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Experimental Study of Hydraulic Jump in Adverse Stilling Basin at Smooth Bed

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Abstract

The effect of changing in the bed slope of stilling basins produces changing in characteristics of the hydraulic jump such as sequent depth ratio, length of jump ratio, length of the roller and energy dissipation ratio, consequently the dimensions of stilling basin changed. In this study hydraulic jump investigated on smooth bed (without any appurtenances) for three adverse slopes (- 0.03, - 0.045, - 0.06) in addition to horizontal bed slope, the experiments were applied for the range of Froude number (Fr_1) between 3.99 and 7.48. The results showed a reduction about10 % in sequent depth ratio, 22.1 % in length of jump ratio, 20.51 % in length of roller ratio and 13.87% in the energy dissipation ratio when the adverse slope (-0.06) used instead of horizontal bed for the same Froude numbers. Empirical equations for the sequent depth ratio, length of roller ratio and the energy dissipation ratio were obtained from the experimental data.

Keywords: hydraulic jump, stilling basin, sequent depth ratio, length of jump ratio, energy dissipation ratio.

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1.Introduction

The hydraulic jump is a phenomenon that occurs when a super critical flow is changed to subcritical flow by an obstruction to the flow. This rapid change in flow conditions is accompanied by considerable turbulence and dissipation of energy, transferring some of the flow's initial kinetic energy into potential energy [1].

The geometry of stilling basin affect in the hydraulic jump and any change in the geometry of stilling basin, such as using adverse slope of stilling basin, would change the characteristics of the hydraulic jump.

Hydraulic jump at the adverse bed slope represent unstable phenomenon which causes some difficulty in controlling it, previous studies showed that the hydraulic jump at adverse slopes more than (-0.025) is impossible to control, and other studies showed an impossible to keep the jump completely on adverse slope [2], [3].

The hydraulic jump can be established at $Fr_1 \geq 9$ and for $Fr_1 \geq 4$ the adverse jump still relatively steady without further tailwater adjustments and for $Fr_1 < 4$ (especially as the adverse bed slope increased) continuous adjustment was required even the stabilize position was obtained [4].

The characteristics of the hydraulic jump represented by dimensionless parameters such as a sequent depth ratio (y_2/y_1), length of jump ratio (L_j/y_1), roller length ratio (L_r/y_1) reduced when the adverse stilling basin is used rather than horizontal bed slope [4, 5 & 6].

The energy dissipation ratio ($\Delta E\ /E_1$) affected when the bed slope change, also increasing the adverse bed slope cause a reduction in the relative energy loss ($\Delta E\ /E_1$) [4 & 6]. Bateni and Yazdandoost (2009) [5] concluded in their study that the effect of adverse slope on the relative energy loss was insignificant. Varaki et al. (2014) [7] investigated the hydraulic jump at adverse bed that formed in a diverging stilling basin, their study showed that for any diverging angle of stilling basin, there was a reduction 35% in the relative length due to increasing in the bed slope up to 8%. They concluded that for any diverging angle of stilling basin, there was a reduction 47% in the sequent depth ratio (y_2/y_1) due to increasing in the bed slope up to 8%, but the relative energy loss at diverging stilling basin increases about 20% when compared with the classic hydraulic jump if the adverse bed slope increase to reach 8%.

2.The Theory

Belanger (1838) predicted the sequent depth ratio (y_2/y_1) (for horizontal smooth bed) by using the equation of momentum with the assumption of neglected friction [8], and can be written as:

$$Y = 0.5\,(-1 + \sqrt{1 + 8{F_{r1}}^2}) \quad (1)$$

Where:
$Y = y_2/y_1$ = sequent depth ratio.

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y_2 = sequent water depth of a hydraulic jump (cm).

y_1=upstream water depth of hydraulic jump (cm).

Fr_1= approach Froud number = $\frac{v_1}{\sqrt{gy_1}}$

v_1= upstream velocity (cm/s).

According to Bernoulli's equation between two points (before and after the hydraulic jump as shown in Figure 1 the equation of relative energy dissipation can be derived as: [9]

$$\Delta E+\frac{v2^2}{2g}+y_2\cos\theta+L_j\sin\theta=\frac{v1^2}{2g}+y_1\cos\theta \quad (2)$$

Where:
$\Delta E=E_1-E_2$
E_1= specific energy in section 1 (at toe of hydraulic jump) (cm).
E_2=specific energy in section 2 (at heel of hydraulic jump) (cm).
Lj = length of jump (cm).
Rearrange the equation (2) gives:

$$\Delta E=(y_1\cos\theta-y_2\cos\theta)+\frac{v1^2-v2^2}{2g}-L_j\sin\theta \quad (3)$$

Let $E_1=y_1\cos\theta+\frac{v_1^{\,2}}{2g}$ (4)

By dividing Equation 3 with Equation 4 gives:

$$\frac{\Delta E}{E1}=\left(\frac{(y_1\cos\theta-y_2\cos\theta)+\frac{v1^2-v2^2}{2g}-L_j\sin\theta}{y_1\cos\theta+\frac{v1^2}{2g}}\right) \quad (5)$$

Simplifying the equation 5 and multiplied by the ratio $\frac{y_1\cos\theta}{y_1\cos\theta}$ gives:

$$\frac{\Delta E}{E1}=\frac{\left(1-\frac{y_2}{y_1}\right)+\frac{v_1^{\,2}-v_2^{\,2}}{2gy_1\cos\theta}-\frac{L_j\tan\theta}{y_1}}{\left(1+\frac{v1^2}{2gy_1\cos\theta}\right)} \quad (6)$$

Equation 6 represents the final equation that used in this study to calculate the ratio of energy dissipation.

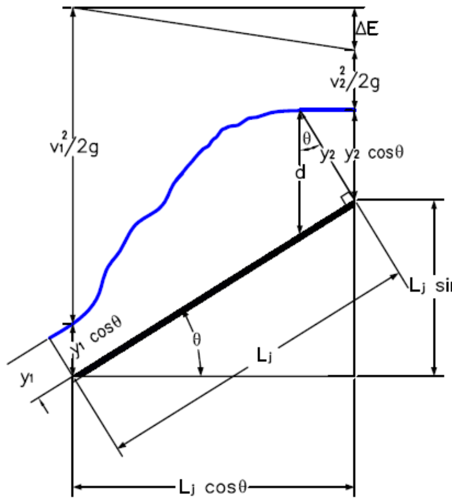


Figure 1: Sketch of hydraulic jump upon adverse slope.

3.Experimental Work

The experimental work has been done in the laboratory of fluid mechanics, Building and Construction Department, University of Technology, Baghdad.

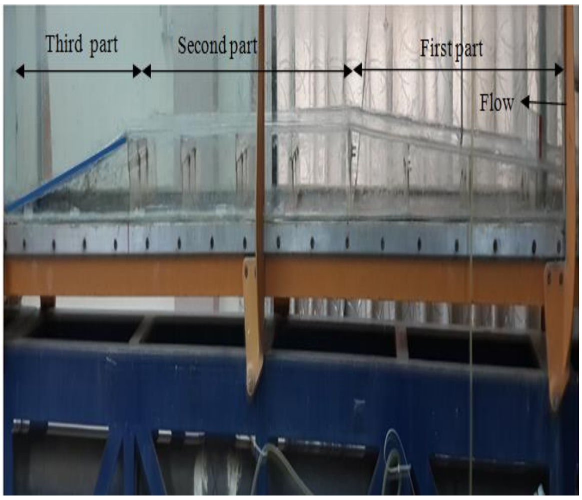
The laboratory flume used in this study divided into two sections, the first one is located upstream the sluice gate which has a rectangular section with 0.3 m wide, 0.55 m deep and 2.30 m long and the second section is located downstream the sluice gate which has a rectangular section with 0.3 m wide, 0.3 m deep and 10.20 m long.

A platform made from plastic sheets (6 mm thick), which installed in the flume to make a various adverse bed slopes (-0.03,-0.045,-0.06) in addition to horizontal bed. The platform consists from 3 parts as shown in Picture 1, the first part of platform represents the stilling basin zone and used to adjust the inclination of the bed slope (adverse and zero slopes) which has a length of 1000 mm, the second part represents a horizontal plane has the same level of end of the first part with a length of 1000 mm, the third part is a transition slope between the level of end of adverse slope and the original level of the bed of the flume.

The sluice gates used to maintain a head of water at the upstream side of the gate and controlling supercritical flow for various values of Froude number (Fr_1), the sluice gate with streamlined lips are used in order to obtain an initial depth of water equals to the gate opening. The flow rate adjusted for each run by the regulating valve that fixed in the feeding pipe and the rotary flow meter was used for the flow rate measuring through the system.

In general, for each run the platform installed on the required slope. The sluice gate adjusted at a certain opening and the required flow rate controlled by regulating valve and flow meter. The range of upstream Froude number (Fr_1) that applied for all runs of this study can summarized in Table 1.

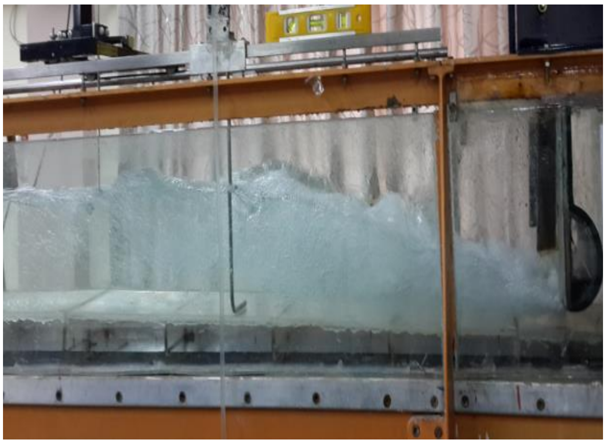
The hydraulic jump at adverse bed slope is difficult to be controlled and continually adjusting to the tailgate is essential to reach a stable position. After the free jump is formed and stabilized in its position as shown in Pictures 2, 3 and 4, then the sequent depth measured by point gage, length of the roller and jump length were measured by measuring tape.



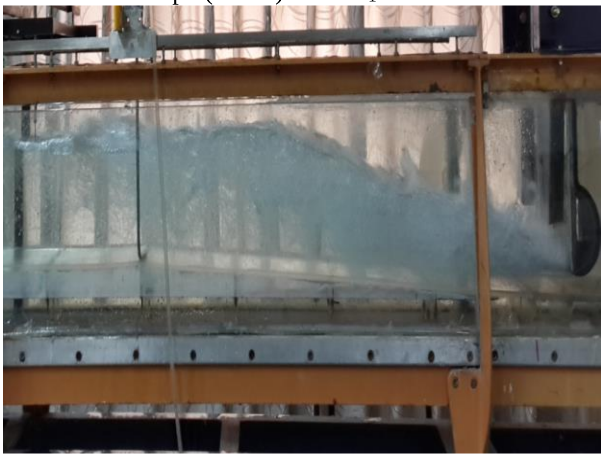
Picture 1: Platform parts

Table 1 The range of upstream Froude number (Fr_1) for all runs of this study.

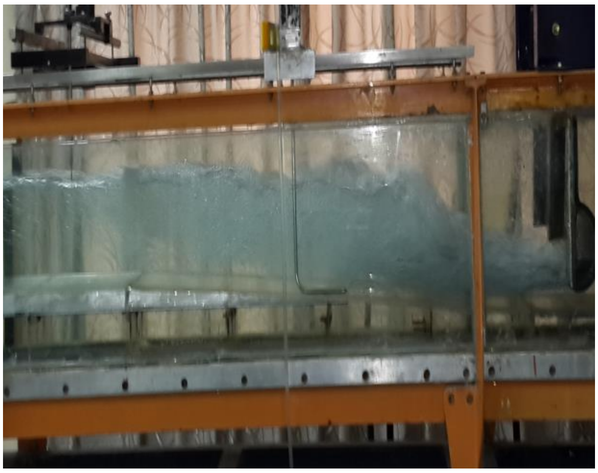
Gate opining (G) (cm)	Flow rate (Q) (m^3/hr)	Approach Froude Number (Fr_1)
3	70	3.983
3	74.9	4.260
3	79.7	4.534
2.5	60	4.487
2.5	65	4.861
2.5	70	5.235
2	55.8	5.836
2	60.6	6.329
1.5	40	6.437
1.5	46.52	7.486



Picture 2: Hydraulic jump at adverse bed slope (- 0.03) with Fr_1= 3.99



Picture 3: Hydraulic jump at adverse bed slope (- 0.045) with Fr_1= 4.53



Picture 4: Hydraulic jump at adverse bed slope (- 0.06) with Fr_1= 4.26

4.The Results

The results of this study represented by dimensionless parameters such as**:** sequent depth ratio (y_2/y_1)**,** length of jump ratio (Lj/y_1)**,** roller length ratio (Lr/y_1) and energy dissipation ratio ($\Delta E/E_1$) which explain in detail.

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4.1 Sequent Depth Ratio

In general the ratio (y_2/y_1) increased as (Fr_1) increased for the smooth condition on horizontal and adverse bed slopes, while the ratio (y_2/y_1) reduced when the adverse bed slope increased for the same (Fr_1) as shown in Figure 2. These results agree with the results of the researchers Mccorquodale and Mohamed (1994) [4], Nikmehr and Tabebordbar (2010) [9] and Pagliara and Palermo (2015) [10].

The average reduction in the ratio (y_2/y_1) reaches to about 10 % when smooth bed with slope (- 0.06) used instead of horizontal smooth bed.

The ratio (y_2/y_1) reduced when the adverse bed slope increased due to the effect of the water weight because increases in the volume of water in the toe of the hydraulic jump lead to make the jump behave as submerged, therefore reducing the tailwater be essential to forming a free hydraulic jump, consequently the ratio (y_2/y_1) is reduced**.**

An empirical equation is predicted from the experimental data of this study and by using the dimensional analysis technique (Bukingham's theorem) and statistical software program (Minitab 17) as:

$$\frac{y_2}{y_1} = f(Fr_1, \tan\theta) \quad (7)$$

$$\frac{y_2}{y_1} = \frac{{Fr_1}^{1.04}}{1.22(\tan\theta)^{0.092}} \quad (8)$$

Equation 8 represents a relation between sequent depth ratio (y_2/y_1), (Fr_1) and adverse bed slope ($\tan\theta$) with determinant coefficient (R^2 =0.989) and root mean square error (RMSE = 0.0217), it is valid for adverse slope ($0 < \tan\theta \leq 0.06$).

Pagliara and Peruginell (2000) [11] predicted an equation to estimate the sequent depth ratio for hydraulic jump on the adverse bed slope as:

$$\frac{y_2}{y_1}=0.5(-1+\sqrt{8\{3.32^{-(1.518\tan\theta)}Fr_1\}^2+1}$$

$0 < \tan\theta < 0.25$ (9)

The sequent depth ratio according to equation 8 satisfy with equation 9 with average reduction value about 3.92% as shown in Figure 3.

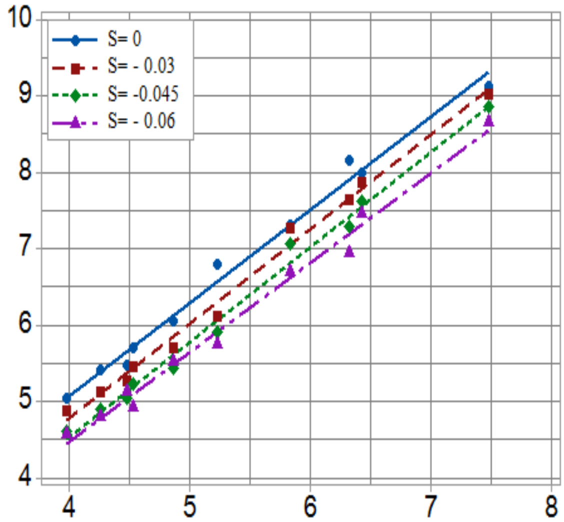

Figure 2: Relation of sequent depth ratio with (Fr_1) for various adverse and horizontal bed slopes for smooth condition

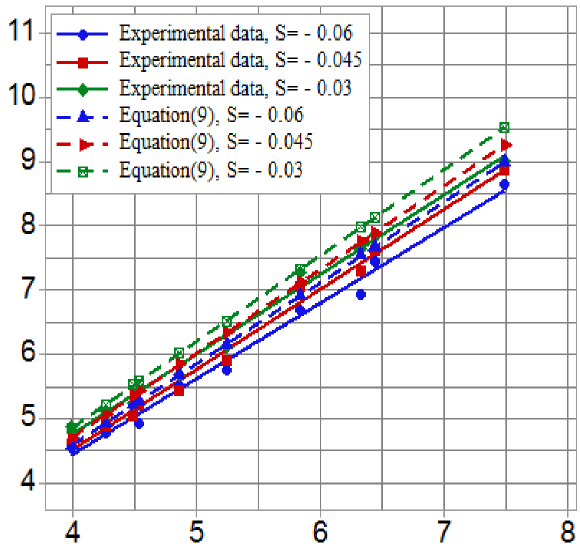

Figure 3: Comparison between experimental data of (y_2/y_1) ratio and theoretical (y_2/y_1) ratio according to equation 9 for smooth adverse bed slopes

4.2 Length of Jump and Roller Length Ratio

Experimental data of this study show increasing in the length of jump ratio (Lj/y_1) and length of roller ratio (Lr/y_1) as (Fr_1) increased for the smooth case of horizontal and smooth adverse bed slopes. Also, the ratios (Lj/y_1) and (Lr/y_1) reduced with increasing adverse bed slope for the same (Fr_1) as shown in Figure 4 and Figure 5. These results agree with results of the researchers Mccorquodale and Mohamed (1994) [4], Bateni and Yazdandoost (2009) [5] and Nikmehr and Tabebordbar (2010) [9]. The average reduction in the ratio (Lj/y_1) and (Lr/y_1) reaches to about 22.1 % and 20.51% respectively due to using smooth bed with slope (- 0.06) instead of horizontal smooth bed.

The reduction in both ratios (L_j/y_1) and (L_r/y_1) due to using the adverse bed slope because of the effect of the weight of water that acts in the direction against the direction of flow and prevent the jump to extend forward.

An empirical equation is predicted from the experimental data of this study and by using the dimensional analysis technique (Bukingham's theorem) and statistical software program (Minitab 17) as:

$$\frac{Lr}{y_1} = f(Fr_1, \tan\theta) \quad (10)$$

$$\frac{Lr}{y_1} = \frac{2.102\, Fr_1^{\,1.2554}}{(\tan\theta)^{0.1492}} \quad (11)$$

Equation 11 represents a relation between length of roller ratio (L_r/y_1), (Fr_1) and adverse bed slope ($\tan\theta$) with determinant coefficient (R^2 =0.9905) and root mean square error (RMSE = 0.024), it is valid for adverse slope ($0 < \tan\theta \leq 0.06$).

Mccorquodale and Mohamed (1994) [4] predicted an equation to estimate the length of roller ratio (L_r/y_1) for hydraulic jump on adverse bed slope as:

$$\frac{Lr}{y_1} = (7.25 + 20.8\sin\theta + 5\sin^2\theta)(Fr_1 - 2) + 5(1 + 50\sin^4\theta) \quad (12)$$

Equation 12 valid for Fr_1 (less than 9) and for bed slopes range (0 to - 0.2), The length of roller ratio (L_r/y_1) according to Equation 12 satisfy with Equation 11 with average reduction value about 6% as shown in Figure 6.

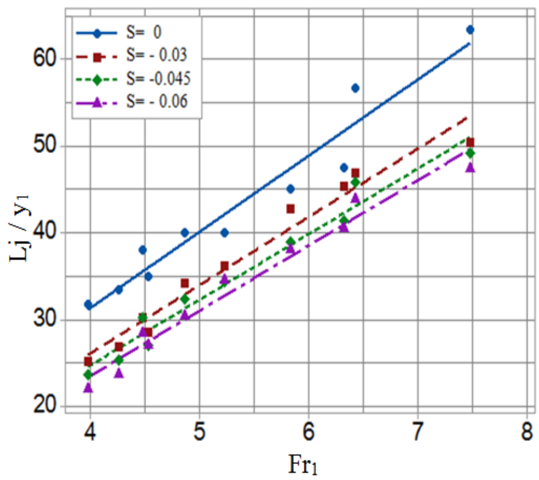

Figure 4: Relation of length of jump ratio (L_j/y_1) with (Fr_1) for various adverse and horizontal bed slopes for smooth condition

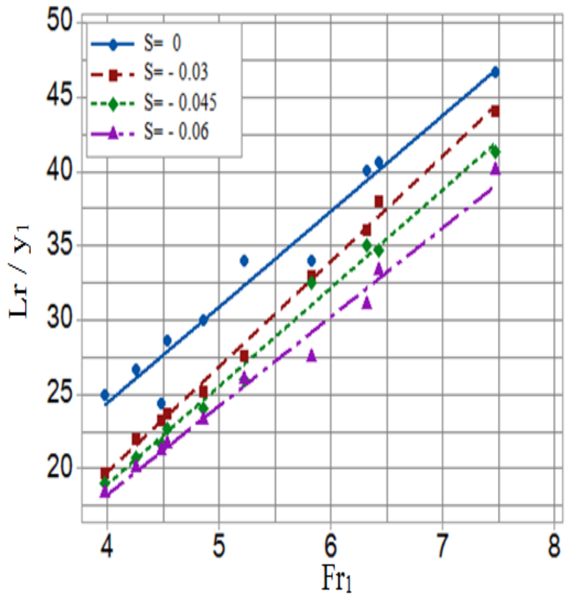

Figure 5: Relation of length of roller ratio (L_r/y_1) with (Fr_1) for various adverse and horizontal bed slopes for smooth condition

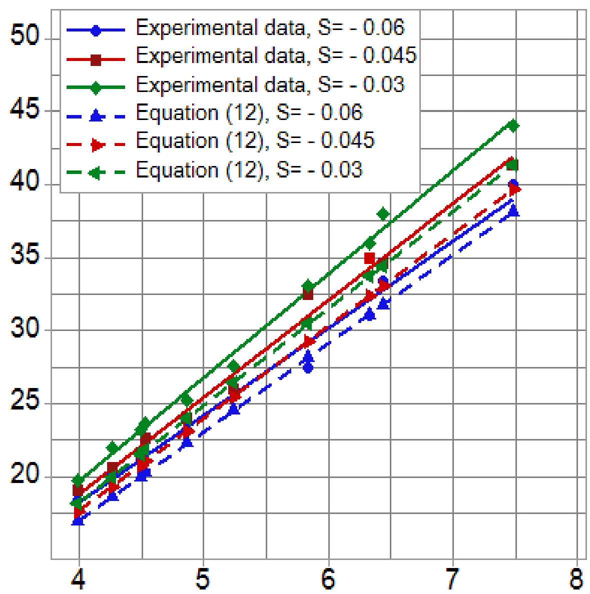

Figure 6: Comparison between experimental data of (L_r/y_1) ratio and theoretically (L_r/y_1) ratio according to equation (12) for smooth adverse bed slopes

4.3 Energy Dissipation

Experimental data of this study show an increasing in the ratio of ($\Delta E/E_1$) with (Fr_1) in the adverse and horizontal bed slopes, but the energy dissipation ratio is reduced when the adverse slope increased for the same (Fr_1) as shown in Figure 7. Thes results agree with the results of the researchers Mccorquodale and Mohamed (1994) [4], Beirami and Chamani (2010) [12] and Nikmehr and Tabebordbar (2010) [9]. Otherwise, the result of this study does not agree with the results of the researchers Bateni and Yazdandoost (2009) [5] and Varaki et al. (2014) [7], because this study investigates the hydraulic jump that formed in the rectangular adverse stilling basin while Varaki et al. (2014) [7] investigated the hydraulic jump in a diverging stilling basin. According to the experimental data of this study, the average reduction in the energy dissipation ratio ($\Delta E / E_1$) reaches to about 13.87 % when smooth bed with slope (- 0.06) used instead of horizontal smooth bed.

The energy dissipation of the hydraulic jump on the adverse bed slope reduced as a result of high specific energy at the heel of jump (E_2) for adverse bed slope, consequently the head losses (ΔE) for adverse slope is reduced, and with regard constant value for (E_1) in adverse and horizontal slope therefore the energy dissipation ($\Delta E / E_1$) in adverse slope is less than that in horizontal slope.

An empirical equation is predicted from the experimental data of this study and by using the dimensional analysis technique (Bukingham's theorem) and statistical software program (Minitab 17) as:

$$\frac{\Delta E}{E_1} = f(Fr_1\ ,\ y_2\ , y_1\ , \tan\theta\ ) \quad (13)$$

$$\frac{\Delta E}{E_1} = \frac{{Fr_1}^{2.06}}{16.73(\tan\theta)^{0186}} \quad (\frac{y_2}{y_1})^{-1.09} \quad (14)$$

Equation 14 represents a relation between the energy dissipation ratio ($\Delta E / E_1$), (Fr_1), (y_2/y_1) and adverse bed slope ($\tan\theta$) with determinant coefficient (R^2 =0.986) and root mean square error (RMSE = 0.022), it is valid for adverse slope ($0 < \tan\theta \leq 0.06$).

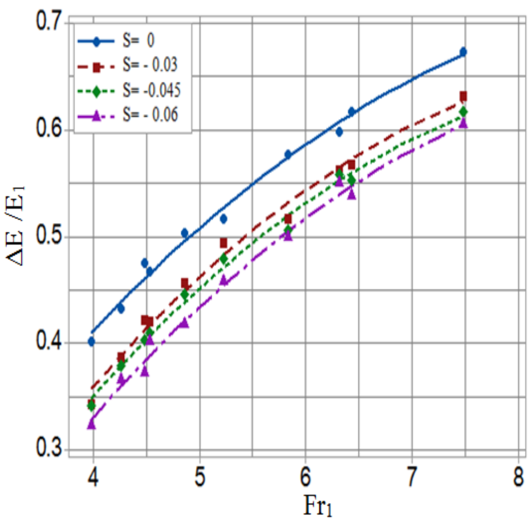

Figure 7: Relation of energy dissipation ratio ($\Delta E / E_1$) with (Fr_1) for various adverse and horizontal bed slopes for smooth condition

5.Conclusions

The control of hydraulic jump at adverse stilling basin is difficult, especially when adverse slope increased due to increasing the effect of water weight in a direction against the direction of flow, therefore continuous adjustment for the tailgate is essential to reach to stable status. Hydraulic jump on the adverse bed slope formed with length, sequent depth and roller length less than that on horizontal bed, consequently the length of the basin and the height of the basin wall reduced and economical requirement will satisfy. Using a stilling basin with adverse slope (- 0.06) instead of a horizontal bed cause reduction in the characteristic of hydraulic jump as: 10% for sequent depth ratio, 22.1 % for length of jump ratio and 20.51 % for length of roller ratio.

The energy dissipation ratio for hydraulic jump on the adverse bed with slope (- 0.06) also reduced when compared with that on horizontal bed, the average reduction value for this case reach to 13.87%, therefore the stilling basin needs more protections when constructed with adverse slope such as using baffle blocks or corrugated bed.

6.References

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