Flow Characteristics and Energy Dissipation Over Traditional and Stepped Spillway with Semicircular Crest

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Abstract-- The main purpose of traditional spillway with semicircular crest is to rise and control upstream (U/S) water level. In this study a new performance was added to this spillway, by making it as an energy dissipater. In order to study the energy dissipation percent \( (\Delta E/E_0) \% \), the face of traditional spillway was making stepped three times as \( (N_s = 3, 5 \text{ and } 7) \). Twenty four experiments were performed in a laboratory horizontal channel of 12 m length, 0.5 m width and 0.45 m depth for a wide range of discharge.

Water surface profile and piezometric head distribution were studied over a traditional and stepped spillway of semicircular crest. The experimental results of the study of flow on traditional spillway show that an increase in \( (d_i/d_h) \) and \( (F_{r1}) \) value causes an increase in \( (\Delta E/E_0)\% \), furthermore an increase in \( (d_i/d_h) \) value causes decreasing in \( (\Delta E/E_0)\% \) value. While, the experimental results of the study on stepped spillway show that an increases in \( (d_i/d_h) \) and \( (Y_2H_c) \) value causes an increase in \( (\Delta E/E_0)\% \), and an increase in the roughness Froude number \( (F^*) \) value causes decreasing in \( (\Delta E/E_0)\% \) value. Two empirical equations were established for calculating the dissipation energy.

Index Term-- Hydraulic structures; Traditional and stepped spillway; Energy dissipation.

1. INTRODUCTION

Spillway with various shapes has been considered the most hydraulic structures which used in open channel flow. They are widely used in water flow measurements and control of water surface levels.

Spillway is a major part of a dam, which is built to release flood flow. Depend on the hydraulic conditions of flow and the geologic characteristics of the dams site spillways can be built in different types and shapes. Due to the high flow discharge over the spillways, their design and construction are very complicated and usually faced with difficulties such as cavitations and high flow kinetic energy [1]. It becomes usual to protect the spillway surface from cavitations erosion by introducing air next to the spillway surface using aeration devices located on the spillway bottom and sometimes on the sidewalls [2].

When the flow is released over the spillway structure, the potential energy is converted to kinetic energy at the toe of spillway. Since the flow is supercritical and has a very high velocity and hence erosive power. Therefore, this energy should be dissipated in order to prevent the possibility of sever scouring of the downstream river bed and undermining of the foundations. For this purpose, several ways were used such as lining by rubbles and riprap, or by constructing steps at D/S ends of weirs [3].

In recent years, various investigators study the characteristics of flow over spillway. Stepped spillways have regained popularity over the last two decades, thanks to financial benefits resulting mainly from the simple economic and rapid construction procedure especially with the Roller Compacted Concrete (RCC) construction method [4]. Stepped spillways allow continuously dissipating a considerable amount of the flow kinetic energy, such that the downstream stilling basin, where the residual energy is dissipated by hydraulic jump, can be largely reduced in dimensions. Also, the cavitation risk along the spillway decreases significantly due to smaller flow velocities and the large air entertainment rate [5]. Chamani and Rajaratnam [6] show that, in a stepped spillway, jet flow would occur at relatively smaller discharges and skimming flow occurs at larger discharges. It also appears that for a wide range of slopes, the transition from the (lower) jet flow to the (higher) skimming flow occurs when \( y_c/h \) is approximately equal to 0.8, where \( y_c \) is the critical depth and \( h \) is the height of the steps. Barani et al. [7] investigated energy dissipation of flow over stepped spillways of different step shapes; a physical wooden model has been built. Experiments have been carried out for different types of step shapes (plain steps, end sill steps with thickness of 1, 2, 3 and 4 cm and steps with bottom adverse slope of 15, 26, 36 and 45°). Overall, the hydraulic parameters of flow over the model were measured and the energy dissipation of flow was calculated. Results show that the energy dissipation of flow on end sill and inclined stepped spillways are more than the plain one, it is increases by increasing the thickness of end sill or the adverse slope size. Comparison of flow energy dissipation over end sill stepped spillway and inclined type show that the inclined type has been dissipated more energy than the equivalent end sill type. Also for stepped spillway of different step shapes investigated in a laboratory study the stepped and unstepped weirs for steep slope channels which is having high difference in head of water between upstream and downstream in order to find their efficiency for dissipating flow energy. Al-Talib [8] found that stepped weirs are more efficient than unstepped weirs and the maximum energy dissipation ratio in stepped weirs was approximately 10% higher than in unstepped weirs. Hussein et al. [9] studied experimentally the
flow characteristics and energy dissipation over step round broad–crested weirs.

In this paper, D/S slope of traditional spillway was making stepped. This special shape gave the spillway a new performance by making it as a water level controller and the stepped spillways are structurally stable, resistant to water loads and significantly increase the rate of energy dissipation on the spillway face. And because of self aeration of flow passing over steps can prevent cavitations damages. So, construction of energy dissipaters especially, stilling basin at the toe of spillway or construction cost of the project reduce significantly. Stepped spillways also can be used for multipurpose systems such as river training, water quality systems and beautiful landscape of dam.

The main objectives of this paper are to study the flow characteristics, energy dissipation, and pressure distribution over traditional and stepped spillway for mild slope channels or zero slope channels. Furthermore, to develop modify empirical relations for percentage of energy dissipation and pressure distribution depending on affecting factors.

2. THEORETICAL ANALYSIS

Based on energy relationships, the general relationship for the flow energy dissipation can be verified. Applying energy equations between U/S and D/S of stepped and traditional spillway, one can get:

\[ E_0 = d_0 + \frac{V_0^2}{2g} \] (1)

\[ E_0 = d_0 + \frac{a_0V_0^2}{2g} \] (2)

\[ \Delta E = (E_0 - E_1) \] (3)

\[ \frac{\Delta E}{E_0} \% = \left( \frac{E_0 - E_1}{E_0} \right) \times 100 \% \] (4)

On the other hand, the functional relationship for \((\Delta E/E_0)\%\) with the main flow parameters for traditional spillway may be expressed as follows:

\[ f_1(\frac{\Delta E}{E_0})\% = q, d_0, d_1, d_c, R, g, v, \alpha = 0 \] (5)

\[ \frac{\Delta E}{E_0} \% = f_2 \left( \frac{R}{d_c}, \frac{d_0}{d_c}, \frac{d_1}{d_c}, \frac{d_c}{d_0}, \frac{d_c}{d_1}, \frac{v}{d_c}, \alpha \right) \] (6)

\[ \frac{\Delta E}{E_0} \% = f_3 \left( \frac{R}{d_c}, \frac{d_0}{d_c}, \frac{d_1}{d_c}, \frac{d_c}{d_0}, \frac{d_c}{d_1}, \frac{Fr_1}{R_c}, \frac{R_c}{d_c}, \alpha \right) \] (7)

Reynolds number \((R_c)\) which has very large values and hence its effect on \((\Delta E/E_0)\%\) will be very little, therefore, \(R_c\) will be neglected in this study. Since, \((R)\) and \((\alpha)\) is fixed in this study then equation (7) can be rewritten as:

\[ \frac{\Delta E}{E_0} \% = f_4 \left( d_0, d_1, d_c, Fr_1 \right) \] (8)

Also; the functional relationship for \((\Delta E/E_0)\%\) with the main flow parameters for stepped spillway may be expressed as follows:

\[ f_5(\frac{\Delta E}{E_0})\% = q, d_0, d_1, d_c, K_S, g, v, N_S = 0 \] (9)

Then equation (9) becomes as:

\[ \frac{\Delta E}{E_0} \% = f_7 \left( d_0, d_1, d_c, F_s, N_s \right) \] (10)

Where:

\[ E_o = U/S \text{ energy (m)} \]

\[ E_1 = D/S \text{ energy (m)} \]

\[ V_o = \text{velocity at sec. 0 (m/sec)} \]

\[ \alpha = \text{kinetic correction coefficient, for turbulent flow, generally equal to 1.1, [Chow, 1959],} \]

\[ \Delta E \% = \text{Relative energy dissipation between U/S and D/S of stepped and traditional spillway,} \]

\[ q = \text{discharge over the spillway per unit width (m}^2/\text{s/m)} \]

\[ d_0 = \text{critical depth over spillway (m)} \]

\[ d_1 = \text{D/S depth of water at toe of stepped and traditional spillway (m)} \]

\[ d_c = \text{D/S depth of water (m)} \]

\[ R = \text{Radius of the spillway crest (m)} \]

\[ v = \text{kinematics viscosity of water (m}^2/\text{sec)} \]

\[ Fr_1 = \text{D/S Froude number} \]

\[ \alpha = \text{Spillway slope} \]

\[ F_s = \text{Friction Froude number defined as \([F_s = q/} \]

\[ \frac{\sqrt{g \cdot \sin \alpha \cdot R_c^2}}{V_o} \] \]

\[ K_s = \text{Roughness height (m) and step dimension normal to the flow:} \]

\[ k_s = h \cdot \cos \alpha \]

\[ N_s = \text{Number of steps.} \]

3. EXPERIMENTAL SETUP AND PROCEDURE

The experimental program of this study was carried out at the hydraulic laboratory of technical institute in Mosul. Tests were conducted in a horizontal, glass-walled rectangular channel of 12m long, 0.5m width and 0.45m depth. Water surface levels were measured at different locations with an accurate point gauge reading to 0.1mm. Discharges were measured by a pre-calibrated triangular sharp-crested weir installed at the channel inlet. U/S flow heads were started to measure at a location \((9H)\) U/S of the spillway model, where \(H\) is the depth of water over the spillway crest.

Four spillway models with crest radius \(R=6cm,\) spillway height \(P=30cm\) and downstream slope is \((\alpha=V): H=1.125\) were constructed and tested to study of hydraulic characteristic of flow over stepped spillway with semicircular crest. The models divided in tow type (A and B) depending upon the profile of spillway. The first type (A) is traditional spillway (without stepping), the second type (B) contains three models of stepped spillway and these models had classified according to the variation of a number of steps \((N_s)\). The number of steps \((N_s)\) for models \((B_1, B_2, B_3=3, 5\) and \(7).\)

As well as to investigate the pressure distribution on the spillway surface, nine to seventeen piezometers were installed on the traditional and stepped spillway surface. These piezometers were connected by rubber tubing to a manometer board with scales that could be read to the nearest \(0.1 \) mm. Details of the testing program are shown in Table (1), Plate (1) and Figure (1). All models were manufactured and construction from concrete. To ensure stability of water surface levels and uniform flow with very low turbulence, the models were fixed by adhesive material at a distance of \(6\) m from the channel inlet. After construction the testing program started by flowing different discharge to overtop the spillway.
model. All measurements were conducted at the center line of the channel width. In each test, U/S flow depth ($d_0$), water surface profile, D/S flow depth ($d_1$), unit discharge ($q$) and piezometric head for traditional and stepped spillway were measured. The measurements along the spillway models were conducted under the free flow conditions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Spillway type</th>
<th>Crest Height P(cm)</th>
<th>Crest Radius R (cm)</th>
<th>Type</th>
<th>Model</th>
<th>Run no.</th>
<th>Upstream slope ($\beta$)</th>
<th>Downstream slope ($\alpha$) (V:H)</th>
<th>Number of step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Traditional spillway</td>
<td>30</td>
<td>6</td>
<td>A</td>
<td>$A_1$</td>
<td>1-6</td>
<td>$90^\circ$</td>
<td>1:1.25</td>
<td>Without step</td>
</tr>
<tr>
<td>2</td>
<td>Stepped spillway</td>
<td>30</td>
<td>6</td>
<td>B</td>
<td>$B_1$</td>
<td>7-12</td>
<td>$90^\circ$</td>
<td>1:1.25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B_2$</td>
<td>13-18</td>
<td>$90^\circ$</td>
<td>1:1.25</td>
<td>5</td>
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<td></td>
<td></td>
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<td>$B_3$</td>
<td>19-24</td>
<td>$90^\circ$</td>
<td>1:1.25</td>
<td>7</td>
</tr>
</tbody>
</table>

Plate (1): A) General view of the laboratory channel with triangular sharp-crested weir, B) location of piezometer and C) piezometer board.
4. RESULTS AND DISCUSSION

4.1 Water Surface Profiles

Water surface profiles over traditional and stepped spillway were shown in Figures (2) , (3), (4) and (5) which were measured in the center line of the channel. It can be seen that water surface profiles were become horizontal when X/P > 3 where (X) is the U/S distance from the spillway crest and (P) spillway height. These water surface profiles were used to determine the average velocities and U/S water heads over the spillway when water surface profiles were essentially horizontal. Skimming flow occur when water flows over traditional spillway, the trend of these water surface profiles for all discharges were mostly similar, smooth and follow the shape of the spillway. Furthermore in Figures (3), (4) and (5), it can be seen clearly the effect of D/S steps on the water surface profiles.

Generally three types of flow occur when water flows over stepped spillway. They are nappe or jet flow, transition flow and skimming flow. This regime of flow depended upon the size and number of steps and classified as follows:

**Type1-Nappe or Jet Flow**

Nappe flow was observed for low discharges and divided in to three types:

1-When water flow over stepped spillway with Nₜ=3, the water impinges on the whole surface of the first step then jet to the bed of channel. The presence of a cell filled with air-between the upper flow, the vertical face of the step and the horizontal face of the step-is the main characteristic of this regime, as is shown in Figures. (3) and (4) and Plate (2). The observations on the physical model built in the laboratory show this jet flow for discharges under the limits dₚ/h = 0.302 and dₚ/h = 0.727.

2-Again when water flow over stepped spillway with Nₜ=5, nappe and jet flow or partial nappe flow is developed. In this flow, the nappe does not fully impinge on the whole step surface, and it disperses with considerable turbulence. It is characterized by water impinges on the whole surface of the first step then jet to impinges the fourth step and then it falls from fourth step to the next one down. The presence of a cell filled with air-between the upper flow, the vertical face of the step and the small plunge formed over the horizontal face of the step-is the main characteristic of this regime, as is shown in Figures (3), (4), (5) and Plate (3). In the partial nappe flow, energy is...
dissipated in two stages, on impact with the flat surface and more significantly, in the turbulence created by dispersal of the nappe. The observations on the physical model built in the laboratory show the partial nappe flow for discharges under the limits $d_c/h = 0.45$ and $d_c/h = 0.74$.

3- As water flow over stepped spillway with $N_s=7$, nappe flow is developed. The nappe does fully impinge on the step surface. It is characterized by water impinges on the whole surface of the first step then it falls from one step to the next one down, as is shown in Figures (3), (4) and (5) and Plate (4). The observations on the physical model built in the laboratory show the nappe flow for discharges under the limits $d_c/h = 0.56$ and $d_c/h = 0.99$. As discharges increase, the cells of air described above are alternately filled with a mesh of water and air showing a steady rotation. The flow regime on a stepped spillway depends on the discharge and the step geometry. [3, 10, 11].

Plate (3): Jet and nappe flow over stepped spillway with $N_s=5$.

Plate (4): Nappe flow over stepped spillway with $N_s=7$.

Plate (5): Transition flow over stepped spillway with $N_s=3$.

Plate (6): Transition flow over stepped spillway with $N_s=5$.

Plate (7): Transition flow over stepped spillway with $N_s=7$.

**Type 2 - Transition flow**

The transition flow occurred as the discharges increasing greater than those which limit nappe flow and continue until the onset of skimming flow was considered to have occurred, the recent works studied by Pinheiro and Fael [12], Amador et al. [13] and Chanson [3] agree that a transition flow is developed, until the onset of skimming flow was considered to have occurred when the air-filled cells trapped beneath the upper main flow and the vertical face of the step filled with an air–water mesh along the entire length of the spillway [14], as can be seen in Figures (3), (4), (5) and Plates (5), (6) and (7). The same criterion had already been used by other authors Pinheiro and Fael [12]. The transition flow observed over the tested experimental spillway for discharges greater than the limit of nappe flow, and lower than a value of $d_c/h$ between 0.977 and 1.41. These values not coincide with the estimated threshold of the onset of skimming flow that had been established by Rajaratnam, [5] by using the expression $d_c/h = 0.80$, which had in turn been obtained from experimental data from Essery and Horner [15].

**Type 3 - Skimming flow**

Skimming flow occurs at moderate to high discharges. No nappe is visible and the spillway is submerged beneath a strong, relatively smooth current. The water flows down the stepped face as a coherent stream, skimming over the steps and cushioned by the recirculation fluid trapped by the momentum transfer to the recirculation fluid.
From this Figures (3), (4) and (5) and Plates (8), (9) and (10), it can be seen that the onset of skimming flow was considered to have occurred when the air-filled cells trapped beneath the upper main flow and the vertical face of the step filled with an air–water mesh along the entire length of the spillway. The last criterion fits quite well with Chanson [14]. The observations on the physical model built in the laboratory show the skimming flow for discharges under the limits $d_c/h = 0.977$ and $d_c/h = 2.75$.

Plate (8) : Skimming flow over stepped spillway with $N_s = 3$.

Plate (9) : Skimming flow over stepped stepped spillway with $N_s = 5$.

Plate (10) : Skimming flow over stepped spillway with $N_s = 7$.

Fig. 2. Water surface profile for traditional model A, (V: H = 1:1.25).

Fig. 3. Water surface profile for stepped model B, $N_s = 3$, (V: H = 1:1.25).
4.2 Pressure Distribution over Traditional and Stepped Spillway

Figure (6) shows piezometric heads for various discharges over traditional spillway. It becomes clear from the figure below that the regions of negative readings is at the crest when the discharge is high and near the end of sloping straight line of spillway at low discharge then these negative readings reduce with the increasing discharge. This agree with Chow [16], as the spillway must be operated under heads other than the design head, the pressure on the crest of spillway will increase under the lower heads and decrease under the higher heads.

When flow rate increased over stepped spillway, this lead to development skimming flow, the lower area beneath the pseudo-bottom, formed by almost triangular cells, contains maximum turbulence. The pressure field in these cells is generating exhibit intense pressure fluctuations and therefore, it is important to know whether fluctuating pressure depressions can cause intermittent cavitations inception. This is particularly important in the region between the crest and the point of inception, because this region does not contain air to mitigate cavitations damage. Far below, in the region of uniform flow, air has reached the bottom layer hence; this reach is well protected against cavitations damage [17].
Figures (7), (9) and (11) show piezometric head distribution for various discharges over horizontal face for stepped spillway. It was found that, the piezometric head on the crest of spillway will increase under the lower heads and decrease until accrue negative readings under the higher heads. Also, the piezometric head on the last step of models \((B_1\) and \(B_3\)) will reduces until occur negative readings under the lower heads and increases under the higher heads.

Figures (8), (10) and (12) show piezometric head distribution for various discharges over vertical face for stepped spillway. It was found that, the piezometric head on the crest of spillway will increase under the lower heads and decrease until occur negative readings under the higher heads. The piezometric head on the last step of models \((B_1, B_2\) and \(B_3\)) will reduces until occur negative readings under the lower heads and increases under the higher heads.

The vertical face of the last steps was subjected to negative pressure at low discharge and reduces at high discharge where as horizontal face of the steps of model \((B_2)\) were free of negative pressure. Matos et al. [18] and Shu-Xun et al. [19] have also reached the same conclusion. They also computed cavitations index \((\sigma)\) based on minimum pressure, which ranged from 2.43 to 13.1.
4.3 Energy Dissipation Ratio ($\Delta E/E_1$) % and Discharge Relation

The dissipated energy of flow over the traditional and stepped spillway model with different step shapes were plotted as a function of flow rate as shown in Figure (13). It can be seen from this figure the energy dissipation decreases by increasing the flow rate over all models. The dissipated energy of flow over the model with large size and little number of steps ($N_S = 3$) is more than the traditional form and other models of number of steps equal to 5 and 7. When the flow rate is 7.5l/sec, the energy dissipation ratio ($\Delta E/E_1$) for traditional 42.5% and for stepped spillway with $N_S$ (3, 5 and 7) is 80%, 77.5% and 72.5% respectively.

Fig. 10. Piezometric head distribution over vertical face for stepped spillway model B$_3$ that D/S slope (1:1.25) and $N_S$=5.

Fig. 11. Piezometric head distribution over horizontal face for stepped spillway model B$_3$ that D/S slope (1:1.25) and $N_S$=7.

Fig. 12. Piezometric head distribution over vertical face for stepped spillway model B$_3$ that D/S slope (1:1.25) and $N_S$=7.
4.4 Factors Effecting the Spillway Energy Dissipation Ratio ($\Delta E/E_1$) %

One of the main objectives of this study is to determine the influence of dimensionless parameters on the energy dissipation ($\Delta E/E_1$) % for traditional and stepped spillway with different step sizes.

4.4.1 Traditional Spillway

*Effect of U/S Water Depth to Critical Depth Ratio ($d_1/d_c$)*

Variation of ($\Delta E/E_0$) % with ($d_1/d_c$) for traditional spillway is shown in Figure (14). From this figure one may observe that for the same shape of spillway an increase in ($d_1/d_c$) value causes an increase in ($\Delta E/E_0$) % value, this could be attributed to the reason that as the head above crest increases the overflowing process becomes easier and developing skimming flow over traditional spillway, trying to speed the jet and consequently increase the flow rate passing over it and increasing the energy dissipation.

*Effect of D/S water depth to critical depth ratio ($d_d/d_c$)*

Variation of ($\Delta E/E_0$)% with ($d_d/d_c$) for traditional spillway are shown in Figure (15). This figure showed that for the same shape of spillway an increase in ($d_d/d_c$) value causes an decreases in ($\Delta E/E_0$)% value, this could be attributed to the reason that as the head above crest increases the flow rate passing over it increases and reduces the depth of water downstream of the spillway and then decreases energy dissipation.
Effect of D/S Froude number

The relation between \((\Delta E/E_0\%)\) and \(F_{r1}\) for traditional spillway are shown in Figure (16). This figure showed that for the same shape of spillway an increase in \((F_{r1})\) value causes an increase in \((\Delta E/E_0\%)\) value, this could be attributed to the reason that as the head above crest increases the flow rate passing over it increases and reduces the depth of water downstream the model. Where Froude number proportional to velocity and inversely with the depth of water downstream the model.

4.4.2 Stepped spillway

Effect of U/S water depth to critical depth ratio \((d_0/d_c)\)

Variation of \((\Delta E/E_0\%)\) with \((d_0/d_c)\) for different D/S step of spillway are shown in Figure (17). From this figure may observed that for the same shape of spillway an increase in \((d_0/d_c)\) value causes an increase in \((\Delta E/E_0\%)\) value this could be attributed to the reason that as the head above crest increases the overflowing process becomes easier and will increase the velocity of water jet over crest trying to throw the jet further downstream face and developing skimming flow over stepped spillway at moderate and high discharge, trying to speed the jet and consequently increase the flow rate passing over it.

While; when water flow over stepped spillway. They are three type of flow occur jet flow, transition flow and skimming flow. The jet flow impinges on the whole surface of the first step then jump to the bed of channel at small discharges. In the jet flow, energy is dissipated in two stages, on impact with the flat surface and more significantly, in the turbulence created by dispersal of the nappe. Skimming flow occurs at moderate to high discharges. No nappe is visible and the spillway is submerged beneath a strong, relatively smooth current. The water flows down the stepped face as a coherent stream, skimming over the steps and cushioned by the recirculating fluid trapped by the momentum transfer to the recirculating fluid.

Previous results show that the energy dissipation of flow on stepped spillway at low discharge is more than at high discharge, whereas from Figure (17), it is interesting to realize that the stepped spillway of number of steps \((N_s=3)\) and ie., large size of step give higher values of \((\Delta E/E_1\%)\) than traditional and those of many number of steps and smaller size.
Effect of D/S water depth to critical depth ratio ($d_1/d_c$)

The variation of ($\Delta E/E_0$)% with ($d_1/d_c$) for stepped spillway with different step size were shown in Figure (18). From this figure it is observed clearly that an increase in ($d_1/d_c$) value cause an increase in ($\Delta E/E_0$)% value. Also, it is observed that the value ($\Delta E/E_0$)% at ($d_1/d_c$)=0.63 for all three type of stepped spillway are equal to 97%, this could be attributed to the reason that as the head above crest increases the flow rate passing over it increases and reduces downstream depth, this lead to converting energy from static to kinematic energy.

Effect of Friction Froude number ($F^*$)

As illustrated in Figure (19), for all experiments of stepped spillway, when the roughness Froude number increased ($F^*$) the relative dissipation ($\Delta E/E_0$)% value decreased. Because it is proportional with discharge per unit width ($q$) and inversely with roughness height $K_s$. 

Fig. 17. Relation between relative dissipation and ratio ($d_0/d_c$) for stepped spillway model with different steps, (V:H=1:1.25).

Fig. 18. Relation between relative dissipation and ratio ($d_1/d_c$) for stepped spillway model with different number of step,(V:H=1:1.25).
Effect of number of step ($N_s$)

Figure (20) revealed the relation between relative energy dissipation with number of steps ($N_s$) for stepped spillway at different discharge, from this figure may observed that the relative energy dissipation decreases when the number of steps increases for all models at the same discharge, also the relative energy dissipation ($\Delta E/E_0$)% value are equal to (75.5%, 60% and 45%) for stepped spillway with ($N_s$=3,5 and 7) at Q=9 L/sec. therefore; stepped spillway with bigger size and less number of step (L=7.5, h=6cm and $N_s$=3) dissipated more energy than smaller size and many number of steps (L=5, 3.75, h=4,3cm and $N_s$=5, 7) as shown in figure below.

5. EMPIRICAL RELATIONS

Based on equation (8), nonlinear regression analysis in (IBM SPSS Statistics 20) was used to correlate ($\Delta E/E_0$)% with ($d_0/d_c$), ($d_1/d_c$) and ($F_{r2}$) in an empirical relation for traditional spillway.

$$\frac{\Delta E}{E_0} \% = 693.72 + 3.482 \times \frac{d_0}{d_c} - 1444.11 \times \frac{d_1}{d_c} - 43.02 \times F_{r2}$$

(11)

With a correlation coefficient = 0.994.

The relation between ($\Delta E/E_0$)% values predicted by equation (11) and experimental values of ($\Delta E/E_0$)% is plotted in Figure (21) which shows a good agreement. Another empirical relation for stepped spillway based on equation (10) was obtained for the variation of ($\Delta E/E_0$)% with ($d_0/d_c$), ($d_1/d_c$), ($F^*$) and ($N_s$).

$$\frac{\Delta E}{E_0} \% = 204.783 \times \frac{d_1}{d_c} - 4.715 \times \frac{d_0}{d_c} - 11.66 \times F_* + 10.63 \times [N_s] - 18.13 \text{ --------- (12)}$$

With a correlation coefficient = 0.965.

A comparison between ($\Delta E/E_0$)% values predicted by equation (12) and observed values experimentally is shown in Figure (22). The maximum and minimum difference between them were 6.76 and -9.46 respectively.

Fig. 19. Relation between relative dissipation and roughness Froude number ($F^*$) for stepped spillway, (V: H=1:1.25).

Fig. 20. Relation between Relative dissipation and No. of steps ($N_s$) for stepped spillway (models B$_1$, B$_2$ and B$_3$) with D/S slope ($\alpha$=V: H=1:1.25).
6. CONCLUSIONS

Based on results and analysis of this study, the following main conclusions were summarized as:

1. The U/S water flow heads can be measured correctly at a location when X/P> 3 U/S of the spillway.
2. Skimming flow occur when water flows over traditional spillway, while three types of flow occur when water flows over stepped spillway. They are nappe or jet flow, Transition flow and skimming flow.
3. The flow regime on a stepped spillway depends on the discharge and the step geometry.
4. From the analysis, it becomes clear that the regions of negative readings is at the crest when the discharge is high and near the end of sloping straight line of spillway at low discharge then These negative readings reduce with the increasing discharge.
5. Energy dissipation decreases by increasing the flow rate over all models. The dissipated energy of flow over the model with large size and little number of steps (N_s =3) is more than the traditional form and other sizes and number of steps (N_s =5and 7).
6. Stepping spillway will improve and increase the energy dissipation, when Q =7.5 l/sec the values of (∆E/E_0) for stepped spillway with N_s =3,5and 7) were higher than in traditional spillway by (37.5%, 35% and 30%).
7. For traditional spillway and different D/S step spillway an increase in (d/d_s) value causes an increase in (∆E/E_0) % value.
8. An increase in ratio (d/d_s) value causes an decreases in (∆E/E_0)% value for traditional spillway and causes an increase in (∆E/E_0)% value for stepped spillway.
9. When downstream Froude number (F_r) of traditional spillway increase causes an increase in (∆E/E_0)% value.
10. When the roughness Froude number (F*) of stepped spillway increased the relative dissipation (∆E/E_0) % value decreased.
11. Two empirical relations were obtained to estimate (∆E/E_0) %, the first for traditional spillway While the second relation for stepped spillway.

REFERENCES
