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Effect of different screen areas on the submerged hydraulic jump characteristics

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ABSTRACT

The hydraulic jump is a natural phenomenon occurs in steep waterways and behind the heading up structures. The main benefit of the hydraulic jump is dissipating the excessive kinetic energy. Tools such as sill, baffle blocks… etc. are used to maximize the energy loss through the hydraulic jump. In the present study, screens with a constant height and width are located downstream the gate at a constant relative distance and examined under the different conditions of submerged hydraulic jump. Screens with different relative holes area are tested to select the best screen relative area. Screen with relative holes area of 0.285 had a maximum energy loss and shortest length with a minimum tail water depth of the submerged hydraulic jump. The theoretical derived equation of the relative depth of the hydraulic jump had a higher asymmetric scatter with the experimental results around the line of equality; however, an acceptable agreement was present when a correction factor was used.
Keywords: screen, submerged hydraulic jump, energy dissipation, sudden expanding stilling basin, supercritical flow

1.INTRODUCTION

In hydraulic structures such as barrages, dams and drop structures stilling basins are designed to resist the hydrodynamics forces due to the high velocity through and downstream stilling basins. The main requirement demanded of a stilling basin is the high energy dissipation. This can be attained by expansions France (1981) [1], steps Bejestan and Neisi (2009) [2]; Negm et al. (2003) [3]; Negm et al. (2002) [4] roughened bed Bejestan and Neisi (2009) [2]….etc. For the necessary of the national development and the increasing of cultivated area, the capacity of the existing canals must increase, consequently the water structures particularly the heading up structures have to check under the application discharges. Sometimes the apron length of the stilling basin is not enough to resist and capable to carry out its duties in maintaining the integrity of a structural safety.

The simple method to solve this problem is to fix or built additional tools to reduce the length of the hydraulic jump. A screen with a certain specification can be used for this purpose. Screens are widely used in prismatic channels stilling basins to accelerate the energy dissipation and minimize the length and sequent depth of the hydraulic jump. Abbaspour et al. (2019) [5] examined the hydraulic jump characteristics on the reverse bed with porous screens. The study results showed that the adverse stilling basin with screens having the ability to dissipate energy greater than that corresponding stilling basin without screen.Fathi-Moghadam et al. (2017) [6] used a perforated sill to control the hydraulic jump. The results were presented in the form of mathematical models to estimate the sill height, sill position and basin length. The screen porosity was studied by Daneshfaraz et al. (2019) [7], Abbaspour et al. (2019) [5] and Sadeghfam et al. (2015) [8] to determine and select the best screen porosity that improve the characteristics of the hydraulic jump in the prismatic stilling basins. It was found that a screen porosity of 40% to 50% gave energy loss more than that of other porosities. Bozkus et al. (2007) [9] examined a vertical screen, while an inclined screen studied by Balkiş (2004) [10], it was found that the vertical screen more effective from the energy dissipation point of view. Bozkuş et al. (2006) [11] and Rajaratnam and Hurtig (2000) [12] investigated the energy dissipation by a triangular screen, while the square screen were studied by Abbaspour et al. (2019) [5] and circular screens and its effect on the hydraulic jump characteristics were reported by Cakir (2003) [13]. It was found that the square screens dissipate energy more than that of other shapes, this finding matched closely with Mahmoud et al. (2013) [14]. Hager (1985) [15], Bremen and Hager (1993) [16] and Bremen and Hager (1990) [17] studied the free and submerged hydraulic jump in a sudden expanding stilling basin. It was found that the hydraulic jump parameters in a sudden expanding stilling basin were improved.

No available studies focused on the characteristics of the submerged hydraulic jump enhanced by screens in a sudden expanding stilling basin. This study aims to investigate the effect of different screen holes areas on the hydraulic jump characteristics in an abrupt expansion. It also aims to build theoretical models for the phenomenon to help the designer to choose the optimum of additional accessories. The paper presents some theoretical equations for the relative energy loss. Finally, the multiple linear regressions (MLR) technique is used to model the H.J. characteristics.

2.EXPERIMENTAL SETUP

The experimental tests were carried out in a re-circulating flume of 0.30 m wide; 0.468 m deep and 15.6 m long with working section of 12.50 m (Fig. 1). A centrifugal pump lifts the water from a sump tank to the flume inlet. The discharge of the flume is measured by using a calibrated orifice meter. To adjust the required tail water depth, the tail gate is screwed gradually until the considered depth is adjusted. A point gauge was used to measure the water levels with ±0.1 mm accuracy.

Screens with a 22 cm width and 3 cm height has 24 holes with diameters 0.4, 0.6, 0.8, 1.00 and 1.2 cm with corresponding different relative holes area (Ar) 0.046, 0.103, 0.183, 0.285 and 0.411, respectively were used to identify the effect of changing of a screen passing area on the hydraulic jump characteristics (Figs. 2&3). The case of no screen is considered a reference base to check the effect of screen with different relative area on the characteristics of hydraulic jump phenomenon.

The vertical screen model was built from Perspex and was placed in a sudden expanding stilling basin with a constant expansion ratio (e=1.35) downstream the vertical gate. For each experiment, the flow rate, water surface profile and the hydraulic jump length were measured. The inflow Froude number ranged from 2.25 to 8.45 with flow rates ranged from 5.99 to 15.85 l/s to cover the different submergence ratios (S= 3, 4, 4.5). About 153 runs had been conducted including 48 runs for a sluice gate with a submerged hydraulic jump without any modifications (i.e., case of no screen) for the comparison. Various models of screen in a stilling basin were tested to investigate the effect of the submergence ratio on the hydraulic jump characteristics.

Figure 1: A general view of the flume

Figure 2: The experimental model

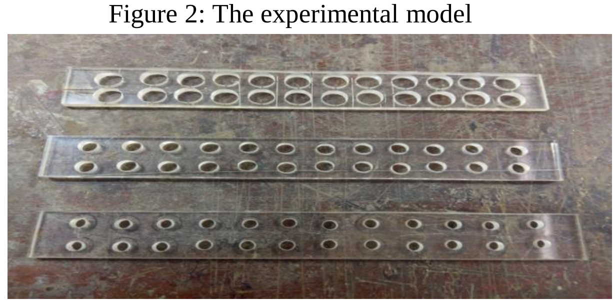


Figure 3: Sample of the tested screens

3.ENERGY EQUATION

Figure (4) represents the schematic illustration of the supercritical flow when it collides the screen forming a hydraulic jump. The energy loss between sections 1-1 and 2-2 can be obtained by applying the energy principle with assuming the energy coefficients equal unity.

$$\Delta E = E_1 - E_2 = \left(y_3 + \frac{v_1^2}{2g}\right) - \left(y_4 + \frac{v_4^2}{2g}\right) \quad (1)$$

Where;

y_3 is the back-flow depth, v_1 is the flow velocity at section 1-1 (i.e., the super critical flow velocity), and y_4 and v_4 are flow depth and velocity at section 2-2, respectively.
From a continuity equation:

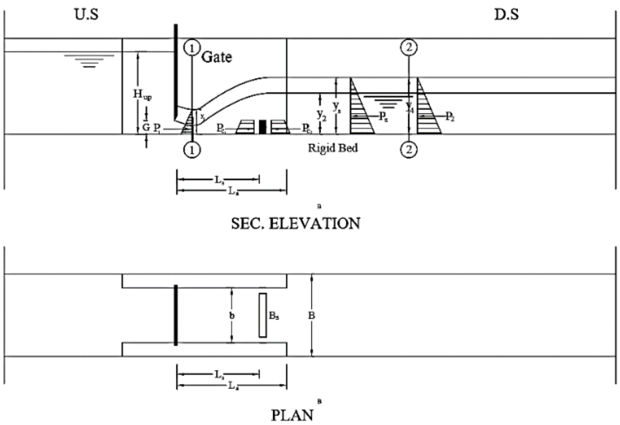


Figure 4: Schematic illustration of the submerged hydraulic jump induced by screen

$$v_4 = \frac{v_1 y_1 b}{y_4 B} \qquad (2)$$

Take $\frac{B}{b} = e$, $\frac{y_4}{y_1} = Y$, $v_4 = \frac{v_1}{Y*e}$ and $\frac{y_3}{y_1} = S$

$$E_2 = y_4 + \frac{v_1^2}{2Y^2 e^2\, g} \qquad (3)$$

$$E_1 - E_2 = y_3 + \frac{v_1^2}{2g} - y_4 - \frac{v_1^2}{2Y^2 e^2\, g} \qquad (4)$$

$$\frac{\Delta E}{E_1} = \frac{\frac{y_3}{y_1} + \frac{v_1^2}{2y_1 g} - \frac{y_4}{y_1} - \frac{v_1^2}{2Y^2 y_1 e^2\, g}}{\frac{y_3}{y_1} + \frac{v_1^2}{2y_1 g}} \qquad (5)$$

Simplifying equation (5)

$$\frac{\Delta E}{E_1} = \frac{2S + F_1^2 - 2Y - \frac{F_1^2}{Y^2 e^2}}{2S + F_1^2} \qquad (6)$$

4.THE RELATIVE DEPTH OF THE HYDRAULIC JUMP

To create a theoretical model for calculating the relative depth of the submerged hydraulic jump, the pressure–momentum relationship between sections 1-1and 2-2 have been applied.

$$P_1 + M_1 = P_2 + M_2 + 2P_s + Pc_{net} \qquad (7)$$

In which;

$P_1 = \frac{\gamma y_1^2}{2}(b)$ $at\ y_1$ (the hydrostatic pressure at the beginning of the hydraulic jump), $P_4 = \frac{\gamma y_4^2}{2}(B)$ $at\ y_4$ (the hydrostatic pressure at the end of the hydraulic jump), $P_s = \frac{\gamma y_s^2}{2}\left(\frac{B-b}{2}\right)$ (the hydrostatic pressure below one side of the contraction), $P_{c1} = \left(\frac{2\gamma h_1 - \gamma h_s}{2}\right)\left(B_s h_s - \frac{n\pi d^2}{4}\right)$ (the hydrostatic pressure before the screen), $P_{c2} = \left(\frac{2\gamma h_2 - \gamma h_s}{2}\right)\left(B_s h_s - \frac{n\pi d^2}{4}\right)$ (the hydrostatic pressure after the screen) and $Pc_{net} = (B_s h_s - \frac{n\pi d^2}{4})\gamma(h_1 - h_2)$ (the net pressure applied on screen).
Where;

h_s is the screen height, B_s is the screen width, h_1 is the water height before screen, h_2 is the water height after screen, d is the diameter of the screen holes, y_s is the water depth just after the abutments contraction, A_s is the total area of screen($A_s = B_s h_s$), A_o is the area of holes ($A_o = 0.25 n\pi D^2$) and n is the number of holes.

By substituting in the momentum equation no. (7)

$$\frac{\gamma y_3^2}{2}(b) + \rho\, Q\, v_1 = \frac{\gamma y_4^2}{2}(B) + \rho\, Q\, V_4 + 2\frac{\gamma y_s^2}{2}\left(\frac{B-b}{2}\right) + \left(B_s h_s - \frac{n\pi d^2}{4})\gamma(h_1 - h_2)\right) \qquad (8)$$

Rearrangement and simplify equation (8)

$$2F_1^2\left(1 - \frac{1}{eY}\right) = Y^2 * e + y_s^2(e-1) + (A_s - A_0)\frac{2e\Delta H}{By_1^2} - S^2 \qquad (9)$$

$$F_1^2 = \frac{Y^2 * e \; + y_s^2\,(e-1) \; + \; (A_s \; - A_0)\frac{2e\Delta H}{By_1^2} - S^2}{2(1 - \frac{1}{eY})} \qquad (10)$$

Taking $A_{net} = A_s - A_0$,

Where, $A_{net}$is the net screen area

$$F_1^2 = \frac{Y^2 * e \; + y_s^2(e-1) \; + \; (A_{net})\frac{2e\Delta H}{By_1^2} - S^2}{2(1 - \frac{1}{eY})} \qquad (11)$$

The equation no. (11) is the general equation of the submerged hydraulic jump occurred in a stilling basin provided by screen.

5.DIMENSIONAL ANALYSIS

Many of flow parameters were characterized to carry out the dimensional analysis.

$$f(B, b, B_s, L_s, G, L_a, h_s, d, n, H_{up}, y_1, y_3, y_4, L_j, v_1, g, E_1, E_2, \Delta E, \rho, \mu) = 0.0 \quad (12)$$

Where;

B is a channel width, b is a contracted width, B_s is a screen width, G is a gate opening, L_a is a length of abutment downstream the gate, h_s is a screen height, d is a screen holes diameter, n is a number of holes, H_{up} is the upstream water depth, y_1 is the initial water depth, $y_3$is the back flow depth, $y_4$is the tail water depth, L_j is the jump length, v_1 is velocity at section 1-1, g is the gravitational acceleration, E_1 is the total energy at y_1, E_2 is the total energy at y_4, ΔE is the energy loss through the hydraulic jump, ρ is the density of water and μ is the viscosity of water.

By merging the resultant dimensionless parameters;

$$f(B/y_1, b/y_1, B_s/y_1, L_s/y_1, G/y_1, L_a/y_1, h_s/y_1, d/y_1, n, H_{up}/y_1, y_3/y_1, y_4/y_1, L_j/y_1, 1/F^2, E_1/y_1, E_2/y_1, \Delta E/y_1, 1/R_n) = 0.0 \quad (13)$$

R_n has a very small effect in the open channel and it can be neglected. $1/F^2$ is replaced by F^2,from (B/y_1) and (b/y_1) yielded to $B/b=e$. From (B_s/y_1) and (b/y_1) we get the relative screen width (B_s/b). From (E_2/y_1) and (E_1/y_1) it can be obtained the efficiency of the hydraulic jump $\eta=E_2/E_1$. Subtract E_2/E_1 from unity $(1-E_2/E_1) = (E_1-E_2)/E_1=\Delta E/E_1$, the relative energy loss through the hydraulic jump, from B_s/y_1 , h_s/y_1 ,d^2/y_1^2 we can get $(y_1/B_s*y_1/h_s*d^2/y_1^2)=d^2/B_sh_s= n\pi d^2/A_s=A_{holes}/A_{screen}$, from (L_s/y_1) and (L_a/y_1)we obtained $L_s/y_1* y_1/L_b= L_s/L_b$ the relative length of the screen.

The screen height, screen position and the expansion ratio were constants through this study then;

$$\frac{l_j}{y_1}, \frac{y_4}{y_1}, \frac{\Delta E}{E_1} = f(F_1, \frac{B_s}{b}, \frac{A_s}{A_0}, S) \quad (14)$$

6.RESULTS AND DISCUSSIONS

6.1. Effect of Screen Relative Area on The Hydraulic Jump Characteristics

The hydraulic jump characteristics include the length and depth of the hydraulic jump besides the energy loss. Presence of the screen in the stilling basin divided the passing discharge to two parts. The first part is the over screen flow, while the second part is the flow through the screen itself. The discharge passing through the screen opening area depended on its area. When the passing area increases, the passing discharge through screen also increases. For the same flow conditions, the discharge above the screen reduces, thence the behavior of the hydraulic jump changes according to the over and through screen passing discharges. The effect of the screen holes relative area is analyzed when the screen fixed at l_s/l_a =0.25.

Figure (5) shows the relation between the initial Froude number F_1 and the relative energy loss through the hydraulic jump for S= 3.0 as a representative example for different screen holes relative areas of (A_o/A_s=0.046, 0.103, 0.183, 0.285, 0.411) when the screen locates at l_s/l_a =0.25. From this figure, the screen with 0.285 relative hole area gives the maximum relative energy loss. Moreover, the relative energy loss decreases as the relative hole area of screen increases. Furthermore, the no screen case gives the minimum values of the relative energy loss. The effect of changing in the screen holes relative area on the relative energy loss has a slight impact. All results of the relative energy loss are close to each other and the screen effect can be neglected for all different flow conditions. The merit of the presence of screen in the stilling basin improves the energy loss through the hydraulic jump. This improvement of the energy loss is triggered from the crossing of jet flow through and over the screen behind it. The crossing flow jets increases the turbulence, thus increases air entrainment and makes a boiling zone back the screen, consequently lead to increase the relative energy loss.

Figure (6) explains the increasing percentage of the energy loss for the different screen holes relative areas at different submergence ratios compared to the case of no screen at F_1=4.00. The increasing percentage of the relative energy loss magnifies when the relative holes area of screen equal 0.285 (A_o/A_s=0.285) for all submergence ratios. The presence of the screen with any relative area maximizes the increasing percentage of the relative energy loss.

Figure (7) show the relation between the relative depth of the hydraulic jump Y and the initial Froude number F1 for submergence ratios S=3.0 for different relative passing areas (A_o/A_s=0.046, 0.103, 0.183, 0.285, 0.411). Under the same flow conditions, the relative depth of the hydraulic jump decreases as the relative passing area increases. The relative passing area of 0.285 gives the minimum values of the relative depth of the hydraulic jump. In fact, the screen passing area plays a paramount role in controlling the relative depth of the hydraulic jump. The discharge passing through the screen increases as the diameter of screen hole increases (i.e., the passing area). For the same discharge, the flow passing above the screen in the case of higher relative passing areas is less than that of lower relative screen area. When the screen diameter is very small, the hydraulic jump characteristics are similar to a solid plate of a submerged lateral sill. Moreover, when the passing screen area is relatively large, the hydraulic jump characteristics are near to the case of no screen. The balance between the over and screen passing discharge leads to the optimum case for the purpose of reducing the sequent depth of jump. This balance point occurs when the relative passing area is 0.285.

(8) introduces the decreasing percentage of the relative depth of the hydraulic jump for different screen holes relative areas and different submergence ratios of (S= 3.0, 4.0 and 4.5) with respect to the case of no screen at Froude number =4.50. The decreasing percentage of the relative depth of the hydraulic jump reaches the minimum values at A_o/A_s=0.285 relative screen area for all submergence ratios. The presence of the screen with any relative screen area increases the decreasing percentage of the relative depth of the hydraulic jump.

The relative length of the hydraulic jump behavior is similar to the pattern of the relative depth of the jump. Any increasing or decreasing in the relative depth of the hydraulic jump certainly causes a corresponding increase or decrease of the hydraulic jump length. When the tail water depth increases, the hydraulic jump needs a greater length to reach the establishment state. Figure (9) shows the relation between the relative length of the hydraulic jump and the initial Froude number at the submergence ratio of 3.0 for different relative screen areas. Again, the best relative area of screen that gives the smallest length of the hydraulic jump happens at 0.285 relative screen areas. Furthermore, as the relative screen area increases, the relative length of the jump magnifies. The magnification of the hydraulic jump length values increase as the relative screen area increases from 0.046 to 0.285.When the relative area was 0.285, the relative length of the hydraulic jump reached the lowest values. In addition, the relative length of the hydraulic jump increased again when the relative screen area was more than 0.285. Finally, the case of no screen gave the largest values of the relative hydraulic jump length for all submergence ratios and same flow conditions (i.e., the presence of screen reduces the hydraulic jump length).

Figure (10) shows the decreasing percentage of the relative hydraulic jump length for different relative areas at the submergence ratios 3.0, 4.0 and 4.5 comparing with the case of no screen at Froude number =4.50. The decreasing percentage of the relative hydraulic jump length reaches the minimum values at the relative screen area of 0.285 for all submergence ratios. The presence of the screen with any relative area maximizes the decreasing percentage of the relative hydraulic jump length.

The water surface profiles of the submerged hydraulic jump were plotted in figure (11) for the submergence ratio 3.0, 4.0 and 4.5. It can be clearly seen that the apex of the jet rises when the relative area of screen changes from 0.046 to 0.411 expect the relative screen area of 0.285. The apex of the jet rises extra as the relative screen area increases. The minimum depth downstream the jet apex moves far away to the downstream as the relative area of screen increases. This elongates the length of hydraulic jump and hence increases the jump depth. It is obvious that as the relative area of screen increases, the flow through the screen increases also. Consequently, the flow in this case pushes the incoming jet back more than the cases of smallest screen relative area. The turbulence happens due to the travelling waves and increases as the screen relative area increases. This explains why the depth and length of the hydraulic jump increases or decreases under the effect of
the variation of the relative screen area. The relative depth of the hydraulic jump is reversely affected by the energy loss changing. In other words, the decrease in the relative energy loss causes a corresponding increase in the relative depth of the hydraulic jump.

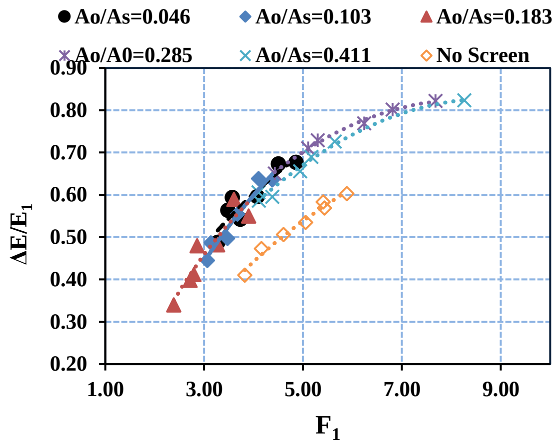


Figure 5: Relationship between F_1 and $\Delta E/E_1$ for **S** = 3.00
at different relative holes area of screen fixed at l_s/l_a =0.25

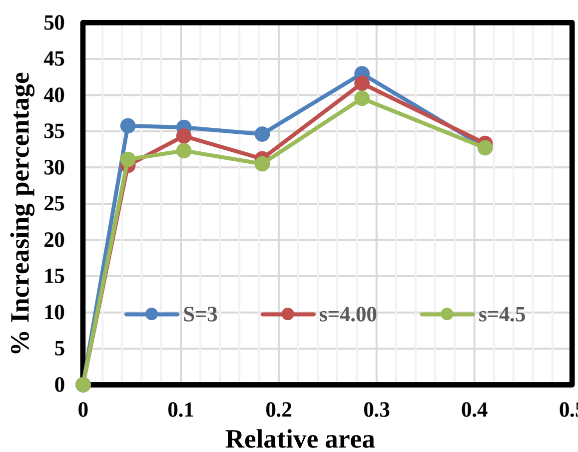


Figure 6: Increasing percentage of energy loss for different
relative screen holes areas, at F_1= 4.00 and S =3, 4.0 and 4.50

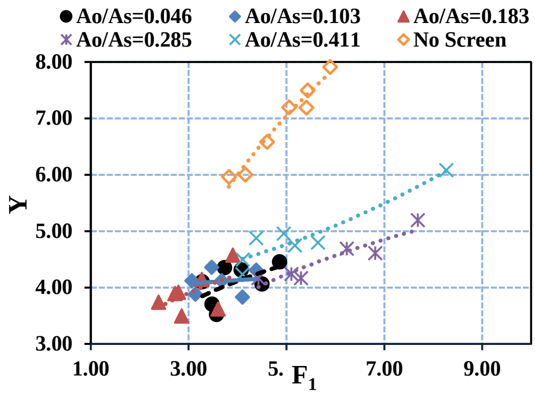


Figure 7: Relationship between $F_1$and Y for S = 3.00 at different relative holes area of screen fixed at l_s/l_a =0.25

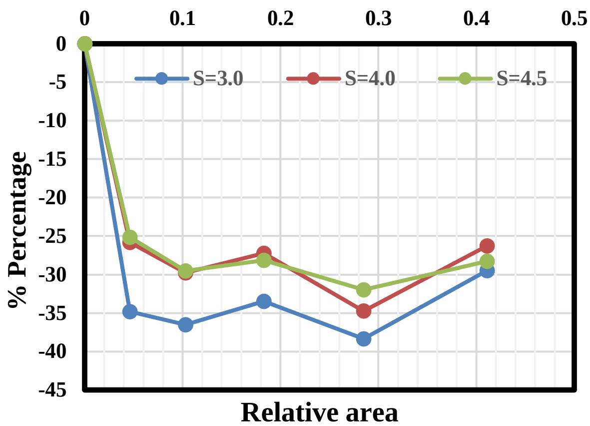


Figure 8: Percentage of relative depth of jump for different
areas of screen at l_s/l_a = 0.25, F_1= 4.50 and S=3, 4 and 4.5

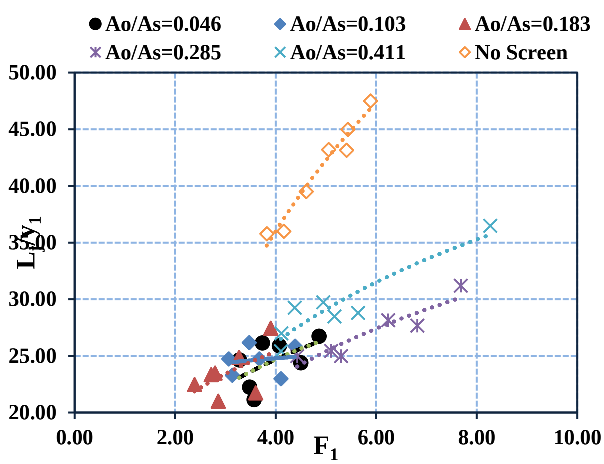


Figure 9: Relationship between F_1 and L_j/y_1 for S = 3.00 at different relative holes area of screen fixed at l_s/l_a =0.25

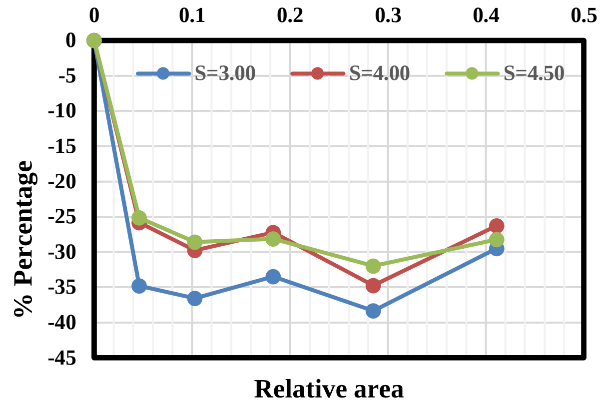


Figure 10: Decreasing percentage of relative length of
jump for different relative holes area of screen at F_1=4.50, S=3, 4 and 4.50

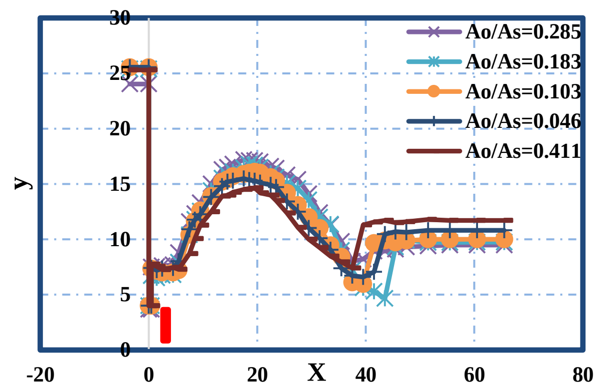


Figure 11: Water surface profiles for different relative holes area of screen for S=3.0, Q≈10.32, G=4.0

6.2. Verification

The relationship between the theoretical results of the relative hydraulic jump depth calculated from equation (11) and the experimental results was shown in

Figure (12). From this figure, it was found a higher asymmetric scatter of results around the line of equality. Thus, a correction factor is required to correct the theoretical Froude number as presented in equations (15 and 16).

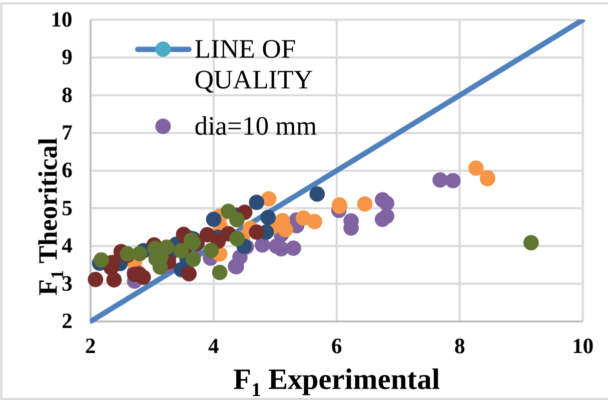
$$Fc_{th} = F_{th} + CF \qquad (15)$$

Where; CF is the correction factor and Fc_{th} is the corrected theoretical Froude number

$$CF = 0.85\,Y - 1.10\,S + 2.0\,A_r - 0.5 \quad (16)$$

The corrected theoretical Froude number and the experimental Froude number are shown in figure (13). From this figure a good agreement between the results of equation (15) and the experimental results. To verify the theoretical relative energy loss from equation (6), substituting the corrected theoretical Froude number calculated from equation (15) and other reminder variables from the experimental data.

Figure indicates the theoretical relative energy loss derived from equation (6) and the experimental results, a well agreement can be clearly seen. Consequently, the derived equations can be used for designing stilling basins



supported with screens in practical applications.

Figure 12: Relationship between theoretical F_1 of equation (11) and experimental Froude number

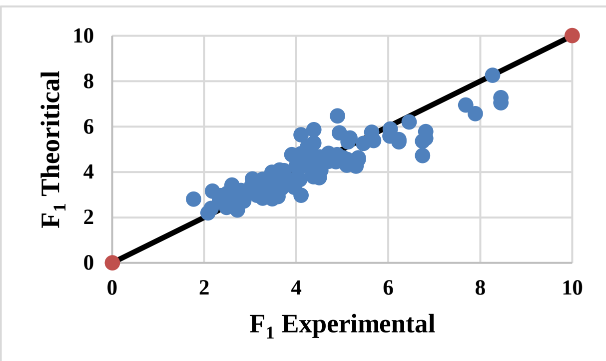


Figure 13: Relationship between corrected theoretical F_1 of equation (11) and experimental Froude number

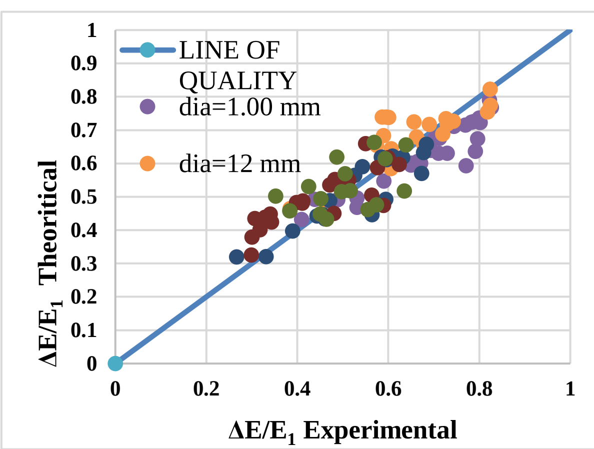


Figure 14: Relationship between theoretical $\Delta E/E_1$ of equation (6) and experimental $\Delta E/E_1$

7.CONCLUSION

Experimental and theoretical studies related to the sudden expanding stilling basin supported by screens were done to show the effect of the presence of screen on the characteristics of the submerged hydraulic jump. The present study introduces the following results:

1. The presence of screen with any relative area improved the characteristics of the submerged hydraulic jump.
2. The best screen holes relative area that increased the relative energy loss and decreased the relative depth and length of the submerged hydraulic jump was about 0.285.
3. The derived theoretical equation of the relative depth of the hydraulic jump had a higher asymmetric scatter with the experimental results around the line of equality; however an acceptable agreement was present when a correction factor was used.
4. The deduced theoretical equation of the relative energy loss had acceptable agreement with the experimental results.

Notation

A_s The total screen area (L^2)
A_o Area of holes (L^2)
b Contracted width (L)
B Channel width (L)
B_s Screen width (L)
d Diameter of holes of screen (L)
ΔE Energy loss through jump (L)
E_1Total energy at y_1.(L)
E_2Total energy at y_4 (L)
e Expansion ratio (-)
F_1 Inflow Froude number (-)
g Gravitational acceleration (LT^{-2})
G Gate opening (L)
H_{up} Upstream water depth (L)
h_s Screen height (L)
ΔH Difference between water depths U.S and D.S the screen
L_a Length of abutment downstream the gate
L_j Jump length (L)
L_s Distance from gate to screen (L)
P_1 Hydrostatic pressure at the beginning of the hydraulic jump
P_4 Hydrostatic pressure at the end of the hydraulic jump
Ps Hydrostatic pressure below one side of contraction
p_{c1} Hydrostatic pressure before screen
p_{c2} Hydrostatic pressure after screen
p_{cnet} Net pressure applied on screen
n Number of holes (-)
S Submergence ratio (y_3/y_1) (-)
v_1Velocity at section 1(LT^{-1})
v_4Velocity at y_4 (LT^{-1})
X distance from the gate at any water depth
Y relative depth of jump

y depth of water at distance X

y_1 Initial water depth (L)

y_2 Sequent water depth (L)

y_3 Back flow depth (L)

y_4 Tail water depth (L)

y_s Depth at the side expansions of the basin (L)

ρ Density of water (ML^{-3})

8.REFERENCES

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