	-0.21	*-0.6%*	4.89	*-0.68*	-5.57	*819.1%*
	848.0	28.12	*28.01*	-0.11	*-0.4%*	4.39	*-0.19*	-4.58	*2410.5%*
	827.0	18.50	*18.43*	-0.07	*-0.4%*	3.99	*0.13*	-3.86	*-2969.2%*
	806.0	9.61	*9.61*	0.00	*0.0%*	-0.03	*0.01*	0.04	*400.0%*
DP10	1032.0	57.41	*57.37*	-0.04	*-0.1%*	-7.57	*-6.87*	0.70	*-10.2%*
	1016.0	54.82	*54.69*	-0.13	*-0.2%*	-6.34	*-5.86*	0.48	*-8.2%*
	998.0	51.86	*51.68*	-0.18	*-0.4%*	-5.53	*-5.28*	0.25	*-4.7%*
	974.0	47.46	*47.40*	-0.06	*-0.1%*	-5.01	*-4.41*	0.60	*-13.5%*
	953.0	41.71	*41.64*	-0.07	*-0.2%*	-4.23	*-3.70*	0.53	*-14.4%*
	932.0	35.38	*35.25*	-0.13	*-0.4%*	-1.88	*-1.56*	0.32	*-20.6%*
	911.0	28.97	*29.55*	0.58	*1.9%*	-3.65	*0.19*	3.84	*2024.2%*
	890.0	22.49	*22.44*	-0.05	*-0.2%*	1.27	*1.93*	0.66	*34.2%*

3. CONCLUSIONS

Preparing precise “shop drawings” of the all instrument and their components is an essential requirement to achieve to reliable monitoring results and correct interpretation and evaluation of the dam behavior.

Based on the case study of Karun 4 arch dam, sometimes even minor deviation in construction procedure might leadto severe and unpredictable effect on the monitoring results. Such ambiguities could make incorrect judgments and unreasonable decisions about the dam stability and the required and appropriate remedies.

4. REFERENCES

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