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ESTIMATION OF HYDRAULIC JUMP CHARACTERISTICS IN STILLING BASIN WITH GUIDE WALLS

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ABSTRACT

A stilling basin is designed to dissipate the kinetic energy of the flow by a hydraulic jump. The main objective of the present study is to investigate the free hydraulic jump characteristics created in a rectangular stilling basin with a modified guide walls as a current deflector to control the hydraulic jump.

A single-vent regulator is tested for different relative deflection angle of the guide walls under the same flow conditions. The characteristics of the jump formed without the guide walls are compared to those of the jump formulated under presence of the guide walls. Theoretical models for U.S Froude number and relative energy losses were derived. The dimensional analysis was employed to drive expressions correlating the different variables affecting the free hydraulic jump phenomena. The derived theoretical models results are in good agreement with the experimental results. Finally, this study yielded conclusions which can be recommended in the design procedure and practical applications.

Keywords: Stilling Basin, hydraulic jump, Energy dissipation, Guide wall, current deflector.

1. INTRODUCTION

In the design of stilling basins, information is required principally with regard to three characteristics of the hydraulic jump namely the length, the sequent depths and the energy losses. Over the decades extensive data have been gathered for the design of stilling basins but most of these data are restricted to jumps in rectangular basins. The U.S. Bureau of Reclamation (USBR) surveyed the state of knowledge in this field and presented practical guidelines for the design of different types of stilling basins **Peterka, 1983)**[8]. However, geometries different from rectangular cross sections are often considered for stilling basins. Sometimes a diverging cross section along the stream wise direction may be preferred with a simple transition structure to reduce cost without sacrificing performance. A diverging stilling basin can easily adapt itself

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to the upstream and downstream conditions in terms of depths and cross sections. A simple expansion of the basin width with straight walls is more economical than a costly transitional structure. Information concerning the flow in stilling basins of constant width cannot be easily transferred to jumps occurring in expanding channels of non-rectangular cross sections. Therefore, information to such stilling basins is required to accurately determine the scale of flow and energy dissipation in the design of interest. **Posey and Hsing (1938)**[9] studied the effect of side slope on the length of hydraulic jumps in a trapezoidal stilling basin. The study showed that decreasing side slope increases the length of jump in comparison with jumps in stilling basins of rectangular cross section. **Diskin (1961)**[2] obtained a theoretical equation for the sequent depths of hydraulic jumps in trapezoidal channels and showed that the downstream depth is smaller than that for a rectangular channel and decreases with decreasing side slopes. **Wanoschek and Hager (1989)**[11] performed an experimental study on the characteristics of hydraulic jumps in channels with a trapezoidal cross section of side slope 1 : 1. They found that the sloping side walls cause reduction in the downstream depth, and increases the energy losses and the length of jump. **Kouluseus and Ahmad (1961)**[6] studied experimentally circular hydraulic jumps and developed a theoretical equation for the sequent depths ratio in the circular jump assuming that the surface profile of the jump is linear. The results showed that the downstream depth and the length of jump decrease, and the energy loss increases in circular jumps as compared to hydraulic jumps in prismatic rectangular channels.

Arabhabhirama and Abella (1971)[1] studied radial hydraulic jumps in a gradually expanding channel of rectangular cross section with divergence angles, assuming that the surface profile of the jump is elliptical. The results showed that the divergence of the walls causes reductions in the downstream depth and the length of jump and an increase in the energy loss as compared to the hydraulic jumps in a straight rectangular channel. **Khalifa and McCorquodale (1979)**[5] studied radial hydraulic jumps in a gradually expanding channel of rectangular cross section and developed a theoretical equation assuming a second degree polynomial for the surface profile. The results showed that the divergence of side walls increases the relative energy losses by about 15% and decreases the length of jump approximately 30% for upstream Froude number greater than three. **Omid (1996)[7]** performed an experimental study on the characteristics of hydraulic jumps in channels with trapezoidal cross section. He found that the sloping side walls increase the length of jump and energy losses and cause reduction in the downstream depth. **Elfiky (2004)[3]** studied free hydraulic jump created DS of regulators considering the different scenarios of gate operation. They used a solid-winged deflector. He found that, locating the deflector within the first quarter of the stilling basin downstream of piers end gives the best performance. **Valle and Pasternack (2006)**[10] investigated submerged and free natural hydraulic jumps in a bed rock step pool mountain channel. **El-Gamel (2001)**[4] studied experimentally the effect of using three lines of angle baffles on scour downstream heading-up structures.

The main objective of this paper is to investigate experimentally the free hydraulic jump characteristics created in stilling basin with a modified guide walls as a current deflector to produce a uniform distribution of the flow along the cross section.

2. EXPERIMENTAL SET- UP

The experimental work was carried out in the Hydraulics Laboratory of the Faculty of Engineering, Zagazig University. The experiments were carried out in a horizontal re-circulating laboratory flume 30 cm wide, 46.8 cm deep with an overall length of 15.6 m. The discharge was measured using a pre-calibrated orifice-meter installed on a feeding pipeline. The model was made from clear perspex of thickness10 mm. The length of the approaching channel was 50 cm. A control sluice gate is made from the same perspex. The gate is installed 5 cm upstream the stilling basin. The length of the apron of the rectangular stilling basin is 100 cm. The model DS of gate consisted of single vent 13 cm wide, and 35.5 cm deep. Trapezoidal channel section of bed width 13cm, and side slope (0.25) was fixed DS stilling basin as presented in Fig. (1). The tailgate at the end of the flume is used to control the tail water depth. The guide wall of 2.5 cm height, 4cm lateral spacing, and 0.3cm thickness was located at L_g/L_b = 0.35. Five values of deflection angles were tested viz. θ = 5.66 º, 7.93º, 10.2º, 17.05 º and 19.34 º. The experiments covered a range of upstream Froud number from (F_1= 1.45 to 8.83).

The following systematic steps are made in conducting the experimental work: a) Adjusting the level of tail gate with the desired discharge and U.S. Fe, b) After the stability conditions (stable velocity and water depths) are attained, the following measurements are taken: the US water depth, the initial water depth y_1, the sequent water depth y_2, the tail water depth y_3 and the length of jump L_j.

3. DIMENSIONAL ANALYSIS

A dimensional analysis is applied to correlate the different factors affecting phenomena under study and the following functional relationship is obtained:

$$\theta = F\,(L_j/y_1,\ y_2/y_1,\ y_3/y_1,\ \Delta E_2/E_1,\ \Delta E_3/E_1) \quad \ldots\ldots(1)$$

In which: θ is the guide wall deflection angle, L_j is the jump length, y_1 is the initial depth of hydraulic jump, y_2 is the D.S. depth of the jump, y_3 is the tail water depth, ΔE_2 is energy losses at the D.S. depth of the jump ($\Delta E_2 = E_1-E_2$) and ΔE_3 is energy losses at the tail depth ($\Delta E_3 = E_1-E_3$).

4. THEORETICAL STUDY

4.1 The Relative Depth of Jump

Using approach involves the following assumptions: the flow is steady, the liquid is incompressible, the pressure distribution is hydrostatic at the beginning and at the end of jump, the velocity distribution at the beginning and the end of the jump is uniform. The turbulence effect and the air entrainment are neglected.

Referring to Fig.(1) which shows the phenomenon under investigation.

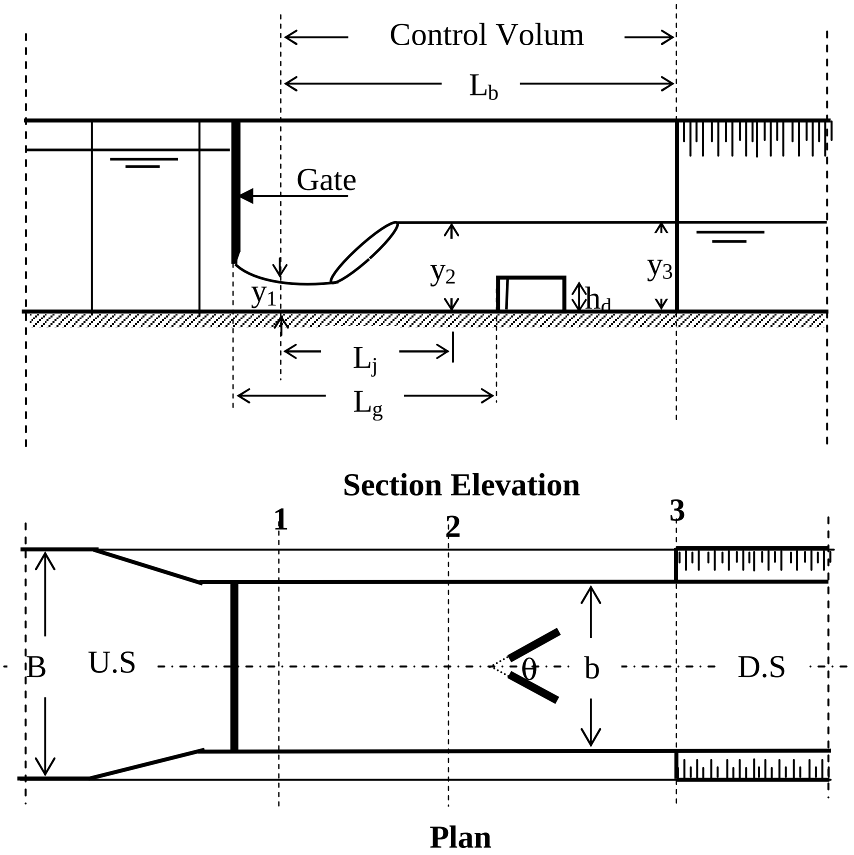

Fig. (1) Definition sketch of Experimental Model

Applying the momentum equation at the control volume 1-3 yields:

$$P_1 - P_3 + P_4 - P_5 + P_S = \frac{\gamma}{g} Q(V_3 - V_1) \quad \ldots\ldots(1)$$

At which, P_1 is pressure force at beginning of hydraulic jump, P_S is the hydrostatic pressure at the two sides of transition section, P_3 the pressure force just DS stilling basin, P_4 is the pressure force at the beginning of guide walls, P_5 is the pressure force at the end of guide walls γ is the specific weight, g is the gravitational acceleration, Q is the flow rate, V_3 the velocity of flow just DS stilling basin, V_1 is the velocity of flow at the beginning of the jump. Where:

$$P_1 = 0.5\gamma b y_1^2 \quad \ldots\ldots(2)$$

$$P_3 = \left(\frac{1}{3}\gamma Z y_3^3\right) + b\gamma \frac{y_3^2}{2} \quad \ldots\ldots(3)$$

$$P_4 = 0.5\gamma b h_d \sin\theta(2y_4 + h_d) \quad \text{.....(4)}$$

$$P_5 = 0.5\gamma b h_d \sin\theta(2y_5 + h_d) \quad \text{.....(5)}$$

$$P_s = \frac{1}{3}\gamma Z {y_3}^3 \quad \text{.....(6)}$$

Where y_1 , y_3 ,y_4 , y_5 are water depths at beginning of jump, downstream the basin, at beginning and at the end of the guide wall respectively, b is the bed width and h_d is the height of the guide wall.

Applying the continuity equation between sections 1 and 3

$V_3=V_1*(A_1/A_3)$.....(7)

Substituting from equations (2 to 7) into Equation (1) one obtains:

$$\frac{1}{2}-\frac{1}{2}y_r^2+\frac{1}{2}h_{dr}\sin\theta\left(2y_{4r}+h_{dr}-2y_{5r}-h_{dr}\right)=F_1^2\left(\frac{1-y_r-Zy_{3r}y_r}{y_r(1+Zy_{3r})}\right) \quad \text{.....(8)}$$

Where:

$$\frac{y_3}{y_1}=y_r,\ \frac{y_3}{b}=y_{3r},\ \frac{h_d}{y_1}=h_{dr},\ \frac{y_4}{y_1}=y_{4r},\ \frac{y_5}{y_1}=y_{5r}$$

Solving Equation (8) for F_1 the following equation can be obtained

$$F_1=\sqrt{\left[y_r\left(1+Z\,y_{3r}\right)\right]\frac{\left\langle 0.5-0.5y_r^2+h_{dr}\sin\theta\left(y_{4r}-y_{5r}\right)\right\rangle}{\left(1-y_r-Z\,y_{3r}\,y_r\right)}} \quad \text{.....(9)}$$

Let $Y=y_{4r}-y_{5r}$

$$F_1=\sqrt{\left[y_r\left(1+Z\,y_{3r}\right)\right]\frac{\left\langle 0.5-0.5y_r^2+h_{dr}\sin\theta\ Y\right\rangle}{\left(1-y_r-Z\,y_{3r}\,y_r\right)}} \quad \text{.....(10)}$$

4.2 Relative Energy Loss:

Applying the energy equation between sections 1 and 3

$$\frac{E_L}{E_1}=1-\frac{E_3}{E_1} \quad \text{.....(11)}$$

Where $E_1=\dfrac{V^2{}_1}{2g}+y_1=y_1\left(1+0.5F_1^2\right)$ .....(12)

And

$$E_3=y_3+\frac{V_3^2}{2g} \quad \text{.....(13)}$$

from the continuity equation

$$V_3 = \frac{A_1 V_1}{A_3} = \frac{(V_1 b y_1)^2}{(b y_3 + 0.25 y_3^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

Substituting from equations (12, 13and14) into Equation (11) one obtains:

$$\frac{E_L}{E_1} = 1 - \frac{\left(y_r + \dfrac{0.5 F_1^2 \left(\dfrac{b}{y_1}\right)^2}{\left(\dfrac{b}{y_1}\right)^2 y_r^2 + 0.5 \dfrac{b}{y_1} y_r^3 + 0.0625 y_r^4} \right)}{(1 + 0.5 F_1^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(15)$$

In which:

E_1 is the specific energy at the beginning of hydraulic jump, E_3 is the specific energy at the end of control volume and E_L is the energy loss between y_1 and y_3.

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

The hydraulic jump occurs when the supercritical stream of high velocity meats a subcritical stream of sufficient depth and lower velocity. In this study, the jump is formed under presence of the guide walls of different deflection angles. The experimental results of the present investigations will be analyzed in this part in comparison with the case without guide walls.

5.1. The relative depth of the jump and the basin (y_2/y_1, y_3/y_1)

The relation between the initial Froude number, F_1 and the relative depth of the jump y_2/y_1 for five values of deflection angles (5.66 ^{o}, 7.93^o, 10.2^o, 17.05 ^{o} and 19.34 ^{o}) and the case without guide wall are shown in Fig. (2). The figure showed that the values of y_2/y_1 increase with the increase of F_1 and the presence of the guide walls reduce the values of y_2/y_1 for the investigated range of Froude number (1.45 to 8.83). It's clear that the guide wall of deflection angle 10.2^o produce a remarkable reduction in comparison with the case without guide walls. The reduction in y_2/y_1 values decreases with the other angles (17.04^o and 19.34^o). On contrary with the smaller angles (5.66^o and 7.93^o) the values of y_2/y_1 are coincide with the case without guide walls.

Figure (3) shows the relation between the values of F_1 and the relative tail water depth of the jump y_3/y_1. The figure showed the same previous results.

5.2. The Relative Length of the Jump (Lj/y_1)

Figure (4) shows the relation between the values of F_1 and the relative length of the jump L_j/y_1 for the five tested angles of deflection (5.66 ^{o}, 7.93^o, 10.2^o, 17.05 ^{o} and 19.34 ^{o}). The figure includes also the same relation for the case without guide walls. It shows that the relative length of jump increases with the increase of F_1 and decreases with the presence of the guide walls. The minimum values of L_j/y_1 are observed with the guide walls of 10.2° angle of deflection, while the guide walls of 5.66° and7.93° angles of deflection give very close values of L_j/y_1 w.r.t. the case without deflectors.

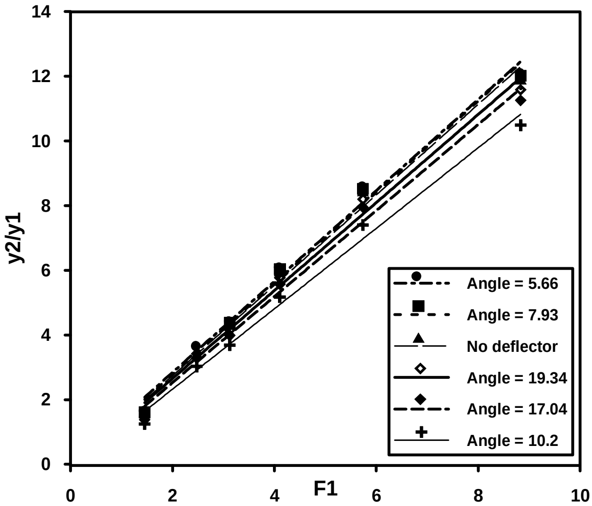

Fig.(2) Relation between F_1 and y_2/y_1 for different angles of guide walls

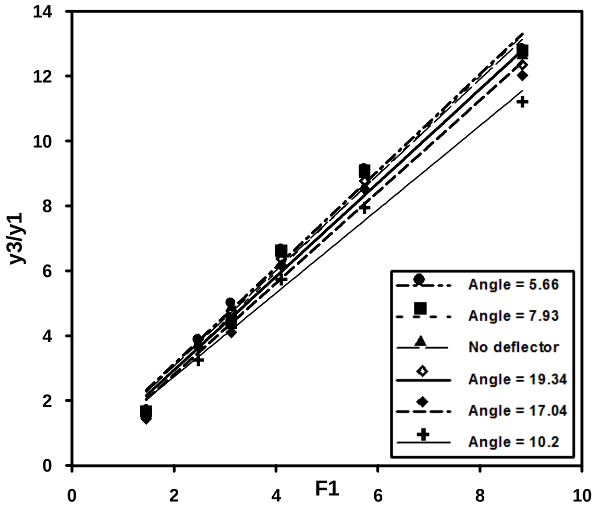

Fig.(3) Relation between F_1 and y_3/y_1 for different angles of guide walls

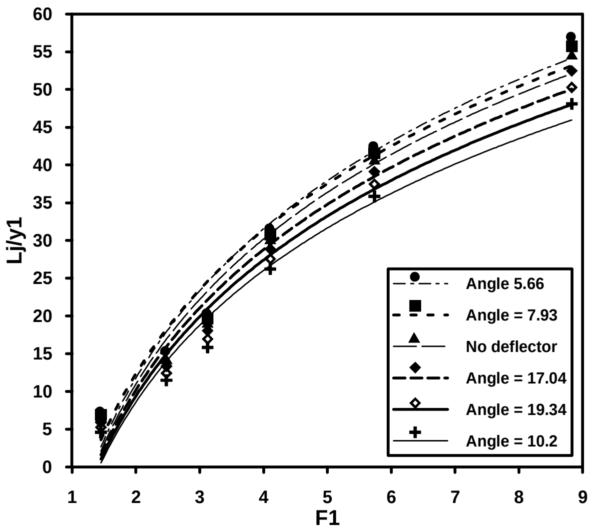

Fig.(4) Relation between F_1 and $L_j/y_1$for different angles of guide walls

5.3. The Relative Energy losses of the Jump and of the basin (EL_{1-2}/E_1, EL_{1-3}/E_1)

Figures (5 and 6) show the relation between the values of F_1 and the relative energy loss of the jump and the basin respectively for the five tested angles of deflection (5.66 º, 7.93º, 10.2º, 17.05 º and 19.34 º). The figures include also the same relation for the case without guide walls. It shows that the relative energy loss increases with the increase of F_1 and increases also with the presence of the guide walls. The minimum values of energy loss are observed with the guide walls of 5.66º angle of deflection, while the maximum values are obtained with the guide walls of 10.2º angle of deflection w.r.t. the case without deflectors.

Finally it is obvious that the using of a guide walls is directing the flow in a specified direction through the basin. The directing of the flow plays an important role for a good distribution of the flow along the cross–section and for the energy dissipation, which leads to more energy loss and less relative length and depth of jump in comparison with the case of stilling basin without guide walls. But this effect decreases with smaller angles of deflection (< 8º) to be very close to or coincide with the case of stilling basin without guide walls.

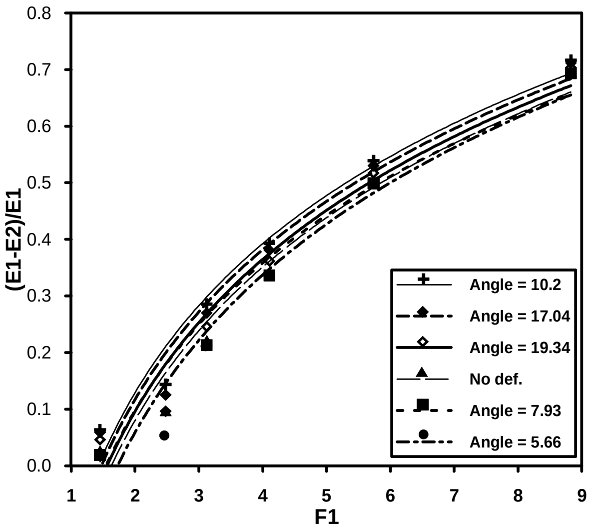

Fig.(5) Relation between F_1 and $(E_1\text{-}E_2)/E_1$ for different angles of guide walls

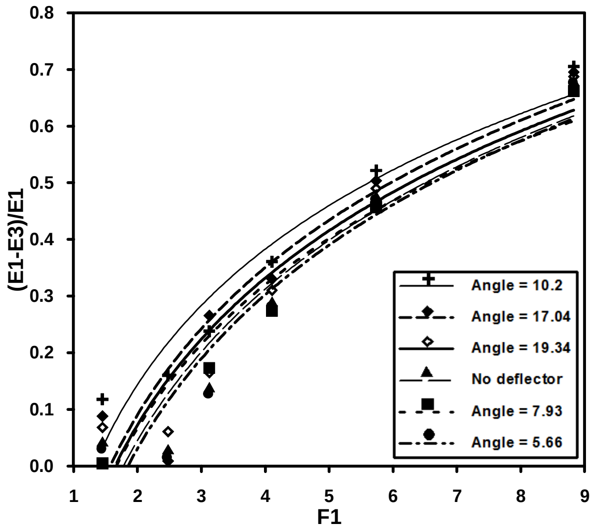

Fig.(6) Relation between F_1 and $(E_1\text{-}E_3)/E_1$ for different angles of guide walls

6. VERIFICATION OF THE DEVELOPED MODELS

Figure (7) presents the comparison between the oretical values of Froude number (F_1The.) as computed from equation (10) and its values as computed from the measurements (F_1 Exp.) of the hydraulic jump formed in a basin with guide walls of different angles of deflection. The coefficient of determination (R- squared) between theoretical and measured values of Froude number is 0.997 and between the residuals and the theoretical values is 0.137 indicating good agreement between theoretical and measured values.

Figure (8) presents the comparison between theoretical values of the relative energy loss EL_{1-3}/E_1 as computed from equation (15) and its experimental values as computed from the measurements. The coefficient of determination (R- squared) between theoretical and measured values of is 0.99 and between the residuals and the theoretical values is 0.14. Inspection of this figure indicates that good agreements between theoretical and measured values are achieved.

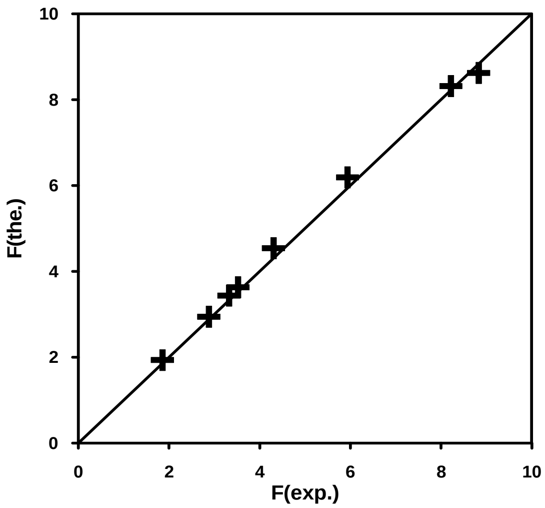

Fig.(7) Relation between experimental and predicted values of F_1 for different θ]

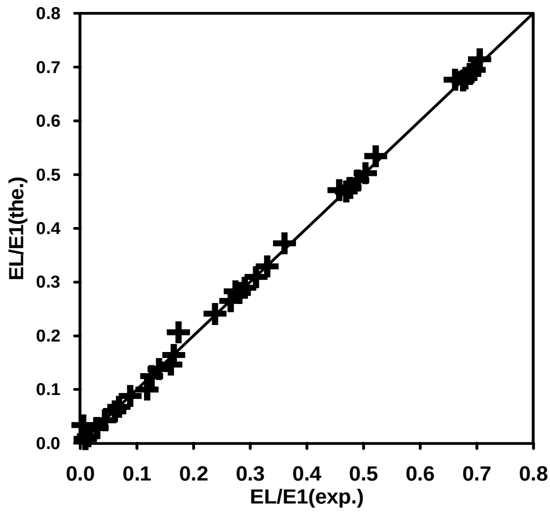

Fig.(8) Relation between experimental and predicted values of EL/E_1

7. CONCLUSIONS

An experimental study was carried out to investigate the guide walls effect on the characteristics of the free hydraulic jump created in stilling basin D.S of single-vent regulators. The results of the experimental and theoretical study on the hydraulic jump are presented. The discussion and analysis of the results highlighted the following conclusions:

1. Analyzing the experimental measurements, it is clear that y_2/y_1, Lj/y_1 and E_L/E_1 show an increase trend with F_1 for different guide walls deflection angles,
2. Guide walls represent an obstruction in the basin so they improve the characteristics of the Hydraulic jump (reduce the depth and the length and increase the energy loss of the jump).
3. The minimum y_2/y_1 and Lj/y_1 have been obtained for deflection angle of 10.2^o. Also, the same deflection angle gives the max. relative energy losses E_L/E_1,
4. The use of the guide walls with $\theta > 8^o$ reduces the values of the relative depth y_2/y_1 by about 7%. Also, it reduces the values of the relative length Lj/y_1 by about 13%, and relative tail depth y_3/y_1 by 12%.
5. The derived theoretical models are in good agreement with the experimental results. So they can be used for the design of stilling basin.

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Notations:

B	Bed width of channel,
b	Bed width stilling basin,
F_1	Initial Froude number,
g	Gravitational acceleration
h_d	Guide walls heights
L_b	Basin length.
L_g	The distance between gate and beginning of angled guide walls
L_g/L_b	Relative longitudinal position of guide walls.
Q	Flow rate.
V_1	Mean velocity at initial water depth
V_3	Mean velocity at tail water depth
y_1	Initial water depth of hydraulic jump
y_2	D.S. water depth of the jump
y_3	tail water depth
θ	Guide wall deflection angle.
γ	Specific weight of the water

تقدير خصائص القفزة الهيدروليكية فى أحواض التهدئة المزودة بحوائط التوجيه

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الملخص العربي:

يهدف هذا البحث إلى دراسة كيفية التحكم فى القفزة الهيدروليكية الحرة خلال أحواض التهدئة المستطيلة الشكل المؤدّية لقنوات ذات القطاعات شبه المنحرفة. تم عمل دراسة نظرية و أخرى معملية أجريت الدراسه المعمليه في معمل هندسة المياه و الهيدروليكا بكلية الهندسة – جامعة الزقازيق فى قناة مستطيلة أفقية طولها 15.6 م وعرضها 30 سم و إرتفاعها 46.8 سم على نموذج لقنطرة ذات فتحة واحدة بعرض 13 سم مركب فيه بوابة رأسية بهذا العرض، و يوجد خلف البوابة حوض تهدئة مستطيل بطول 1م يتبعه قناة ذات قطاع شبه منحرف ذات ميل جانبي (1:4) و تم استحدام حوائط مُوجِهه ذات زوايا (θ) مختلفة (5.66^{o}، 7.93^{o}، 10.2^{o}، 17.34^{o}، 19.34) على بعد ثابت من بداية الحوض(35.0 سم).تم عمل تحليل بعدي لإيجاد علاقة بين الخصائص الأساسية للقفزة الهيدروليكية الحرة بالمتغيرات التي تؤثر على تلك الخصائص وكذلك بالمتغيرات الخاصة بموجهات السريان. كذلك تم استخدام معادلتي كمية الحركة و الاستمرارية لاستنباط نموذج نظري للعمق النسبي للقفزة الهيدروليكية و كذلك استخدام نظرية بقاء الطاقة لحساب الطاقة النسبية المفقودة. وبمقارنة النماذج الرياضية المستنتجة مع النتائج المعملية ثبت وجود توافق جيد بينهما مما يعزز النتائج التي تم التوصل إليها ويجعلها مفيدة في مجال تصميم أحواض التهدئة.