Journal of University of Duhok, Vol. 20, No.1 (Pure and Eng. Sciences), Pp 654-661, 2017
eISSN: 2521-4861 & pISSN: 1812-7568
https://doi.org/10.26682/sjuod.2017.20.1.57

CHARACTERISTICS OF HYDRAULIC JUMP ON A STRIPED CHANNEL BED

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ABSTRACT

The substantive conditions are affecting the subjective process of creating rapid turbulent changes in flow. Such character happens in hydraulic jump phenomenon, which depends on how much of flow kinetic energy changes into potential energy. During this process part of the kinetic energy is dissipated by taking other types of energy in the channel. The quantity of energy dissipated reflects on the height and length of the jump. The effects of lowering the bed of channel by means of square strips of six different spaces (2, 3, 4,5,6,7 cm) respectively are studied experimentally with additional smooth bed. The investigation leads that bed strips increases the energy dissipation by 6%. The energy dissipation increases with the increase of strips spacing, the best spacing is between 5 and 6 cm. Consequently jump height decreases which is reflected by the reduction of the relative sequent depth value by (6%-15%). While the relative length of jump decreases by 22% and 28% compared with the smooth bed. The mean dimensionless depth deficit is 0.15 and normalized jump length is 2.5. Within the limitations of this work, different relationships are suggested to predict hydraulic jump characteristics with coefficient of determination more than 0.9.

***KEYWORDS*:** Energy Dissipation, Hydraulic Jump, Jump Length, Sequence Depth,

1. INTRODUCTION

Hydraulic jump as a tool for energy dissipation at outlet works of hydraulic structures such as spillways has been used widely. Therefore, study of hydraulic jump properties including its length, sequent depth ratio and energy dissipation has been of interest for researchers for decades. To stabilize the location of a hydraulic jump and reduce its length, stilling basins with accessories such as baffle blocks and end-sills were standardized by Peterka (1958). A hydraulic jump occurring in a horizontal, wide rectangular channel on a smooth bed is known as classical jump (Chow, 1959). The subcritical sequent depth Y_2* for an incoming supercritical flow of depth Y_1 and mean velocity $V_1$with a Froude number $Fr_1=\frac{V_1}{\sqrt{gY_1}}$is given by the Belanger equation:

$$\frac{Y_2^*}{Y_1}=\frac{1}{2}\left[\sqrt{1+8{Fr_1}^2}-1\right] \qquad (1)$$

Hydraulic jumps on roughened beds were investigated by Rajaratnam (1968), Hughes and Flack (1984). The findings showed a reduction in both required tail water depth to form a jump and its corresponding length comparing with classical jumps of similar Fr_1.Roughness elements of different shapes, intensities, arrangement and length extent have been investigated thoroughly by researchers such as Mohammed Ali (1991),Negm (2002),Pagliara et al. (2008),Ezizah et al. (2012),AboulAtta et al. (2011)and Elnikhely(2014). However, the concern in regard to jumps on rough beds is the separation of flow and occurrence of cavitation and erosion at the roughness elements upstream of the jump (Ead and Rajaratnam, 2002). Therefore, Ead and Rajaratnam(2002) investigated hydraulic jumps on corrugated beds in which the crest of the corrugation was at the same level of the upstream bed i.e. not protruding into the flow, thus minimizing the occurrence and impact of cavitation. After that research, a number of researches have been carried out using different shapes of corrugations, varying relative roughness t/Y_1 (t is the thickness of corrugation) andwave steepness t/s (s is the wavelength).

Sinusoidal shape as bed corrugation was investigated by Ead and Rajaratnam (2002). In their research, t/Y_1 ranged from 0.25-0.5, Fr_1 was from 4 to 10 and two values of t/s of 0.19 and 0.32 were used. The dimensionless depth deficit D=(Y2*-Y2)/ Y2* was 0.25. The normalized jump lengthLj/Y2* was about 3. Tokyay (2005) extended the work on the sinusoidal corrugation by using t/Y_1 of 0.6-1.2, t/s of0.2 and 0.26 and $Fr_1$was 5-12. Compiling the experimental data of Ead and Rajaratnam (2002), Tokyay (2005) found out that, D was 0.2, Lj/Y2* was 4 for Fr_1>6 and higher energy losses were achieved using

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corrugated beds comparing to smooth bed. Also, Abbaspour et al. (2009) studied the sinusoidal corrugation further by using wide ranges of t/Y_1 and t/s of (0.32-1.67) and (0.286-0.625) respectively and Fr_1range of 3.8-8.6. The findings of the research were, D was 0.2, Lj/Y2* was 3 (Fr_1<6) and 3.5 (Fr_1>6). Izadjoo and Bejestan (2007) studied a corrugation of trapezoidal shape. In their experiments, t/Y_1 was (0.371-1.733), t/s was (0.208-0.382) and $Fr_1$was (4-12). They found D to be 0.2 and Lj/Y2* as 3. Elsebaie and Shabayek (2010) studied five different shapes of sinusoidal, triangular, trapezoidal with two different side angles and rectangular. The parameters were, t/Y_1 was 0.36 and 0.72, t/s was 0.276 and $Fr_1$was 3-7.5. The findings were, D was 0.37 and Lj/Y2* was 2.1. Moreover, they concluded that for the same amplitude and wavelength the shape of corrugation does not have a significant influence. Samadi et al. (2013) studied triangular shape with five different side slopes with Fr_1 (6.1-13.1), t/Y_1 (0.7-4.5) and t/s (0.22-0.29). They found an average D of 0.25 and Lj/Y2* was 2.5 for Fr_1<9.5 and 3.17 for Fr_1>9.5. Tokaya et al. (2011) studied three types of corrugation, sinusoidal, strip (rectangular cross-section) shapes and staggered configuration. For the strip shape, w/L was (2-11), w/z was (3-16.5) and Fr_1 ranged from 2.13 to 11.92. In that study, w was the clear spacing between strips, L was the width of strips and z was their thickness. It was reported that tail water depth reduction was in the range of 5 to 13%, length of jump was shortened by 40% and energy losses was enhanced by 3 to 7%. A common outcome that was stated by all the above researchers was that the relative roughness t/Y_1 does not have a sensible influence on hydraulic jump parameters namely, depth ratio and jump length. This is because the corrugation acts as cavities in bed (Ead and Rajaratnam, 2002). In addition, lower tail water depth, shorter jump length and higher energy losses were attributed to increased bed shear stress at the crest of corrugation. Therefore, influence of wave steepness t/s has been recommended to be studied further.

The aim of the current study is to investigate the impact of a square shaped corrugation with wave steepness $0.14 \leq t/s \leq 0.5$ and relative roughness of (t/Y_1) of 1.67 on the characteristics of hydraulic jump, namely; sequent depth ratio, length of hydraulic jump and energy dissipation. Range of Froude number5.7 and 9.7

2. BACKGROUND and EXPERIMENTAL WORK

The hydraulic jump can be characterized by, sequent depths, percent of energy loss and jump length. These characters are affected by physical properties of incoming flow and geometrical properties. The bed of the channel was roughed by strips. The strips were constructed using 1 cm by 1cm cross section of Plexiglas. The strips located at different spaces S (center to center). Figure 1 illustrates a definition sketch illustrating hydraulic jump on lowered bed by strips.

Basically the physical properties of incoming flow to the jump can be presented by Y_1 the depth of flow before the jump and its velocity V_1. The flow after the jump presented by depth Y2 and velocity V2. As the jump and flow occurs on rough bed of varying distance S, so that these parameters and the fluid property are the effectors of the flow phenomena characteristics. The functional relation including the above properties presented in variables is presented in equation (1).

$$f\left(Y_1, Y_2, L_j,, V_1, V_2, g, \rho, \mu, S\right) = 0 \qquad (2)$$

in which L_j is the length of jump, ρ is the density of water, g is the gravitational acceleration, μ is the dynamic viscosity. The variables in equation (2) are related to each other in one phenomenon as three dimensionless functional relationships can be written for each jump character as in equation (3)

$$\left.\begin{aligned} \frac{Y_2}{Y_1} &= f(Fr_1, \mathrm{Re}_1, \frac{S}{Y_1}) \\ \frac{E_{dissip}}{E_1} &= f(Fr_1, \mathrm{Re}_1, \frac{S}{Y_1}) \\ \frac{L_J}{Y_1} &= f(Fr_1, \mathrm{Re}_1, \frac{S}{Y_1}) \end{aligned}\right\} \qquad (3)$$

Fr_1= incoming Froude Number before the jump
Re1 = Reynolds number before the jump
E dissip = E1 – E2

Reynolds number has quite high values indicating that the viscosity has limited effect which can be omitted.

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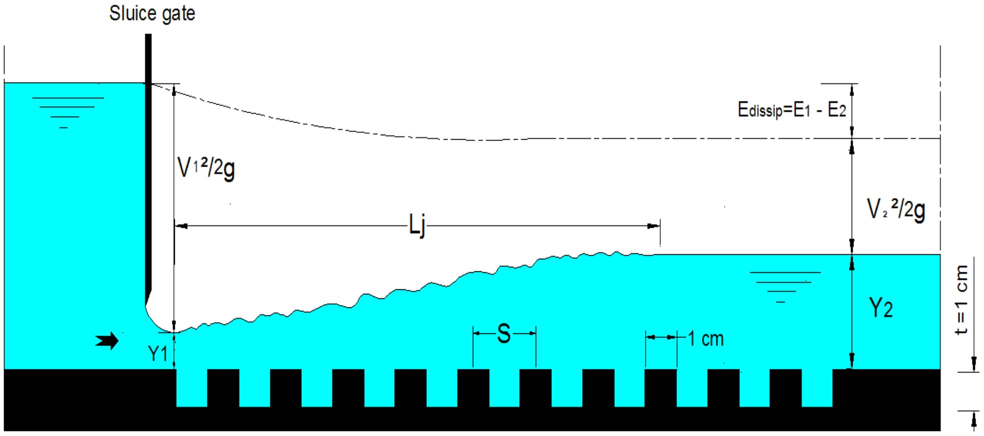

Fig.(1):- Definition sketch

To achieve the characteristics of the hydraulic jump an experimental measures was carried out in a horizontal flume of 2.4 m long with a rectangular cross section of 25 cm height and 7.5 cm width. The supercritical flow was generated using a sharp-edged sluice gate. Plexiglas was used to prepare strips of square shaped corrugation of 1 by 1 cm. The corrugated beds were placed such that the crest of the corrugation was at the same level of the bed upstream of the sluice gate. The spacing between the square elements was 2, 3, 4, 5, 6, and 7 cm c/c, in addition a smooth bed is also tested. Using a tailgate, all jumps were forced to occur at the beginning of the corrugation and close to the sluice gate at a distance of (4-7) cm. The sequent depth of the jump Y2was measured by point gauge at a place where the water surface fluctuation of hydraulic jump finished. Length of jump was measured from the beginning of the jump to a point where surface rollers and fluctuations became less violent and started to be vanished. Figure 2showsa photo for the models and the flow performance. Hager 1992 stated that the length of hydraulic jump cannot be easily defined in actual experiments, so an additional measure has been taken from four different image photo for each run find the length of the jump. The average value of image and direct laboratory measures were taken to fix the length of jump. The flow discharge was measured using a volumetric tank.

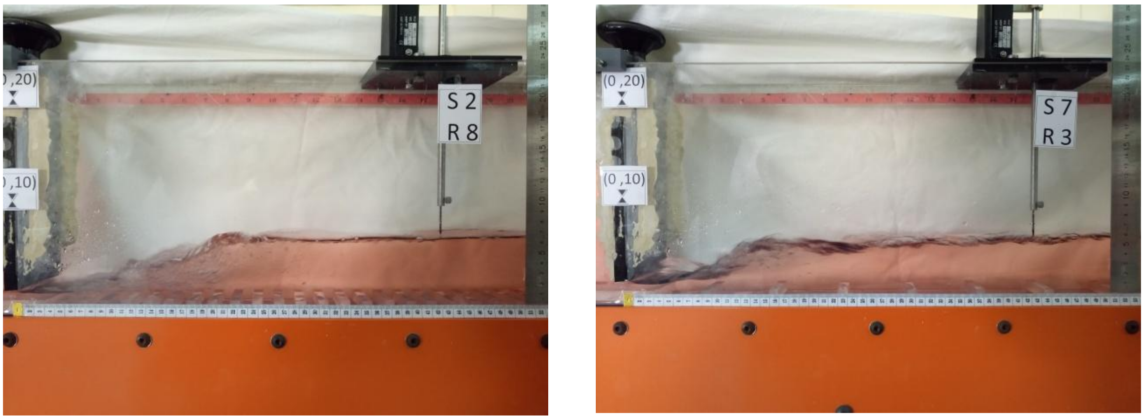

Fig.(2):-Photo representation of hydraulic jump and bed strips

3. RESULTS AND DISCUSSION

The dimensionless parameters in equation (3) are calculated from the experimental measures and geometric data. The three jump's characteristics which are energy dissipation percent (E_{loss}/E1), relative sequence depth ($Y2/Y_1$) and the relative jump length (Lj/Y_1) were highly correlated to the values of Froude (Fr_1) and to the relative roughness length (S/Y_1) at the 0.01 level (2-tailed). Pearson's correlation factor is more than 0.917 for Fr_1 and is - 0.438 for (S/Y_1), more over all the dimensionless parameters which were correlated in matrix show asignificant correlation between them at the 0.01 and 0.05 levels (2-tailed).The incoming flow Froude numberFr_1 varies between 5.67 and 9.66 with standard deviation0.9754680, this type of jump is mainly considered as a stable and well-balanced jump (steady jump) according to the US Bureau of Reclamation (1987), and there are some runs of Strong jump. The open channel flow literatures such as Chow 1957,Chanson 2004, and Chaudhry2008 stated that the energy dissipation in a horizontal rectangular channel caused by steady jump is between 45–70% and up to 85% for the strong jump. Figure 3 illustrates variation of the percentage of energy dissipation with Froude number, it can be noted the logical increase of the dissipated energy with increase of Froude number, also it can be notices an excepted quantity of energy dissipations as mentioned by the above fundamental literatures. Figure 3 shows also the positive effect of bed strip roughness on the energy dissipation, it can be seen that all roughened beds cause more dissipation of energy than the smooth bed. The dissipated energy depends on strip spaces S. The incoming jet flow is partially slipping on the strips (not impacted as buffer), so that its positive effect is mainly caused by turbulence generated in the flow due the bed roughness. The increase in energy dissipation is 6% compared with the smooth bed. The best strip for dissipation energy (S) is between 5 and 6 cm as presented in Figure 4.

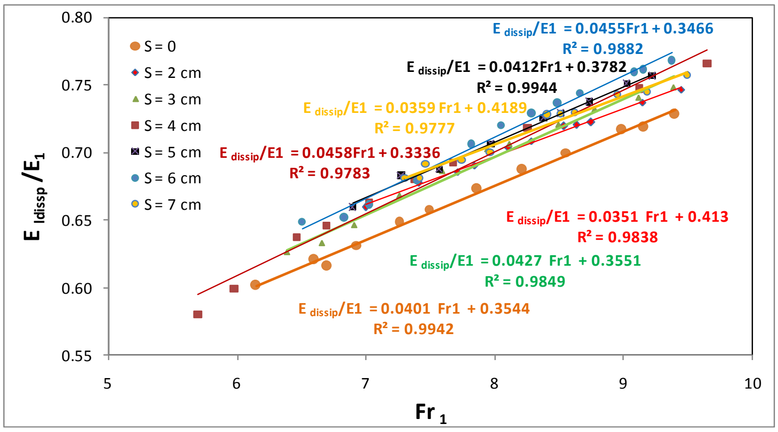

Fig.(3):-Relation between relative energy dissipation and Froude number

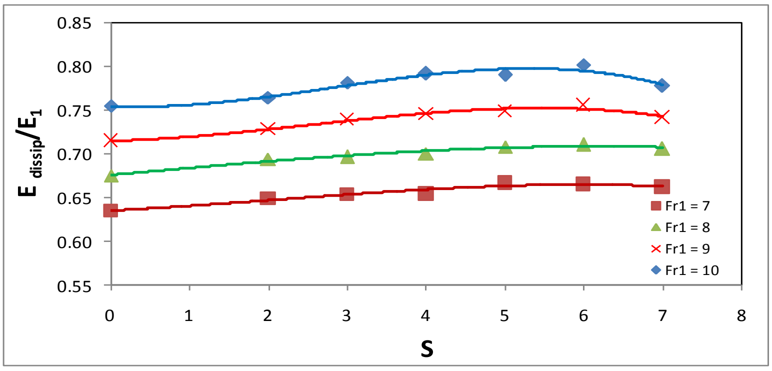

Fig.(4):- Relation between relative energy dissipation and space of stripe roughness

The relative sequent depth ($Y2/Y_1$) logically increases with increase of incoming Froude number (Fr_1) for all types of channel beds, but the values of this parameter are less for the rough beds as illustrates Figure 5. That means the hydraulic jump on rough bed has a lower height of jump. The relative jump height $(\Delta Y)/Y_1$ is illustrated in Figure 6. The percent reduction in jump height due to bed stripes varies between 6% forFr_1 =6 to 15% for Fr_1= 9.

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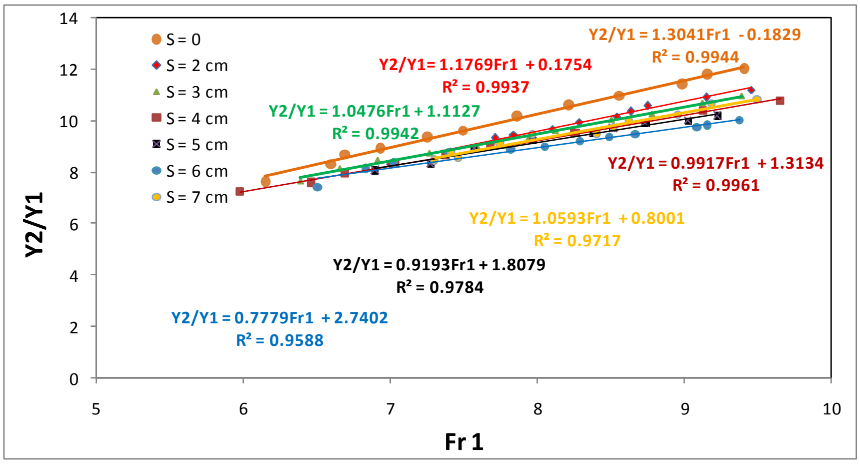

Fig.(5):- Relation between sequent depths and Froude number

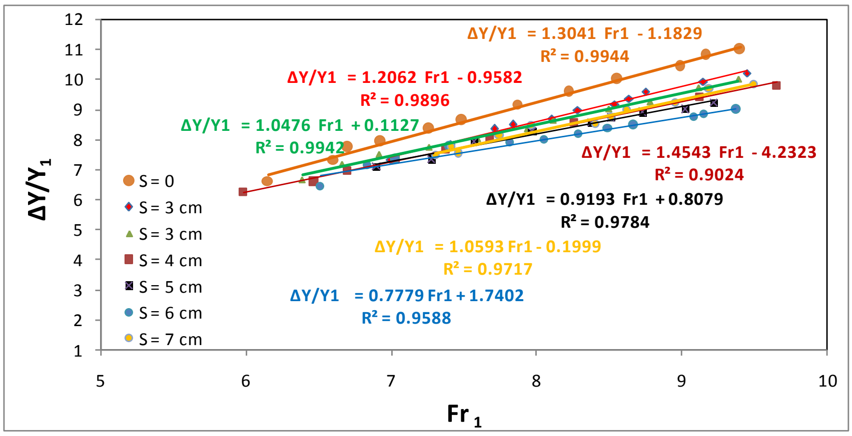

Fig.(6):- Relation between relative height of jump and Froude number

To also show how the roughness effect the quantity of dissipated energy Figure 7 demonstrate that for a certain value of relative height of jump the stripes in the bed of the channel causes more dissipation compared with the smooth one.

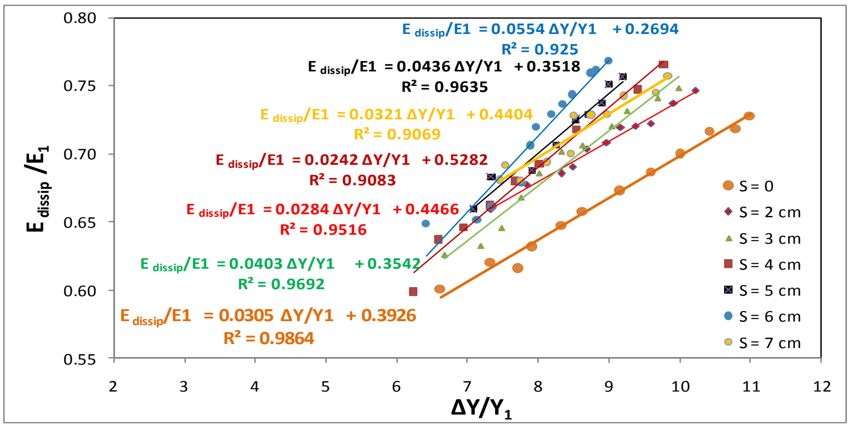

Fig.(7):- Relation between relative energy dissipation and relative jump height $\Delta Y/Y_1$

The relative length of hydraulic jump is illustrated in Figure 8, it shows how the bed roughness reduces the relative length of jump. The turbulent eddies caused by bed roughness increases the process of dissipation of kinetic energy and changing it to potential energy. This dissipation and changing process will happen in shorter distance due to bed roughness. The

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percentage of redaction in the relative length is 28% for Fr_1=7 when the roughness distance increase from smooth to 7 cm and equal to 22% for Fr_1=9.

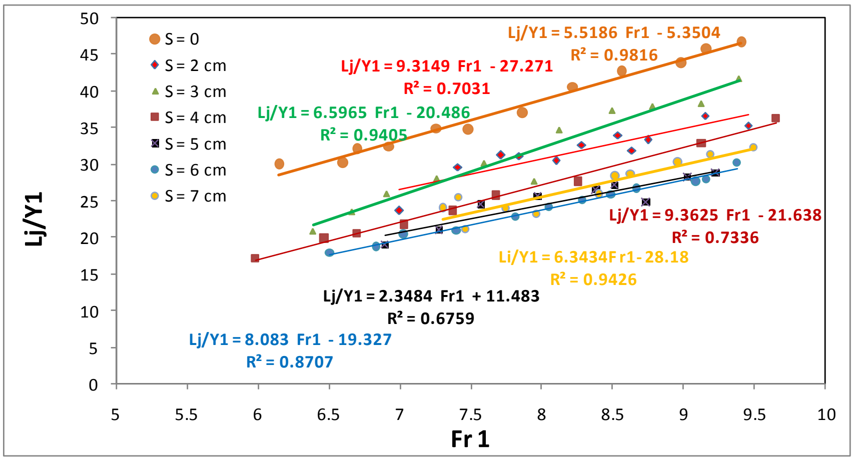

Fig.(8):- Relation between relative jump length and Froude number

It is also useful to present the decreasing relation between the energy dissipation percent and (Y_1/Yc) in Figure 9.The decrease of the energy dissipation is evident with the increase of (Y_1/Yc), related to the fact that when the gap between the depth Y_1 and Yc decreases on the supercritical stage part of the specific energy curve, that means the flow tends to be critical and the consequence of that is the decrease of the energy dissipation due to jump until toward the critical flow. This can be noted in Figure 9 that the line presenting the roughness width became near each other with the increase of Y_1/Yc.

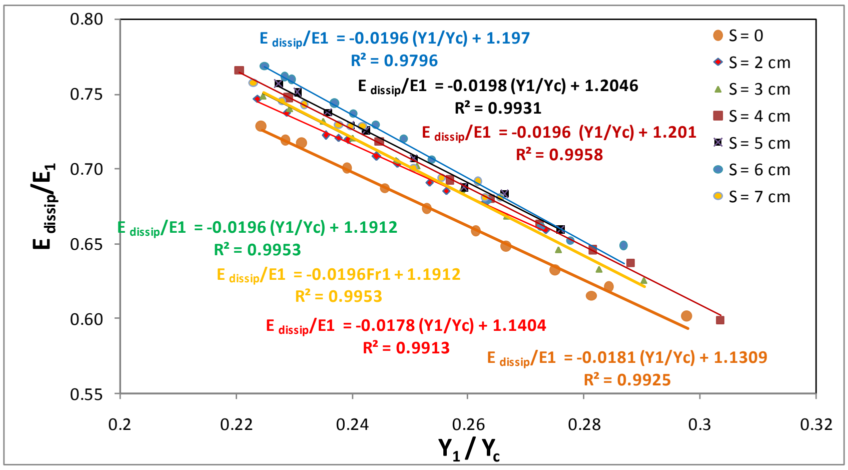

Fig.(9):- Relation between relative energy dissipation and (Y_1/Yc)

The subcritical sequent depth Y_2* is calculated corresponding to incoming supercritical flow. The calculations based on values of Froude number Fr_1 and depth Y_1. The dimensionless depth deficit D is calculated for all roughened beds, its value varies between 0.11 and 0.22with mean equal to 0.15 and standard deviation of 0.0295135. The normalized jump length (Lj/Y_2*) varies between 2.01 and 3.26 with a mean equal to 2.5 and standard deviation of 0.3371308.

The linear regression has been employed to find the mathematical models between the three dependent variables characterizing the hydraulic jump in equation (3) and independent variables (Fr_1, S/Y_1). Nonlinear Regression Analysis also employed to ensure if there are better mathematical models with reasonable

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mathematical form. These regression models were carried in SPSS package version 20 and tabulated nine of them in Table 1. The mathematical expressions in Table 1 show good and acceptable relations with R square more than 0.9 at confidence level of 95%, moreover the linear models are simplest forms which may be adopted.The equations listed in Table 1 are nearly of the same prediction accuracy, but linear models are simplest forms, so they can be adapted.

Table (1):-The regression models analysis

No.	Equation	R^2
1	$\frac{E_{loss}}{E_1}=0.343+0.042Fr_1+0.003\frac{S}{Y_1}$	0,971
2	$\frac{E_{loss}}{E_1}=0.243Fr_1^{0.493}+0.011\left(\frac{S}{Y_1}\right)^{0.447}$	0.983
3	$\frac{E_{loss}}{E_1}=0.515+.0.003Fr_1^{2}+0.001\left(\frac{S}{Y_1}\right)^{2}$	0.942
4	$\frac{Y_2}{Y_1}=1.535+1.060Fr_1-0.091\frac{S}{Y_1}$	0.945
5	$\frac{Y_2}{Y_1}=1.839Fr_1^{0.825}-0.456\left(\frac{S}{Y_1}\right)^{0.477}$	0.958
6	$\frac{Y_2}{Y_1}=5.432+0.067Fr_1^{2}-0.006\left(\frac{S}{Y_1}\right)^{2}$	0.901
7	$\frac{L_j}{Y_1}=-3.277+5.015Fr_1-1.233\frac{S}{Y_1}$	0.876
8	$\frac{L_j}{Y_1}=4.539Fr_1^{1.031}-3.701\left(\frac{S}{Y_1}\right)^{0.572}$	0.907
9	$\frac{L_j}{Y_1}=13.277+0.317Fr_1^{2}-0.087\left(\frac{S}{Y_1}\right)^{2}$	0.758

4. FINDINGS and CONCLUSION

The characterstics of hydraulic jump represented by relative sequent depth, relative energy dissipated and length of jump are studied experimantally on rough channel bed constructed by lowering bed strips with diffirent spaces.Within the limitations of the present experimental workthe following conclusions may be forwarded:

1- The bed lowered strips increase energy dissipated by6 %, and the best strip apace is between 5 and 6 cm.

2- The percentage reduction in relative sequent depths (Y_2/Y_1) is between 6% and 15% depending on the value of incoming Froude number and roughness space S.

3- The percentage reduction in relative length (Lj/Y_1) is 22% and 28% compared with the smooth one.

4- Mathematical models are proposed for predicting jump characteristics.

5- The dimensionless depth deficit mean D=0.15 and the normalized jump length (Lj/Y_2*)=2.5

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