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Hydraulic Performance of Mandali Dam Spillway in Iraq

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Abstract

A physical model was designed and constructed with a scale of 1:50 to simulate Mandali Dam spillway and its approaches. Twenty six measuring were carried out with different discharges that cover the range of expected discharges. Analysis of the collected data showed that the discharge coefficient, Cd, of the spillway was 1.7 at low discharges and it was 2.05 in case of high discharges. The model showed that the relative losses of energy dissipated through the stilling basin were varied inversely with the discharge between 71.7% and 64.6%. The measurements of the three piezometers sets located on the spillway indicated that all the measured pressures along the weir surface are positive for full range of discharges. The hydraulic model confirmed that the approach flow to the spillway inlet was generally smooth and without disturbances.

Key words: Dam spillway, hydraulic modeling, physical models, stilling basin.

Introduction

Dam modeling usually used for many purposes depending on the field of the engineering. Applications of simulation modeling to civil engineering construction and in particular to earthmoving often focus on the interaction between dissimilar equipment, such as loaders and haulers or pushers and scrapers (Photios G., 1999). Applications of simulation modeling to water resources engineering often focus on the interaction between pressure distribution on the spillway and the type of ogee curve, as well as the coefficient of discharge and the efficiency of stilling basin to energy dissipation. Hydraulic jumps on the steps of a stepped spillway usually modeled to provide preliminary design criteria to propose application of computational fluid dynamics to such problems, (Rita F., 2009). A numerical model using the finite-element and finite-volume methods is also used for the resolution of two-dimensional free-surface flow equations including air entrainment and applied to calculation of the flow in a spillway. The investigations prove that such model is valid as a primary analysis tool for hydraulic design of spillways (Unami K., 1999). Computer simulation model or finite element computational fluid dynamics software, ADINA based on finite elements or finite differences may be useful to provide a very good prediction for the free surface over an ogee spillway and thus model the flow field supporting the results with hydraulics laboratory tests (Jean Chatila, 2004).

This paper presents the experimental work and data analysis carried out to investigate the hydraulic performance of Mandali Dam spillway in the north of Iraq. A physical model was designed and constructed with a scale of 1:50 for this purpose. The model was constructed in the Faculty of Engineering of Al-Mustansiriya University.

The main goals of the model are to provide information about the following features:

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a- Flow characteristics at the entrance of spillway front channel,and the effect of the curvature of the upstream left wing wall, looking especially for the formation of vortices at different discharges up to maximum design discharge.
b- Performance Characteristics of the spillway weir (discharge coefficient with head and the resulting rating curve, pressure variation along the weir surface) for the full range of discharges up to maximum design discharge.
c- Flow characteristics along the spillway chute for the full range of discharges (with water level measurement and pressure distribution on the floor slab and walls together with investigation for the need of aeration).
d- Investigation of the efficiency of energy dissipation in the stilling basin for the full range of discharges, and checking the adequacy of downstream protection works in view of the expected scour.

General Site Description and Dam Details

Mandali Dam is constructed in Harran Wadi, at the Governorate of Diyala. The dam site is situated upstream Koma sang pipe line headwork. Harran Wadi originates in Iran and crosses the Iraqi borders north east of Mandali Town. The dam and its reservoir is bounded by 373700-378500 N and 554500- 565000 E coordinates of UTM system. The lowest Wadi level is at elevation of about 162 *m.a.s.1*. The right abutment level is about 190 *m.a.s.1*, and the left abutment level is about 195 *m.a.s.1*. The relation between the water level and discharge in Wadi Harran at the dam site is given by (figure 1).

The spillway is designed as an uncontrolled ogee weir, (figures 2 and 3), with a length of 250 *m* and height of 10 *m* with a crest level at elevation 180.0 *m.a.s.l.* The design discharge is 1724 m^3/s and the heading up over the crest at this discharge is about 2.42 m. The rating curve of the weir was calculated and is given by (figure 4) of Mandali Dam Design Report.

Based on the hydraulic jump calculations, performed and presented in the design report of Mandali Dam, the stilling basin floor level was set to 165 *m.a.s.l* with a length of 21.5 *m*, (Figure 2). Chute blocks and dentated sill were provided. The chute blocks have a width of 0.5 *m* and height of 0.5 *m*. The dentated sill has a height of 1 *m*, width top of 0.1 *m*, distance between teeth of 0.75 *m* and the out slop of 2:1.

The coefficient of permeability for different materials was ranged from (1.37*10-4 to 9.88*10-4) cm/s and the permeability in the left bank of the river below elevation 157 *m.a.s.l.* was found to be equals zero, Mandali Dam- Geological Report.

The dam has the following characteristics:

- Dam Height: 14 *m*.
- Dam length = 1150 *m*.
- Dam crest level = 184 *m.a.s.l.*
- Spillway crest elevation= 180 *m.a.m.s.l.*
- Maximum water level= 182.5 *m*.
- Maximum Discharge = 1724 m^3/s.
- Spillway length = 250 *m*.
- Maximum head over spillway= 2.5 *m*.

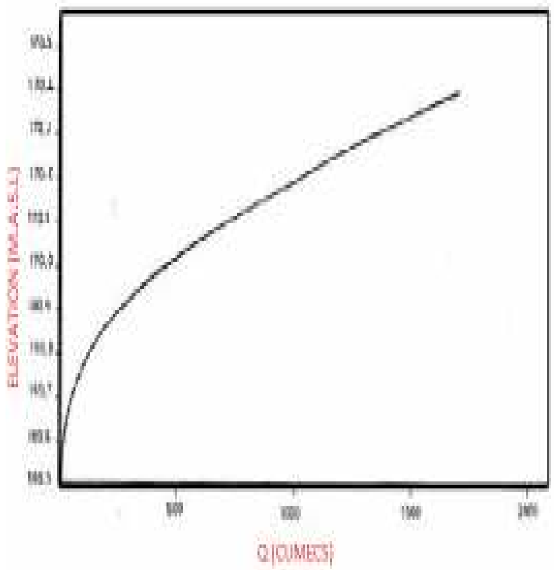

Figure 1. Wadi Harran rating curve at dam site, *(Mandali Dam Design Report, 2004)*.

Scale Factors

The modeling of the spillway, chute, and stilling basin, are based on the following theoretical aspects, (Streeter 1979; Vennard, 1996).

1- The inertia and gravitational forces will be represented well by Froude Number, Fr.
2- The viscous force, represented by Reynolds Number, is negligible for free flow condition, unless the Reynolds number falls in the range of laminar flow.

Depending on the above bases and with a model scale factor of Lr=50, the scale factors were obtained and presented in (Table 1), (Bureau, Preliminary report, 2008). (Table 2). represents the full range of expected discharges of Mandali Dam and the corresponding values of the model according to the scale factor of 1:50.

Parameter	Scale factor
Velocity	$Vr = V_p/V_m = \sqrt{\dfrac{lp}{lm}} = \sqrt{lr} = \sqrt{50} = 7.07$
Time	$Tr = T_p/T_m = \dfrac{lp * Vm}{Vp * lm} = \dfrac{lr}{\sqrt{lr}} = \sqrt{lr} == \sqrt{50} = 7.07$
Pressure	$Pr = P_p/P_m = \rho_p/\rho_m * V_p^2 / V_m^2 = 1 * lr = 50$
Force	$Fr = Pr * lr^2 = lr * lr^2 = lr^3 = 50^3 = 125\ 000$
Discharge	$Qr = Vr * lr^2 = \sqrt{lr} * lr^2 = 50^{2.5} = 17677.7$
Reynolds Number	$Rr = R_p/R_m = \rho_p/\rho_m * V_p / V_m * l_p / l_m = 1 * \sqrt{lr} * lr$ then, $Rr = lr^{1.5} = 50^{1.5} = 353{,}55$

Table 1: The used scale factors

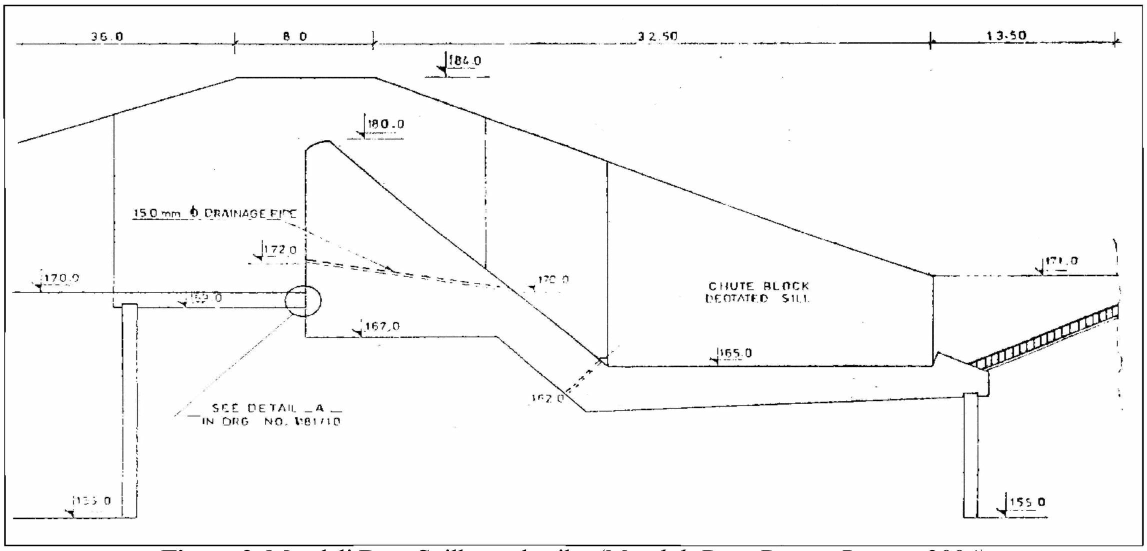

Figure 2. Mandali Dam Spillway details, *(Mandali Dam Design Report, 2004).*

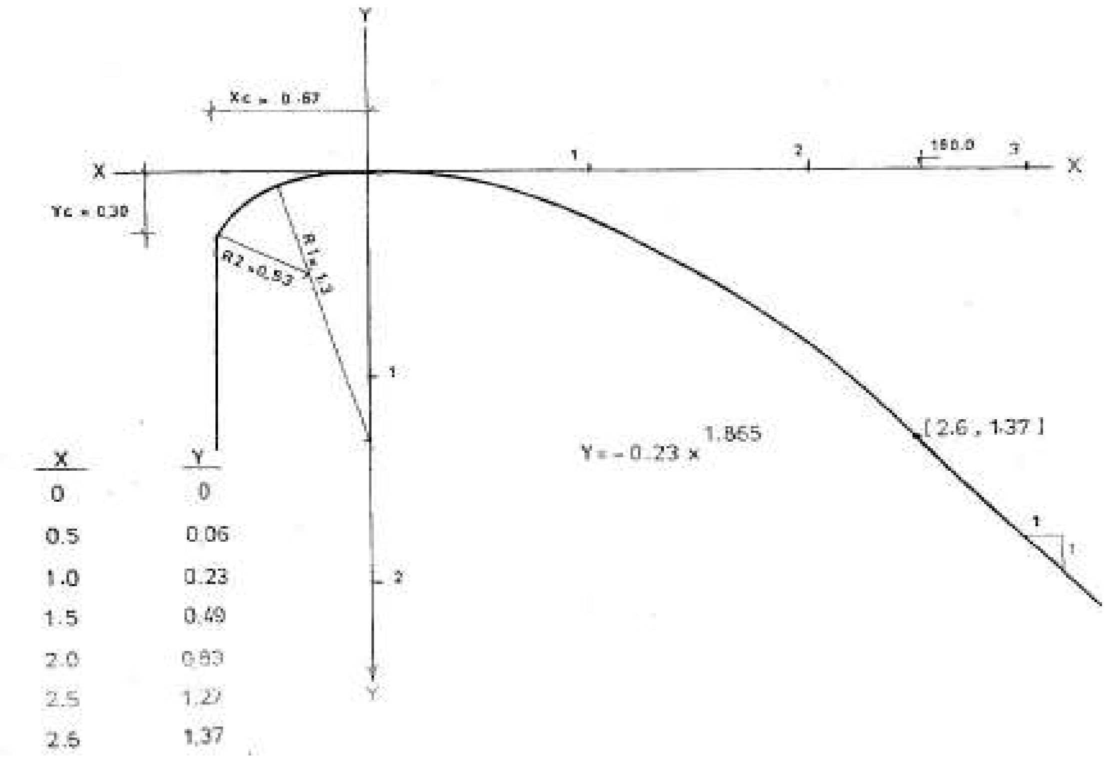

Figure 3. Details of Weir Crest and Ogee Spillway Shape, *(Mandali Dam Design Report, 2004).*

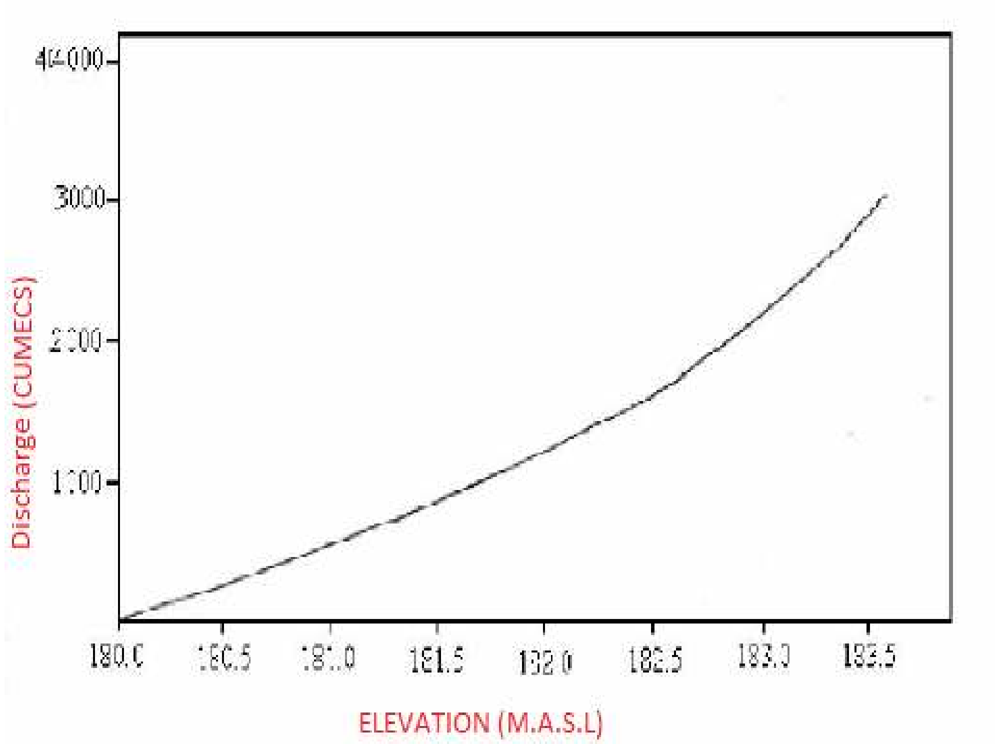

Figure 4: Weir rating curve, *(Mandali Dam Design Report, 2004).*

(Table 2). represents the full range of expected discharges of Mandali Dam and the corresponding values of the model according to the scale factor of 1:50.

Mandali Dam Expected Discharges m^3/s	**Corresponding Model Discharges** *l/s*
1725	97.5
1500	85
1220	69
1000	56.5
500	28
100	5.6
50	2.8

Table 2. Mandali Dam expected discharges and its corresponding model discharges.

Hydraulic model

The hydraulic model includes an area approximately 750x750 *m* upstream of the dam spillway as shown in (figure 5). A 75 m downstream of the stilling basin was modeled also.

In constructing the model, steel bars and precise level instrument were used to project the developed 3D terrain on the dam model site. Three layers of compacted clean soil, compacted dry sand and cement mixture, and concrete layer reinforced by chicken wire were used to simulate the model reservoir topography. The concrete surface was coated with water-proof epoxy. To insure smooth entrance conditions into the reservoir, an inlet basin of 15x1.5 *m* was constructed. Moreover, concrete blocks and two-ply plastic screens, of 2x2mm openings, supported by a steel frame were used in the model inlet basin. Brick, cement, and water- proof coating were used in all parts of model, model basin, spillway, and sump.

The spillway was constructed of concrete by two identical steel moulds of 0.5 *m* in length, were manufactured based on the spillway shape to produce the concrete blocks of the spillway, (figure 6).

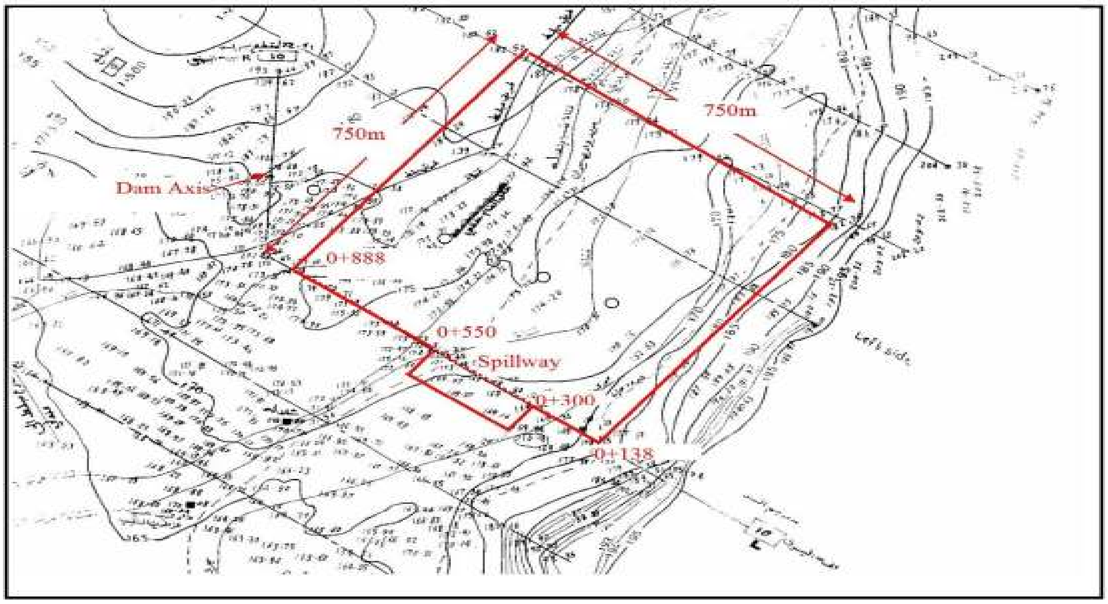

Figure 5. The modeled spillway side of the Mandali Dam and its reservoir.

Figure 6. Physical model of Mandali Dam spillway.

Testing program and testssetup

The testing program consisted of twenty six runs, covering the full range of expected water surface levels in the model were measured by point gages upstream of the spillway entrance and at the end of the stilling basin to measure the elevation of the sequent depth. The accuracy of the gages is 0.1 mm.

Three groups of piezometers, each group consists of eight piezometers, were installed along the spillway surface for piezometric head measurements, (figure 7). The first group was installed at 50 *m* away from the right side of the weir, the second was installed at the center of the spillway, and the third group was installed at 50 *m* away from the left side of the weir. These piezometers were connected by rubber tubing to a manometer board with scales that could be read to the nearest 1.0 mm.

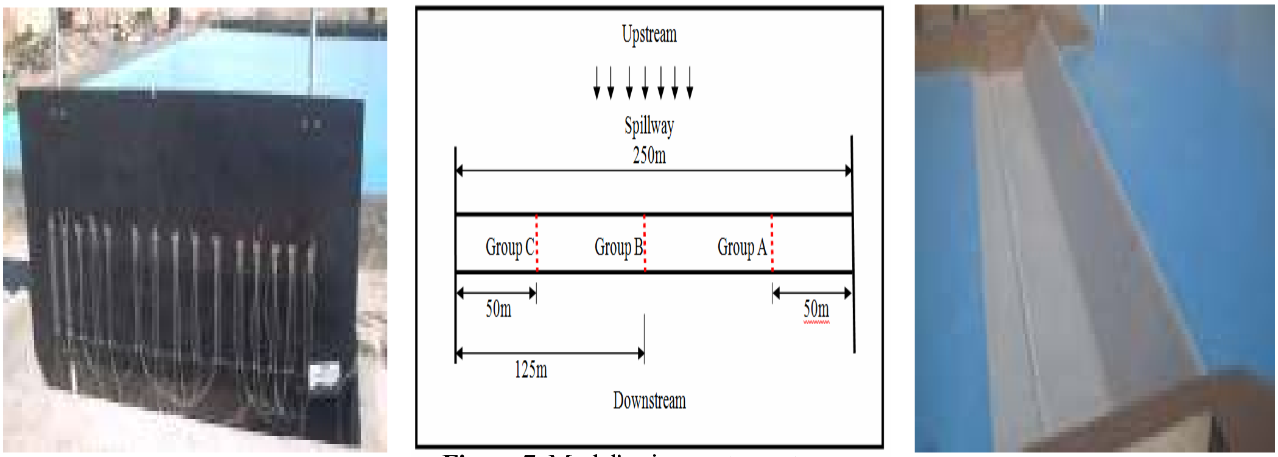

Figure 7. Model's piezometers sets.

(Table 3). shows location of piezometers openings along the spillway surface and their levels. The used coordinate system origin is at the lower point of the weir face at elevation 170 *m.a.s.l.*

Water was delivered to the reservoir from a sump using a recirculation centrifugal pump. Discharge measurements were made using a flow meter which was installed on the discharge side of the pump. Readings were taken after steady state conditions had been established in the model.

Results and discussion

The free flow discharge equation over an ogee crested spillway is given as:

$$Q = C_d \, L \, H^{1.5} \qquad (1)$$

Where:
Q = discharge, m^3/s.
C_d = discharge coefficient.
L = effective length of crest, *m*.

H = the head above the crest including velocity of approach head, *m*.

It is useful to say that the discharge coefficient, Cd, is influenced by a number of factors, (Chaudhry 2008; Hubert 2004; Rajput, 2009). such that:

1. Depth of approach
2. Relation of the actual crest shape to the ideal nappe shape
3. Upstream face slope
4. Downstream apron interference, and
5. Downstream submergence

Based on the measured data of the twenty six runs, the values of the discharge coefficient, C_d, were calculated and are presented in (Table 4). The approach velocity is too small and may be neglected without affecting the calculations of the discharge coefficient. The discharge coefficient at low discharges, less than 100 m^3/s, was found to be about 1.7 while, at high discharges greater than the design discharge, it was about 2.05.

The rating curve of the spillway weir was obtained based on the discharges measurements, which represented a full range of expected discharges on the spillway. The best fit curve is shown in (figure 8) and has the following power function with a correlation coefficient, R^2, of 0.99, (Bayliss 2001; Wiley, 2004).

$$Q_{ac} = 466\,(EL - 180)^{1.583} \qquad (2)$$

where
Q_{ac} = actual Discharge, m^3/s.
EL = Water level, *m.a.s.l.*

(Figure 8). indicates that the design discharge of 1724 m^3/s will be passed with a reservoir level of 182.285 *m.a.s.l,* whereas the level given by the design report is at 182.5 m.a.s.l. So, the model shows that at the design reservoir water level, 182.5 *m.a.s.l*, the spillway discharge will be 1987.6 m^3/s.

Group A				Group B				Group C			
Piezometer code	**X Coordinate *m***	**Y Coordinate *m***	**Level *m.a.s.l***	**Piezometer code**	**X Coordinate *m***	**Y Coordinate *m***	**Level *m.a.s.l.***	**Piezometer code**	**X Coordinate *m***	**Y Coordinate *m***	**Level *m.a.s.l..***
PGA1	0.37	9.964	179.964	PGB1	0.345	9.956	179.956	PGC1	0.35	9.963	179.963
PGA2	0.85	9.991	179.991	PGB2	0.8	9.995	179.995	PGC2	0.83	9.992	179.992
PGA3	1.5	9.841	179.841	PGB3	1.48	9.848	179.848	PGC3	1.45	9.855	179.855
PGA4	2	9.603	179.603	PGB4	2.1	9.545	179.546	PGC4	2.05	9.580	179.580
PGA5	2.95	8.930	178.9303	PGB5	3.02	8.859	178.859	PGC5	3	8.894	178.895
PGA6	5.1	6.833	176.833	PGB6	5.195	6.733	176.733	PGC6	5	6.833	176.833
PGA7	7.9	4.033	174.033	PGB7	8.045	3.833	173.833	PGC7	7.99	3.933	173.933
PGA8	10.9	1.033	171.033	PGB8	10.8	1.033	171.033	PGC8	10.7	1.133	171.133

Table 3. Location of piezometers opening along the spillway surface

Run No.	Discharge m^3/s	Head *m*	Approach velocity *m/s*	Velocity head *m*	Total head *m*	C_d
1	368.23	0.88	0.14	0.000935	0.88	1.80
2	367.70	0.85	0.14	0.0009	0.85	1.87
3	666.45	1.25	0.24	0.003	1.25	1.90
4	163.52	0.53	0.06	0.000	0.53	1.72
5	813.17	1.40	0.29	0.004	1.40	1.95
6	1022.65	1.65	0.35	0.006	1.66	1.92
7	1039.80	1.67	0.36	0.006	1.67	1.92
8	40.13	0.21	0.02	0.00001	0.21	1.67
9	1473.08	2.03	0.49	0.012	2.04	2.03
10	1359.77	1.95	0.46	0.011	1.96	1.99
11	841.81	1.46	0.29	0.004	1.46	1.90
12	388.91	0.88	0.14	0.001	0.88	1.90
13	180.31	0.55	0.07	0.0002	0.55	1.77
14	1359.77	1.94	0.46	0.011	1.95	1.99
15	1511.44	2.08	0.50	0.013	2.09	2.00
16	67.18	0.29	0.03	0.00003	0.29	1.77
17	1178.57	1.78	0.40	0.008	1.78	1.98
18	172.36	0.55	0.07	0.0002	0.55	1.69
19	67.18	0.30	0.03	0.00003	0.30	1.68
20	436.46	0.98	0.16	0.001	0.98	1.81
21	795.67	1.45	0.28	0.004	1.45	1.82
22	1140.39	1.78	0.39	0.008	1.78	1.92
23	1309.38	1.90	0.44	0.010	1.91	1.98
24	1590.99	2.18	0.52	0.014	2.19	1.97
25	1822.57	2.31	0.59	0.018	2.32	2.06
26	1803.12	2.30	0.59	0.018	2.32	2.04

Table 4. Calculated discharge coefficient.

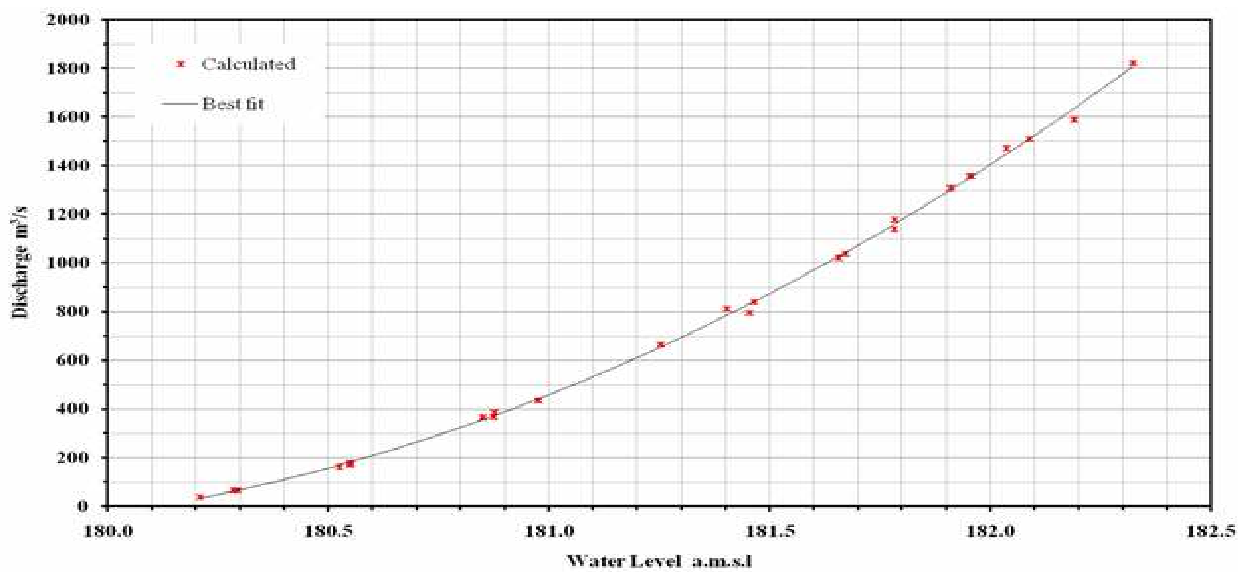

Figure 8. The obtained rating curve of the spillway weir

(Figure 9). shows a comparison between the calculated discharge coefficient based on the model measurements, based on the design calculations, and that obtained using the charts given by (Chow, 1986). The design rating curve was based on a discharge coefficient of 1.84 so it gives low values at high discharges.

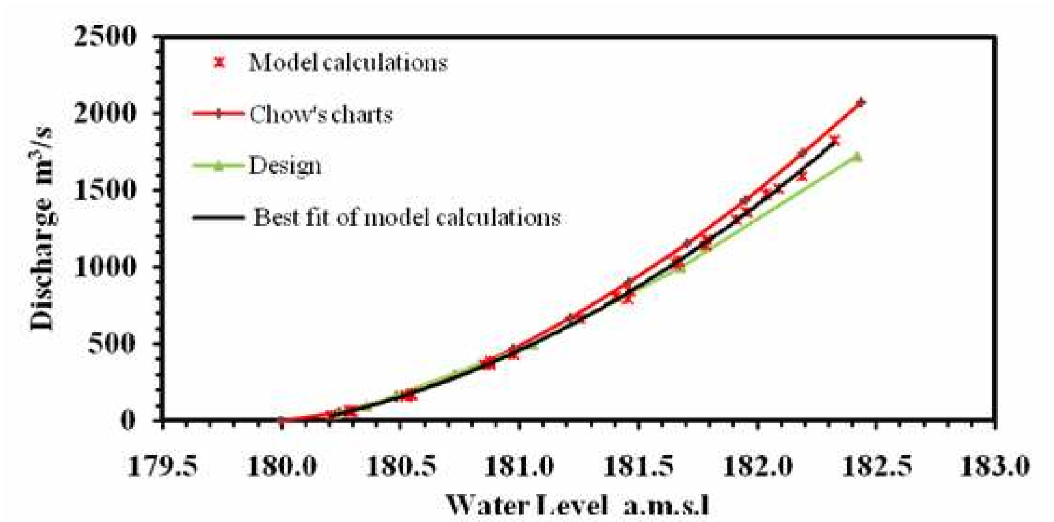

Figure 9. Comparison between the rating curves obtained using model data, design calculation, and that of Chow's charts.

The hydraulic model confirmed that the approach flow to the spillway inlet was generally smooth without disturbances or eddies. (Figure 10). shows the flow conditions in the hydraulic model as it approaches the spillway. It was clear that there is no threat of scour along the face of the dam.

Figure 10. Approach flow to the spillway.

All of the measured pressures along the weir surface are positive for full range of expected discharges, which indicates that there is no danger of cavitations to take place along the ogee curve. Some of the measurements of the piezometric head of the three groups of piezometers are shown in (figures11 to 18), that ware selected out of 26 runs, which cover the flowrate range from 40 to 1823 m^3/s.

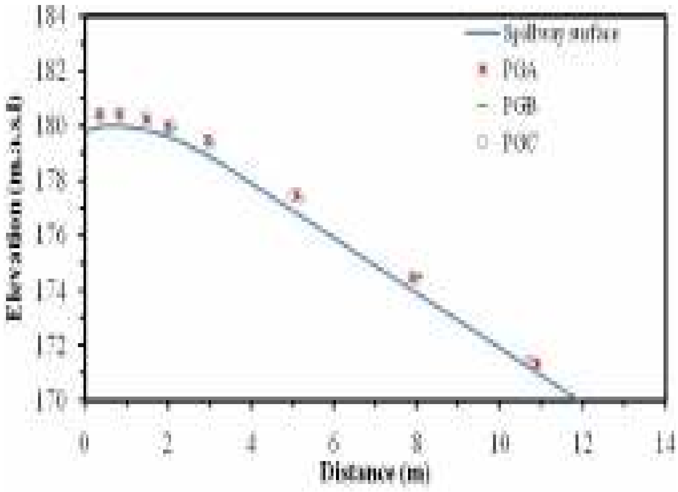

Figure 11. Pressure distribution profile on the spillway. Run no.8, Q=40.1 m^3/s.

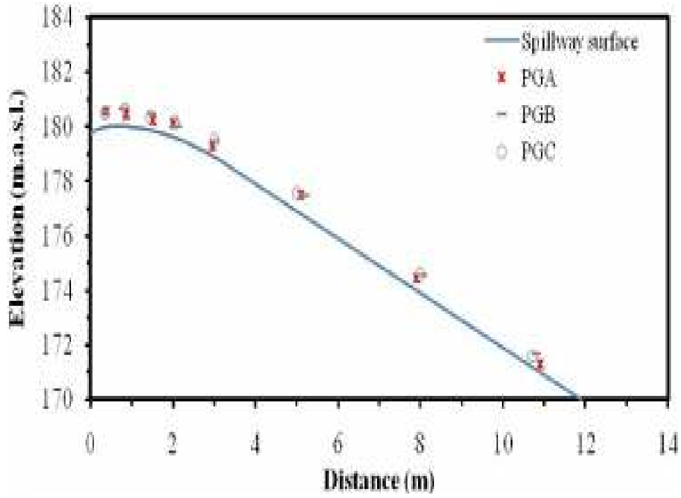

Figure 12. Pressure distribution profile on the spillway. Run no.13, Q=180.3 m^3/s.

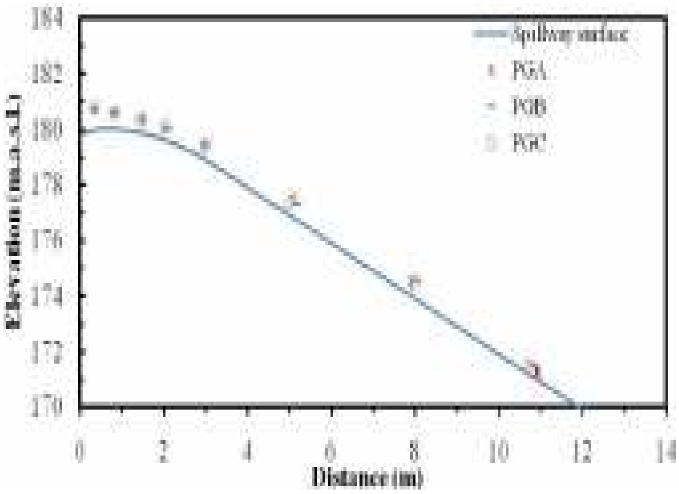

Figure 13. Pressure distribution profile on the spillway. Run no.1, Q=368.2 m^3/s.

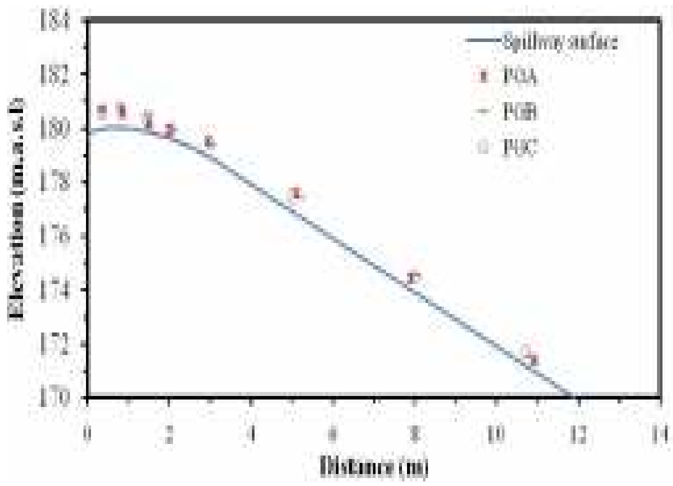

Figure 14. Pressure distribution profile on the spillway. Run no.5, Q=813.2 m^3/s.

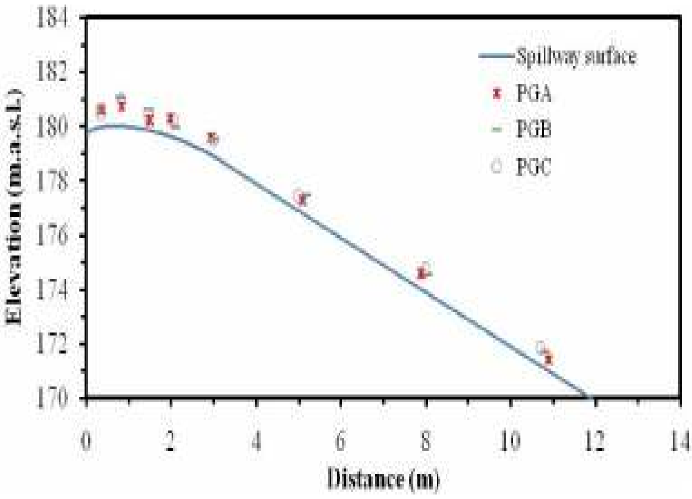

Figure 15. Pressure distribution profile on the spillway. Run no.7, Q=1040 m^3/s.

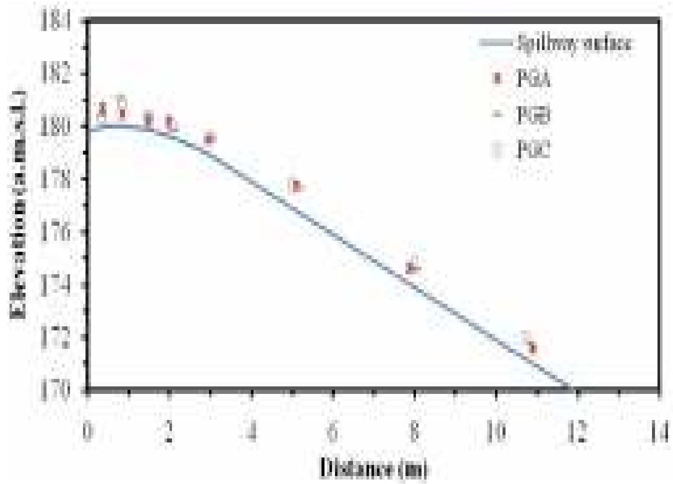

Figure 16. Pressure distribution profile on the spillway. Run no.14, Q=1360 m^3/s.

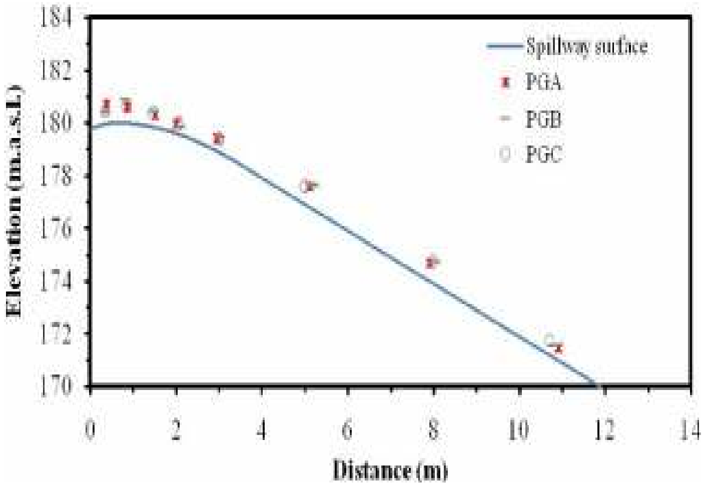

Figure 17. Pressure distribution profile on the spillway. Run no.24, Q=1591 m^3/s.

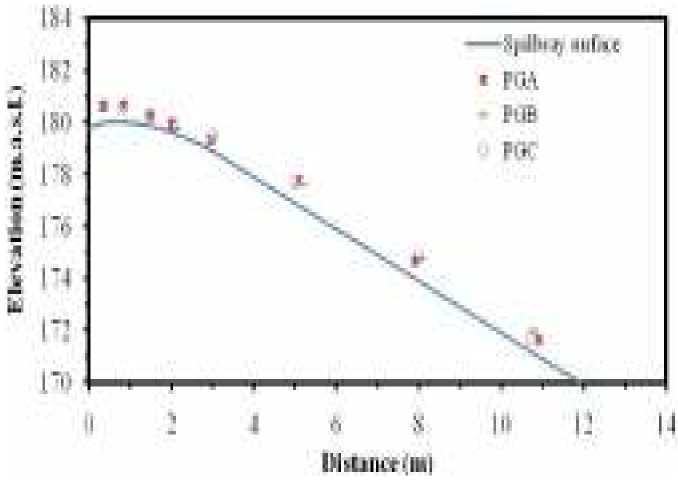

Figure 18. Pressure distribution profile on the spillway. Run no.25, Q=1823 m^3/s.

(Figure 19), shows the hydraulic jump within the stilling basin at different discharges. The loss of energy in a jump is equal to the difference in energies before and after the jump, E1-E2. The ratio of this loss to E1 is known as the relative loss, RL, (USBR, 1987). (Table 5), shows the calculated relative loss of the stilling basin. The calculations were based on the model energy measurements at the reservoir and that at the end of the hydraulic jump at the stilling basin. The energy loss along the spillway surface was considered small and it was included within the overall loss of the energy. The calculated RL varies inversely with discharge between 71.7% and 64.6%.

According to the data presented by Mandali Dam Design Report the calculated RL at the design discharge of 1724m^3/s is 70.74% while it is about 64.95% according to the model measurements. The values of (y2) given by that report for other discharges are too low to drive the flow downstream and RL calculations couldn't be carried out for comparison purposes,

Figure 19. The hydraulic jump within the stilling basin with different discharges.

Run no.	Dam reservoir		Stilling basin			Relative loss %
	Discharge m^3/s	Total energy level *m.a.s.l*)	y2 (*m*)	Velocity head *m*	Total energy level *m.a.s.l*	
1	368.23	180.88	4.93	0.0046	169.930	68.95
2	367.7	180.85	4.95	0.0045	169.954	68.74
3	666.4	181.25	5.43	0.0123	170.437	66.54
4	163.5	180.53	4.64	0.0010	169.636	70.14
5	813.2	181.40	5.53	0.0177	170.543	66.20
6	1023	181.65	5.53	0.0279	170.558	66.62
7	1040	181.67	5.63	0.0279	170.653	66.08
8	40.13	180.21	4.30	0.0001	169.300	71.73
9	1473	182.03	5.75	0.0535	170.804	65.91
10	1360	181.95	5.75	0.0456	170.796	65.80
11	841.8	181.46	5.50	0.0191	170.519	66.47
12	388.9	180.88	4.95	0.0050	169.955	68.79
13	180.3	180.55	4.65	0.0012	169.651	70.09
14	1360	181.94	5.75	0.0456	170.796	65.79
15	1511	182.08	5.79	0.0556	170.846	65.77
16	67.18	180.29	4.35	0.0002	169.350	71.54
17	1179	181.78	5.66	0.0354	170.695	66.05
18	172.4	180.55	4.65	0.0011	169.651	70.09
19	67.18	180.30	4.41	0.0002	169.410	71.17
20	436.5	180.98	5.08	0.0060	170.081	68.19
21	795.7	181.45	5.41	0.0176	170.428	67.01
22	1140	181.78	5.75	0.0321	170.777	65.56
23	1309	181.90	5.76	0.0422	170.797	65.70
24	1591	182.18	5.95	0.0583	171.008	65.02
25	1823	182.31	6.00	0.0752	171.075	64.89
26	1803	182.30	6.05	0.0724	171.122	64.61

Table 5. Relative loss dissipated through the stilling basin.

Conclusions

The following conclusions where conducted during the experiment work.

1. Observations on the hydraulic model indicate that the spillway will perform properly as designed.
2. No formation of vortices was observed on the model.
3. The spillway rating curve indicates that the maximum discharge will be passed with reservoir elevation of 182.28 *m.a.s.l.*
4. All of measured pressures along the weir surface are positive for full range of expected discharges.
5. The calculated RL varies inversely with discharge between 64.6%. and 71.7% .

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Nomenclature

m.a.s.1: Meter above sea level

UTM: Universal transverse Mercator

Vr : Velocity ratio

Vp: Prototype velocity

Vm: Model velocity

Tr : Time ratio

Tp: Prototype time

Tm: Model time

Pr: Pressure ratio

Pp: Prototype pressure

Pm: Model pressure

Fr: Force ratio

lr: Length ratio

lp: Prototype length

lm: Model length

Qr: Discharge ratio

Rr: Reynolds number ratio

Rp: Reynolds number in prototype

Rm: Reynolds number in model

ρ_p: ***Density of fluid used in prototype***

ρ_m: ***Density of fluid used in model***

Q = ***Discharge,*** m^3/s.

C_d = ***Discharge coefficient.***

L = ***Effective length of crest***

H = ***The head above the crest including velocity of approach head***

Q_{ac} = ***Actual Discharge***

EL = Water level.

Y2 = Water depth at the end of stilling basin

الملخص العربى:

لقد تم في هذا البحث تنفيذ نموذجا هايدروليكيا لمحاكاة السد والمسيل المائي والمقتربات الخاصة بسد مندلي في العراق .تم تشغيل النموذج واخذت ٢٦ قراءة من التصاريف التي تغطي جميع التصاريف الحقيقية المتوقعة الحدوث. لقد بين التحليل الرياضي والاحصائي للبيانات ان معامل التصريف Cd للمسيل المائي هي بحدود 1.7 في حالة التصاريف القليلة وبحدود 2.05عند التصاريف العالية. كما وبينت نتائج النموذج ان نسبة الطاقة المتبددة خلال حوض التهدئة كان يتغير عكسيا مع قيمة التصاريف المشغلة حيث تراوحت نسبة الطاقة المتبددة بين 64.6% الى 71.7%. لم تسجل مجاميع البيزومترات الثلاثة المثبتة على مختلف نقاط المسيل المائي للنموذج الهايدروليكي اية قراءة سالبة للضغط المسلط على سطح المسيل المائي لجميع قيم التصاريف المشغلة .لقد اثبت التشغيل الهايدروليكي للنموذج ان الجريات عند مداخل ومقتربات المسيل المائي يجري بشكل هاديء وخالي من الاضطرابات او الدوامات المائية .