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Dissipation of Hydraulic Energy by Curved Baffle Blocks

Aziz F. Eloubaidy[1], J.H. Al-Baidhani[2] and Abdul Halim Ghazali[1]

[1]*Department of Civil Engineering*
University Putra Malaysia, Serdang, Malaysia
[2]*Department. of Civil Engineering*
University of Babylon, Hilla, Iraq

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ABSTRAK

Penilaian secara ujikaji mengenai kesan saiz relatif, lengkungan dan lokasi blok bafel lantai berlengkung ke atas kehilangan tenaga dan pengawalan lompatan hidraul dikemukakan. Dengan menggunakan teknik analisis berdimensi, keterangan mengenai aliran di atas blok berlengkung (pada pandangan atas) dinyatakan dengan satu set nisbah tak berdimensi. Penilaian dibuat di dalam makmal dengan merujuk kepada unsur-unsur aliran yang boleh diukur. Keputusan yang diperolehi menunjukkan bahawa, di dalam semua keadaan, blok berlengkung adalah lebih berkesan dalam mengurangkan tenaga kinetik berbanding dengan blok bersisi lurus. Dengan ini blok berlengkung boleh menghasilkan keadaan aliran optimum yang boleh mengurangkan penghakisan dasar saluran serta keperluan struktur yang lebih ekonomik.

ABSTRACT

Experimental evaluation of the effects of relative size, curvature and location of curved floor baffle blocks in the dissipation of energy and control of hydraulic jump is presented. The flow over floor blocks with curved upstream edges (in plan) was described by a set of dimensionless ratios using dimensional analysis techniques. The solution was evaluated in the laboratory with respect to measurable elements of the flow. The results have indicated that, for all flow conditions, the curved blocks are generally more effective in lowering the downstream kinetic energy than regular straight edges blocks; thereby, creating optimum flow conditions having lower capacity for erosion of the downstream channel bed together with economy in structural requirements.

Keywords: hydraulic energy dissipation, hydraulic-jump control, curved baffles

INTRODUCTION

Energy dissipation at locations where water is discharged through gates or over spillway crests is generally accomplished by causing a hydraulic jump to be formed in stilling basin. Certain structural arrangements of obstructions, including floor blocks, permit the realization of economic benefits through a reduction in the size of the basin and favorable flow conditions having a capacity for erosion of channel downstream to a minimum. Based upon basic principles of hydraulics, it is reasonable to state that with curved blocks one should expect, as a result of more eddies and turbulence, more dissipation of surplus energy with a shorter distance of structure.

All of the available evaluations of floor blocks stemmed from experimental and field observations made on regular (straight-edged) blocks. Such previous studies include those of Forster and Skrinde (1950), Rajaratnan (1964), Pillai and Unny (1964), Basco and Adams (1971) and Mirajgaoker (1967).

No attempts have been made using floor baffle blocks with curved upstream edges such as those proposed in this study except that of El-Gawhary *et al.* (1986) who experimented in a small laboratory flume a circular curved end sill of specified diameter and height with narrow range of discharges. Another case that could be mentioned is that of floor blocks with circular face, concaved vertically, used in the stilling basin of Pit River Hydroelectric Project (U.S.A.), as reported by Murthy and Divatia (1982).

ANALYSIS OF THE PROBLEM

A study of the conditions of flow with curved floor blocks reveals the problem to be a consideration of the following variables:

$$f_1\ (Y_1, V_1, Y_2, Y_2', V_2', r, x, h, s, w, \rho, \mu, \gamma) = 0 \qquad (1)$$

in which ρ and γ are the mass and weight density of liquid, respectively; and m denotes the fluid viscosity. Schematic illustration of the remaining symbols is given in *Fig. (1)*. It should be noted that the thickness of baffles, t, was kept constant at one value which was equivalent to the height of models, h, used.

By the Pi-Theorem and with the selection of V_2', Y_2' and ρ as repeating variables, and after rearranging terms, the problem reduces to:

$$f_2\ (F_2', F_1, Re_2, Y_2/Y_1, Y_1/Y_2', r/h, x/Y_2, h/Y_1, s/h, w/h) = 0 \qquad (2)$$

where F_1 and F_2' denote the Froude number upstream and after the forced hydraulic jump, respectively; and Re_2 is the Reynolds number after the jump.

The solution to the problem is extremely complex and a complete evaluation would be impractical. If one assumes that the force of fluid viscosity is insignificant as compared to those of inertia, the Reynolds number, Re_2, could be eliminated. Also, it could easily be shown, Chow (1959), that for a normal jump the ratio Y_2/Y_1 is functionally related to F_1. Then, the factor Y_2/Y_1 in the Eq. (2) can be eliminated. Further simplification of the problem could be achieved by stating that:

$$F_2'^2 = (q^2/g)\ (Y_2'^3) \qquad (3)$$

also, $$F_1^2 = (q^2/g)\ (Y_1^3) \qquad (4)$$

in which q is the flow discharge per unit width. Combining Eqs. (3) and (4), the following expression is obtained:

$$F_2'^2 = F_1^2\ (Y_1/Y_2')^3 \qquad (5)$$

The above equation shows that:

$$F_2' = f_3 (F_1, Y_1/Y_2') \quad (6)$$

which indicates that the factor Y_1/Y_2' could be eliminated.

According to the definition of blockage ratio which could be denoted by η, as reported by Ranga Raju *et al.*(1980), one can state that:

$$\eta = f_4 (w/h, s/h) \quad (7)$$

Based upon Eq. (7), if one considers η and w/h as an independent parameters in the functional relationship relating the problem of flow with curved floor blocks, the term s/h could be eliminated.

The process of elimination mentioned above permits the problem to be restated as:

$$f_5 (F_2', F_1, r/h, x/Y_2, h/Y_1, \eta, w/h) = 0 \quad (8)$$

Then, adopting a constant value of 0.5 for the parameter η, as recommended by Elevatorsky (1959), and, also, for a given baffle shape Eq. (8) may be reduced to:

$$f_6 (F_2', F_1, r/h, x/Y_2, h/Y_1, w/h) = 0 \quad (9)$$

The solution illustrated in Eq. (9) is to be investigated in the laboratory with respect to measurable elements of the flow; thereby, rendering the results readily available for standardization and general evaluation of the effectiveness of the curved floor blocks.

EQUIPMENT AND PROCEDURES

The laboratory flume used in this study consisted of truss supported channel which was 20 m long, 0.9 m wide and 0.6 m in depth. Water was supplied from a sump by centrifugal pump and flowed over a calibrated v-notch weir. A sharp edged sluice gate provided a means of obtaining and controlling supercritical flow with various values of Froude number. The downstream depth was regulated by means of a flap gate installed at the end of the flume.

The laboratory equipment consisted of the basic facility (the flume) and devices to measure the discharges, depths and velocities of flows. The baffle blocks were made of teakwood and fastened to the false floor of the flume by screws. Four groups of baffle blocks models were used in carrying out the experimental works. Every group was divided into subgroups which had a different radius of curvature and, therefore, different curvature ratio (radius-height ratio, r/h). Dimensions of models used in the experiments and their designations are given in Table (1).

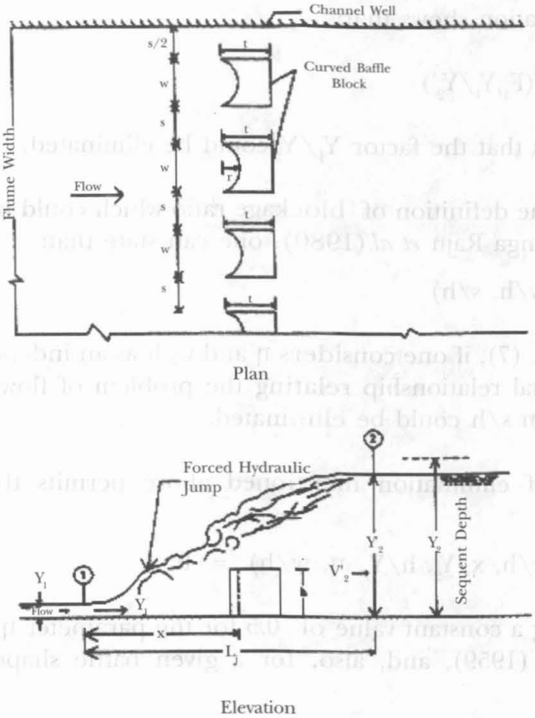

Fig 1. Definition sketch for forced hydraulic jump with curved baffle blocks

TABLE 1
Characteristics of models tested

Group Designation	Sub Group Designation (Model No.)	Dimensions (cm) Height	Width	Thickness	$\frac{r}{h}$
A	1	4.5	4.5	4.5	Straight Edge
	2	–	–	–	0.4
	3	–	–	–	0.6
	4	–	–	–	0.8
B	1	4.5	9.0	4.5	Straight Edge
	2	–	–	–	0.4
	3	–	–	–	0.6
	4	–	–	–	0.8
C	1	2.3	4.5	2.3	Straight Edge
	2	–	–	–	0.4
	3	–	–	–	0.6
D	1	5.0	5.0	5.0	Straight Edge
	2	–	–	–	0.6
	3	–	–	–	0.8

The experimental works could be divided into fourteen series, each consisted of different models and/or flow conditions. A summary of all experimental series is given in Table (2).

RESULTS AND DISCUSSION

Since the primary purpose of dissipating energy in stilling basin is to create flow conditions having minimum capacity for erosion of channels downstream, it would be logical to adopt the downstream Froude number, F_2', as the dimensionless parameter used as a criterion in assessing the hydraulic performance of stilling basins with curved baffles.

TABLE 2
Summary of experimental runs taken

Series Runs	Group of Models	Flow Parameters h/Y1	F1	x/Y2	Purpose
1	A	2.5	4.0, 4.5, 5.0 5.5, 6.0, 6.5, 7.0	1.30	To show the effect of (r/h) on Residual Kinetic Energy
2	A	3.0	–	–	–
3	A	2.5	5.0	1.30, 2.10, 2.99, 3.83, 4.67, 5.52	To show the effec of (x/Y2) on Residual Kinetic Energy
4	A	3.0	6.0	1.30, 2.13, 2.97 3.80, 4.63, 5.47	–
5	B	2.5	4.0, 4.5, 5.50, 5.5, 6.0, 6.5, 7.0	1.30	To show the effect of (r/h) on Residual Kinetic Energy
6	B	3.0	–	–	–
7	B	2.5	5.0	1.30, 2.14, 2.99, 3.83, 4.67, 5.52	To show the effect of (x/Y2) on Residual Kinetic Energy
8	B	3.0	6.0	1.30, 2.13, 2.97, 3.80, 4.63, 5.47	–
9	C	1.5	5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0	1.30	To show the effect of (r/h) on Residual Kinetic Energy
10	C	2.0	–	–	–
11	C	2.5	–	–	–
12	C	3.0	5.0, 6.0, 7.0, 7.8, 8.0, 9.0, 10.0	–	–
13	C	2.5	6.0	1.30, 2.24, 3.10, 4.13, 5.00	To show the effect of (x/Y2) on Residual Kinetic Energy
14	D	2.5	4.5	–	–

The results of this study are presented in the form of dimensionless plots which show the variation of variables developed through the dimensional analysis. The plots are presented in four types. Four typical plots, one for each type, are shown in *Figs. (2), (3), (4) and (5)*. It should be noted that the observed variation of F_2' for straight edge blocks with respect to the other ratios has been drawn on each plot to show the comparison with experimental data of curved blocks.

The resultant effect of the curvature ratio, r/h, on performance is illustrated in *Fig. (2)*. The figure reveals that, for all flow conditions, the curved baffles are generally more effective in lowering the downstream kinetic energy as compared to that of straight baffles. In addition, the figure illustrates that as the curvature ratio increases the amount of energy dissipation through the hydraulic jump increases. The increases in energy dissipation with curved baffles could be attributed to the fact that with curved baffles, the supercritical jet, issuing in a shooting state through gate or over spillway crests, will strike the stationary curved face of blocks and be diverted with a velocity component in the opposite direction of flow. This splitting and interaction within the upstream curved region of baffles, augmented by a corresponding excessive localized eddies and turbulence due to rolling of fluid masses, will cause a

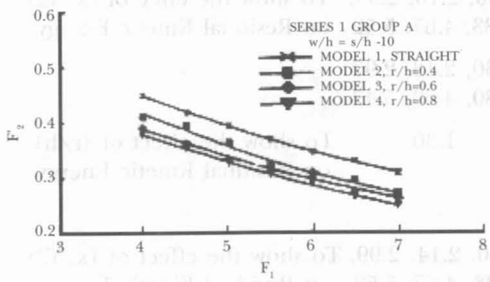

Fig 2. Effect of curvature ratio on residual kinetic energy

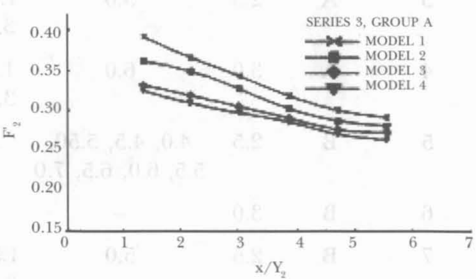

Fig 3. Variation of downstream froude number with location ratio (For F1 = 5.0)

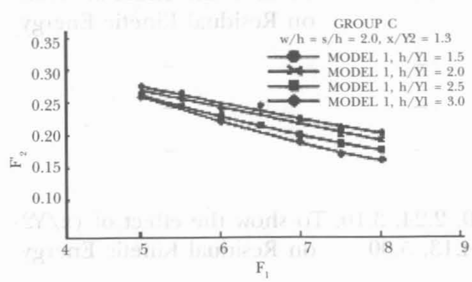

Fig 4. Effect of height ratio on residual kinetic energy

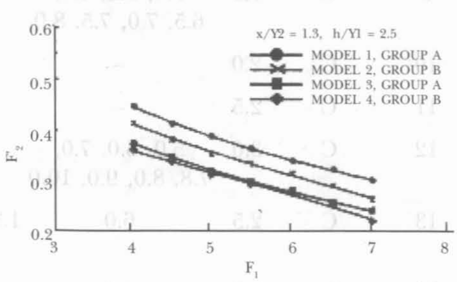

Fig 5. Effect of width ratio on residual kinetic energy

larger energy dissipation with curved baffles compared to that of straight baffles. Furthermore, as the curvature ratio increases, the region and the strength of rolling and interaction activities will increase and thus a further reduction in residual energy amounts after the jump. With the curvature ratio of 0.6, the largest additional dissipation of 33.3% was achieved with model no. 3 of group C tested under the following flow conditions: upstream Froude number "F_1" = 10.0, height ratio "h/Y_1" = 3.0 and location ratio "x/Y_2" = 1.3.

The effect of location ratio, x/Y_2, on the variation of F_2', as illustrated in *Fig. (3)*, decreases as the location ratio increases as would normally be expected from well known basics used in the design of stilling basins. The continuity and energy principles imply that for a given discharge, reduction in water depth leads to a corresponding increase in average velocity and vice-versa. The behaviour of flow with baffle blocks along the various locations is a combination of these two phenomena. The analysis of experimental data indicates that the minimum value of Y_2' occurs with baffles at a location of 1.3 Y_2 and then increases with the increase of x/Y_2. With this respect, it is worth noting that visual observations during experiments illustrated that better stability and control of hydraulic jump was achieved at location ratio of 1.3 for both straight and curved baffles.

The effect of the height ratio, h/Y_1, on performance is shown in *Fig. (4)*, which reveals that as h/Y_1 increases the residual kinetic energy tends to decrease. This increase in kinetic energy dissipation is achieved, for a given baffle height, because of a decrease in Y_1 and accordingly a stronger shooting for a given flowrate with a consequent higher velocity and loss of energy due to rolling and turbulence. The data analysis indicates that 36% additional dissipation of kinetic energy would be attained with an increase in value of h/Y_1 from 1.5 to 3.0 for model no. 3 of group C and 27% for model no. 1 of group C (both models were tested under the same flow condition with F_1 = 8.0).

To illustrate the effect of width ratio, w/h, on performance, utilizing the results of data analysis, *Fig. (5)* is drawn. It seems from this figure that the downstream kinetic energy tends to decrease as w/h increases. This finding is both logical and expected, especially for curved baffles, since an increase in the width of baffles, for a given curvature, the upstream curved flow region increases with more interaction processes between fluid masses, i.e. more eddies and turbulence, with a resultant increase in the amount of energy dissipation. Another contributing effect stemming from the fact that using a larger width of blocks will provide a larger surface area to be in contact with flow and thus a larger dissipation in kinetic energy due to skin friction.

The upper and the lower amounts of the % additional dissipation of kinetic energy achieved with curved floor baffle blocks as compared to straight edges blocks are given in Table (3). For each subgroup of models the reduction of kinetic energy is related to arrangements of models and/or flow conditions.

TABLE 3
Percent additional dissipation of kinetic energy for models used

Group of Models	Subgroup Designation (Model No)	% Additional Dissipation	
		Minimum	Maximum
A	1	Straight Edge	
	2	3.2	14.3
	3	6.5	19.6
	4	10.6	25.7
B	1	Straight Edge	
	2	3.2	8.0
	3	4.2	12.5
	4	9.1	22.1
C	1	Straight Edge	
	2	7.3	22.5
	3	12.2	33.3
D	1	Straight Edge	
	2	1.6	7.8
	3	8.7	16.5

CONCLUSION

Utilizing dimensional analysis techniques a formulation was developed describing the flow over curved baffle blocks. The solution was evaluated in laboratory where fourteen models of curved blocks having different sizes, curvatures and arrangements were tested under different flow conditions.

The experimental evaluation regarding the hydraulic performance of stilling basin with curved baffle blocks in comparison with regular straight blocks has indicated that, for all flow conditions, the curved blocks are 3.2%-33.3% more effective in dissipating the excessive kinetic energy of the flow. In addition, the curved blocks provided better stability to the hydraulic jump.

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APPENDIX – NOTATION

F_1 = upstream Froude number
F_2' = Froude number after the forced jump
f = function
h = height of baffle blocks
q = flow discharge per unit width of the flume
r = radius of curvature of a curved baffle blocks
R_{e2} = Reynolds number after the forced jump
s = spacing between baffle blocks
V_1 = upstream velocity (prejump velocity)
V_2 = velocity corresponding to sequent depth of a free jump
V_2' = velocity corresponding to downstream depth after the forced jump
w = width of baffle blocks
x = horizontal distance from the toe of jump to front of baffle blocks
Y_1 = upstream water depth (prejump depth)
Y_2 = sequent depth
Y_2' = downstream water depth after the forced jump
η = blockage ratio
μ = dynamic viscosity
ρ = mass density
γ = weight density