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Effect of End Step Shape in the Performance of Stilling Basins Downstream Radial Gates

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Stilling basins are in common use when designing heading-up hydraulic structures such as barrages, dams, weirs …etc. This research paper investigates the effect of stilling basin shapes with different heights of end step on the characteristics of submerged hydraulic jump and the energy dissipation downstream the radial gate. Generally, this research investigate the main characteristics and parameters of the submerged hydraulic jump such as; the vertical velocity distribution, the near bed velocity decay along stilling basin, and the stability of bed protection downstream the stilling basin. In the present research paper, these characteristics will be tested in a pool-type stilling basin with end steps downstream (DS) the radial gate of new spillway of Assuit Barrages. The experimental program was conducted on a re-circulating flume with 1.0 m wide, 26.0 m long and 1.2 m deep, with discharges range from 40 to 190 l/s. Statistical equation was developed to correlate the length of submerged jump with the other independent parameters. Finally, clear matching of results from the length of jump and velocity analysis was obtained.

Keywords: Stilling basin; end sill; radial gate; submerged hydraulic jump; submerged ratio.

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1. INTRODUCTION

In order to reduce the excessive kinetic energy of flowing water downstream of the structures such as spillways, sluices, pipe outlets, etc., stilling basins with appurtenances are used [1]. The flat apron provided with positive multi-steps at the end of apron creates a smaller length of relative submerged hydraulic jump and also lowest values of maximum relative velocity and shear Reynolds number. The flat apron produces good results by decreasing the length of submerged jump compared to sloped or sudden drop shape below the radial gate [2,3] studied the submerged flow characteristics in a pool-types stilling basin with multi-end steps. Alikhani et al. [4] studied the hydraulic jump in stilling basin with Vertical End Sill. Tiwari et al. [5] studied experimentally the effect of sill downstream the stilling basins for pipe outlet. It is due to fact that dissipation of energy in a basin having sloping end sill is more as compared to other shape of end sill tested, because slope of the end sill reduces the momentum of water thereby reduction in energy is promoted. Similar observation was also reported by some past investigators [6-9] analyzed the submerged hydraulic jump formed in a radial stilling basin provided with sudden drop theoretically and experimentally. They also investigated the effects of various parameters, on the characteristics of the formed jump, such as submergence, height of vertical drop, the position of the drop measured from the beginning of the basin and supercritical flow Froude number. Tiwari et al. [10] investigated the effect of end sill on the performance of stilling basin models for a non circular pipe outlet. Chen et al. [11] investigated the flow structure of vertical and horizontal planes in a stilling basin with five parallel offset jets in a twin-layer configuration for four offset ratios. Pagliara and Palermo [12] studied the effect of stilling basin geometry on the dissipative process in the presence of block ramps.

The present study aims to investigate the effect of end step of stilling basin's shape on the length of submerged jumps, the near bed velocity along stilling basin and the energy losses downstream the radial gate. Moreover, this study will clarify the stability bed protection downstream the stilling basin for typical cases for all studied shapes of stilling basin.

2. EXPERIMENTAL WORK

The experiments were conducted using double sided glass rectangular channel (flume) with 1.0 m wide, 26.0 m long and 1.2 m deep as shown in Fig. 1. Radial gate with radius of 57.1 cm was constructed at a distance of about 12.0 m downstream the flume inlet. The stilling basin was provided with two half-piers (9.5 cm thick each) symmetrically installed on both wall sides. The stilling basin has total length of 420 cm with end step was used. There were four end step were used has the same height with different radii of 0.cm, 0.5 cm, 1.0 cm and 1.7 cm. Also, the rip rap with mean grain size D_{50} of 2.6cm was used to aid in the stabilization of bed after stilling basin. The flume is provided with a re-circulating system using two centrifugal pumps, with capacities 500 and 150 l/s which were connected with two pipelines 16 and 10 inch, respectively. Fig. 1 shows the different components of the used model.

Fig. 1. The used model in 2D flume

3. MEASUREMENTS

An electromagnetic flow-meter was used for measuring the discharge during the tests. The flow velocity profiles were measured at different cross sections along the stilling basin using an electromagnetic current-meter type EMS, manufactured by Delft Hydraulics, Holland. Moreover, an electromagnetic current-meter was used to allocate the length of submerged jump by tracing the positive and negative values of the flow velocity on the water surface layer. The zero velocity point represents the length of the submerged hydraulic jump to the radial gate. Different shapes of end step were experimentally tested in 2D flume as shown in Fig. 1. For each end step shape, twelve different flow conditions were tested. Table 1 provides typical conditions used in experimental work for this research paper. The discharge was changed from 40 to 190 l/s, to cover the different submergence and Froude numbers for each shape. The flow velocity was measured at ten cross sections along the stilling basin as shown in Fig. 2. The first cross section was located at distance of 1.0

m downstream the gate. The velocity profiles were measured at five point depth at relative distances from the surface 0.2, 0.4, 0.6, 0.8 and 0.9 of the total water depth.

4. TEST PROGRAM

For each end step shape there were twelve discharges with different head difference were used as shown in Table 1. The upstream water depth was kept constant with all test runs to simulate the operational conditions of grand barrages along the Nile River. Different end step radius was used with the same height. The thickness of the flow jet at vena contracta downstream the radial gate and the backup water depth just downstream the radial gate were defined for each test run.

5. RESULTS AND ANALYSIS

The analysis procedure was categorized to investigate length of submerged hydraulic jump, the Energy dissipation, near bed velocity and the stability of bed protection downstream the stilling basin. The effect of end step shape on the velocity distribution at different cross sections along channel was also presented.

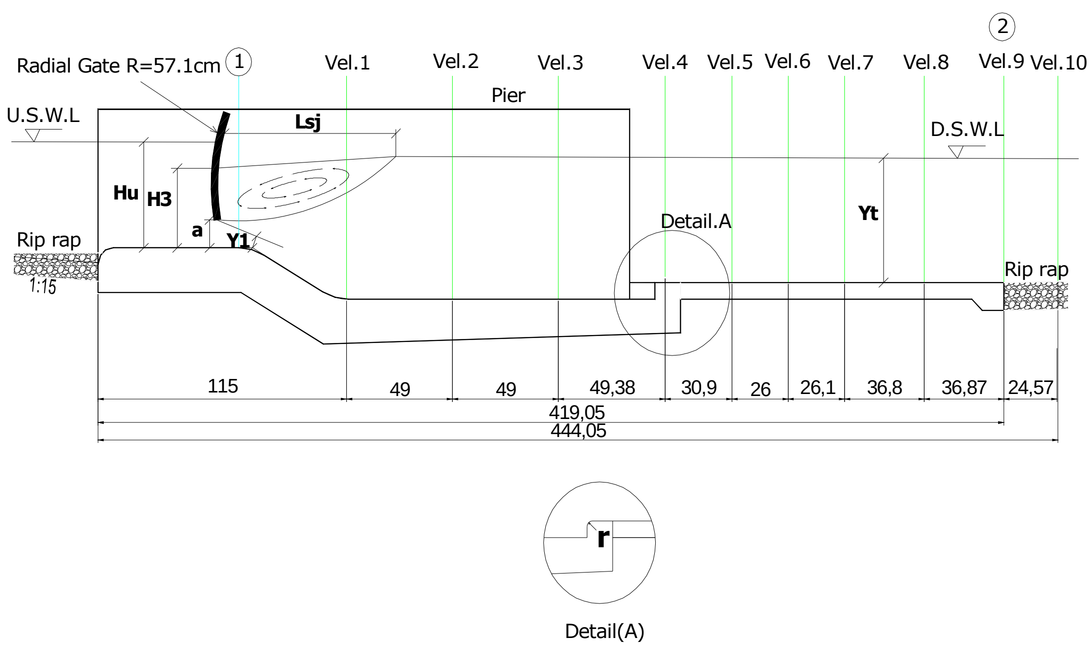

Fig. 2. Definition sketch of the experimental mode and location of c.s. velocity

Table 1. The experimental program

Run No.	Disch. Q (L/s)	Head diff. (h) cm	Depth of vena contracta (y_1) cm	Y_3 cm	End step (I) r	End step (I) Shape	End step (II) r	End step (II) Shape	End step (III) r	End step (III) Shape	End step (IV) r	End step (IV) Shape
1	247.40	7.5	19.0	58.0	0		0.5	r=0.5cm	1		1.7	
2	179.37	12.0	11.5	52.0								
3	136.10	15.7	8.0	48.0								
4	99.00	19.8	5.5	42.0								
5	74.20	23.1	4.0	40.0								
6	49.50	27.0	2.0	37.0						r=1cm		
7	142.2	12.0	9.5	51.0								r=1.7cm
8	92.80	15.7	5.0	47.0								
9	49.50	19.8	2.0	44.0								
10	136.10	14.1	8.5	46.0								
11	99.00	18.1	5.5	41.0								
12	74.20	21.4	3.0	38.0								

5.1 Length of Submerged Hydraulic Jump

Fig. 3 shows the relation between the relative length of submerged jump (L_{sj}/y_1) and the Froude number Fr1for different radius of the end step of cases I, II, III and IV. It can be observed that as Froude number F_{r1} increased the relative length of submerged jump (L_{sj}/y_1) increased. It is obvious that shape V with end step radius of 1.7cm produces a highest value of L_{sj}/y_1 compared to the other shapes. On the other hand, shape I with end step radius of zero cm produces small relative length of submerged jump comparable to other shapes. This means that the bigger end step radius results in bigger relative lengths of submerged hydraulic jump. The multiple linear regressions were applied to predict a statistical equation that correlates L_{sj}/y_1 with other Froude number F_{r1} which represented by equation 1.

$$L_{sj}/y_1 = 11.43\ (F_{r1}) + 9.1,\ \text{with } R^2=0.96 \qquad (1)$$

Where: L_{sj} is the length of hydraulic jump, and y_1 is the depth of Vena Contracta.

Fig. 4 shows the relation between the relative length of submerged jump (L_{sj}/y_1) and the submergence ratio (S= H_3/y_1; H_3 is the backup water depth, McCorquodale et al. [13] for different radius of end step. It is found that as the submergence ration increased the relative length of submerged jump increased. This may refer to that as the submergence ratio increases the efflux under gate increases and that leads to generate more turbulence distance along the apron length of the barrage.

The multiple linear regressions were applied to predict a statistical equation that correlates L_{sj}/y_1 with the submergence ratio S=H3/y1 which represented by equation 2.

$$L_{sj}/y_1 = 19.6\ (H_3/y_1) - 19.87,\ \text{with } R^2=0.97 \qquad (2)$$

Moreover, the multiple linear regressions were applied to predict a statistical equation that correlates L_{sj}/y_1 with other independent parameters (F_{r1}, $S=H_3/y_1$, r/z,). Where F_{r1} is the Froude number at vena contracta, $S=H_3/y_1$ is the submergence ratio and r/z is the relative radius of end step and z is the step height. Equation 3 represents the correlation between L_{sj}/y_1 and the other independent parameters.

$$L_{sj}/y_1 = 7.11(Fr1) + 8.27(S) - 24.66(r/z),\ \text{with } R^2 = 0.985 \qquad (3)$$

5.2 Energy Dissipation

The energy loss was calculated between the cross section 1 which located downstream the radial gate at the location of vena contracta and the cross section 2 at the end of the stilling basin

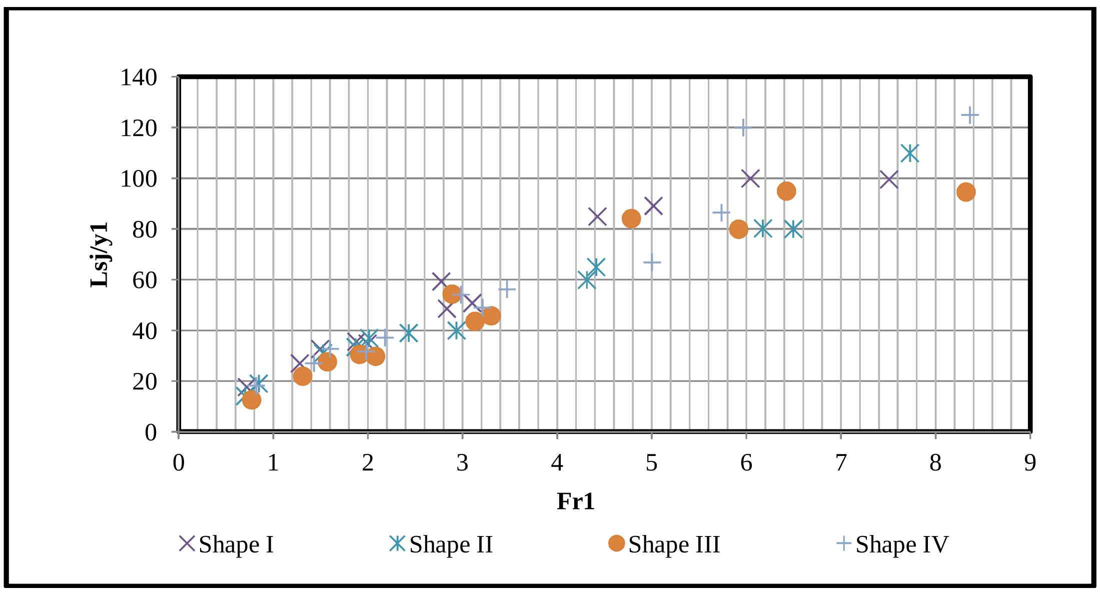

Fig. 3. The relation between L_{sj}/y_1 and F_{r1} for different radius of end step

through the hydraulic jump is obtained by applying the energy equation between upstream the stilling basin and downstream the end step as follow, The energy losses at section 1 (at vena contracta) was calculated by using the following formula:

$$E_1 = \frac{H3}{Hc} + \frac{(Fr1)^2}{2} \quad (4)$$

Where: E_1 is the energy at section 1(at vena contracta), H3 is the back up water depth (water depth just downstream the radial gate), Hc is the height of the jet at vena contracta, and Fr1 is the Froude No. at vena contracta). Also, the total energy losses between section 1 and section 2 were calculated by using the following formula Rajaratnam [14]:

$$E_L = \frac{H3}{Hc} - \left(\frac{1+S_t}{2}\right) \times \left(\sqrt{\left(1+8(Fr1)^2\right)} - 1\right) + \frac{(Fr1)^2}{2}\left(1 - \frac{4}{(1+S_t)^2 \times \left(\sqrt{\left(1+8(Fr1)^2\right)} - 1\right)^2}\right) \quad (5)$$

Where: S_t is the submergence ratio $(y_t-y_2)/y_2$, y_t is tail water depth, and y_2 is sequent water depth of the classical hydraulic jump

In addition, the relative energy losses E_L/E_1 *100 was also calculated in order to check the efficiency of the design of new spillway stilling basin.

$$\Delta E = y_1 + \frac{v_1^2}{2g} - y_2 - \frac{v_2^2}{2g} \quad (6)$$

Where: v_1 is the velocity pre hydraulic jump, and v_2 is the velocity after hydraulic jump

Fig. 5 shows the relation between the Fraud's number and the relative energy loss. The predicted the relative energy loss can be obtained from the following equation:

$$\frac{\Delta E}{E_1} = 25.2 * F_{r1}^{0.54} \quad \text{, with} \quad R^2=0.98 \quad (7)$$

The relative energy decreases by about 40% with increasing the Froude number by about 50%.

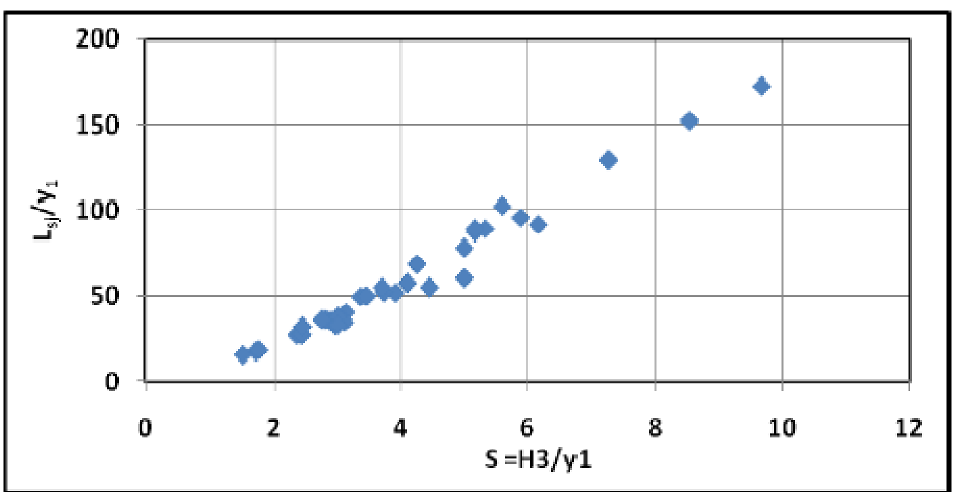

Fig. 4. The relation between L_{sj}/y_1 and $S=H_3/y_1$ for different radius of end step

5.3 Stability of Bed Protection

The flow phenomena require that certain care is applied to determine stability of rip rap particles used to prevent scouring downstream of the stilling basin. The stability coefficient was formulated by the following Römisch et al. [15].

$$B' = \frac{V_{bed}(1 + SDV)}{\sqrt{d_{50} \cdot g \cdot \Delta'}} \qquad (8)$$

Where B' is the stability coefficient, V_{bed} is the bottom velocity, d50 is the mean size of rip rap, Δ' is relative density of the submerged rip rap, and SDV is the standard deviation of the velocity fluctuations. Shape I, II, and V give smaller value of stability coefficient for different Froude number than IV and V as shown in Fig. 6.

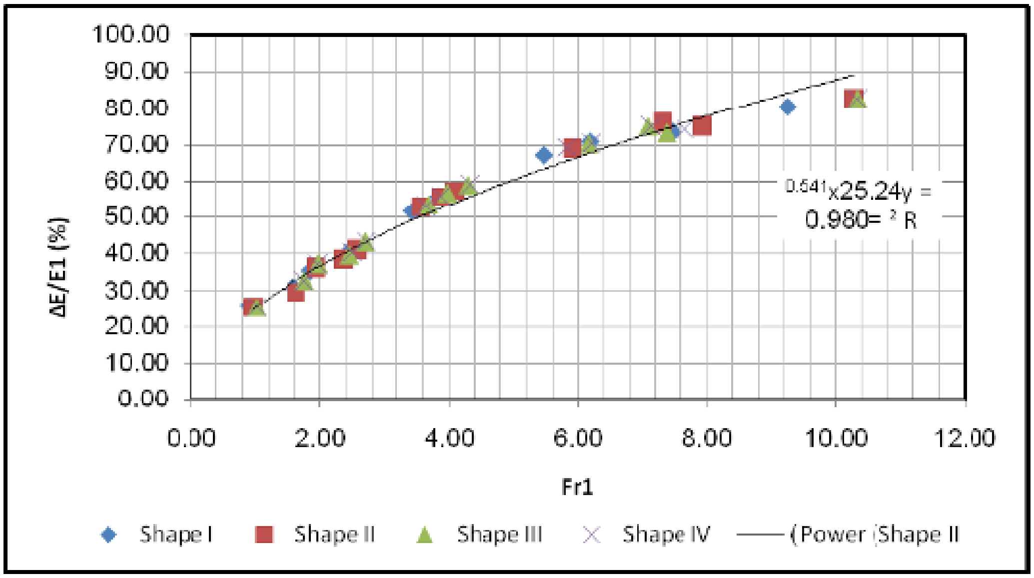

Fig. 5. The relation between the relative energy loss and the Froude's number

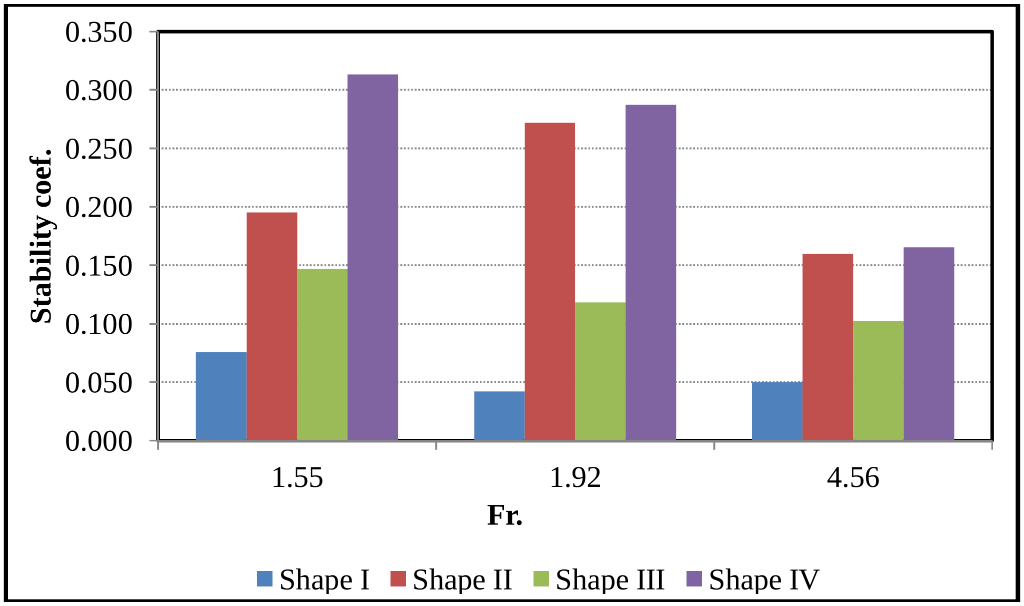

Fig. 6. The stability coefficient for different Froude number

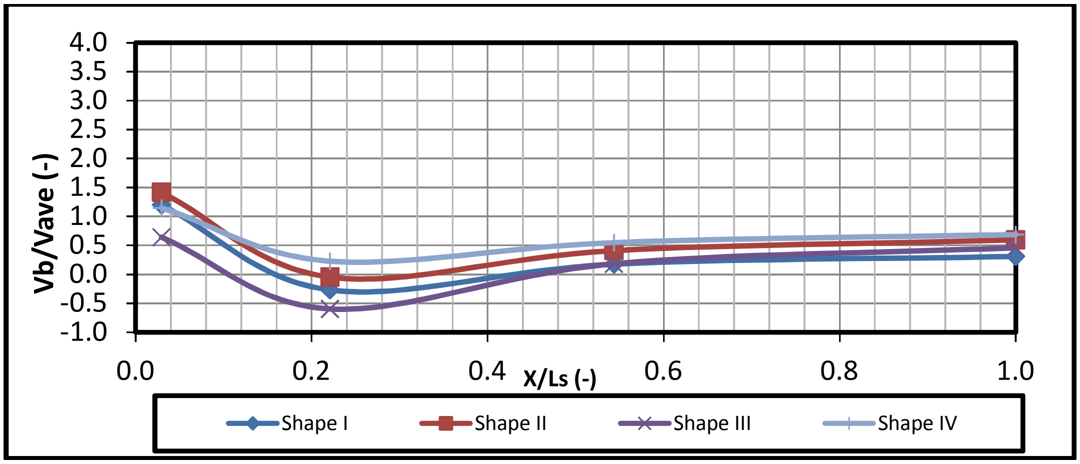

Fig. 7. Relationship between v_{bed}/v_1 and X/Lb for different shape at Fr = 6.0

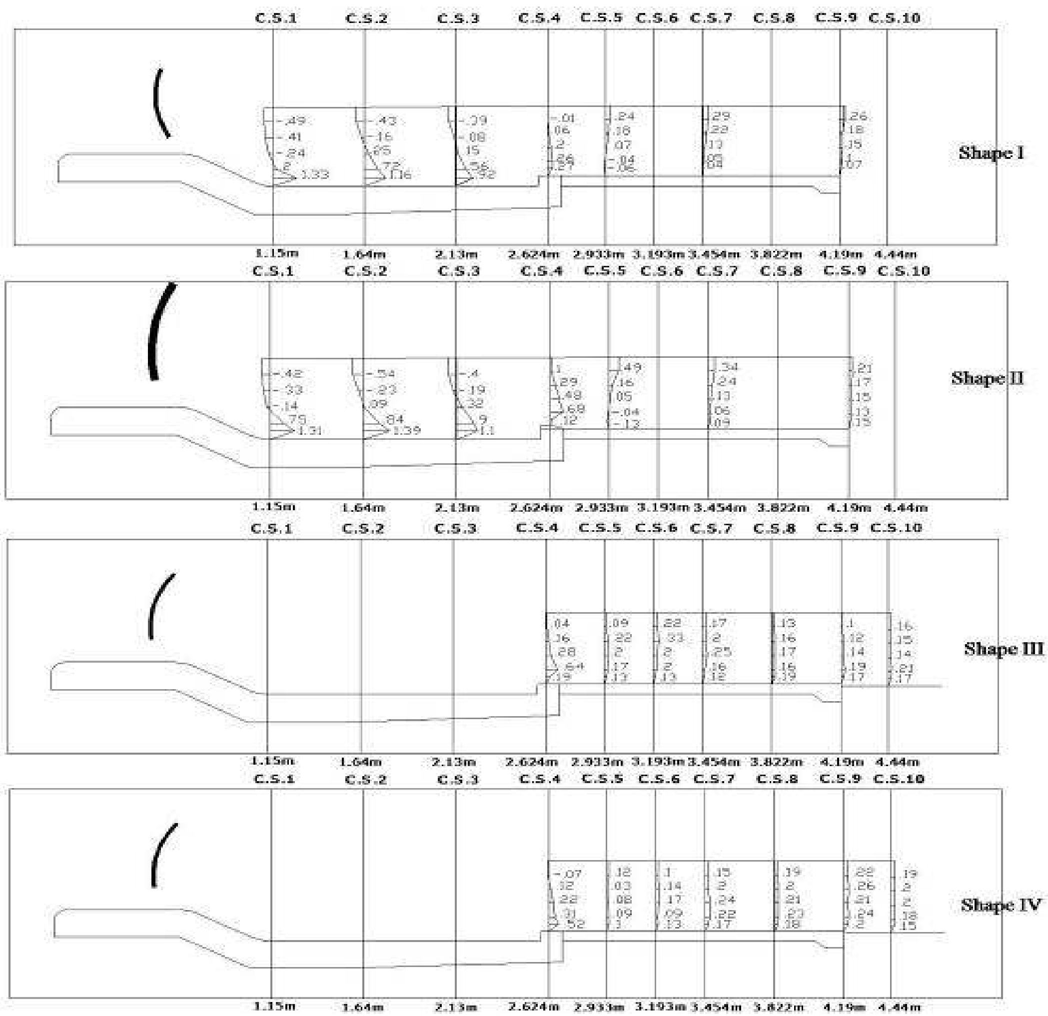

Fig. 8. The velocity profile for different shapes

6. THE VELOCITY DISTRIBUTION ALONG THE CHANNEL

To define the influence of end sill shape under the radial gate in stilling basin on the longitudinal velocity distribution at the mid channel; above Figs. 7, and 8 were plotted under constant Froude number of 6.0. The velocity distributions at different locations along the stilling basin were plotted in a dimensionless form (V_b/V_{ave}) by dividing the measured bottom velocity "Vb" at each point depth by "Vave" average velocity. Fig. 7 indicates the relation between (X/Ls) versus (V_b/V_{ave}). Shape I gives the smallest bed velocity at the end of stilling basin. Atypical case of velocity profiles for different shapes I, II, III, and IV at Fr =5.5 is shown in Fig. 8. The x-axis shows the relative velocities (V/V_{ave}) in which V is velocity at different relative heights (Y) over the bed), and at nine-sections over the sluiceway apron and beyond it (sec. 1 to sec. 9). The y-axis shows the relative depth of the current-meter, started from the water surface, on the vertical directions (Y =0.2, 0.4, 0.6, 0.8y). From these profiles, it was found that the wall jet in case of both shapes I vanished early at the end of stilling basin (sec. 4), and normal well distribution of the velocity profiles at different sections was obtained compared to the other shapes II, III, and IV. The wall jet of submerged jump may be extended to or beyond the end of apron that means longer lengths of submerged jump will be obtained. Shape IV creates high values of near bed velocity which are considered as greatly harmful to the movable bed downstream of the regulator stilling basin.

7. CONCLUSIONS

Within the experimental set-up and limitations, the analysis and discussions presented above highlighted the following conclusions:

1. The statistical equation, predicting the length of submerged hydraulic jump, agrees well with the experimental measured data.
2. The relative energy decreases by about 40% for increasing the Froude number by about 50%.
3. The relative energy near the bed increases by about 25% for increasing the Froude number by about 50%.
4. The minimum values of the Stability of bed protection were observed when the pool of the stilling basin had square and 1.0cm curvature of end step.

ETHICAL APPROVAL

All authors hereby declare that all experiments have been examined and approved by the appropriate ethics committee and have therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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