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Characteristics of submerged hydraulic jumps in radial basins with a vertical drop in the bed

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In this paper, the submerged hydraulic jump formed in a radial stilling basin provided with sudden drop is theoretically and experimentally analyzed. 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 are investigated. The experimental investigations were conducted on a 30 cm wide, 45 cm deep and 12 m long laboratory flume. In the theoretical study, the one-dimensional momentum and continuity equations were used to develop theoretical model for the relative depth ratio of the jump. Also, the energy equation is used to develop an expression for the energy loss ratio. The developed equations were verified using the obtained experimental data. Also, a model to predict the length of the submerged radial hydraulic jump was developed using both dimensional analysis and statistical methods. The model was calibrated and checked using the collected experimental data. Results of such statistical models were compared to the measured data and good agreement is existed.

في هذا البحث أجريت دراسة نظرية ومعملية للقفزة الهيدروليكية المغمورة الحادثة في أحواض التهدئة القطرية علي قاع ذي انخفاض رأسي مفاجئ. في الدراسة النظرية استخدمت المعادلات الأساسية للتدفق مثل معادلات الاستمرار وكمية الحركة والطاقة لعمل نموذج نظري يمكن منه حساب العمق النسبي للقفزة وكذلك حساب الفاقد في الطاقة خلالها. وفى الدراسة المعملية أجريت التجارب المعملية لاستخدام نتائجها في مراجعة وتحقيق العلاقات النظرية المستنتجة وكذلك لتعين المعاملات والثوابت المستخدمة في النموذج الإحصائي. في هذا البحث تم دراسة ومناقشة العوامل التي تؤثر على خصائص القفزة الهيدروليكية المغمورة مثل نسبة الغمر وكلا من ارتفاع الهبوط في القاع وبعد الهبوط عن بوابة التحكم ورقم فرويد. ولقد وجد أن زيادة كلا من نسبة الغمر وارتفاع الهبوط وكذلك بعد الهبوط عن البوابة يسبب زيادة في كلا من العمق والطول النسبيين للقفزة الهيدروليكية المغمورة, في نفس الوقت تقل قيمة الفاقد النسبي في الطاقة. أما رقم فرويد فيعطى تأثيرا لا يختلف كثيرا عما يحدث للقفزة الحرة أو المغمورة الحادثتين علي قاع ليس به هبوط. هذا وقد استخدم التحليل البعدي و الإحصائي لإيجاد علاقة تجريبية لحساب الطول النسبي للقفزة الهيدروليكية المغمورة .

Keywords: Submerged hydraulic jump, Radial stilling basins, Drop, Energy dissipators

1. Introduction

The presence of a drop in the bed of the channel is sometimes necessary and can not be avoided based on the topography of the land where the channel is to be constructed. The effect of existing a vertical drop in a radial stilling basin, on the jump characteristics, has not been yet investigated to the best knowledge of the authors. However, the effect of the drop on the flow characteristics in rectangular prismatic channels was studied in horizontal channels by Hager [1], Hager and Bretez [2] and Ohtsu et al. [3]. Hager [1] studied B-jumps at an abrupt drop, he found that the relative energy dissipation becomes insignificant when F_1=8.0, and maximum energy dissipation occur for relative drop height equal to 2.5. Hager and Bretez [2], studied the positive and the negative steps in a horizontal channel. They derived analytically the relationship for A-jump and B-jump. Ohtsu et al. [3] investigated the transition from supercritical to subcritical flow at an abrupt drop. Negm [4] studied the hydraulic jumps at positive and negative steps on sloping floors, and a predicting model for computing the sequent depth ratio of the hydraulic jump was developed. Armenio et al. [5] investigated the effects of vertical drop in pressure fluctuations at the bottom of a hydraulic jump.

The characteristics of submerged jump in rectangular channels were presented and discussed by many investigators e.g. Goivanda and Rajaratnam [6]. Long et al. [7] and Ma et al. [8] studied numerically submerged jump in rectangular channels. Ohtsu et al. [9] presented a systematic investigation on transition from supercritical to subcritical flow for submerged jump below an expanding outlet. The submerged radial jump was investigated theoretically and experimentally by McCorquodale and Khalifa [10]. They found that the dimensionless water depths and hydraulic grade line follow a fourth degree polynomial in Froude number F_1 and submergence ratio S. Also, they derived a theoretical equation for the submergence ratio. They found that the length of jump may be estimated as a function of F_1 and S where,

$$\frac{L_j}{y_1} = a(F_1 + S)^2 + b(F_1 + S) + c\,. \qquad (1)$$

The results of their study are applicable for a total divergence angle of (13.5°), r_o of 1.7 to 2.0, $2<S<10$ and $2.5<F_1<8$ where, r_o is the dimensionless radius of the jump. It was concluded that the length of the radial submerged hydraulic jump is shorter than that of the rectangular one and may be longer than the free radial jump especially for lower submergence. This is due to the effect of the increased jump weight that causes the jet to take longer distance to decay. The length of hydraulic jump is needed to design the stilling basins. Shorter the length of jump means shorter length of basin and hence the basin will be more economic.

2. Development of the theoretical models

2.1. Relative depth of jump

Fig. 1 presents a definition sketch for submerged hydraulic jump in radial basin provided with a vertical drop.

Both the 1-D momentum and continuity equations are used to develop a theoretical design model for computing either the submergence ratio or the sequent depth ratio (in terms of the other one) for the submerged

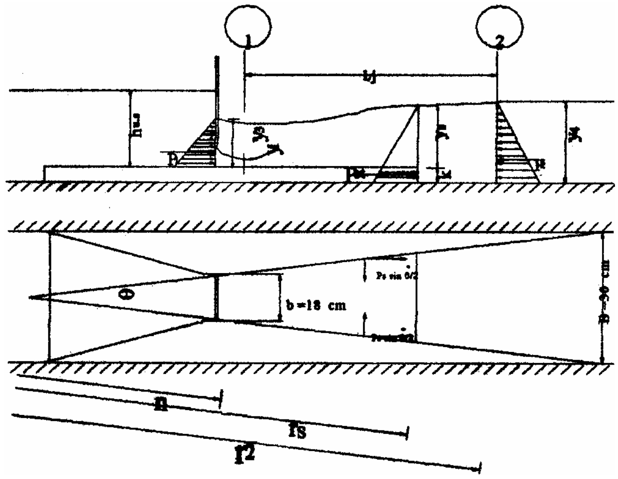

Fig. 1. Definition sketch for radial stilling basin with vertical drop.

hydraulic jump formed in radial stilling basin provided with a drop. The present development is based on the following assumptions: (a) the flow is radial and steady (b) the liquid is incompressible (c) The channel is horizontal and has smooth boundaries, (d) hydrostatic pressure distribution along the considered reach of flow (e) uniform velocity distribution, i.e. the values of the kinetic energy correction factor and the momentum correction factor, α and β are considered unity, and (f) the effects of air entrainment and turbulence are neglected.

In the present study, the control volume where the momentum equation is applied starts from the vena contracta (if a free flow occurs) and ends at the end of jump in the direction of the flow fig. 1. The momentum equation is written as follows:

$$P_1 - P_2 + 2P_s \sin\frac{\theta}{2} + P_{st} = \frac{\gamma}{g} Q(V_2 - V_1)\,. \qquad (2)$$

In which P_1 is the hydrostatic pressure force at vena contracta at a radial distance r_1 where the average velocity is V_1, the contracted depth of flow is y_1 and the depth just downstream the gate is y_3, P_2 is the hydrostatic pressure force at the end of jump at radial distance r_2 where the average velocity is V_2 and the depth of flow is y_4, P_s is channel side pressure, P_{st} pressure force acting on the drop of height k at a radial distance r_s and depth of flow y_s, Q is the discharge, γ is the specific weight of water, g is the gravitational acceleration and θ is the angle of divergence of the radial basin.

$$P_1 = \gamma r_1 y_3^2 \sin\frac{\theta}{2}, \tag{3}$$

$$P_2 = \gamma r_2 y_4^2 \sin\frac{\theta}{2}, \tag{4}$$

$$P_s = 0.5\gamma\left[(r_2 - r_1)\bar{y}^2 - (r_s - r_1)k^2\right]. \tag{5}$$

In which $\bar{y} = (\sqrt{(y_3 + k)y_4})$ is the representative depth (geometric mean of y_3+k and y_4).

The pressure force acting on the drop is,

$$P_{st} = 2\gamma\left(y_s k + 0.5k^2\right) r_s \sin\frac{\theta}{2}. \tag{6}$$

Keeping in mind that,

$$V_1 = Q/(2r_1 y_1 \sin\frac{\theta}{2}), \text{ and}$$

$$V_2 = Q/(2r_2 y_4 \sin\frac{\theta}{2}). \tag{7}$$

Substituting eqs. (3-7) into eq. (2) and dividing it by ($\gamma\, r_1 y_1^2 \sin\theta/2$), yields:

$$\begin{aligned} S^2 &+ SY_\circ(r_\circ - 1) + Y_\circ(r_\circ - 1)K_\circ \\ &- (r-1)K_\circ^2 - r_\circ Y_\circ^2 + 2(Y_S K_\circ + 0.5K_\circ^2)\, r \\ &- 2F_1^2(1/(r_\circ Y_\circ) - 1) = 0. \end{aligned} \tag{8}$$

The solution of eq. (8) gives,

$$S = -0.5A_* + \sqrt{\begin{aligned}&0.25A_*^2 - K_\circ A_* + (r-1)K_\circ^2 + r_\circ Y_\circ^2 \\ &- 2(Y_s K_\circ + 0.5K_\circ^2)r + 2F_1^2(1/(r_\circ Y_\circ) - 1).\end{aligned}} \tag{9}$$

In which $S = \frac{y_3}{y_1}$, $Y_\circ = \frac{y_4}{y_1}$, $r_\circ = \frac{r_2}{r_1}$, $r = \frac{r_s}{r_1}$, $K_\circ = \frac{k}{y_1}$, $Y_s = \frac{y_s}{y_1}$ and $A_* = Y_\circ(r_\circ - 1)$

For stilling basin without drop (K_0=0), eq. (8) tends to the previously equation developed by McCorquodale and Khalifa [10].

Eq. (9) may be rearranged in another form to enable the trail and error computation of Y_o, as follow:

$$\begin{aligned} &r_\circ Y_\circ^3 - (S + K_\circ)(r_\circ - 1)Y_\circ^2 \\ &- [S^2 + 2F_1^2 + 2(Y_S K_\circ + 0.5K_\circ^2)r - (r-1)K_\circ^2]Y_\circ \\ &+ 2F_1(1/r_\circ) = 0. \end{aligned} \tag{10}$$

2.2. Relative energy loss

Applying the energy and continuity equations between sections 1 and 2, as shown in fig. 1, the energy loss through the radial hydraulic jump is obtained as follow,

$$\frac{E_L}{E_1} = 1 - \frac{Y_\circ + 0.5F_1^2/(r_\circ Y_\circ)^2}{K_\circ + S + 0.5F_1^2}. \tag{11}$$

When the drop is not existed, the term K_0 becomes zero, and eq. (11) reduces to the previously developed one by McCorquodale and Khalifa [10].

2.3. Relative length of jump

The use of the dimensional analysis showed that the length of jump ratio (L_j/y_1) of the submerged radial hydraulic jump formed in radial basin with a vertical drop is a function of the F_1, S, r and K_o as follows,

$$\frac{L_j}{y_1} = f(F_1, S, K_o, r). \tag{12}$$

The function f is to be determined using the experimental data.

3. Collection of experimental data

The experimental work of this study is conducted using a re-circulating adjustable flume of 12.0 m long, 45 cm deep and 30 cm wide. The discharges were measured using pre-calibrated orifice meter fixed on the feeding pipeline. The tailgate fixed at the end of the flume was used to control the depth of flow for each run. The radial basin was made from a clear prespex to enable visual inspection of the phenomenon being under investigation. The model length was kept constant at 130 cm and the angle of the divergence was kept constant to 5.28^o. The model was fixed in the middle third of the flume between its two side-walls fig. 1. A smooth block of wood was formed to fit well inside the basin model extending from upstream the gate by 5.0 cm to position where the drop was desired. The wood was painted very well by a waterproof material (plastic) to prevent wood from changing its volume by absorbing water. A fixed height of the drop of 2.5 cm was used. Different positions of the drop (r_s=r_1, 1.16r_1, 1.33r_1 and 1.5r_1) downstream from the gate opening were tested under the same flow conditions. The range of the experimental data were as follows: Q (4 lit/s – 11 lit/s), Froude numbers (2.0-7.0), submergence ratio (4 – 9), Y_o (4 - 12), r_o (1.4 – 1.6), relative position of the drop, r (1.0 –1.50) and relative height of the drop, K_o (0.9 – 1.5).

Each model was tested using five different gate openings and five discharges for each gate opening. The measurements were recorded for several submergence ratios for each discharge. The total number of runs was 335. A typical test procedure consisted of (a) a gate opening was fixed and a selected discharge was allowed to pass. (b) the tailgate was adjusted until a submerged jump is formed. (c) once the stability conditions were reached, the flow rate, length of the jump, water depths upstream and just downstream of the gate in addition to the tail water depth and the depth of water above the drop were recorded. The length of jump was taken to be the section at which the flow depth becomes almost horizontal (d) the position of the tailgate was changed to obtain another submergence ratio and then step (c) is repeated. (e) step (d) was repeated several times then the procedure is repeated for another discharge till the required discharges were covered (f) the procedure was repeated for another gate opening and so on till the required ranges of the parameters being under investigation were covered.

4. Analysis and discussions of results

4.1. Water surface profile

Typical water surface profiles are presented in figs. 2-a and 2-b for the submerged hydraulic jump in radial stilling basins with and without drop at a relative distance of r =1.33. As shown in fig. 2-a, two typical water surface profiles for submerged radial hydraulic jump without drop as obtained by McCorquodale and Khalifa [10]. The discrepancies between the present profiles and those of McCorquodale and Khalifa are referred due to the difference in the divergence angle and the model setup details. In the present case, the divergence angle is 5.28^o while it was 13.5^o for the McCorquodale and Khalifa. They used a completely radial basin with a control radial gate while in the present study a radial basin preceded with a parallel contracted small length of the channel and the control vertical sluice gate is fixed 5.0 cm upstream the radial basin. The present setup of the radial basin simulates the actual conditions in the field because the stream is normally contracted for construction purposes and then enlarged again to restore the original dimensions of the channel.

The water surface profiles for submerged jump in radial basin with drop have a similar nature to those obtained for a basin without drop. It was noticed that the water surface profiles considering a drop are higher than the corresponding ones for basins without drop due to the effect of the drop height at particular location. Fig. 2-b shows that the location of the drop in the radial basin causes an increase in the water surface profiles due to the pressure forces acting on the drop and on the sides. This increase in the depth of the water surface profiles is easily interpreted with the help of the specific energy diagram. The flow away from the gate is subcritical (upper limb of the diagram) and just downstream (DS) of the drop the specific energy E is higher than that just upstream (US) from the drop and hence the depth of flow is increased. The specific energy DS and US of the drop is given by E_{US}=E_{DS}+k-h_L where k is the drop height and h_L is the energy loss through the length

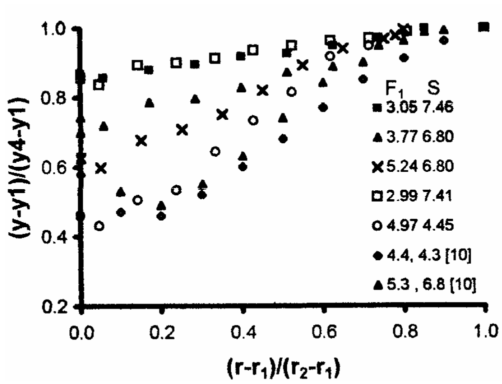

Fig. 2-a. Experimental water surface profiles for submerged radial jump for smooth case.

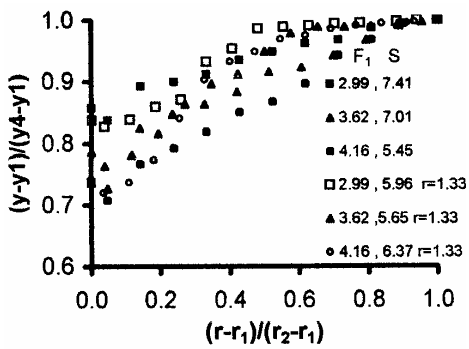

Fig. 2-b. Experimental water surface profiles for submerged radial jump for both smooth case.

from US to DS of the drop where the specific energy equation is applied. The rate of increase of the depth depends on the height of the drop and the rate of energy loss through the jump. If the rate of the energy loss is equal to the energy added by the height of the drop, no appreciable increase in the depth of water is observed.

4.2. The relative energy loss

The relative energy loss by the jump in radial basin without drop is presented in fig. 3-a for three ranges of submergence ratio S with average values of 4.1, 6.5 and 8.5 for r_o in the range 1.4-1.67. Eq. (11) is plotted for S = 4, 6 and S=9. Shown also in the figure the relative energy loss due to submerged jump formed in radial basin with divergence angle equals 13.5° due to McCorquodale and Khalifa [10] at S = 2-4, the relative energy loss by the submerged jump formed in rectangular basin at S = 4.5 due to Govinda and Rajaratnam [6], the relative energy loss by the free radial hydraulic jump due to Khalifa and McCorquodale [11] and the relative energy loss of the free rectangular hydraulic jump, Chow [12]. This figure shows that the energy loss by the submerged radial jump is more than that of the corresponding one in rectangular basin and similar observation is valid for the free jumps. These results corporate well with the results obtained by McCorquodale and Khalifa [10] regarding the same comparison. However, the small difference between present results and those of McCorquodale and Khalifa [10] is due to the difference in the value of the divergence angle. Moreover, the figure indicated that the equation is in good agreement with the experimental results and the lesser energy loss is associated with the greater submergence. The relative energy loss when a drop is present in the basin follow the same trend as that when the drop is absent as indicated in fig. 3-b. Also, eq. (11) is in good agreement with the experimental results of the submerged jump formed in radial basin provided with a drop of fixed height k (relative heights in the range K_o =0.9-1.50) at particular location (r=1.0) and r_o in the range 1.4-1.67. The position of the drop in the radial basin affects the relative energy loss as the rate of energy loss is increased at r=1 compared to the case of radial basin without drop and then it is decreased by the increase of the distance between the gate and the drop location (greater r) as indicated on fig. 3-c (the experimental data are not shown). The prediction of eq. (11) is plotted against all the experimental results for different values of S (S = 4 – 8.5, r (r= 1 – 1.5) and Froude numbers, F_1 (F_1 = 2 - 7). The figure shows a good agreement between the theoretical eq. (11) and the experimental results (mean relative absolute error equals 0.04 and R^2 = 0.97). Figs. 4-a, 4-b and 4-c shows theoretically the effects of the different parameters S, r and K_o on the relationship between the relative energy loss and the initial Froude number based on eq. (11). The relative energy loss increases with the increase of F_1 at constant values of S, r and K_o, while it decreases with the increase of the submergence S, relative position of the

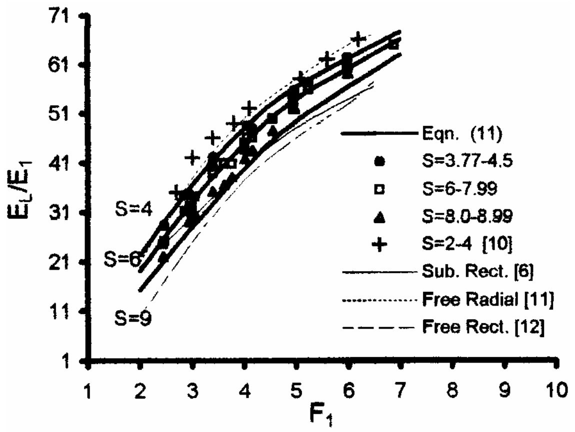

Fig. 3-a. The relationship between F_1 & E_L/E_1 for different S for smooth case.

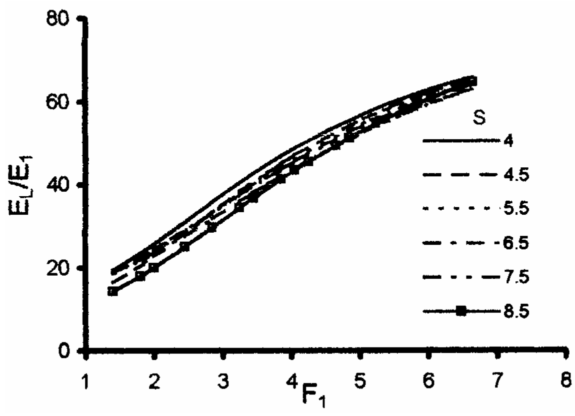

Fig. 4-a. Theoretical relationship between E_L/E_1 &F_1 for different submergence ratios at r =1 and K_o =1.25.

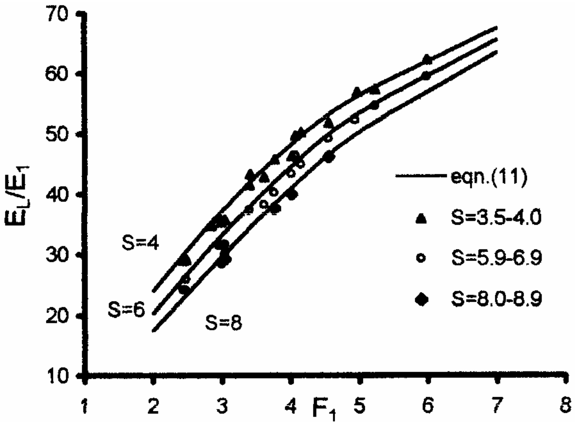

Fig. 3-b. The relationship between F_1 & E_L/E_1 for different S at r =1.0.

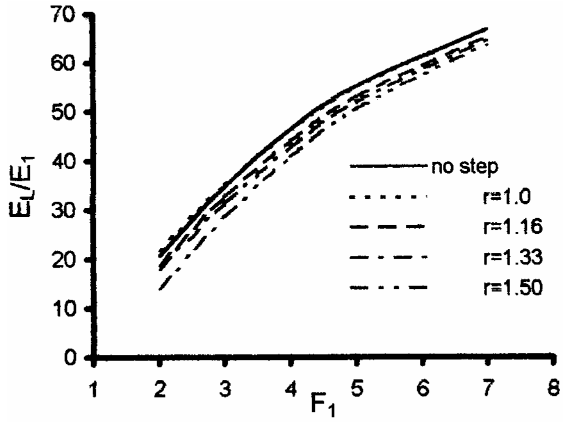

Fig. 4-b. Theoretical relationship between F_1 & E_L/E_1 for different positions of step at S=5.0 and K_o=1.25 according to eq.(11).

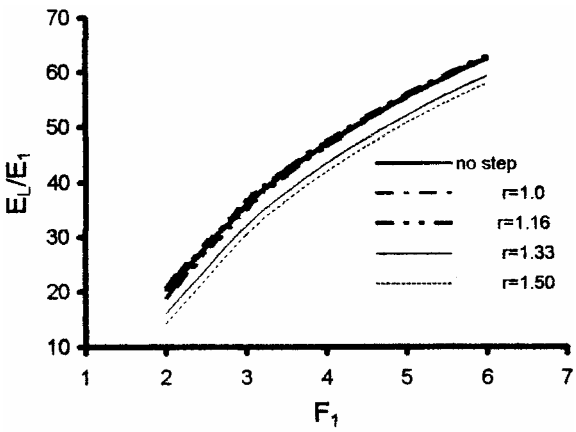

Fig. 3-c. The relationship between F_1 & E_L/E_1 for different positions of step at S =4.0-4.9.

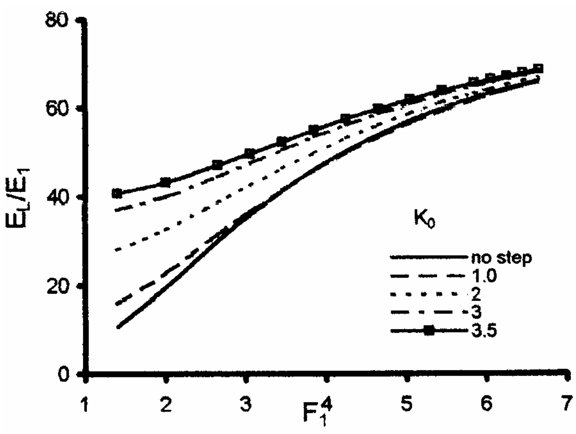

Fig. 4-c. Theoretical relationship between E_L/E_1 & F_1 for different relative heights of step at S =4.0 and r =1.0.

drop *r* and relative height of the drop K_o at constant F_1.

4.3. The relative depth ratio

The effect of submergence on the depth ratio of the submerged jump in radial basin without drop is indicated in fig. 5-a for values of *S*=3.5-4.49, 6.0-6.99 and 8.0-8.99. The values of *S*=6-8 obtained by McCorquodale and Khalifa [10] are also plotted on the figure. Eq. (10) is also plotted for *S*=4, 6 and 8. Reasonable agreement between present and previous results is obtained. Eq. (10) shows good agreement with the observations (mean relative absolute error equals 0.05 and R^2=0.94). The figure indicates that the relative depth ratio increases nonlinearly with F_1 at fixed value of *S* and increases with the increase of *S* at fixed value of F_1. The depth ratio for the free radial hydraulic jump given by Khalifa and McCorquodale [11] is also shown in the figure.

Fig. 5-b presents the results of eq. (10), for *S* = 4, 6 and 8, compared with the experimental results for *S* in the range 3.5-4.0, 5.9-6.9 and 8.0-8.9 at *r*=1.0, K_o in the range 0.9-1.50 and r_o in the range 1.4-1.67. The effect of the drop position on the depth ratio is indicated in fig. 5-c where only the fitting of the experimental data is shown. Clearly, the depth ratio is increased as the distance between the drop and the gate is increased (greater r produces higher depth ratios) at the same F_1. The effects of *S*, *r* and K_o on the relationship between Y_o and F_1 obtained from eq. (10) are *presented* in figs. 6-a, 6-b and 6c, respectively. Clearly, Y_o increases with the increase of *S*, *r* and K_o at fixed Froude number confirming the experimental results.

4.4 Relative length of jump

The results of the length of submerged jump formed in radial basin without drops are presented in fig. 7-a. The results due to McCorquodale and Khalifa [10] for submerged jump (*S*=4, 6), and due to Govinda and Rajaratnam [6] for submerged rectangular jump (*S*=4) are also presented. Submerged radial jump produces shorter length of jump compared to the rectangular submerged jumps. The general trend of the results of the present study corresponds well with those of the previous ones. Higher submergence yields longer jumps. This result was reached also by other authors such as Govinda and Rajaratnam [6] for rectangular submerged

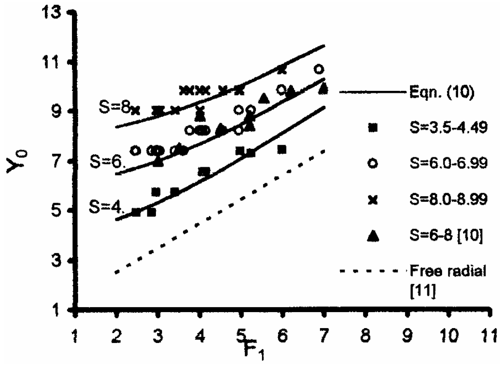

Fig. 5-a. The relationship between Y_0 & F_1 for different *S* for smooth case.

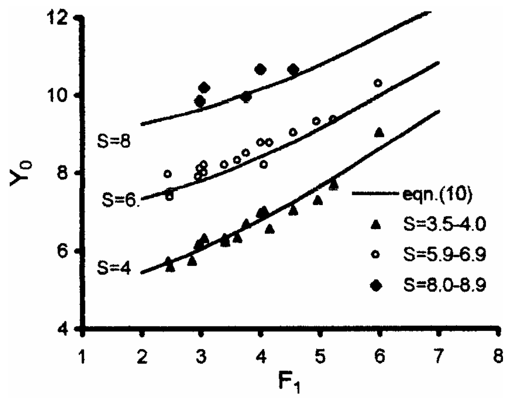

Fig. 5-b. The relationship between Y_0 & F_1 for different *S* at *r* =1.0.

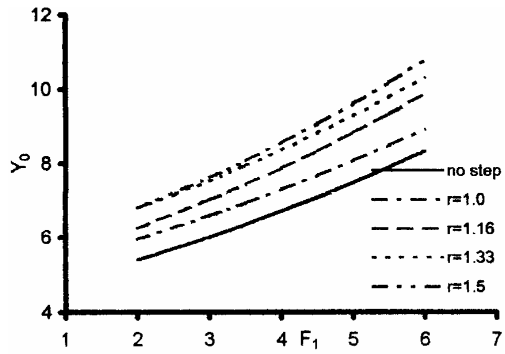

Fig. 5-c. The relationship between Y_0 & F_1 for different step positions and *S* =4.1-4.9.

jump and McCorquodale and Khalifa [10] for submerged radial jump.

The effect of submergence in case of a basin with a drop at r =1.0 is shown in fig. 7-b. Similar trend is observed as for the case of radial basin without drop. The drop positions affect the length of the jump as in fig. 7-c because as the distance between the gate and the drop is increased (greater r), the length of jump is longer at constant S K_o in the range 0.9-1.50 and r_o in the range 1.4-1.67). Experimental data are used to determine the function of eq. (12) in order to enable the prediction of the length of jump. Hence, the length of the basin can be designed for any drop position. Many prediction models based on eq. (12) were tested utilizing all the collected data. Once the most reasonable model is obtained, the Neural Connection [13] software was used to estimate the coefficient of the equation based on 70% of collected experimental data while 30% is kept for testing the prediction of the equation. Both data sets are selected randomly. The following model is found to be the best model representing the experimental data with R^2= 0.75 and mean relative absolute error 0.07.

$$\frac{L_j}{y_1} = -24.286 + 5.101 F_1 + 3.37\,S + 35.79\,r + 4.558\,K_o \,. \tag{13}$$

It is possible to improve the prediction of eq. (13) by excluding the odd points (that may contain some experimental errors). In this case eq. (13) becomes (13-a) with R^2= 0.85 and mean relative absolute error 0.051.

$$\frac{L_j}{y_1} = -23.75 + 5.95\,F_1 + 3.27\,S + 37.92\,r + 0.579\,K_o \,. \tag{13-a}$$

Figs. 8-a and 8-b show the comparison between the model results and the experimental results for the test data set. Fig. 8-a shows good agreement between prediction of eq. (13) and the experimental results. Fig. 8-b shows that the residuals are relatively small, distributed around the line of zero error and they are uncorrelated with R = 0.114.

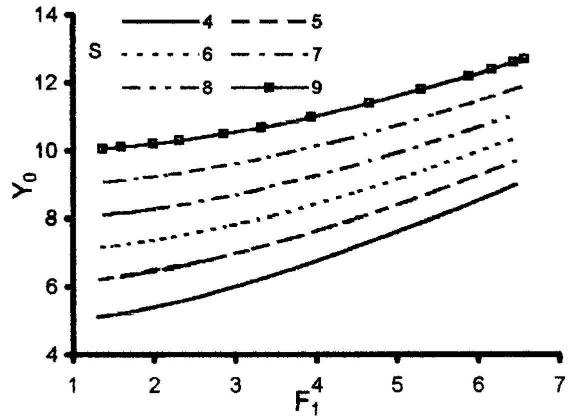

Fig. 6-a. Theoretical relationship between Y_0 & F_1 for different degrees of submergence at r =1.0 and K_0=1.25.

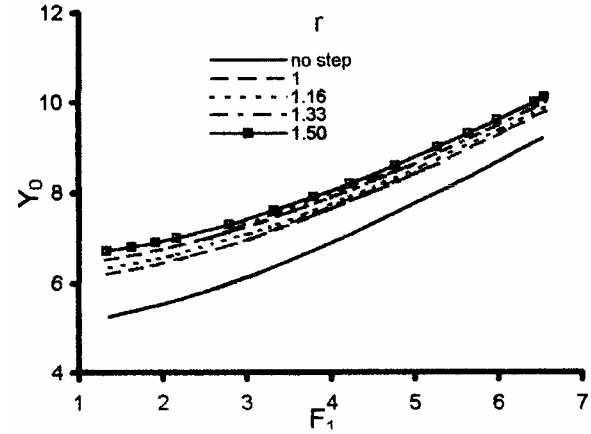

Fig. 6-b. Theoretical relationship between Y_0 & F_1 for different step positions at S=5.0 and K_0=1.25.

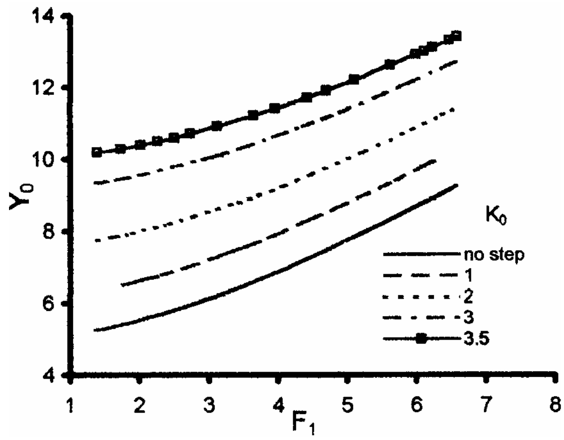

Fig. 6-c. Theoretical relation between Y_0 & F_1 for different relative heights of step at S= 5.0 and r =1.33.

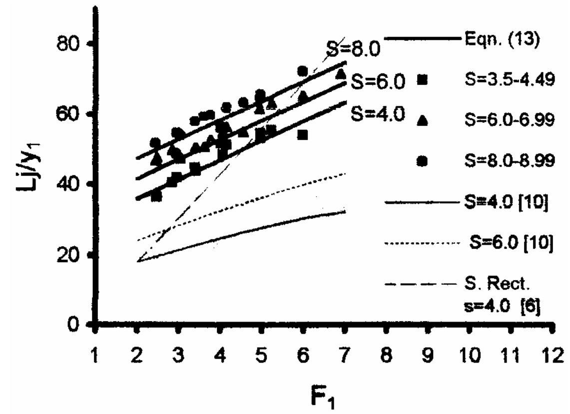

Fig. 7-a. The relationship between Lj/y_1&F_1 for different submergence for no step case.

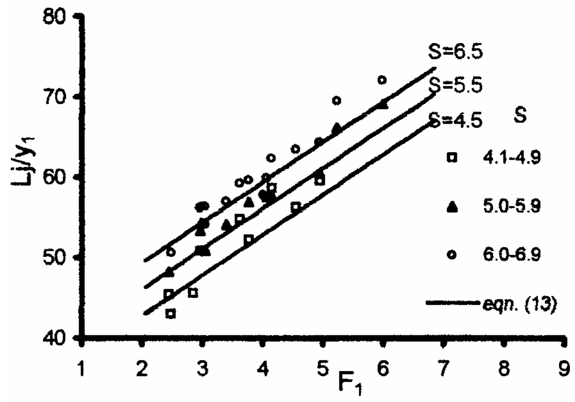

Fig. 7-b. The relationship between Lj/y_1&F_1 for different submergence at r =1.0.

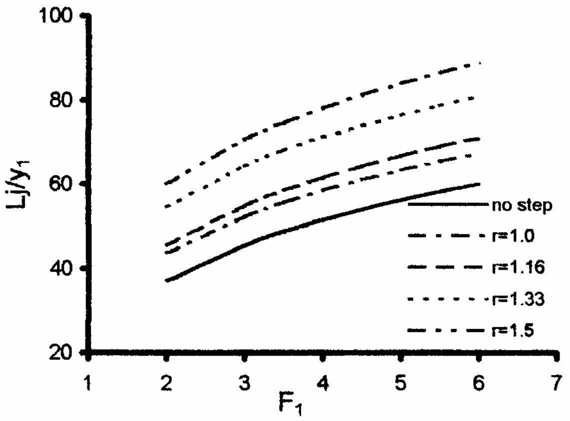

Fig. 7-c. The relationship between Lj/y_1&F_1 for different step positions and S = 5.0-5.9.

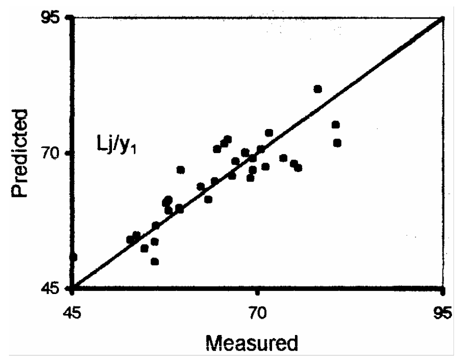

Fig. 8-a. Predicted versus measured for Lj/y_1 for test data set.

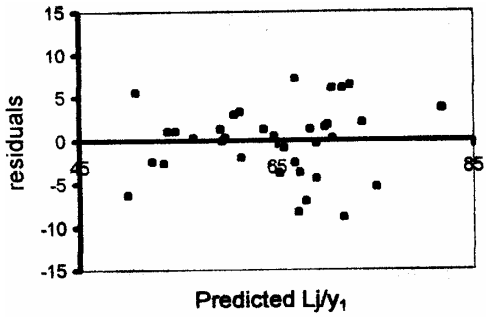

Fig. 8-b. Residuals versus predicted Lj/y_1.

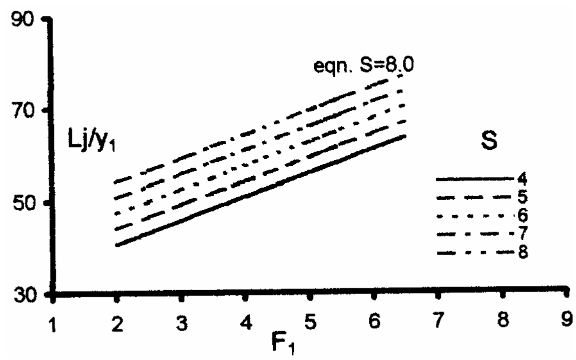

Fig. 9-a. Theoretical relationship between Lj/y_1&F_1 for different S at r =1.0 and K_o=1.25.

The use of eq. (13) in the computation of the length of the hydraulic jump for different values of the flow and basin parameters is shown in figs. 9-a, 9-b and 9-c to indicate the effect of S, r and K_o on the relationship between L_j/y_1 and F_1.

5. Conclusions

Theoretical models were developed for computing the relative depth and relative energy loss of submerged hydraulic jump formed in non-prismatic channel reach in the

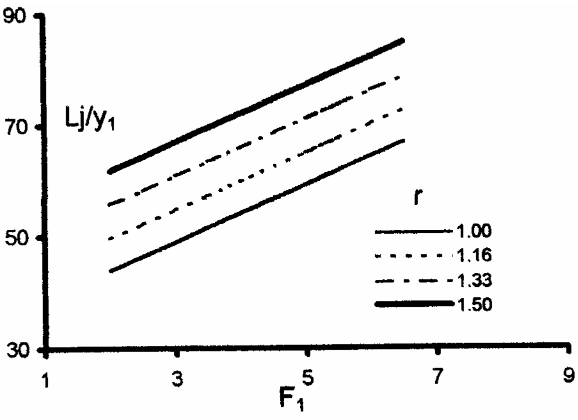

Fig. 9-b. Theoretical relationship between Lj/y_1&F_1 for different step positions at S =5.0 and K_0=1.25.

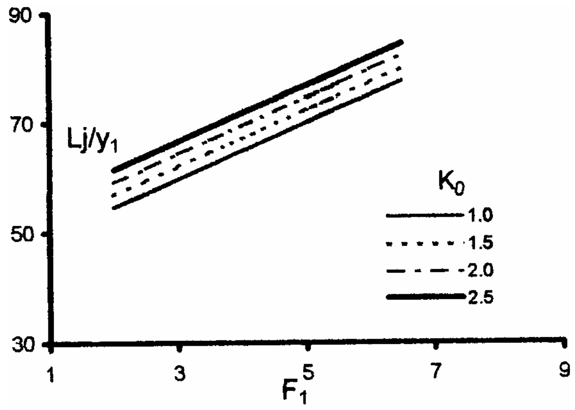

Fig. 9-c. Theoretical relationship between Lj/y_1&F_1 for different K_0 at S =5.0 and r =1.33.

form of radial stilling basin with a vertical drop. The developed and verified models were used to predict the jump relative depth and the relative energy loss of the hydraulic jump. The prediction of the models agreed well with the experimental results. The obtained results were used to investigate the effect of the different parameters as the submergence ratio and the relative position of the drop on the relative depth of the hydraulic jump and on its relative energy loss. The predicting equations may be recommended to be used in the design of the radial stilling basins provided with vertical drops. Both the dimensional and multiple linear regression analysis were employed to develop predicting equation for the length of the hydraulic jump. The experimental data were used to calibrate (70% of the data) and to test (30% of the data) the validity of the model.

Both the experimental results and the developed equations indicated that at a particular relative location of the drop, the relative water depth, relative energy loss and relative length of jump increase by increasing Froude number keeping the submergence unchanged. Also, it is proved that relative water depth and relative length of jump increase by increasing the submergence ratio (at a specific Froude number). Increasing the submergence reduces the relative energy loss keeping other factors unchanged. Also, moving the drop away from the gate (within the basin) increases the relative water depth and relative length of the submerged jump and decreases the energy loss ratio.

Nomenclature

- b_1 is the contracted width of the channel,
- B is the width of the channel,
- E_1 is the total energy at the jump toe,
- E_2 is the total energy at the jump heel,
- E_L is the relative energy loss,
- F_1 is the Froude's number at the initial depth,
- G is the gate opening,
- k is the drop height,
- K_o is the ratio of k to y_1,
- L_j is the length of the hydraulic jump,
- P_1 is the hydrostatic pressure before the jump,
- P_2 is the hydrostatic pressure after the jump,
- P_s is the channel side pressure force,
- P_{st} is the pressure force due to drop,
- Q is the rate of flow,
- r_1 is the radius at the beginning of the jump ,
- r_2 is the radius at the end of the jump ,
- r_o is the ratio of r_2 to r_1,
- r_s is the radius at the end of the drop,
- r is the ratio of r_s to r_1,
- R^2 is the coefficient of determination:
- S is the degree of submergence, y_3/y_1,
- V_1 is the average velocity at the initial depth,
- V_2 is the average velocity at the sequent depth,
- y_3 is the back up water depth just downstream the gate ,
- y_4 is the tail water depth at the end of the jump,

Y_o is the relative tail water depth, y_4/y_1,
y_s is the depth of water above the drop,
Y_s is the ratio of y_s to y_1,
$\overline{y}$ is the representative depth,
γ is the specific weight, and
θ is the angle of divergence.

References

[1] W. H. Hager, "B-Jumps at Abrupt Channel Drops," Journal of Hydraulic Eng., Vol. 111 (5), pp.861-866 (1985).

[2] W.H. Hager and N.V. Bretz, "Hydraulic Jumps at Positive and Negative Step," Journal of Hydraulic Research, Vol. 24 (4), pp. 237-253 (1986).

[3] I. Ohtsu, and Y. Yasuda, "Transition From Supercritical to Subcritical Flow at an Abrupt Drop," Journal of Hydraulic Research, Vol. 29 (3), pp. 309-327(1991).

[4] A.M. Negm, "Hydraulic Jumps at Positive and Negative Steps on Sloping Floors," Journal of Hydraulic Research, IAHR, Vol. 34 (3), pp. 409-420 (1996).

[5] V. Armenio, P. Toscand, and V. Fiorotto, "The Effects of a Negative Step in Pressure Fluctuations at the Bottom of a Hydraulic jump," Journal of Hydraulic Research, IAHR, Vol. 38 (5), pp. 359-368 (2000).

[6] N. S. Govinda Rao, and N. Rajaratnam, "The Submerged Hydraulic Jump, Journal of Hydraulic Div.," ASCE, Vol. 89 (HY1), pp.139-162 (1963).

[7] D. Long, P. M. Steffler, and N., A. Rajaratnam, "Numerical Study of Flow Structure in Submerged Jumps," Journal of Hydraulic Res., Vol. 29 (3), pp. 293-307 (1991).

[8] F. Ma, Y. Hou, and P. Perinos, "Numerical Calculation of Submerged Hydraulic Jumps," Journal of Hydraulic Research, IAHR, Vol. 39 (5), pp. 493-503 (2002).

[9] I. Ohtsu, Y. Yasuda and M. Ishkikawa, "Submerged Hydraulic Jump Below Abrupt Expansions," Journal of Hydraulic Engineering, ASCE, Vol. 125 (5), pp. 492-499 (1999).

[10] J. A. McCorquodale, and A.M. Kalifa, "Submerged Radial Hydraulic Jump," Journal of the Hydraulic Div., ASCE, Vol. 106 (HY3), pp. 355-367 (1980).

[11] A.M. Khalifa, and J.A. McCorquodale, "Radial Hydraulic Jump," Journal of the Hydraulic Division, ASCE, Vol. 105 (HY9), pp.1065-1078 (1979).

[12] V.T. Chow, Open Channel Hydraulics, McGraw-Hill Book Co., Inc., New York (1959).

[13] Neural Connection, ANN Software and manuals, SPSS/Recognition Systems Limited (1998).

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