Investigation of Energy Dissipation in Stepped Spillway with Semicircular Steps Treads

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***Abstract*— The construction of spillway with steps represents an efficient technique to decrease the energy of water that flows over it. Steps shape, or geometry of the spillway, has a significant effect on the residual energy at the toe of the spillway. In this study, a traditional stepped spillway model designed with six steps of 5*cm* height, 5*cm* length, and 30*cm* width. The stepped spillway model modified twice by curving the horizontal treads using sectors of PVC pipe with 7.5*cm* diameter. The first modification done by curving the treads up to make convex treads with height of 1.1*cm* and the second modification was done by curving the treads down to make-concaved treads with depth of 1.1*cm*. Eleven tests carried out for the three cases with flow rates varied from 0.64*l/s* to 24.95*l/s*. The experimental results showed that the discharge affected reversely on the energy dissipation, and the concaved treads case produced higher dissipation than the horizontal and the convex cases. The energy dissipation for concaved treads case ranged from 48.84 to 87.82%, 41.38 to 84.08% for convex treads case and 34.93 to 78.23% for horizontal treads case. In addition, the total energy dissipation produced by the spillway and hydraulic jump together, for concaved treads case ranged from 62.51 to 94.38%, convex treads case from 60.74 to 93.81%, and horizontal treads from 59.64 to 93.25%. The other relation that noted were the decrease of Froude number at the toe, with the increase of flow rate, and concaved treads case produced lower values of Fr than the other two cases. In addition, the values of y2/y1, conjugate depths of the hydraulic jump, decreased with the increase of flow rates, and concaved treads case produced lower values of y2/y1 than the other two cases.**

***Index Terms*— Stepped Spillway, Horizontal Treads, Convex Treads, Concaved Treads and Energy Dissipation.**

I. INTRODUCTION

THE flow of water over the spillways creates a high velocity and high energy at the toe of the spillway. This high velocity creates a severe force may produces a damage in means of erosion at the downstream channel of the spillway and resulting in scouring of the channel bed and sides, and increase the scour depth at the toe of the spillway. Therefore, this high velocity of flow should be reduced as much as possible to a minimum value, so that the downstream protection works are lowered. Energy dissipaters have the main role in reducing the incoming energy to the downstream channel and help in reducing this high velocity. Energy dissipaters are downstream protection structures used to reduce the energy of flow. They are including many types and their selection depending on the incoming energy by the means of Froude Number, Fr, and other parameters such as tail water depth, type of channel material; ...etc. Therefore, as the value of Fr be lowered, the cost of downstream energy dissipater will be minimized, because the cost of construction is depending on the type of the dissipater and protection works.

The roughness of the spillway has a significant role that affects the value of Fr, in which the increase in the roughness of the spillway flow surface will reduce it. Therefore, researchers investigated many ways to increase the roughness of the spillway. The construction of the spillway with steps is one of the ways that baffling the flow over the spillway and creating high turbulences, in which the baffling of the flow reduces the velocity, and then the total energy of the flow.

Stepped spillways are hydraulic structures used to release surplus water from a dam, or a storage reservoir, supplied with steps to increase the roughness of the flow surface [3], and reduce the velocity of flow, and then energy, at the toe of the spillway. Their main advantage is dissipating the energy of flow, and the energy dissipation may attain 99% [6]. This leads in no need to use the downstream stilling basin [9], which may reduces 20% of the project cost, with bear in mind the comparison with the other techniques [11].

The flow over the stepped spillway classified in to three regimes, which are the nappe flow, transitional flow, and skimming flow. Nappe flow is the most efficient regime in dissipating the total flow energy [10], and this is because the jet flow of water that increase the interference of air and water. The regime of flow is depending upon the geometry of steps and discharge [7]. Therefore, as the geometry of the steps increases the range of nappe flow, with same discharge, as the stepped spillway be more efficient in dissipating the energy of flow.

This research aims to investigate the effect of steps geometry on the energy dissipation by curving the steps treads, concave and convex shapes, with maintaining the same size and number of the steps.

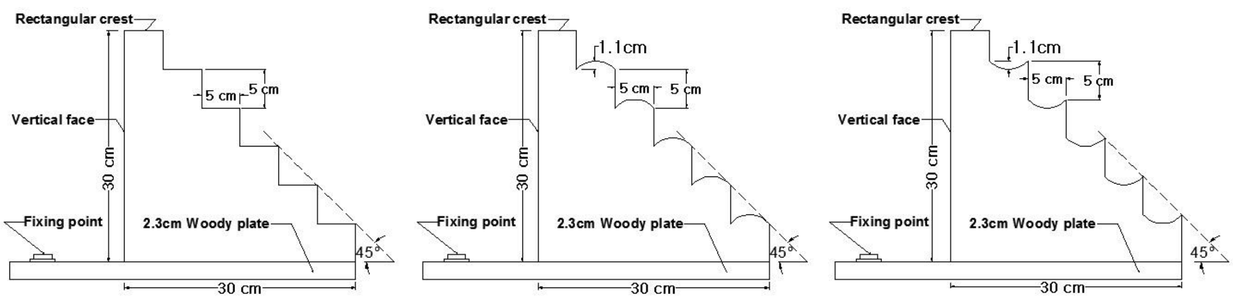
II. MATERIALS AND METHODS

This part presents a description of the experimental work that conducted the models design, preparation, and setup; also, a brief description of the laboratory measurements and the theoretical calculations of energy dissipation.

2.1 Stepped Spillway Design, Preparation, And Setup

One stepped spillway model designed to investigate the effect of curving the steps treads, horizontal step length, on the dissipation of energy. Therefore, the model was carried out with a traditional design and two treads modifications (i.e. the steps size and number; spillway length, width, and height were all maintained constant with the three cases). This done to prevent any effect of the spillway gross shape and, approximately, to maintain the same roughness value of the frame works with the three cases. The smooth woody stepped spillway model, which is the traditional case, (named as Horizontal Treads Stepped Spillway, HTSS) was made with six steps of 5*cm* vertical riser, d, and 5*cm* horizontal tread, l, as shown in Figure 1a, to make an inclined pseudo-bottom, tan-1(d/l), of 45°. The spillway installed on a 2.3*cm* woody plate, befit with the spillway base, and fix the spillway with the flume bed. Therefore, the net spillway length and height were 30*cm* and 32.3*cm*, respectively. The step height was more than the minimum critical height of 2*cm*, so that the model, and modifications, does not subjected to scale effects [9], also, this angle of pseudo-bottom is more than 27°, the critical value, to reduce the effect of friction factor on the flow [4]. The model made with a constant width of 30*cm* along the model to fit the laboratory flume. A strong glue used to create a stable structure and to maintain a zero side and facial infiltration, in which the infiltration influences the energy dissipation [5], and may attain to 30% [8].

The treads of HTSS was modified twice; the first modification was made by curving down the treads of the steps (named as Concaved Treads Stepped Spillway, ConcTSS); as shown in figure 1b. The second modification done by curving the treads up (named as Convex Treads Stepped Spillway, ConvTSS); as shown in figure 1c. The curved treads carried out using a 7.5*cm* diameter PVC pipe, in which the pipe cut to make sectors with length of 30*cm* and width of 5*cm*, to set on the steps treads and befit their dimensions. These sectors were making a concave depth and convex height of 1.1*cm*. The available commercial pipes for this manner were 5, 7.5, and 10*cm*. 5*cm* pipe will make a vertical water shoot and then will lead to inactivity in high flow rates, and 10*cm* gives unnoticeable convex or concave.



a- HTSS case. b- ConcTSS case. c- ConvTSS case.

Fig. 1. Stepped spillway with the three cases.

The model of ConcTSS also modified by making slots in the outside edges of the steps, shoot side, each 5*cm*; as shown in figure 2, named as Modified ConcTSS. This process made to investigate the increase of roughness on the ConcTSS.

An adjustable slope rectangular flume of 0.3*m* in width, 0.45*m* depth, 18*m* length, glassy sides, and smooth steel bed used in this manner. The flume was part of Laboratory of Hydraulics of the Department of Structures and Water Resources Engineering, Faculty of Engineering, University of Kufa.

Fig. 2. Modified ConcTSS case with slotted buckets.

The flume kept with zero bottom slope, to prevent the effect of slope on the velocity of flow through the spillway and maintain the steps treads in horizontal position. The length of the flume helped in reducing the effect of water surface fluctuation that may affects the accuracy of flow measurements and the water level upstream of the stepped spillway model, in which the entrance length was maintained more than the recommended value of 25 times the diameter of the flume [13]. The flume supplied with a stilling tank installed at the upstream end of the flume; also, reduce the water surface fluctuation; and the pump discharging water to the flume with a maximum flow rate of 40*l/s*.

2.2 Flow Measurements

Discharges were measured using a calibrated sharp crested weir was placed at the end of the flume, to prevent any fluctuation of water surface which may effects the accuracy of measurements. The three cases operated, approximately, under the same range of discharges, as shown in table 1. This table shows the flow rates that applied to quantify the behavior of the three models in dissipation of energy, and were ranging from 0.64*l/s* to 24.95*l/s*. The reasons of using such range were; the first, is to contain the two regimes of flow (i.e. nappe and skimming flows), in which the skimming flow occurs when y_c/d value is equal to 0.8 or more [12]. The second reason was the flume limitations, in which the minimum flow rate of the flume pump, for 0.64*l/s*, and the maximum flow rate, for 24.95*l/s*, where the flume does not flooded with existence of spillway. The flow rates, for the three models, were divided into two, approximately, equally intervals. The first interval was 2*l/s* from 0.64*l/s* to 10.18*l/s*; and, the second interval was 3*l/s* from 10*l/s* to 24.95*l/s*. These two intervals were bear in mind to show an actual behavior of the three models in the dissipation of the energy.

The modified ConcTSS case, with slots, operated under three flow rates only to see the slots effect, which are 4.07, 13.21, and 24.95*l/s*.

Other parameters that are measured were the depth of flow after the jump, namely the sequent depth, to calculate the initial depth, before the hydraulic jump. The initial depth before the jump was hardly to be measured, because the interference of the air and water, two-phase flow, which gives unreal depth of flow [2]. The hydraulic jump was formed to be maintained, approximately, at a close distance from the downstream end of the stepped spillway, toe. Because the location of the jump affects the value of energy dissipation, in which the energy will be overestimated for the submerged jumps, may attain 13%, and underestimated if the jump is far of the toe, may attain 3% [1]. This close distance done using the downstream gate to maintain the value of energy that dissipated only by the means of stepped spillway and to prevent any effect on energy dissipation from sidewalls or the flume floor.

An eye observation used to monitor the shape, beginning, and the end of nappe, transitional, or skimming flow.

2.3 Energy Dissipation Calculations

The energy dissipation that the stepped spillway attained calculated using the following equation:

$$\%\frac{\Delta E}{E_o} = \left(\frac{E_o - E_d}{E_o}\right) * 100\% \quad \dots\dots\dots (1)$$

Where E_o is the energy of the flow at upstream end of spillway, at the crest, and E_d is the energy at the downstream of the spillway, at the toe. E_o can be calculated using the following equations [11]:

$$E_o = Z_o + E_c \dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Where Z_o, in *m*, is the elevation of crest and equal to spillway height, in which flume bed considered as datum. E_c, in *m*, is the critical energy over crest, which computed as following:

$$E_c = \sqrt[3]{\frac{q^2}{g}} + \frac{v_c^2}{2g} \dots\dots\dots\dots\dots\dots\dots (3)$$

Where q, in $m^3/s.m$, is the discharge per unit width, v_c, in *m/s*, is critical velocity, and g is the gravitational acceleration, equal to 9.81m/s^2. Also, E_d is calculated by the following formula:

$$E_d = Z_i + y_1 + \alpha\frac{v_1^2}{2g} \dots\dots\dots\dots\dots (4)$$

Where Z_i, in *m*, is equal to zero, bed level, and y_1, in *m*, is the water depth at downstream end of spillway, i.e. initial depth of the jump. The depth at this section, y_1, backward calculated from the sequent depth of the hydraulic jump at the downstream end of spillway. v_1, in *m/s*, is the velocity of flow at the downstream end of the spillway, before the jump, and α is the kinetic energy correction coefficient and equal to 1.1 [2]. The value of y_1 calculated by the hydraulic jump formula, Blanger's equation:

$$y_1 = 0.5\, y_2 \left(\sqrt[2]{1 + 8F_{r2}^2} - 1\right) \dots\dots (5)$$

Where y_2, in *m*, is the sequent depth of the jump and Fr_2 is corresponding to y_2.

TABLE 1
The flow rates applied to the three cases.

Test No.	Model case		
	HTSS case	ConcTSS case	ConvTSS case
1	0.69	0.69	0.64
2	1.98	1.91	1.91
3	4.07	4.07	4.07
4	6.1	6.32	6.32
5	8.04	8.04	8.04
6	10.18	10.18	10.18
7	13.21	13.21	13.21
8	16.2	16.2	16.2
9	19.07	19.07	19.07
10	21.77	21.77	21.77
11	24.95	24.95	24.95

III. RESULTS AND DISCUSSIONS

This part presents a discussion of the resulted energy dissipation values, observed flow shape on the steps, and other relations that recorded through the operated model and its modifications.

3.1. Energy Dissipation

Discharge, as will known, has a reverse effect in the behavior of the stepped spillways in energy dissipation. Figure 3 shows that when the discharge increases, the energy dissipation decrease for the three cases (HTSS case, ConvTSS case, and ConcTSS case). Discharge is not the only affecting parameter in the dissipation, in which HTSS produced a sudden increase in the energy dissipation records. This can be noted at the discharges that are more than 13.21*l/s*, and this may ascribed to the effect of vortices in the skimming flow that are taking place in the inside corners of the junction between the treads and the raiser. Also, ConvTSS produced a better dissipation than HTSS in the, approximately, nappe flow regime and lower removal in skimming flow regime. This could be resulted by the effect of the convexities that are work as a detention hump, in nappe flow, which increased the friction of the spillway. In skimming flow the humps affected passively on the energy dissipation, in which the humps and vortices in the inside corners made the spillway steps as a smooth surface for the flow. Also, ConvTSS was not shooting the water as in the other two cases, and the air pockets were very small in nappe flow, as shown in figures 4a, b, and c.

Generally, ConcTSS produced a better dissipation than the other two cases in most of the tests, as shown in figure 3, in which the energy dissipation for ConcTSS ranged from 48.84

to 87.82%, 41.38 to 84.08% for ConvTSS, and 34.93 to 78.23% for HTSS. This ascribed to shape of the steps treads in which the concaved treads shoot the water for longer distance than the other two cases and produced high mixing of water and air in nappe flow; and, work as a rough surface in the skimming flow.

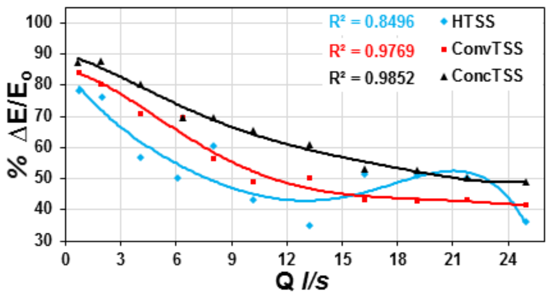
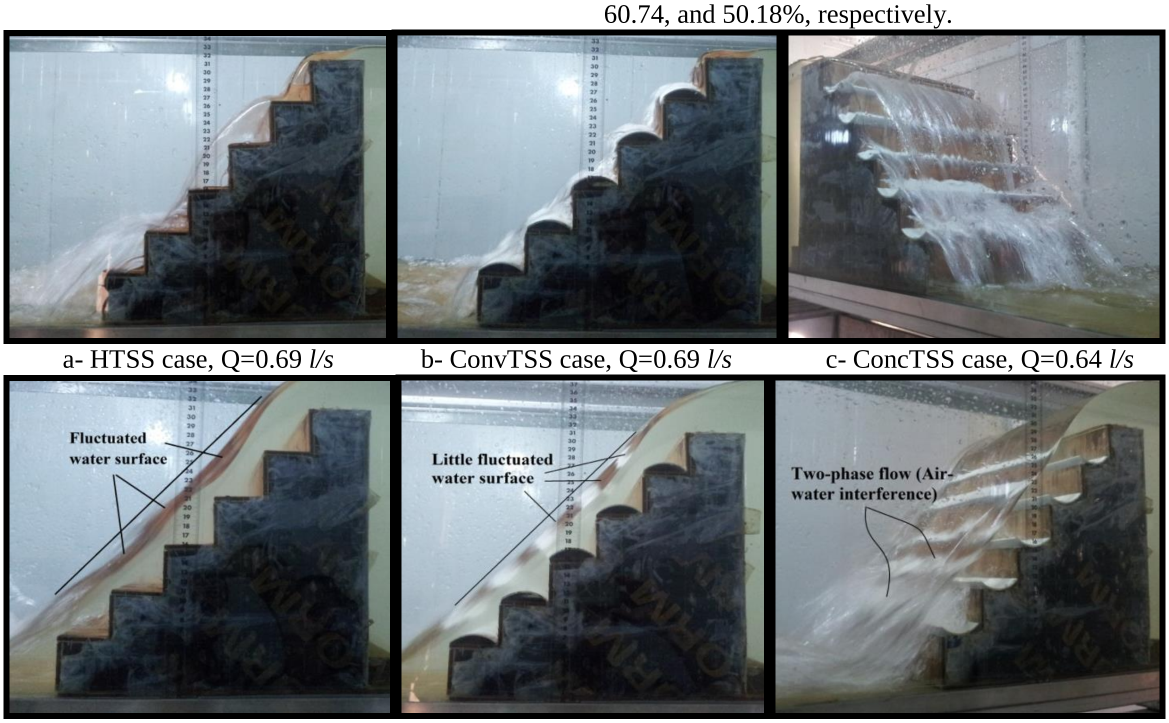


Fig. 3. Variation of % $\Delta E/E_o$ of the spillway with the flow rate for the three cases.

Figures 4 shows the behavior of the spillway for the three cases in two flow rates, one in the nappe flow and the other in the skimming flow. As shown in figures 4a, b, and c, these figures show that in the nappe flow condition, the friction plays a role in dissipating the energy with ConvTSS, in which the flow takes the shape of the steps. While, the shooting of water played the role in dissipation with HTSS and ConcTSS. Figures 4d, e, and f show that the vortices, in the inside corners of the steps, relatively, smoothed the flow surface and reduced the energy dissipation in HTSS and ConvTSS, while the shape of the treads in ConcTSS reduced the effect of vortices and made the spillway steps relatively as a rough surface. This can noted on the last two steps in figure 4f, in which a considerable mixing of water and air taken place.

The modified ConcTSS case, with slots, produced a little higher dissipation than that with ConcTSS, in which the slots, that made, do not have a significant effect on the resulted dissipation. The energy dissipation for the three flow rates that are applied; which are 4.07, 13.21, and 24.95*l/s*; were 82.57, 60.74, and 50.18%, respectively.



a- HTSS case, Q=0.69 *l/s* b- ConvTSS case, Q=0.69 *l/s* c- ConcTSS case, Q=0.64 *l/s*

d- HTSS case, Q=13.21 *l/s* e- ConvTSS case, Q=13.21 *l/s* f- ConcTSS case, Q=13.21 *l/s*

Fig. 4. Nappe and skimming flow behavior on the stepped spillway with the three cases.

Figure 5 shows the energy dissipated with the spillway and hydraulic jump, together. The results show that, in most of the tests that are carried out, ConvTSS case have better dissipation than HTSS case; and, ConcTSS case have better dissipation than ConvTSS case. In which the total energy dissipation for ConcTSS ranged from 62.51 to 94.38%, ConvTSS ranged from 60.74 to 93.81%, and HTSS ranged from 59.64 to 93.25%. Namely, ConcTSS case is most economical in downstream protection works than the other two cases. To make an accuracy comparison of the total efficiency, the jump position were generated at a closed distance of the toe in all three cases.

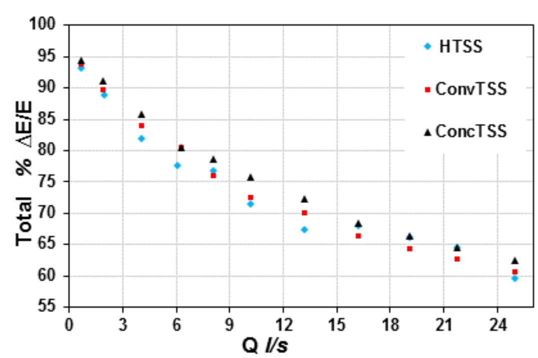


Fig. 5. Total % $\Delta E/E$ of the spillway and hydraulic jump together for the three cases.

3.2. Relations Governing the Flow Parameters

Froude number at the toe of the spillway decreased with the increase of the flow rate, as shown figure 6. This could attributed to the relative higher increase in water depth in comparison with the increase of flow velocity, in which the flume maintained with one slope along the experimental work. ConcTSS produced lower values of Fr than the other two cases in all the tests that carried out. This perhaps ascribed to the energy that dissipated, in which the ConcTSS produced for the same flow rates, a higher energy dissipation as discussed in figure 3.

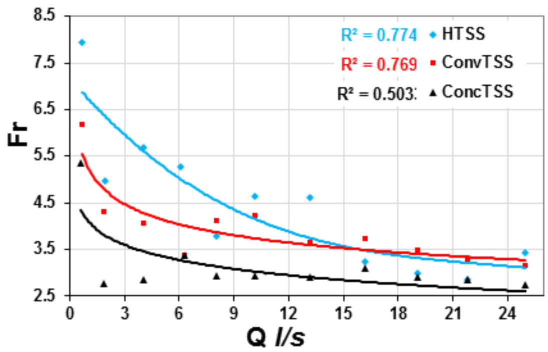


Fig. 6. Variation of Fr at the toe of the spillway with the flow rate for the three cases.

Figure 7 shows that the ratio of y_2/y_1 decreased with the increase of discharge. This ascribed to the decrease of Fr, as presented, in which the decrease of Fr produces lower duplication of y_2 to y_1. ConcTSS, also, produced lower values of y_2/y_1, for the same flow rate, than the other two cases in all the tests that carried out. This lower duplication of y_2 to y_1 produces, structurally and economically a lower downstream protection requirements.

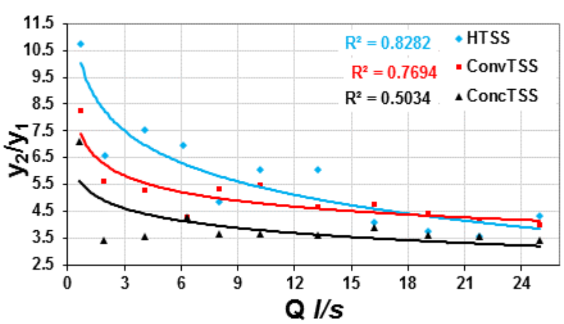


Fig. 7. Variation of y_2/y_1 with the flow rate for the three cases.

IV. CONCLUSION

The model that conducted, with its modifications, showed that the shape of shooting part of the step, tread, has a significant effect on the residual total energy at the toe of stepped spillway, in which this study deduced the following:

1- The energy dissipation decreased with the increase of discharge.
2- ConcTSS case produced a higher dissipation than HTSS and ConvTSS cases by the effect of jet flow, in which the energy dissipation for ConcTSS ranged from 48.84 to 87.82%, 41.38 to 84.08% for ConvTSS, and 34.93 to 78.23% for HTSS.
3- The modified ConcTSS, with slots, produced a little higher dissipation than ConcTSS.
4- The energy dissipated with the spillway and hydraulic jump, together, for ConcTSS case was higher than ConvTSS and HTSS, in which the total energy dissipation for ConcTSS ranged from 62.51 to 94.38%, ConvTSS from 60.74 to 93.81%, and HTSS from 59.64 to 93.25%.
5- Froude Number at the toe of the spillway decreased with the increase of the flow rate, and ConcTSS produced lower values of Fr than the other two cases in all the tests that carried out.
6- The ratio of y2/y1 decreased with the increase of discharge, and ConcTSS produced lower values of y2/y1 than the other two cases in all the tests that carried out.

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