Experimental Study of a Hydraulic Jump Controlled by Positive Step Evolving in a Rectangular Channel with a Rough Bottom

M. Zidani, S. Kateb, S. Saggai K.Baouia

Research laboratory exploitation and development of natural resources in arid zones (EVRNZA), University of Kasdi Merbeh-Ouargla, PB 147 RP, 30000 Ouargla, Algeria
Author Correspondence, e-mail: katebsamir30@gmail.comdoi:
http://dx.doi.org/10.4314/jfas.v13i1.34

Received: 13-04-2023 **Accepted**: 25-10-2023 **Published**: 25-11-2023

The study proposes to examine, by the experimental route, the effect of roughness on the hydraulic jump length in rectangular channel. A comparative study between the characteristicsof the jump controlled by a threshold with a smooth and rough bottom is proposed. The results of this research can be applied in the hydraulic load dissipation basins of dams and also in irrigation lines, using the ability of the jump to raise the water level downstream of the flow.
Keywords: Hydraulic jump, controlled by threshold, rectangular channel, energy dissipation basin, smooth bottom, rough bottom

Tob Regul Sci. ™ 2023 ;9(2): 1295-1307
DOI : doi.org/10.18001/TRS.9.2.79

1. Introduction

Retention structures, such as hydraulic dams, are often subject to severe flooding. During high water periods, the reservoir being full, the water is returned through a spillway to the river. The bed of the river is then confronted with a torrential flow with high kinetic energy. This generates traction forces that are harmful by their erosive nature. in order to avoid major modifications to the river bed located downstream of the dam, it would be necessary to dissipate this energy. The cheapest and most practical way is certainly the hydraulic jump.

The principle consists in transforming the torrential flow into a fluvial flow generating a reduction in the traction forces. The hydraulic jump being the most practical and the least expensive means of dissipating the hydraulic load, in particular downstream of a dam, it has already been widely studied. We can cite [4,5] who studied the hydraulic jump in a horizontal rectangular channel, [1,2,4] whose works are relating to the horizontal triangular jump. Furthermore, [8], studied the hydraulic jump in a rectangular channel. The first in-depth studyof the inclined hydraulic jump was that of [9], who mentioned in their study the surface profile, the length of the jump and the distribution of speeds. classified positive-sloped jumps into four main types: type A, type B, type C, and type D. Recent studies concerning the jump in inclined channels were led by [4], but still in a rectangular channel. [1] theoretically studiedthe hydraulic jump in a symmetrical triangular channel with an opening angle of 90 ° inclined with a positive slope. In 2010, the most important works relating to hydraulic jumps evolving in a rectangular channel with a rough bottom. The best-known studies in this field arecertainly those of [8], corresponding respectively to the hydraulic jump evolving in a rectangular channel with a wavy bottom. In the light of this research work on the hydraulic jump, evolving in a rectangular channel, we experimentally present the study of the effect of roughness on the length of the hydraulic jump. Therefore, the effect of energy dissipation, for both jump configurations, is almost identical.

2. Position Du Problème

The modification of the conditions upstream (heights, flow, etc.) and downstream (type of obstacle, its position, height, etc.), can lead to different configuration of jump. The jump is said to be classic when it forms in a rectangular channel of little or no slope, without obstacle to the downstream. It is said to be controlled when its formation is conditioned by theinstallation of an obstacle downstream of the flow.

In our case, it is a jump controlled by a thin threshold in a rectangular-to-rectangular channel, with a rough bottom. Different rough nesses have been tested. Indeed, for a fixed initial height h1, the increase in flow results in both the displacement of the jump downstream and the increase in its roll length Lr. The distance (x) over which the jump extends increases
also, and to bring it back to its initial position, that is to say about 5 cm from the exit of the convergent, the first height threshold s must be raised. Thus, for each value of the flow Q, corresponds a length Lj of the jump, as well as a height h2 downstream of the jump and a height (s) of the threshold (Fig.1).

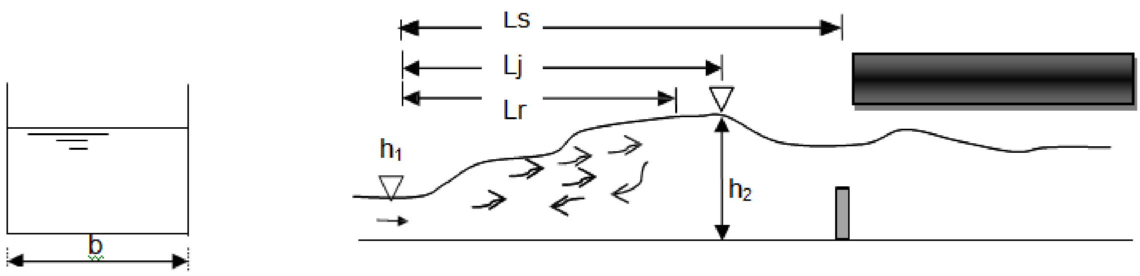

Fig.1. Spring controlled by thin threshold. h1 upstream water height, h2 downstreamwater height, s threshold height, Lj length of the hydraulic jump

3. Description Du Protocole Experimentale

The physical model that served us as a test bench (Fig. 2; 3; 4) consists essentially of a rectangular channel 10 meters in length, 25 centimeters in width and 50 centimeters in depth fed by the means of '' a circular pipe 150 mm in diameter. The latter is connected to the channel by means of a closed metal box, on which is inserted a converging sheet of rectangular section opening directly into the channel, but the existence of a curved plate and fixed to the bottom of the end upstream of the canal forced us to place a wall valve (bottom valve) just after this obstacle. The converging and the part of the channel upstream of the wallvalve constitute the loaded box which ensures the high speed of the incident flow. The location of this valve will be used to adjust the height of the incident flow h1 of the jump butit caused the overflow of water in the box under load when switching to large flow.

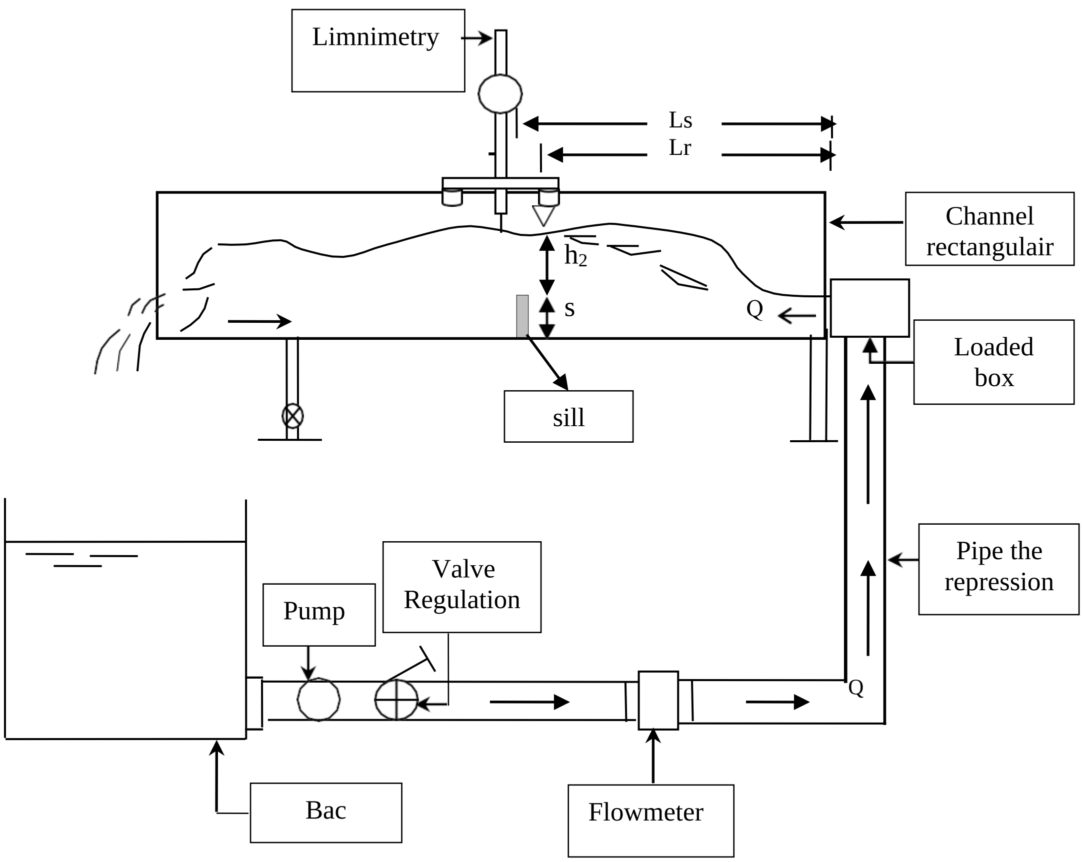

Fig.2. experimental model

Fig .3. Photograph of the section measurement channel

The whole works in closed circuit in which is inserted an axial pump (Fig. 4) delivering up to 44l / s, drawing water from an accumulation tank, increasing the flow using a valve (Fig. 4). At the downstream end of the canal, a rectangular weir without shovel height with lateral contraction was placed, allowing direct flow measurement. The upstream side of the channelis placed on a screw nut system (thread) to allow us to vary the slope of the channel.

a) b)

Fig.4. control valve and pump

3.1. Experimentation

The Experimental Study focused on the hydraulic jump controlled by a threshold in a rectangular channel, with a rough bottom. Four values of absolute roughness were tested: (mm) = 6; 8; 10; 12. The experiment was carried out under seven initial heights of flow:h1 (mm) = 20; 30; 40; 50. A wide range of the Froude incident number was thus obtained, corresponding to 2 <F1 <16. The formation of the controlled jump is conditioned by the establishment of a threshold downstream of the flow. for this purpose, thresholds of different heights have been used. For a threshold height s placed at the downstream end of the channel and for a height h1 of the incident flow, the increase in the volume flow Q causes the appearance of a jump. The couple (Q, h1) also allows the calculation of the Froude number F1 of the incident flow. The increase in F1 involves both the displacement of the jump towards the downstream and the increase in its length Lj. Thus, to each value of the Froude number F1 corresponds a value of the jump length Lj as well as a value of the height s of the threshold. A

Sample made up of around sixty experimental measurement points, for each of the absolute roughness values tested, thus led to significant results. The hydraulic and geometric characteristics of interest in this Experimental Study are: the volume flow Q, the height h1 of the incident flow, the final height h2 of the jump, the length Lj of the latter and the absolute roughness of the walls of the channel. In addition, attention is paid to the evolution of the following dimensionless parameters:

i. The number of Froude F1 such as:
ii. The relative length Lj / h1 of the jump.
iii. The ratio Y = h2 / h1 of the combined heights of the jump.

Protocol Experimental

The main characteristics studied in a hydraulic jump caused by roughness are: the volume flow Q, the initial depth h1, the final depth h2, the height s of the step, the length Lj of the jump. These are formulated in dimensionless form to compose the following ratios: the Froude number of the incident flow, the ratio Y = h2 / h1 of the combined depths of the jump, the relative length λj = Lj / h1 of the jump. Note that the rectangular channel is not very suitable for dissipation basins, but has some practical advantages in irrigation lines. In fact, the ability of the hydraulic jump to raise the downstream body of water is used for priming siphons. The literature shows that the rough bottom channel provides the stability of the jump, its efficiency and its compactness.

4. Résultats Et Discussion

This present stage of our experimental study consists in making a comparative study between the characteristics of the jump Controlled by threshold with smooth bottom and the jump with rough bottom

Relative length Lj / h1 of the jump as a function of the number of Froude F1 Figure 6 shows the graphic representation of the variation of the relative length Lj / h1 of thejump as a function of the Froude number F1 of the incident flow, for four absolute roughnesses : (mm) = 6, 8, 10, 12.Four distinct point clouds are perceptible, each corresponding toan absolute roughness. We note that for a fixed absolute roughness, the increase in theFroude number generates that the relative length of the jump. In addition, for a fixed value ofthe incident Froude number, the increase in absolute roughness causes the relative length ofthe jump to decrease.

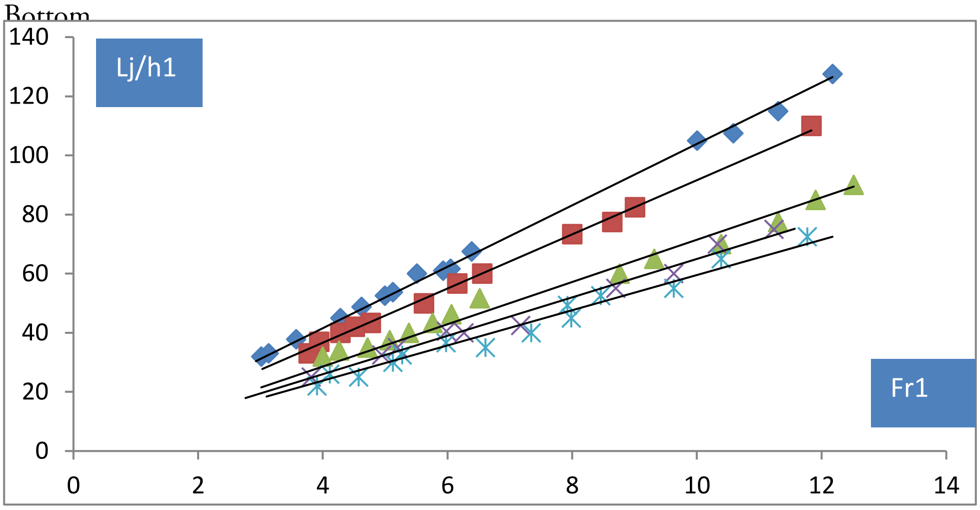

Fig.5. Variation of the relative length Lj / h1 as a function of Froude number F1, for fivedifferent values of absolute roughness: (mm) = ( ) 0.00 (smooth), (◇) 6mm, (Δ) 8mm,( ) 10mm and (ж) 12mm

Furthermore, the statistical analysis of the experimental measurement points by thenon-linear least squares method, shows that for each absolute roughness, a linear fit of the shape $\frac{L_j}{h_1} = aF_1$ is possible. Fig. 5 shows this well.Table 1 groups the values of the coefficient (a).

Table 1: coefficients to adjustment curves

ε/B	Coefficient a	R^2
0	10.38	0.998
0.024	9.161	0.998
0.032	7.147	0.978
0.04	6.497	0.982
0.048	5.953	0.973

Table 1 shows that the coefficient ‘a’ gradually decreases with increasing absolute roughness. Statistical adjustment of the pairs of values (**ε/B**, a) by the least method Carrés gives the following linear type relation: $a = -98{,}01\,\frac{\varepsilon}{B}+10{,}65$, this is represented in fig. 6

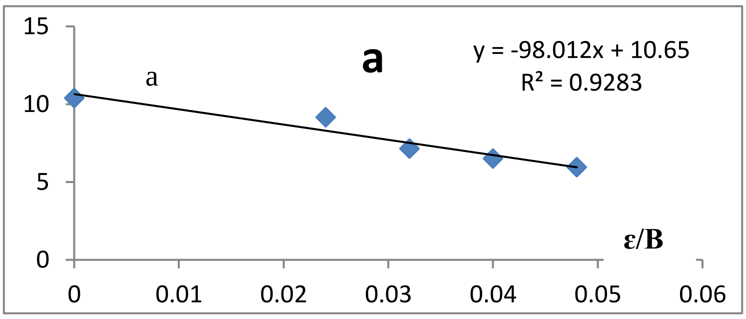

Fig.6. Variation of the coefficient ‘a’ as a function of the absolute roughness‘’

By replacing the coefficient 'a' by its expression in the relation $\frac{L_j}{h_1} = \mathrm{a}F_1$, the equation linking the relative length $\frac{L_j}{h_1}$ of the jump to the number of incident Froude F_1 and to the absolute roughness is

$$\frac{L_j}{h_1} = -98{,}01\frac{\varepsilon}{B}{+}10{,}65 \qquad (1)$$

$$\text{For} \quad 0 < \varepsilon \leq 12\,mm$$

Fig. 7 shows that the relation $\frac{L_j}{h_1} = \left(\frac{\varepsilon}{B}.F_1\right)$adjusts the experimental measurement points with good correlation and the latter perfectly follow the first bisector, thus showing the reliability of the relation.

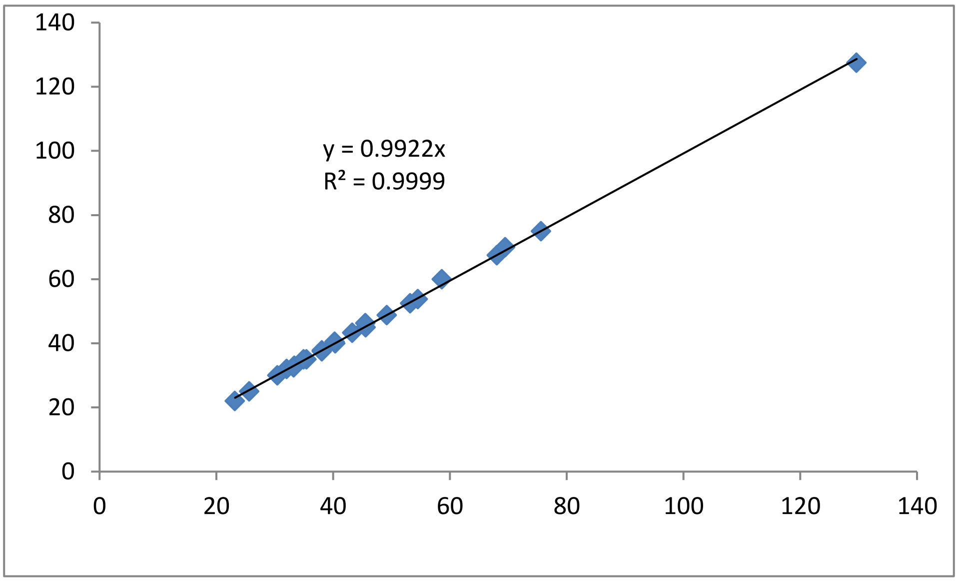

Fig.7. Variation of the relative length Lj / h1 as a function of (**ε/B**, F1). (●) Experimental points of the controlled jump with rough walls. (_) First bisectorof equation $\frac{L_j}{h_1}$exp = $\frac{L_j}{h_1}$calcu

Ratio Y of the Combined Heights as a Function of the Froude Number F1

Fig. 8 represents the variation of the ratio Y of the combined heights as a function of the number of incident Froude F1, for the four absolute roughnesses: (mm) = 6, 8, 10, 12. First of all, note that for the three roughness, the increase in the number of incident Froude leads to that of the ratio Y of the combined heights. Also, we can clearly see the influence ofthe roughness of the walls of the channel on the relation Y (F1). Indeed, for the same number of Froude F1s, the increase in absolute roughness generates the decrease in the Y ratio of the combined heights. Fig. 9 shows four-point clouds, each corresponding to a well-known value of absolute roughness. The solid lines represent the adjustment of the measurement points by the linear least square's method.

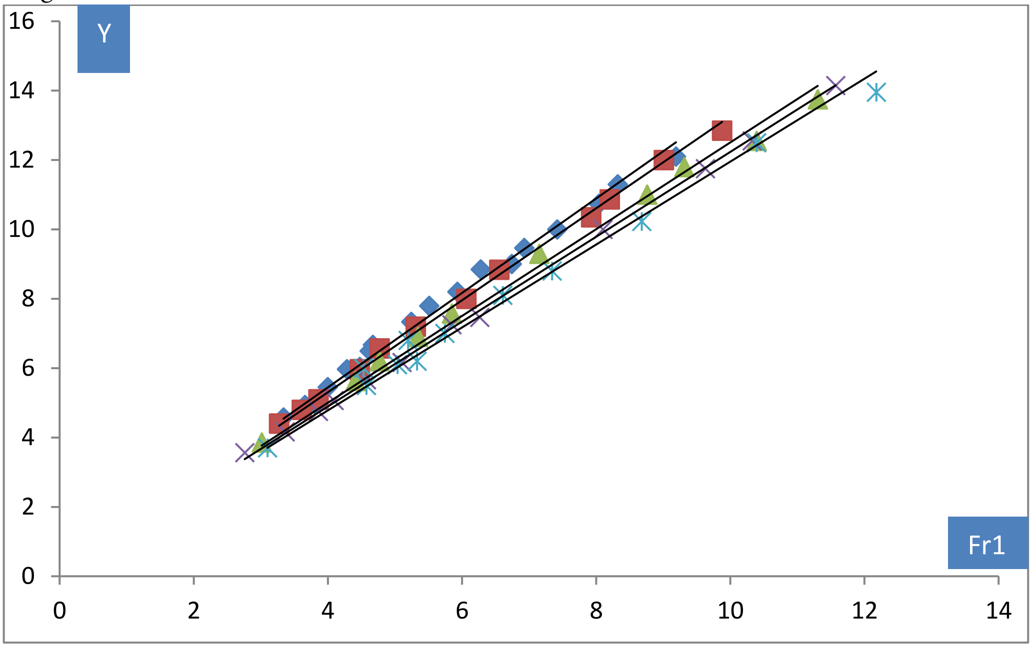

Fig.8. Variation of the Y ratio of the combined heights as a function of F1, for five different values of absolute roughness: (mm) = (◇) 0,00 (smooth), (□) 6mm, (Δ) 8mm, (×)10mm et (ж) 12mm.

Analysis of the points of experimental measurements, clearly shows that for each value of, a linear adjustment is possible, of the form $Y = aF_{r1}$ Table 2 groups the values of the coefficients of b

Table 2: Coefficients b of the adjustment curves

ε/B	Coefficient	R^2
0	1.361	0.992
0.024	1.325	0.997
0.032	1.25	0.993
0.04	1.223	0.999
0.048	1.195	0.988

Table 2 shows that the coefficient 'a' decreases with increasing absolute roughness. The statistical adjustment of the couples of the values (, b) by the method of least squares gives a relation of linear type of equation: $a = 3.622\frac{\varepsilon}{B} + 1.375$. This is shown in Fig.9

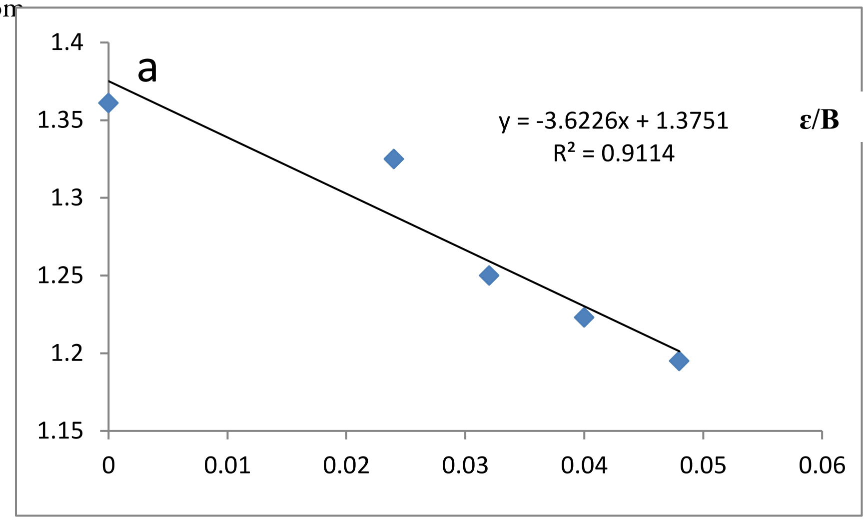

Fig.9. Variation of coefficient b as a function of absolute roughness **ε/B** for five different values of absolute roughness

The equation linking the ratio of heights combined with the number of incidentFroude and absolute roughness becomes:

$$Y = \left(3.622\frac{\varepsilon}{B} + 1.375\right)F_{r1} \quad (2)$$

For $\mathbf{0 < \varepsilon \leq 12\ mm}$

Hydraulic jump efficiency

The dissipation of hydraulic energy is defined as the ratio between the pressure drop ΔH and the upstream load H1, the efficiency of the hydraulic jump in a rectangular channel, is written as follows:

(3)

$$\eta = \frac{\Delta h}{h_1} = 1 - \frac{Y + \frac{F_1^2}{2Y^2}}{1 + \frac{F_1^2}{2}}$$

Fig. 10 shows that the measurement points of the rough bottom jump are above their smooth bottom counterparts for a range of incident Froude numbers 2 <F1 <14. However, forFroude numbers F1> 14, all the measurement points tend to join to form a single point cloud

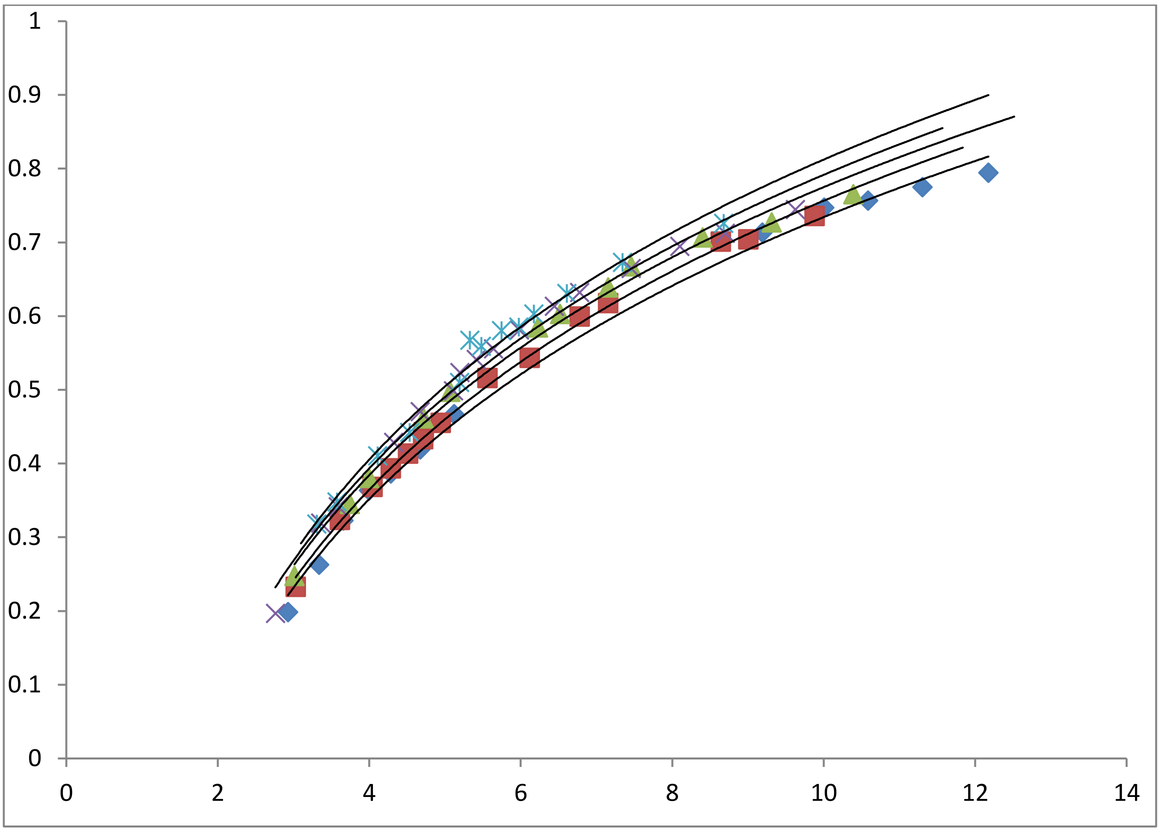

Fig.10. Variation of the yield according to the number of Froude F1, for five different valuesof absolute roughness: (mm) = ( ) 0,00 (smooth), (□) 6mm, (Δ) 8mm,( ) 10mm et (ж) 12mm

Fig. 10 shows that for a practical range of incident Froude the measurement points of the jump with rough walls are below those with smooth bottom. Indeed, the hydraulic jump in the rough-walled channel dissipates the load better than its smooth-walled counterpart. In addition, Fig.9.8 shows that the dissipation of the hydraulic load increases with the increase in roughness. However, for high Froude numbers, the measurement points meet and the effect of the roughness diminishes. This can be explained by the fact that beyond a certain number of practical Froude, the jump becomes choppy and cannot constantly adhere to the bottom of the canal [3].

5. Application Example

Either to determine the characteristics of a hydraulic jump controlled by threshold at the bottom of the smooth channel, and the bottom of the rough channel in a rectangular channel, knowing the volume flow Q = 5m^3 / s, the conjugate depth upstream of the jump h1 = 0.8 m, width of channel b = 0.5m.

Calculation of the number of Froude F1

The number of Froude F1 of the incident flow in the initial section 1-1- that is to say at the foot of the jump this number is expressed as a general rule by the relation Example of application Either to determine the characteristics of a hydraulic jump controlled by threshold at bottom of the smooth channel, and bottom of the rough channel in a rectangular channel, knowing the volume flow Q = 5m3 / s, the combined depth upstream of the jump h1 = 0.8m, channel width b = 0.5m

The number of Froude F1 of the incident flow in the initial section 1-1- that is to say at the foot of the jump this number is expressed as a general rule by the relation

$$F_1^2 = \frac{Q^2}{gA_1^3}\frac{\partial A_1}{\partial h_1}$$

The study shows that this derivative represents the width of the water body whatever the geometric shape of the flowing liquid profile.

$$F_1 = \left[\frac{Q^2}{g}\left(\frac{b}{(bh_1)^3}\right)\right]^{\frac{1}{2}}$$

Replace each parameter with its value in the equation F1 =4,40

Rough bottom jump = 0

Relative length of hydraulic jump Lj / h1

The experimental results lead to another relationship, relating the relative length of the hydraulic jump and the number of Froude F1 is written as follows:

$$\lambda_J = \frac{L_J}{h_1} = 12.5F_1 = 107.534$$

hence the length of the jump $L_J = 86.02\ m$..

Report of the combined heights

The analysis of the experimental results of the smooth controlled threshold jump assessing ina rectangular channel, gave us a relationship between the ratio of the conjugate heights and the number of Froude F1 Is written as follows:

$$Y = (1.132 - 0.0556\varepsilon)F_1 = 5.05$$

Rough bottom jump = 12mm

Relative length of hydraulic jump Lj / h1

The graphical representation of the experimental points of the relative length of the step

$\lambda_J = \frac{L_J}{h_1}$ as a function of the Froude number F1 resulted in a single curve:

$$\lambda_J = \frac{L_J}{h_1} = (12.5 - 0.53\varepsilon)F_1 = 37.03$$

hence the length of the $L_J = 29.62\ m$.

Report of the combined heights

The analysis of the experimental results of the smooth controlled threshold jump assessing ina rectangular channel, gave us a relationship between the ratio of the conjugate heights and the number of Froude F1 written as follows: $Y = (1.132 - 0.0556\varepsilon)F_1 = 2.07$

It emerges from this example of application that for the same numbers of Froude F1s, the length of the reduced jump in the rough-bottomed jump than their counterparts the smooth-bottomed jump.

6. Conclusion

The study allowed the experimental analysis of two types of jumps namely: the controlled jump with smooth bottom and rough bottom. Indeed, it has been found, for the two jump configurations the relative lengths of the basin and of the positioning at the roughness of the bottom are not very dependent on . They are reduced to linear functions λj = f (F1) for the two types jumps. The lengths are maximum for the controlled bottom smooth jump, minimum for the rough bottom jump. The efficiency of the dissipation is expressed by the function η = f (F1), corresponding to an increase of η with F1. rough bottom is the most effective and the smooth bottom jump the least. The rough bottom jump -to- would therefore have all the advantages: lower.

7. References

[1] Achour, B., Debabeche, M., (2003), Control of Hydraulic jump by sill in a triangular channel, J. Hydraulic Research, Vol. 41, No. 3, pp. 97-103.

[2] S Kateb, M Debabeche, A Benmalek (2013) Étude expérimentale de l'effet de la marche positive sur le ressaut hydraulique évoluant dans un canal trapézoïdal Canadian Journal of Civil Engineering 40 (10), 1014-1018

[3] Debabeche, M., (2003), Le ressaut hydraulique dans les canaux prismatiques, Doctorat d'état, Département d'Hydraulique, Université de Biskra. Debabeche, M., (2008), Les écoulements brusquement variés, cours de 1ère année magister, polycopié, Université de Biskra. Debabeche, M.

[4] Bradley, J.N., Peterka, A.J., (1957), The hydraulic design of stilling basins: Hydraulic jumps on a horizontal apron, paper 1401, proc. Amer. Soc. Civ. Engnrs., J. Hydraulic. Division, Vol.83, HY5.

[5] Hager, W.H., Wanoschek, R., (1987), Hydraulic Jump in Triangular Channel, J. Hydraulic Research, Vol. 25, Nr. 5, pp. 549-564.

[6] Rajaratnam, N., (2002), Hydraulic jump on corrugated beds, J. Hydraulic Engrg., Volume 128,

Issue 7, 656-663.

[7] Debabeche, M., Achour, B., (2007), Effect of sill in the hydraulic jump in a triangular channel, J. Hydraulic Research Vol. 45, No. 1, pp. 135–139.

[8] Mc Corcodal, 1994, Journal of Hydraulic Research, VOL. 32, 1994, NO.1; 119-130.

[9] Hager, W.H., Sinniger, R., (1985,1986), Flow Characteristics of the hydraulic Jump in astilling basin with an abrupt bottom rise, J. Hydraulic Research, Vol. 23, pp. 101-113, 1985, Vol. 24, pp. 207-215, 1986. Hager, W.H., Sinniger, R., (1987), Construction hydraulique, Ecoulement stationnaire, Edition suisse romande.

[10] Bakhmeteff, B.A., and Matzké, A.E. 1938. The hydraulic jump insloped channel. Transactions, ASME, 60(HYD-60-1): 111-118