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 (Photosios 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-Mustansirya University.

The main goals of the model are to provide information about the following features:
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.l. The right abutment level is about 190 m.a.s.l, and the left abutment level is about 195 m.a.s.l. 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 m³/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 m³/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 \( L_r = 50 \), 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>( V_r = V_p / V_m = \sqrt{\frac{lp}{lm}} = \sqrt{l_r} = \sqrt{50} = 7.07 )</td>
</tr>
<tr>
<td>Time</td>
<td>( T_r = T_p / T_m = \frac{lp * V_m}{V_p * lm} = \frac{l_r}{\sqrt{l_r}} = \sqrt{50} = 7.07 )</td>
</tr>
<tr>
<td>Pressure</td>
<td>( P_r = P_p / P_m = \frac{rp}{rm} * \frac{V_p^2}{V_m^2} = 1 * \sqrt{l_r} = 50 )</td>
</tr>
<tr>
<td>Force</td>
<td>( Fr = Pr * 1^2 = l_r * l_r^2 = 50^3 = 125000 )</td>
</tr>
<tr>
<td>Discharge</td>
<td>( Q_r = V_r * l_r^2 = \sqrt{l_r} * \sqrt{l_r} = 50^2.5 = 17677.7 )</td>
</tr>
</tbody>
</table>
| Reynolds Number   | \( R_r = R_p / R_m = \frac{rp}{rm} * \frac{V_p}{V_m} * \frac{l_p}{l_m} = 1 * \sqrt{l_r} * l_r \\
then, \( R_r = l_r^{1.5} = 50^{1.5} = 353.55 \) |

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.

<table>
<thead>
<tr>
<th>Mandali Dam Expected Discharges ( m^3/s )</th>
<th>Corresponding Model Discharges ( l/s )</th>
</tr>
</thead>
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<tr>
<td>1725</td>
<td>97.5</td>
</tr>
<tr>
<td>1500</td>
<td>85</td>
</tr>
<tr>
<td>1220</td>
<td>69</td>
</tr>
<tr>
<td>1000</td>
<td>56.5</td>
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<tr>
<td>500</td>
<td>28</td>
</tr>
<tr>
<td>100</td>
<td>5.6</td>
</tr>
<tr>
<td>50</td>
<td>2.8</td>
</tr>
</tbody>
</table>

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.
Testing program and test setup

The testing program consisted of twenty six runs, covering the full range of expected water surface levels in the model. Water 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.

(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:

\[ Q = C_d \cdot L \cdot H^{1.5} \]  

(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, \( C_d \), 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).

\[
Q_{ac} = 466 \ (EL - 180)^{1.583} \\
(2)
\]

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 \( m^3/s \).

<table>
<thead>
<tr>
<th>Piezometer code</th>
<th>Group A</th>
<th>Group B</th>
<th>Group C</th>
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<td>X Coordinate m</td>
<td>Y Coordinate m</td>
<td>Level m.a.s.l</td>
<td>X Coordinate m</td>
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Table 3. Location of piezometers opening along the spillway surface
Table 4. Calculated discharge coefficient.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Discharge $m^3/s$</th>
<th>Head $m$</th>
<th>Approach velocity $m/s$</th>
<th>Velocity head $m$</th>
<th>Total head $m$</th>
<th>$C_d$</th>
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</tr>
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</table>

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.

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.

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 (figures 11 to 18), that were selected out of 26 runs, which cover the flow rate 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 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, E\textsubscript{1}-E\textsubscript{2}. The ratio of this loss to E\textsubscript{1} 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 1724 m\textsuperscript{3}/s is 70.74% while it is about 64.95% according to the model measurements. The values of (y\textsubscript{2}) 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 17). Pressure distribution profile on the spillway.
Run no.24, Q=1591 m\textsuperscript{3}/s.

(Figure 18). Pressure distribution profile on the spillway.
Run no.25, Q=1823 m\textsuperscript{3}/s.

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

The following conclusions were 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%. 

Table 5. Relative loss dissipated through the stilling basin.
References


Nomenclature

m.a.s.l: 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

ρp: Density of fluid used in prototype

ρm: Density of fluid used in model

Q = Discharge, m³/s.

Cd = Discharge coefficient.

L = Effective length of crest

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

Qc = Actual Discharge

EL = Water level.

Y2 = Water depth at the end of stilling basin
المنشور العربي:

لقد تم في هذا البحث تنفيذ نموذجا هيدرولوجيًا لمحاكاة السم السطح والمسيل المائي والمقترحات الخاصة بسد مدني في العراق. تم تشغيل النموذج واخذت 22 قراءة من التصاميم التي تغطي جميع التصاميم الحقيقية المتوقعة للحوادث. لقد بين التحليل الرياضي والأحصائي للبيانات أن معامل التصريف (Cd) للمسيل المائي هو 1.7 في حالة التصريف الفعلي وحدود 0.05 عند التصريف العالية. كما وبحثت النتائج النموذجية أن نسبة الطاقة المتبقية خلال حوض التهيئة كان يغير عكسيا مع قيمة التصريف المشتقة حيث تراوحت نسبة الطاقة المتبقية بين 64.6% إلى 71.7%. تم تسجيل مجموع البذور بثلاثة مساحة على مختلف نقاط المسيل المائي النموذج الهيدرولوجي ايا قراءة سالبة للضغط المسطح على سطح المسيل المائي لجميع قيم التصريف المشتقة. لقد أثبت التشغيل الهيدرولوجي النموذج أن الجريان عند مداخل ومقترحات المسيل المائي يجري بشكل هادي، وخالي من الاضطرابات أو الدوامات المائية.