New Shapes of Baffle Piers Used in Stilling Basins as Energy Dissipators

Ashraf BESTAWY

***Abstract* — Energy dissipation arrangements are the most important part in the design of a spillway for a dam. Various types of baffle piers and stilling basins have been tried so far. However, the hydraulic jump type-stilling basin is found to be the most efficient one. The main goal of this study is to introduce a shape of baffle pier, which has maximum energy dissipation. In this study, 14 different models of baffle piers were used for dissipating water energy downstream a heading up structure. One row of each model of baffle piers was used with a fixed position. Bed material used for runs was a uniform sand d_{50}=0.8 mm. The dimensions of the scour hole for each run were measured and used for the comparison between the performances of the used models for energy dissipation. Results in general show that, models with concave surfaces make the flow to change its direction more than the others with low turbulence intensity in recirculation zone downstream baffle piers and dissipate more energy than other forms. This leads to a stable hydraulic condition and shorter stilling basins. In addition, the study shows that the vertical semi-circular section (model No. 7) has the most effect among other tested models for dissipating water energy.**

***Index Terms*— Baffle piers – Stilling basins – Energy dissipators – Spillways – Hydraulic jumps.**

I. INTRODUCTION

ENERGY dissipation downstream a spillway is very critical problem which has been faced by design engineers. Following types of energy dissipation devices have been tried so far [1]: (1) Hydraulic jump type stilling basin, (2) Solid roller bucket type energy dissipater, (3) Slotted bucket type energy dissipater, and (4) Interacting jet type energy dissipator. However, they concluded that a hydraulic jump type stilling basin, though a bit expensive, is the ideal type of energy dissipation device.

Basically, the baffled apron or chute consists of a sloping apron with multiple rows of blocks or baffle piers equally spaced across the chute. The extent of acceleration and ultimate velocity at the base of the chute depends on the discharge and height, width, and spacing of the baffle piers [2].

Using flip buckets and ski jumps to through overflowing water into the air for downstream became popular also for high head dams. Moreover, chute blocks, baffle piers and end sills were added at the end of stilling basins to enhance energy dissipation [3].

The existing stilling basins are: The U.S. Bureau of Reclamation (USBR) stilling basins I, II, III and IV, Saint Anthony Falls (SAF) stilling basin, and Indian of wedge-shaped baffle piers stilling basin [4].

The SAF stilling basin has been recommended for use in small structures with inflow Froude numbers above 1.7. The reduction in basin length is more than 70% [5]. In 1975, Bhowmik [6] used piers with different inclinations to the incoming flow below a sluice gate. However, the tests showed that the required length of the basin was excessive.

The Indian Standards Institution [7] adopted a stilling basin design using baffle piers, chute blocks and end sills. The length of the basin is about four times downstream water depth.

Earlier studies [8],[9] had shown good results in developing stilling basins for Froude numbers between five and nine. In his study, a wedge-shaped baffle pier of vertex angle 120º cut back at angle of 90º was used. Finally, Pillai et al. [10] increased the vertex angle of the baffle pier to 150º to be used for developing stilling basins having low inflow Froude number.

The main objective of the present study is to develop a shape of baffle pier has a maximum energy dissipation which in turn increases the efficiency of the stilling basin (USBR, SAF, and Indian stilling basin). Different shapes of a single line baffle piers are used to dissipate water energy behind a weir.

II. EXPERIMENTAL SET-UP

Experiments were performed in a recirculation, rectangular open tilting flume at the Irrigation and Hydraulic laboratory of Civil Engineering Department at Assiut University, Egypt. As shown in Fig. 1, the flume is 17.50 m. long, 0.30 m. wide and 0.50 m. depth with adjustable slope. The erodible sediment was a uniform sand of mean diameter d_{50}= 0.8 mm. A Perspex spillway, 22.5 cm height with downstream slope of 6 (horizontal): 1(vertical), was fastened inside the flume at 6.50 m from the upstream inlet. The discharge was delivered by a pump and measured using a calibrated orifice meter with manometer. Measurements of water depth and scour hole were taken using a point gauge mounted on an aluminum frame so it could be moved longitudinally and transversely over any point on the channel bed. The gauge was equipped with a vernier, readable to within 0.10 mm. Measurements of the

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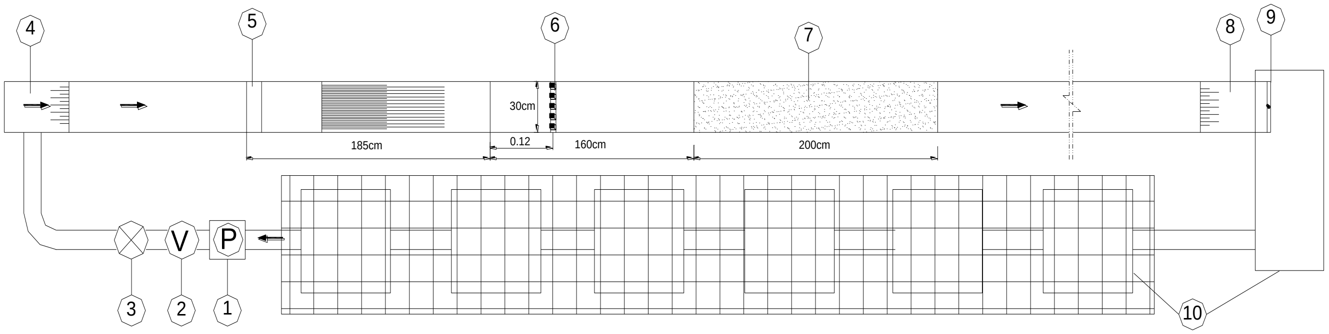
A. Bestawy is Assistant Professor with the civil Engineering Department, Taif University, Taif, KSA, on leave from the Civil Engineering Department, Assiut University, Assiut, Egypt (e-mail: bestawy25@yahoo.com).



(1) Pump
(2) Valve
(3) Orifice meter
(4) approach basin
(5) Spillway
(6) Baffle piers
(7) Movable bed
(8) Downstream ramp
(9) Tail gate
(10) Collecting tanks

Fig. 1.Experimental Set-up

location and length of the scour hole were made using a scale attached to the right side above the flume. A tailgate was used to control the downstream water depth of the flow.

III. Experimental Procedure

Fourteen different shapes of baffle piers were tested as energy dissipators downstream of the spillway model. A total of 90 runs were made. Six different discharges were considered (Q= 19.62, 17.75, 16.33, 12.5, 10.7 and 8.50 *l/s*). For each discharge one fixed water depth Y_2 downstream the spillway was used.

All Models that used were arranged in the flume to have nearly the same pass of waterway which around 40%. The row location of baffle piers model from the toe of the spillway (X_0) as used by Pillai et al. [10] to be (X_0/Y_2= 0.8) where Y_2 is the downstream water depth. The arrangements and dimensions of the spillway and different parts of the flume are given in Fig. 2. Detailed dimensions and arrangements of the tested baffle models are shown in Fig. 3.

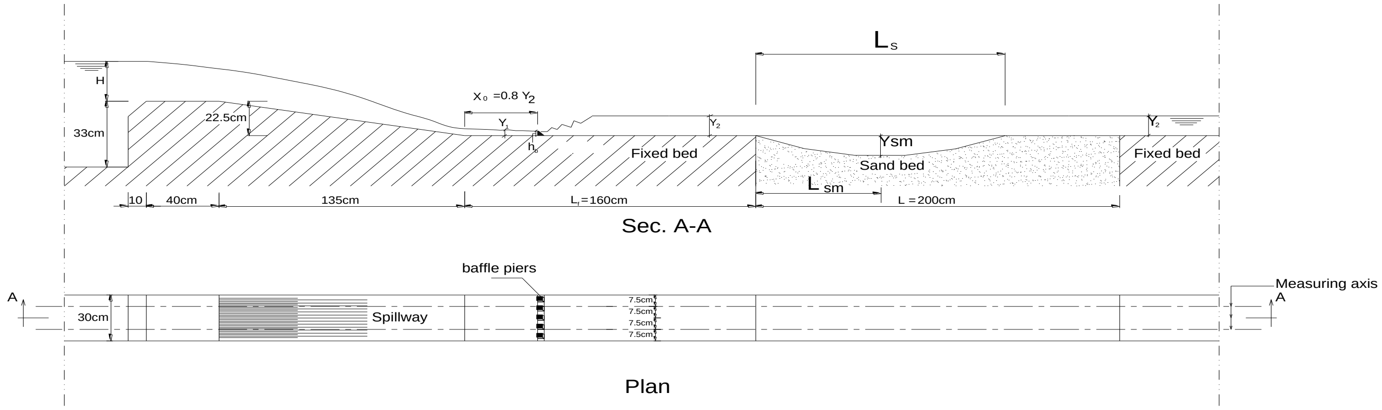


Fig. 2. Model dimensions and measured parameters

Since for the given discharge, the hydraulic jump should be formed steadily in the stilling basin, there should be some limitations for the Froude number of the incoming flow F_{r1} to prevent the highly waviness and instability of the water surface. Laboratory tests show that, if the range of F_{r1} equals 4.5 to 9, a steady jump may be observed in stilling basins [11]. Therefore, in this study, the following limits have been assigned to the value of approaching Froude number to be $5 \le F_{r1} \le 9$.

Runs were started with a backwater feeding first, until the downstream water depth reaches higher than the desired water depth of a certain discharge. Then, the upstream feeding was started gradually and adjusted. The tailgate was carefully lowered until the desired downstream water depth Y_2 was obtained. When there was no appreciable changes in scour hole dimensions (from this experimental work, it was noticed that a run took around 2 hours to reach a nearly stable condition); the feeding valve at inlet of the flume was closed. Finally, scour hole dimensions were measured using a point gauge and scale.

The measurements of the scour hole profile were made in three longitudinal axis of the flume at *b/4*, *b/2*, and *3b/4*, in which *b* is the flume width, and then the average values were determined. For a comparative performance between the tested baffle piers, hydraulic characteristics, dimensions, and spacing of each individual baffle block are identical. To ensure this, the water discharge, downstream water depths, as well as the pass of water way are kept constant for experiment. The pass of water way is around 40 % for each individual baffle block except the solid model (M10).

The proposed models of baffle piers which have curved surfaces appear to be non-constructible, but they are possible fabricated easily from concrete or steel. Again the goal of this study is not to propose a new stilling basin, but to improve the efficiency of the existing ones.

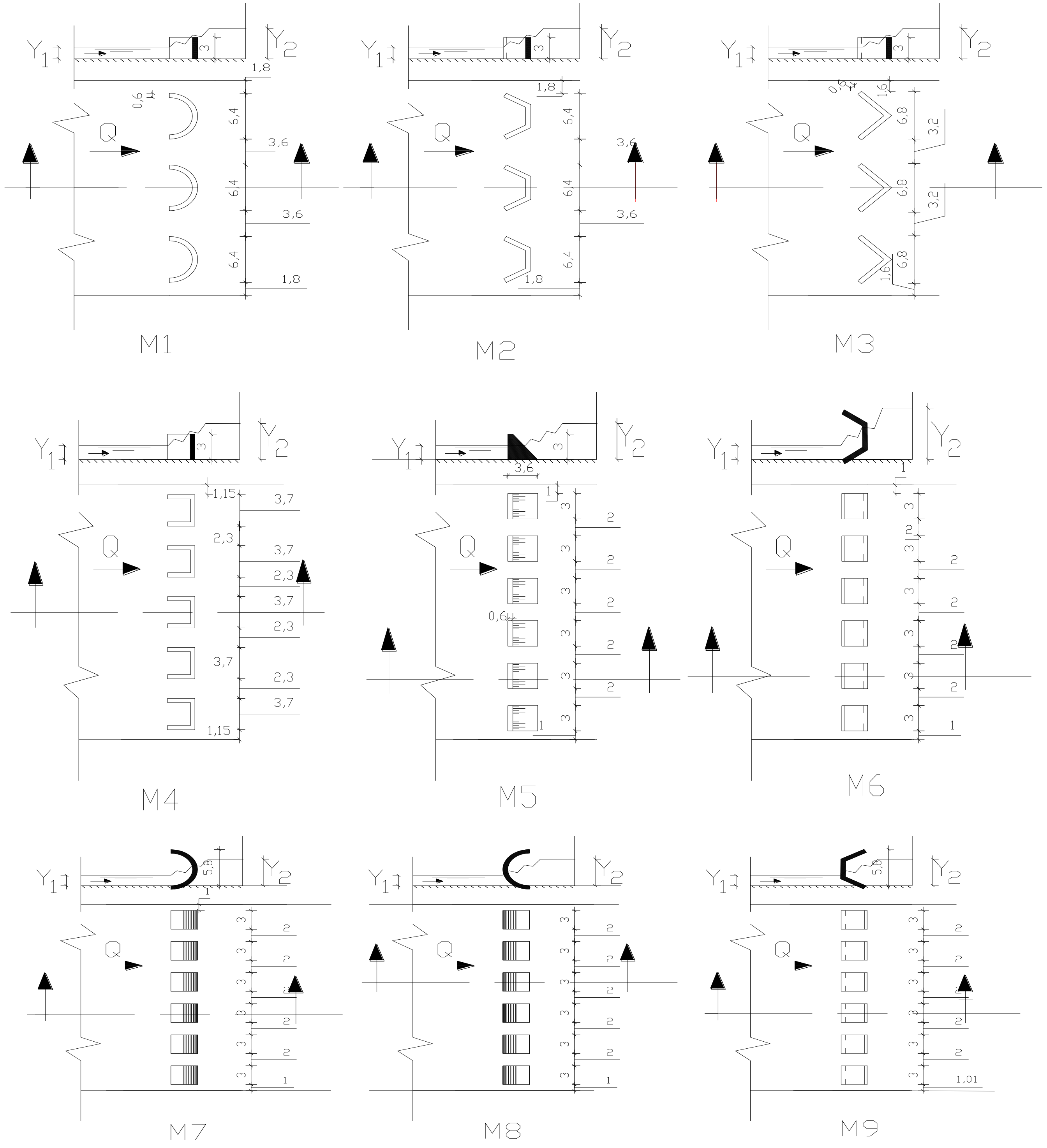


Fig. 3a. Tested models of baffle piers (M1 to M9)

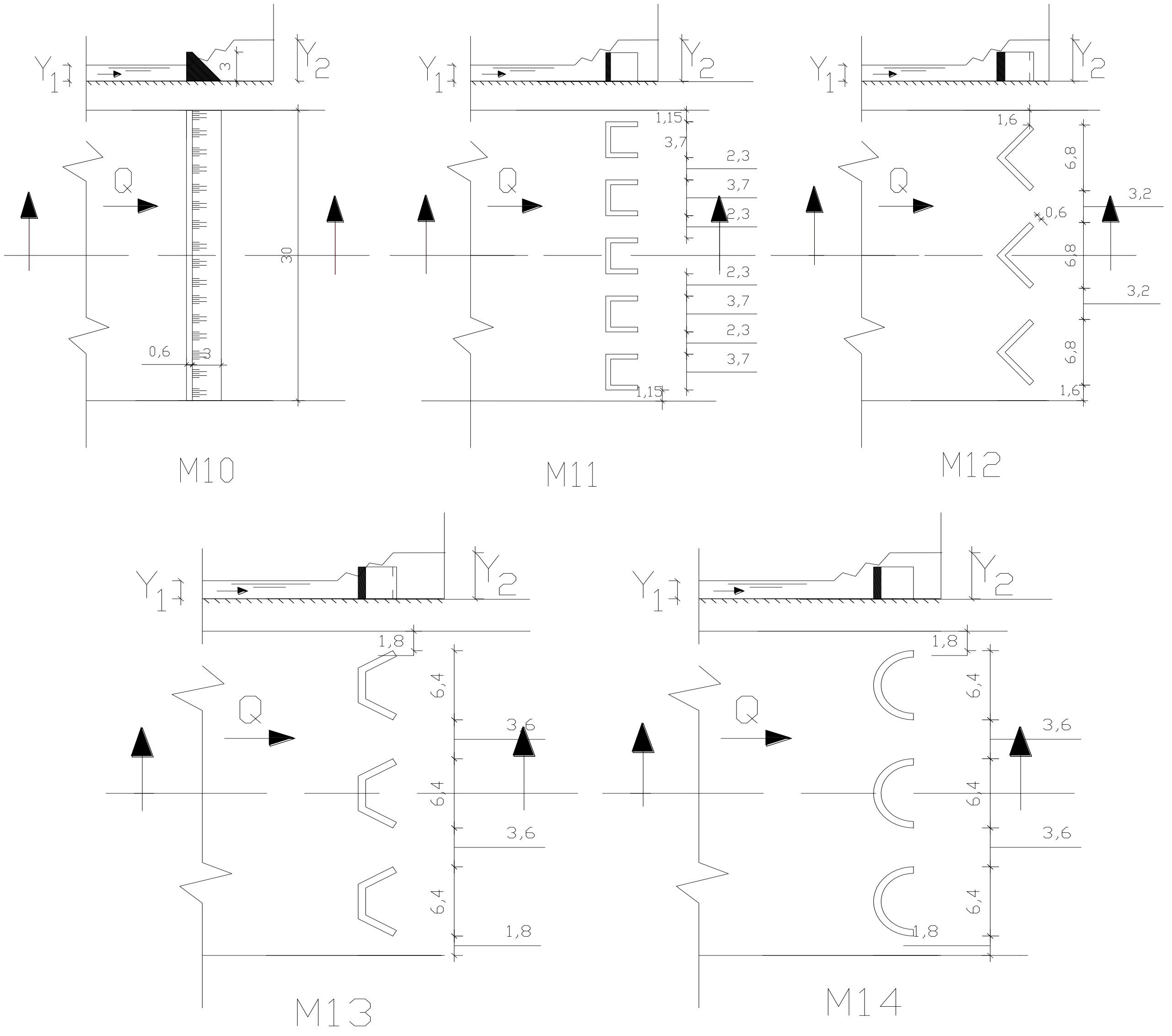


Fig. 3b. Tested models of baffle piers (M10 to M14)

IV. RESULTS AND ANALYSIS

Experimental results were expressed in dimensionless forms and represented graphically to study the effect of the used models on scour hole dimensions (maximum scour depth Y_{sm} & scour hole length L_s) and the location of the maximum scour depth measured from the end of solid floor, L_{sm}.

Performance of each model to dissipate energy is measured as an indication of scour hole dimensions behind the spillway. Relationships between the values of relative maximum scour depth Y_{sm}/Y_2 and the downstream Froude number F_{r2} are illustrated as shown in Figs. 4 and 5. From these figures, it is clear that, increasing the values of F_{r2}, increases the value of Y_{sm}/Y_2, as well. For further increases of F_{r2} the differences of Y_{sm}/Y_2 for different models increases. Models M7 and M6 have the most effect results in reducing maximum scour depth, Y_{sm}. However, for low values of F_{r2} until 0.24 models M7 and M6 gave the same result of reducing Y_{sm}. Further increasing of F_{r2}, the performance of M7 is better than M6. Model M1 gave nearly the same result as M6 for the value of $F_{r2} \geq 0.27$, while M10 gave the worst results of reducing Y_{sm}. The performance of the tested models in reducing of Y_{sm} is listed in descending order in Table 1.

Figures 6 and 7 show the relation between relative scour hole length L_s/Y_2 and downstream Froude number F_{r2} for the used models of dissipating energy. From these figures, it is clear that L_s/Y_2 increases with increasing of F_{r2} . For further increase of F_{r2} the differences in L_s/Y_2 of used models increase. Models M6 and M7 are the best among others and gave nearly the same result of reducing the length of the scour hole. Models M11 and M13 gave the worst results of L_s/Y_2. Also, the performance of the models in reducing L_s is listed in descending order in Table 1.

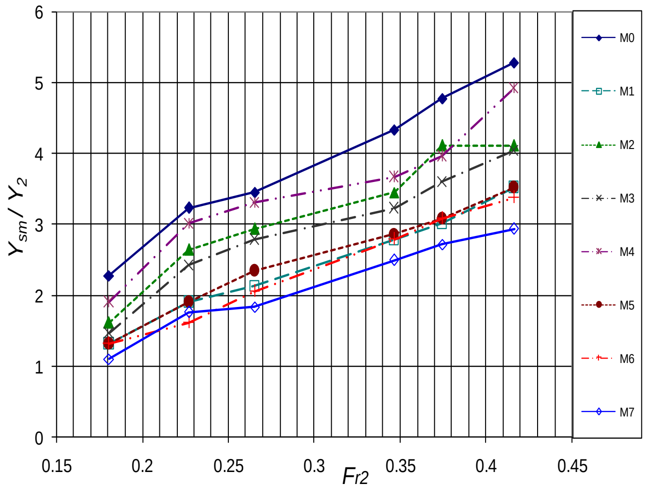


Fig. 4. Relationship between the maximum relative scour depth, Y_{sm}/Y_2, and the downstream Froude number, F_{r2}.

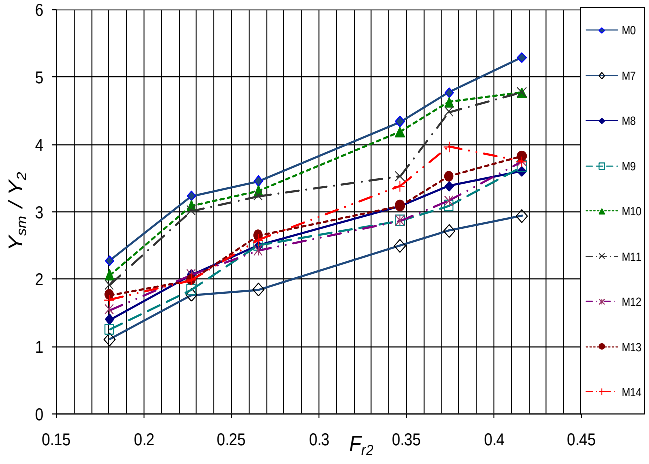


Fig. 5. Relationship between the maximum relative scour depth, Y_{sm}/Y_2, and the downstream Froude number, F_{r2}.

TABLE 1. Comparison of the performance of used Models

Rank number	Performance of reducing relative max. scour depth (Y_{sm}/Y_2)	Performance of reducing relative scour length (L_s/Y_2)	Performance on decreasing the relative distance of the max. scour depth (L_{sm}/Y_2)
1	M7	M6 & M7	M7
2	M6	M5	M1
3	M1	M3	M8 & M9
4	M5 & M9	M1	M3 , M5 & M6
5	M12	M9 & M12	M2
6	M8 &M13	M2	M12
7	M14	M10	M14
8	M3	M8	M4, M10 & M13
9	M2	M4 & M14	M11
10	M4 & M11	M13	-------
11	M10	M11	-------

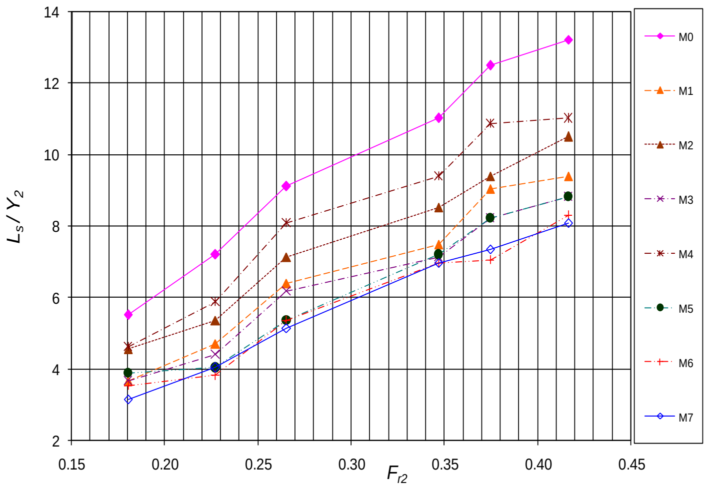


Fig. 6. Relationship between the relative scour length, L_s/Y_2, and the downstream Froude number, F_{r2}.

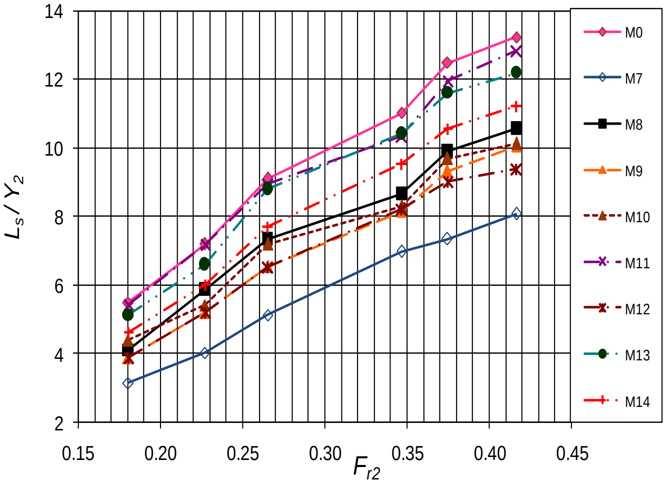


Fig. 7. Relationship between the relative scour length, L_s/Y_2, and the downstream Froude number, F_{r2}.

The distance from the end of the solid floor to the point of maximum scour depth L_{sm} was recorded and used to illustrate the variation of L_{sm}/Y_2 with F_{r2} as shown in Figs 8 and 9. It is clear that, the values of L_{sm}/Y_2 decrease by increasing the values of F_{r2}. Model M7 gave minimum distance of L_{sm} while M11 gave the maximum L_{sm}.

Figures 4 to 7 show that by increasing F_{r2}, the scour volume (Y_{sm} &L_s) for tested models increases as well but with different rates. For the comparison between the studied models in dissipating water energy, different fitting curve methods were applied to the relations between Y_{sm} &L_s and F_{r2} in Figs 4 to 7.

A linear regression analysis was chosen, because it yielded to satisfactory high coefficients of determination r^2 $(0.91 \le r^2 \le 0.99)$. The slope of the regression line ($tan\theta$) was considered a measurable of the energy dissipation for the studied models. The values of $tan\theta$ for some of the tested models (familiar ones) are given in Table 2.

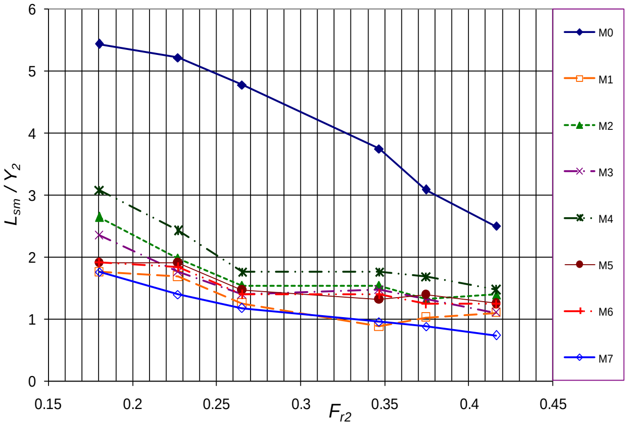


Fig. 8. Relationship between the relative distance of the maximum scour depth, L_{sm}/Y_2, and the downstream Froude number, F_{r2}.

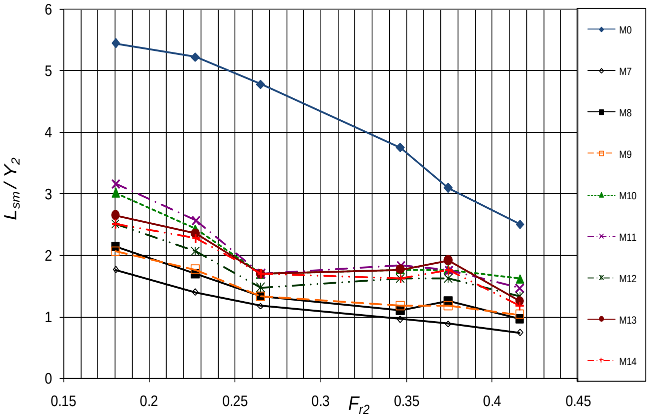


Fig. 9. Relationship between the relative distance of the maximum scour depth, L_{sm}/Y_2, and the downstream Froude number, F_{r2}.

TABLE 2. Comparison of the measurable energy dissipation (*tanɵ*) for some of the studied models

Model No.	Mo (without baffle)	M5 (dentate sill)	M7 (the best one)	M10 (solid sill)
tanɵ for Y_{sm}/Y_2	12	8.8	7.5	11.2
tanɵ for L_s/Y_2	32.9	22.3	21.5	24.7

When the value of *tanɵ* is a high value, the scour volume is large and consequently the energy dissipation is low. Table 2 shows that M7 has the minimum value of *tanɵ* for both Y_{sm} and L_s . M5 and M10 show a good and bad performance for energy dissipation, respectively.

In general, with respect to energy dissipation, models M6 and M7 gave good results, while M4, M10 and M11 gave the worst results. On the other hand, models M1, M3 and M5 gave moderate good results of reducing scour hole.

It is observed that, the common used models M5 (dental sill) gave a reasonable result (ranking No.4) , while M10 (solid sill) gave a bad result.

It is obvious that, model M7 (vertical semi-circular section) which proposed in this study gave the best performance of reducing scour volume and consequently has a maximum energy dissipation and ranked No.1.

Results of the experiments show that, the models which have the ability to circulate the water jet in a vertical transverse direction behave better than others for energy dissipation. The rotation water jet interrupts the jump action to the extent in which there is a complete dissipation of energy. This leads to give a minimum scour volume.

V. CONCLUSIONS

The following conclusions are drawn from the present experimental study on fourteen different models of baffle piers in stilling basin for inflow Froude number $5 \le F_{r1} \le 9$ to test their performance for water energy dissipation:

- Models generate vertical rollers that acting in a transverse direction of flow (water turnover) are better than the others.
- The suggested models of baffle piers M7 (vertical semi-circular section) and M6 (vertical trapezoidal shape) could be effectively used in a stilling basin rather than familiar ones with a high efficiency for energy dissipation. The two models have ranked number one and two among the other studies models, respectively.
- Popular used models M5 (dental sill) and M10 (solid sill) have shown a fairly good and bad performance of energy dissipation, respectively.

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NOTATIONS

The following symbols are used in this paper:

b = width of the flume;
d_{50} = median particle size of sand bed;
F_{r1} = Froude number upstream the jump;
F_{r2} = downstream Froude number;
h_b = height of the baffle pier;
L_s = length of the scour hole;
L_{sm} = distance of the location of maximum scour hole from the end of solid floor;
M_* = model number;
Q = water discharge;
r^2 = coefficient of determination;
X_o = distance between the toe of the spillway and the row of the baffle block model;
Y_1 = initial depth before hydraulic jump;
Y_2 = conjugate depth to Y_1;
Y_s = depth of scour ;
Y_{sm} = depth of maximum scour hole; and
$\tan\theta$ = measurable of the energy dissipation.

Ashraf BESTAWY born in El Dokki, Giza, Egypt, in 1961, He received the B.S. and M.S. degrees in Civil Engineering from the University of Assiut, Assiut, Egypt, in 1984, and 1990, respectively. He got the Ph.D. degree in Civil Engineering from Catholic University, Leuven, Belgium, in 1997.

From 1997 to 2010, he was a lecturer with the Civil Engineering Department, Assiut University, Egypt. Since 2010, he has been an Assistant Professor with the Civil Engineering Department, Taif University, Taif, Kingdom of Saudi Arabia.

Dr. Ashraf is the member of Engineering Syndicate of Egypt.