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Flume Experiments to Improve Sant Anthony Falls Stilling Basin Efficiency

Thulfikar R. Al-Husseini, Hussin Janna and Marwah M. Al-Khuzaie
Department of Civil Engineering, College of Engineering, University of Al-Qadisiyah,
Al-Qadisiyah, Iraq

Abstract: The dimensions and the shapes represent the major role for the efficiency of stilling basin. The Sant Anthony Falls (SAF) type basin was constructed in the University of Minnesota to be used in various structures like canal structures, outlet works and spillways. Although, this type of stilling basin used for a wide range of discharges and Froude number compared to other types of stilling basins but has a deficit of hydraulic stability in large discharges, mildly high cost and a powerful of efficiency at high discharges. This study presented flume experiments to improve the efficiency of the SAF type stilling basin. Twelve new shapes of stilling basin were hydraulically designed and experimentally implemented in the laboratory and compared with the standard shape. The results showed that all the new designed shapes were more hydraulically stable with more efficiency and with low cost compared to the standard one. The results also showed that when doubling the height of baffle pier and decreasing the length of floor by 20%, the efficiency increased to 73% using the shape and dimensions of model #5 which is more efficient, more hydraulic stable and more economically. Moreover, by increasing the distance between baffle pier and chute block and the distance between first and second row of baffle pier, the efficiency of stilling basin was improved at low discharge and decreased at high discharge.

Key words: Flume experiments, energy dissipation, froude number, stilling basin efficiency, SAF, baffle pier

INTRODUCTION

The hydraulic structures such as drops, outlets and stilling basin are frequently used to minimize the kinetic energy of the flow passes over these structures. Furthermore, to increase the dissipation of flow energy, hydraulic structures particularly stilling basin were provided with additional devices such as sills, chute blocks and baffle piers. These devices lead to additional costs for the structure. If the flow energy over these structures is not dissipated, the bed of canal would be eroded causing structure failure. Therefore, many researches have been carried out to improve the efficiency of the stilling basin and to decrease the energy of flow.

Taebi *et al.* (2010) designed a riprap for stilling basin to increase the tail water and to control the scouring. Moreover, Smith and Klassen suggested a hydraulic design of two-stage stilling basins which were used for high Energy Dissipation (ED) of structures. The suggested two stages stilling basins were proved to be effective for the two hydraulic jumps that occurred over stilling basin (Smith and Klassen, 1981). Al- Husseini *et al.* studied the effect of size of gravels on energy dissipation on stepped spillway. They concluded that when increasing the size of gravels by ratio 50% of step height the energy dissipation was increased by triple (Abdul-Mehdi *et al.*, 2016).

On the other hand, Hinge *et al.* (2010) introduced a new design for stepped weir which was located at the end of stilling basin to improve its efficiency. The modified design prevented the hydraulic jump that swept out the stilling basin (Hinge *et al.*, 2010). Shahmirzadi *et al.* (2014) presented an assessment of the ED of in-ground stilling basin and a correlation between flow patterns and the in-ground stilling basin. They summarized that there was a clear correlation between the flow patterns with geometry of in-ground stilling basin (Shahmirzadi *et al.*, 2014). Tiwari *et al.* (2015) conducted an experimental study of new design of US Bureau of Reclamation (USBR) type 4 stilling basin model for pipe outlet. The new design was more efficient and more economic compared with the other models due to changing in the location and geometry of impact walls and splitter blocks (Tiwari *et al.*, 2015).

Kantoush and Sumi studied the effect of geometry of the stilling basin on the sediment transport and pattern of flow at flood mitigation dams. They developed a new method of the optimum design of stilling basin that dissipate more energy and deposit minimum sediment (Kantoush and Sumi, 2010). Padulano *et al.* (2017) added

Corresponding Author: Thulfikar R. Al-Husseini, Department of Civil Engineering, College of Engineering, University of Al-Qadisiyah, Al-Qadisiyah, Iraq

some consideration for the design of USBR type 2 such as type of hydraulic jumps, forces acting on end sill, pressure regimes and ED assessment (Padulano *et al*., 2017) while Vittal and Al-Garni (1992) presented a new method for designing stilling basin type 3 over a range of discharges passing over it. They improved the distribution of velocity over this type of stilling basin (Vittal and Al-Garni, 1992). Champagne *et al*. (2016) performed a laboratory study on scour behind the stilling basin. Their experiments reduced the scour by 59% using air injection and showed that the optimal air-water velocity ratio was 251 (Henderson, 1996). Pagliara and Palermo studied the effect of stilling basin geometry on the ED in the presence of block ramps. The study showed that the ED was increased when the stilling basin was enlarged. Some empirical equations were derived to represent the ED for the stilling basin (Champagne *et al*., 2016). Mohsen studied the effect of semicircular elements in the stilling basin and compared them with elements of smooth basins, basin type 1, SAF stilling basin, type 1, type 3 and Lozenge. His experimental study showed that the stilling basin length was decreased by 56% and the sequent depth by 25% for the semicircular elements compared to the smooth basin (Pagliara and Palermo, 2012).

The Sant Anthony Falls (SAF) stilling basin was developed by Sant Anthony Falls Hydraulic Laboratory in the University of Minnesota. The SAF was used in various structures like outlet works, small spillways and small canal structures. The froude number for this type of stilling basin has a wide range of 1.7-17 compared to other types of stilling basins.

The objective of this study was to perform flume experiments to improve the efficiency of the SAF type stilling basin using new twelve physical models made from plywood in addition to the standard basin. The energy dissipation, hydraulic stability and the construction cost reduction for the SAF type stilling basin were improved in the new models. Different accouterments were used in the design of SAF stilling basin to reduce the basin length up to 80% of the original length increasing the energy dissipation and increasing the hydraulic stability over SAF stilling basin.

MATERIALS AND METHODS

Theory of energy dissipation: The relationship between the upstream energy of spillway and downstream energy of stilling basin can be expressed as follows (Hayder, 2017):

$$E_1 = y_1 + a_1 \frac{V_1^2}{2_g} \quad (1)$$

$$E_3 = y_3 + a_3 \frac{V_3^2}{2_g} \quad (2)$$

$$RED = \frac{E_1 - E_3}{E_1} \% \quad (3)$$

Where:

E_1 = The upstream energy (m)
E_3 = The downstream energy (m)
V_1 = The upstream velocity before spillway (m/sec)
V_3 = The downstream velocity after stilling basin (m/sec)
y_1 = The upstream water depth of before spillway (m)
y_3 = The downstream water depth after stilling basin (m)
RED = The relative energy dissipation (%)
a_1 and a_3 = The kinetic correction coefficients at upstream and downstream

Respectively which were equal to 1.1 for turbulent flow according to Hayder (2017) and *g* is the gravity acceleration, m/sec^2. A computer program was coded for using the energy, relative energy equations and Froude number for all models.

Description of saf models: Chow (1959) presented the standard design dimensions of SAF stilling basin. The stilling basin length (L_b) was presented as (Henderson,1996):

$$L_b = \frac{4.5 y_2}{F_{r2}^{0.76}} \quad (4)$$

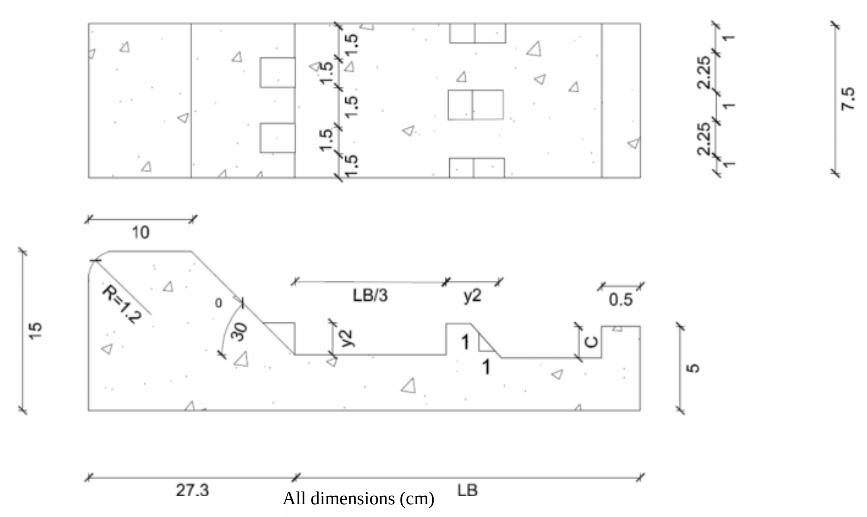
Where:

F_{r2} = Froude number at the downstream sloping face of spillway, ranged from 1.7-17
y_2 = The water depth at the downstream of stilling basin

The chute blocks and floor blocks heights are referred to as y_2 while the width and spacing are approximately equal to ($0.75y_2$). The distance between the floor blocks and the upstream end of the stilling basin was ($L_b/3$). Floor blocks should be located behind the openings between the chute blocks. Floor blocks were occupied (40-55) % of the stilling basin width. The values of end sill height were taken as C equal to ($0.07y_4$) where y_4 is the tail water depth of y_2. In this study, the values of y_2 and y_4 are 25 and 83 mm, respectively for standard SAF (Henderson,1996).

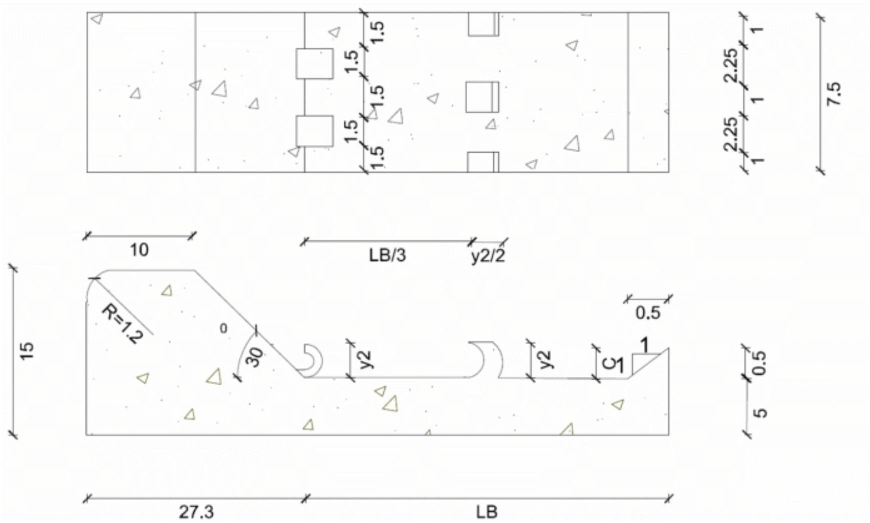
The length of crests and radius of curvature of upstream face in all models used in this study were designed using the following formulas (Hayder, 2017; Henderson,1996):

$$\frac{K_{crest}}{H_T - h_e} > 1.5\text{-}3 \quad (5)$$



All dimensions (cm)

Fig. 1: Schematics of standard SAF stilling basin



All dimensions (cm)

Fig. 2: Schematics of group 1 stilling basin proposed in this study

$$R = 0.2(H_T - h_e) \quad (6)$$

Where:

L_{crest} = The crest length for spilway (m)

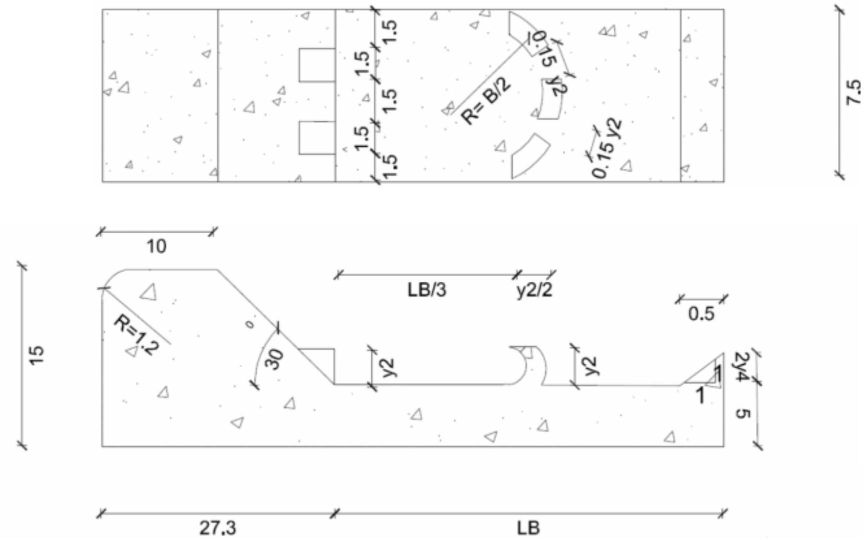
H_T = The total head at upstream above the bed of channel (m)

h_e = The height of spillway above the bed channel (m)

R = The radius of curvature for upstream face

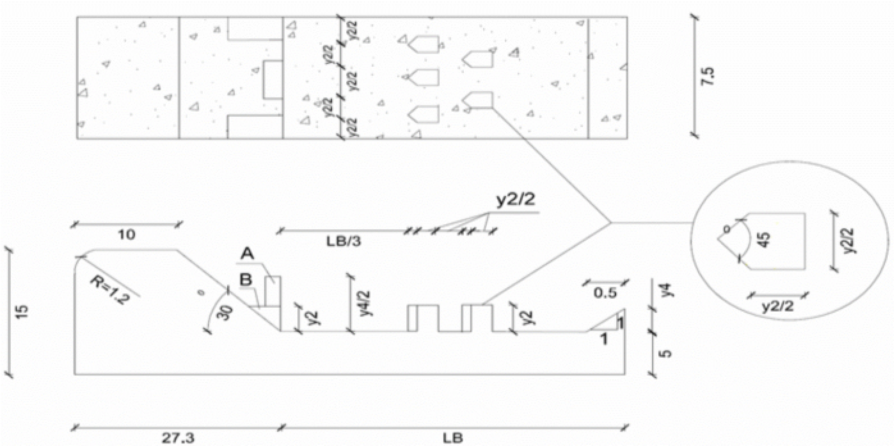
Using Eq. 5 and 6, the above standard dimensions and downstream slope equals to 30° (which is greater than the critical value of 27° according to Chanson (1994) and Chafi *et al*., (2010) for stepped spillway), the standard model of spillway and stilling basin was designed and constructed from plywood as shown in Fig. 1.

The technical base and criteria for the SAF proposed modifications in this study were to modify the shape and dimension of chute blocks, baffle piers and the end sill to increase the energy dissipation, improve the hydraulic stability and decrease the construction cost of stilling basin. These new proposed basins were designed and constructed from plywood with dimensions shown in Fig. 2-4. Three groups were constructed with 12 new models: Group 1 included model numbers of 2-5, Group 2 included model numbers of 6-9 and Group 3 included model numbers of 10-13. Table 1 and 2 showed the geometric dimensions of chute blocks, baffle piers and the end sill of these new 12 models proposed in this study. Model #1 referred to standard SAF stilling basin in this



All dimensions (cm)

Fig. 3: Schematics of group 2 stilling basin proposed in this study



All dimensions (cm)

Fig. 4: Schematics of group 3 stilling basin proposed in this study

Table 1: Geometric dimensions for group 1 and 2 proposed in this study

Model numbers of group 1	Model numbers of group 2	Height of chute blocks and baffle piers	Distance between chute block and baffle piers	Floor length
2	6	y_2	$L_b/3$	L_b
3	7	1.5 y_2	$L_b/2$	L_b
4	8	1.5 y_2	$2L_b/3$	L_b
5	9	2 y_2	$L_b/2$	0.8 L_b for model #5 and L_b for model #9

Table 2: Geometric dimensions for group 3 proposed in this study

Models numbers	Height of block A	Height of block B	Height baffle piers	Distance between 1st and 2nd raw of baffle piers	Area of baffle piers
10	y_2	$y_2/2$	y_2	0.5 y_2	$0.5y_2$H$0.5y_2$
11	y_2	$y_2/3$	1.5 y_2	0.6 y_2	$0.6y_2$H$0.6y_2$
12	y_2	$y_2/4$	1.5 y_2	0.7 y_2	$0.7y_2$H$0.7y_2$
13	y_2	$y_2/4$	2 y_2	0.7 y_2	$0.7y_2$H$0.7y_2$

Fig. 5: A photo of Model #1 setup of standard SAF stilling basin at the flume

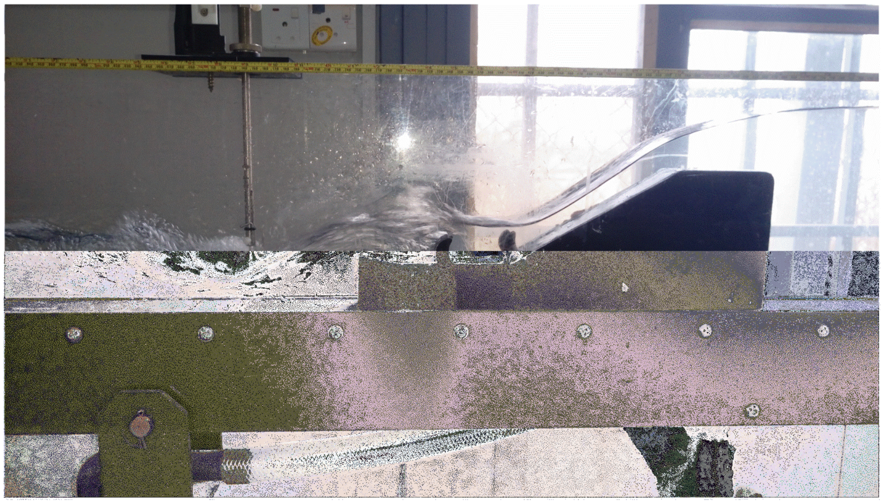


Fig. 6: An example of Model #2 of group 1 setup of new proposed SAF stilling basin at the flume

study (Fig. 1). To avoid the overflow, the height of each model was selected to be 60% (15 cm) of the flume height and remains constant throughout the experimental tests. To eliminate the turbulence, all models were placed at the location of 0.75 m from the beginning of flume.

Practicality, the proposed modifications included end sills, chute blocks, baffle piers, length of floor which provided in stilling basin to reduce the kinetic energy of the flow passes over them. The proposed modifications lead to increase the dissipation of flow energy and reduce the construction cost of stilling basin since these devices lead to additional costs for the structure. If the flow energy over these structures is not dissipated, the bed of canal would be eroded which lead to failure. All the proposed modifications are applicable and can be practically applied. The applicability of the proposed modifications was in SAF stilling basins which used under spillway of dams to reduce the high energy of flowing water that lead to failure due to bed of canals erosion.

Implementation of experimental work: The experimental tests were conducted using ARMFIELD flume at the Hydraulic Laboratory, Civil Engineering Department, Al-Qadisiyah University (Fig. 5-8). The dimensions of the rectangular flume were 245 cm long, 25 cm high and 7.5 cm in width. A sharp crested weir (with height of 2.5 cm) was located at the end of channel to establish the second hydraulic jump produced from stilling basin. The depth of flow upstream was measured at a location of ($9y_c$) before

Fig. 7: An example of Model #9 of group 2 setup of new proposed SAF stilling basin at the flume

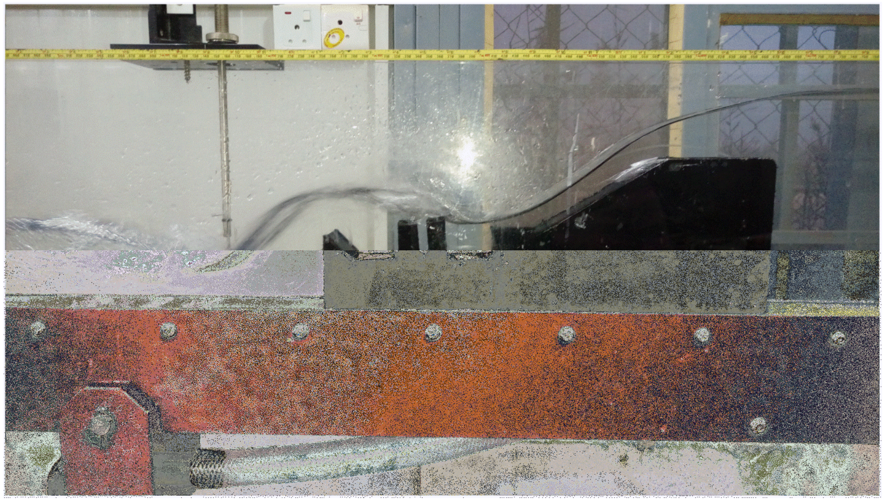


Fig. 8: An example of Model #11 of group 3 setup of new proposed SAF stilling basin at the flume

the spillway where y_c is the flow depth at the crest of spillway. The flow was obtained using a calibrated flow meter. The peak flow of the flume was 2.65 m^3/sec. The depths of flow were measured using a point gauge with accuracy of±0.1 mm.

For each model, twelve runs were performed with different flow. The following hydraulic parameters were measured for each run: the discharge (Q), upstream flow depth (y_1) before spillway, the downstream flow depth (y_3) at the toe of stilling basin, depth of water at crest (y_c) and the sequent depth of the second hydraulic jump (y_4) which was swept out from the stilling basin. After the hydraulic variables were measured, the efficiency of dissipation of flow was obtained. The maximum ratio of (y_1/y_c) corresponding to each model of the experiment study was equal to 31.20 which was less than the largest limit of ($y_1/y_c< 35$) as recommended by Chanson (1994). A total of 156 runs were performed and all the previous hydraulic parameters were measured for all models.

RESULTS AND DISCUSSION

All proposed models were divided into three groups (Group 1-3) according to the shape and dimensions of the component of the stilling basin. The experimental results are shown in Fig. 9-12. It was observed from these Figures that the RED decreased as the Froude numbers increased as a result of discharges increased due to reduction of

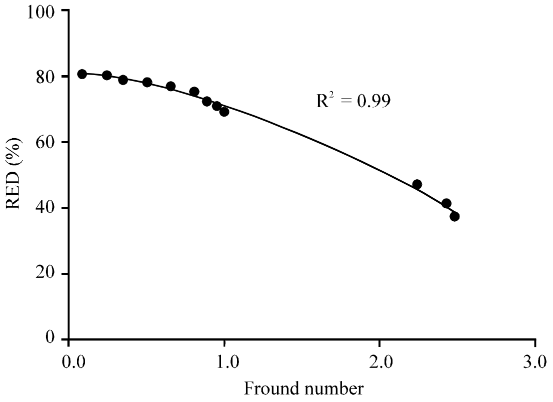


Fig. 9: A relationship between relative energy dissipation and froude number for Model #1 of standard SAF stilling basin

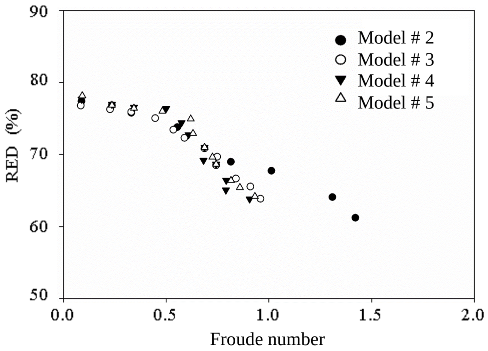


Fig. 10: A relationship between relative energy dissipation and Froude number for group 1 of Model #2-5 of SAF stilling basin

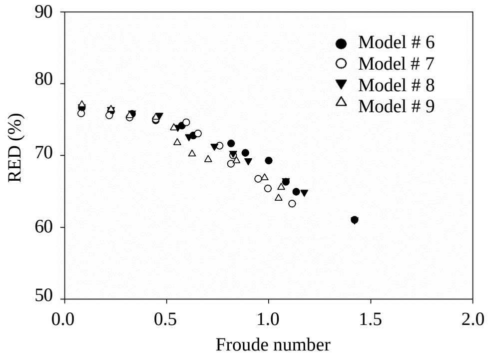


Fig. 11: A relationship between relative energy dissipation and Froude number for group 2 of Model #6-9 of SAF stilling basin

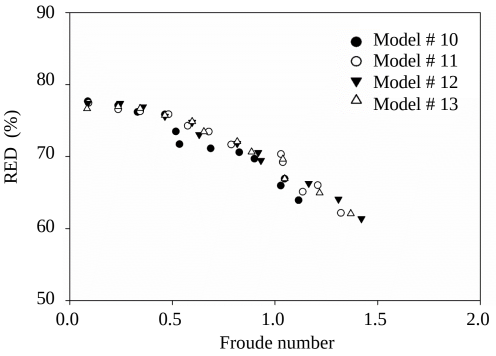


Fig. 12: A relationship between relative energy dissipation and Froude number for group 3 of Model #10-13 of stilling basin

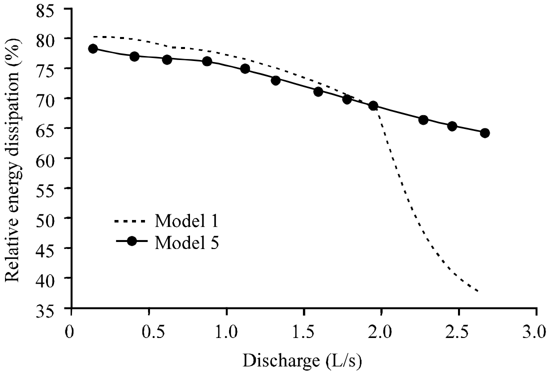


Fig. 13: Comparison relationships of relative energy dissipation versus discharge between Model #1 and 5 of SAF stilling basin

effectiveness of all stilling basin components. The depth of water became high compared with the height of these components. Therefore, the efficiency of stilling basins was decreased at high discharges for all models. In general in standard SAF stilling basin (Model #1), the energy dissipation suddenly dropped at high discharge and this is referred to “Hydraulically is not stable”. While all the proposed modifications (Model #2 through Model #13) dropped slowly and smoothly (Fig. 13) and this is referred to “Hydraulically is stable”. This was due to the new shapes and dimensions of the proposed models.

All the proposed models were more efficient in term of energy dissipation, especially for Model # 5. The efficiency of this model reached about 73% at high discharges and 2.5% at low discharges in comparison to standard SAF (Model #1). On the other hand, the floor length was decreased by 20%. Moreover, the results indicated that when the distance between chute block and baffle piers increased, the efficiency of stilling basin also increased at low discharges and decreased at high discharges. At low discharges increased in distances allowed the flow to hit by chute blocks and baffle piers

Table 3: Results of red versus different discharges for 13 models used in this study

Model #	RED (%)										
Q, l/s	0.14	0.41	0.62	0.87	1.12	1.32	1.59	1.77	1.95	2.27	2.67
1	80.1	79.9	78.6	78.0	76.3	75.0	72.2	70.4	68.9	46.9	37.1
2	77.4	76.8	75.8	75.0	73.8	72.3	70.9	69.7	69.0	67.7	61.2
3	76.8	76.3	75.9	75.0	73.4	72.3	70.9	69.7	68.5	66.7	63.9
4	77.7	77.0	76.6	76.4	74.4	72.8	71.0	69.2	68.7	66.4	63.8
5	78.2	76.8	76.4	76.0	74.9	72.9	71.0	69.6	68.7	66.4	64.2
6	76.6	76.1	75.8	74.9	74.2	72.8	71.7	70.4	69.3	66.3	61.0
7	75.9	75.6	75.3	75.0	74.6	73.1	71.4	70.0	68.8	66.7	63.3
8	76.8	76.4	75.9	75.6	73.9	72.6	71.3	70.3	69.3	66.5	61.0
9	77.1	76.4	75.6	75.3	73.9	71.8	70.2	69.4	69.3	66.9	64.0
10	77.7	77.1	76.2	75.9	73.5	71.7	71.1	70.6	69.7	66.9	63.9
11	77.5	76.6	76.3	75.9	74.3	73.5	71.7	70.4	69.2	66.0	62.2
12	77.4	77.1	76.9	75.6	74.5	73.1	71.8	70.6	69.5	66.3	61.4
13	77.0	76.7	76.6	75.7	74.9	73.5	72.1	70.7	69.7	66.9	62.1

Table 4: Results of red versus different discharges for 13 models used in this study

Model #	λ	β	R^2
1	160.5	1.54	1.00
2	97.5	1.36	0.98
3	146.1	1.49	0.99
4	189.5	1.59	0.99
5	151.6	1.51	1.00
6	151.6	1.49	1.00
7	151.7	1.49	0.99
8	169.3	1.54	1.00
9	176.6	1.57	1.00
10	176.6	1.58	1.00
11	131.0	1.45	0.99
12	147.2	1.50	1.00
13	164.2	1.66	1.00

over the floor and dissipated more than one times. While at high discharges, decreased in distances allowed the chute blocks and baffles piers to work together as one piece leading to more dissipation of flow.

Additionally when the height of baffle piers was increased, the efficiency was increased also and considered more significant than the floor length. When the distance between the first row of baffle piers and the second one was increased, the efficiency at low discharges was increased while it was decreased at high discharges which were more compatible with the results interpretation for the matter of the distance between chute blocks and baffle piers. Figure 13 shows the relationship between the RED and discharges for Model #1 and 5. All other proposed models have the same trend as Model #5. Table 3 summarized the relationship between RED and discharge for 13 models used in this study. The general trend indicated that the energy dissipation was decreased slightly rather than standard one.

Figure 14 shows the comparison of relationships between y_4/y_3 versus Froude number for Standard SAF of Model #1 versus Model #3-5. The Froude number for the proposed models was decreased from 3 of Model #1-1 of Model #5 which was indicted to the flow changed from supercritical for Model #1 to subcritical flow for Model #5.

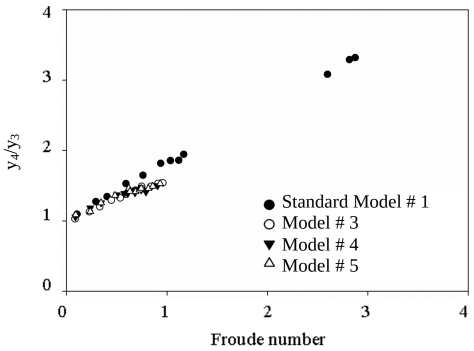


Fig. 14: Comparison of relationships between y_4/y_3 vs froude number for Standard SAF of Model #1 versus Model #3-5

This was due to use the new shapes and dimensions of the proposed models. Moreover, all proposed models have values of Froude number less than the standard one. Table 4 shows the fitting constants and the correlation between measured upstream heads and downstream discharge that was established using DataFit 90 software according to the following equation which is the general form for the relation between discharge and head for all models:

$$Q = \lambda H^{\beta} \tag{7}$$

where, $\lambda$and β are constants varies from model to another and their values were shown in Table 4.

CONCLUSION

In this study, a new experimental study to investigate the improving the efficiency of SAF stilling basin using new physical models was presented. Twelve physical plywood models were designed and constructed to achieve this aim. A total of 156 experiments were conducted and the hydraulic parameters were measured for each run and the RED were performed accordingly. The experimental results showed that the RED of flow on stilling basin decreases when the discharge and Froude number were increased. Generally, the risk of damage of any hydraulic structure was occurred at high discharges not at the low discharges. So, all the proposed models obtained higher efficiency at high discharges than the standard SAF type, especially for Model #5. This model was more economically since it has floor length less by 20% and more efficient by 73% at high discharges and 2.5% at low discharges compared to the standard one. All the proposed models were hydraulically more stable compared to standard SAF model and have more efficiency, especially for Models #3-# 5 where the flow was changed from supercritical to subcritical flow.

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