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Comparative Analysis of the Positive and Negative Steps in a Forced Hydraulic Jump

S. Bakhti [1] ***and A. Hazzab*** [2]

[1] M.A., Laboratoire de Modélisation et de Méthodes de Calculs, C.U., SAIDA
[2] M.C., Laboratoire de Modélisation et de Méthodes de Calculs, C.U., SAIDA. Email: kiessouad@yahoo.fr

ABSTRACT

In the field of hydraulic constructions, restoring water within a stream is a very common issue. To avoid important and non-controlled modifications in streams, energy dissipation is often essential to convert a flow with high mechanical energy into a flow with low mechanical energy. In the works of dissipation, a regime change of the flow intervenes: at the entry of these works, it is torrential, at the exit it is fluvial, and this transition causes a hydraulic jump. The damping basin is the central element of the energy dissipation. The step (or steps (positive or negative)), represents the particular device related to such a work to support the formation of the jump in the basin, which makes the dissipater more compact, to improve the stability of the process and to increase the capacity of dissipation.

In the intention not to move away from the physical reality of the phenomenon of the jump, this work is based on an experimental research. The attention is mainly related to the jump forced by a positive and a negative step. The comparisons between the two types of steps concerning stability, effectiveness and compactness were conducted and analyzed through experimental measurements.

KEYWORDS: Damping basin, Forced jump, Positive step, Negative step.

INTRODUCTION

It seemed to us judicious, in this study, first the principal characteristics that steps must have, either they are positive or negative, to ensure their roles in better conditions.

Hager and Bretz (1986) proposed a complete analysis of the hydraulic jump with negative and positive steps, where one of their main concern was the total comparison of the two types of steps with regard to the stability of the jump, its effectiveness and its compactness. Their analysis revealed that the negative step would be more stable and more effective than the positive one, on the other hand this last seems to offer a better compactness. We will make an effort, for our part through an experimental study, to confirm or cancel these data.

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STABILITY STUDY

In the consulted theory (Walter, 1993), stability of a damping basin is the capacity of the work to maintain the position of the jump under variable downstream heights h_u, by fixing the upstream height h_1 and the corresponding number of Froude (F_1). It is quantified by the parameter ΔY.

Let $\Delta Y = Y_A - Y_B$: the acceptable maximum change in downstream water height.

Y_A: jump of type A.

Y_B: jump of type B for the positive step, or jump of type

B_{min} for the negative step.

The goal of our experimental study will be to determine ΔY to be compared against the various jumps obtained; namely the jump A^+ and B^+ for the positive step and A^- and B^- for the negative step. The results obtained are listed in tables.

Positive Steps

Jump of Type A^+

Table 1: Values of the combined height ratios Y_{ex} and Y_{th} in terms of the number of Froude for s=5cm and s_0=5%

N° of the test	F_1	$h_1(cm)$	$h_2(cm)$	$h_2/h_1 = Y_{ex}$	Y_{th}
1	3.6	1	2.2	2.1	1.90
2	5.8	2	6	3	2.8
3	7.7	3.1	24	7.7	7.0
4	8.6	4.8	48	10	9.5

Note: Y_{th} represents the theoretical combined height ratio obtained by the relations corresponding to each jump type.

Jump of Type B^+

Table 2: Values of the combined height ratios Y_{ex} and Y_{th} in terms of the number of Froude for s=5cm and s_0=5%

N° of the test	F_1	$h_1(cm)$	$h_2(cm)$	$h_2/h_1 = Y_{ex}$	Y_{th}
1	3.2	1.5	2.1	1.4	1.15
2	5.4	3	7.2	2.5	2.23
3	7.2	3.8	16	4.21	3.9
4	8.2	4.2	23	5.47	5.13

Negative Steps

Jump of Type A^-

Table 3: Values of the combined height ratios Y_{ex} and Y_{th} in terms of the number of Froude for s=5cm and s_0=5%

N° of the test	F_1	$h_1(cm)$	$h_2(cm)$	$h_2/h_1 = Y_{ex}$	Y_{th}
1	4	1.5	12	8.9	8.7
2	6	2.2	22	10.5	10.3
3	8	3.4	42.5	12.5	12.10
4	8.9	3.7	47.7	12.9	12.4

Note: Y_{th} represents the theoretical combined height ratio obtained by the relations corresponding to each jump type.

Jump of Type B^-

Table 4: Values of the combined height ratios Y_{ex} and Y_{th} in terms of the number of Froude for s=5cm and s_0=5%

N° of the test	F_1	$h_1(cm)$	$h_2(cm)$	$h_2/h_1 = Y_{ex}$	Y_{th}
1	4	1.6	9.6	6.8	6.4
2	6	2.3	20.7	9	8.3
3	8	3.2	36.8	11.9	11.73
4	8.8	3.9	48.6	12.3	12.1

From the values in the tables, we can plot the following curves, each one corresponding to a type of jump.

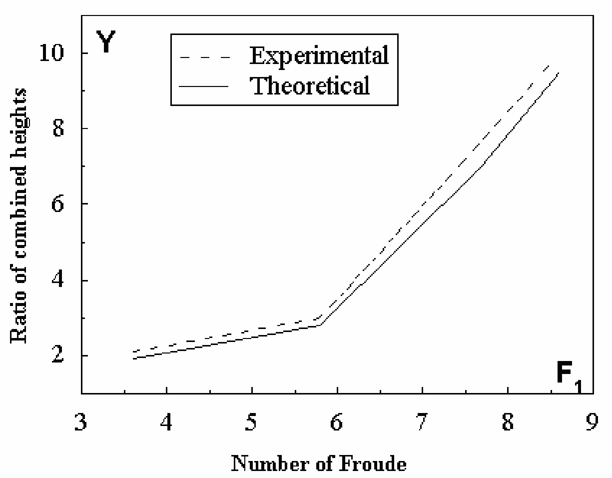

Figure 1: Ratio of Combined Heights in Terms of the Number of Froude F_1 for the Jump of Type A^+ with s=5cm and s_0=5%

The analysis of our experimental results shows that they are often as a straight line parallel to that of the theoretical results, but shifted, i.e.; that for the same number of Froude F_1, the experimental value is higher than the theoretical one. We also notice that for a given value of the number of Froude, the ratio of the combined heights Y is always more important for the jump with a negative step than that with a positive step.

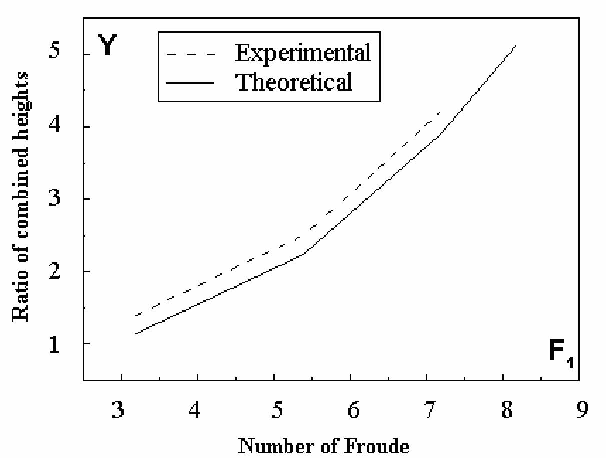

Figure 2: Ratio of Combined Heights in Terms of the Number of Froude F_1 for the Jump of Type B^+ with s=5cm and s_0=5%

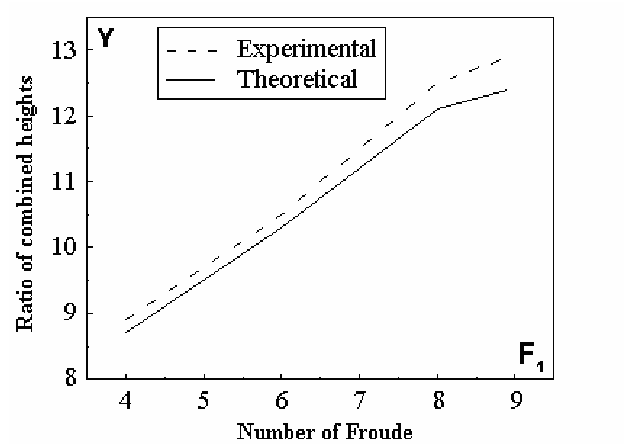

Figure 3: Ratio of Combined Heights in Terms of the Number of Froude F_1 for the Jump of Type A^- with s=5cm and s_0=5%

So, the difference $\Delta Y = Y_A - Y_B$ for the negative step is practically always higher than that corresponding to the positive step. In other words: $(Y_{A-} - Y_{B-}) > (Y_{A+} - Y_{B+})$.

Consequently, to stabilize the jump, a damping basin with a negative step is more effective than one with a positive step.

Our results confirm the work of Moore and Morgan (1959) and more recently that of Hager and Bretz (1986), as well as Husain et al. (1994). Hager and Bretz (1994) could estimate ΔY only in terms of the height s of the step, independently of the number of Froude (Corquadale and Mohamed, 1994).

The obtained results are:

$$\Delta Y = \frac{s}{6} \quad \text{for the positive step.}$$

$$\Delta Y = \frac{13s}{12} \quad \text{for the negative step.}$$

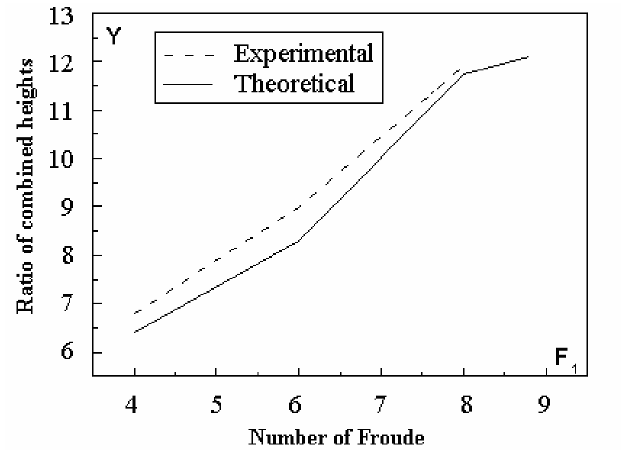

Figure 4: Ratio of Combined Heights in Terms of the Number of Froude F_1 for the Jump of Type B^- with s=5cm and s_0=5%

EFFECTIVENESS STUDY

In the consulted theory (Sinniger and Harger, 1993), the effectiveness or relative dissipation of energy η is defined as the ratio of ΔH and H_1. In other words, it is the relationship between the pressure loss ΔH through the hydraulic jump, compared with the upstream energy; that is to say, respectively:

$$H1 = h_1 + \frac{q^2}{2gh_1^2} \quad \text{for the positive step.}$$

$$H1 = s + h_1 + \frac{q^2}{2gh_1^2} \qquad \text{for the negative step.}$$

Unfortunately, there exists no established relation allowing the determination of the efficiency and taking account of the effect of the step. In 1985, Hager and Sinniger established a simplified equation on the dissipation of energy related to the upstream load.

$$\eta = \frac{\Delta H}{H_1} = \left[1 - \left(\frac{\sqrt{2}}{F_1}\right)\right]^2 \qquad \text{for } F_1>1.5$$

However, this one is independent of the height of the step. It corresponds thus to the case when s=0, i.e.; the classical jump. We will be satisfied, consequently, to use the graph shown in Figure (5) which represents the efficiency according to the number of Froude and the height of the steps, either it is positive or negative (Sinniger and Harger, 1993).

The analysis of the graph makes it possible to establish the following conclusions:

For fixed F1 and S, the minimal output is for the standard jump with a negative functioning/walk (A); supposing that for a+ jump the output is still lower and thus not being reproduced on the graph. A slightly more important efficiency is allotted to the jump B on a positive step B+, and then comes the jump B minimum on a negative step.

As a conclusion, the jump of type B minimum on a negative step (B_{min}) reached the maximum efficiency in comparison with all other types of jumps.

COMPACTNESS STUDY

As defined in the theory (Husain et al., 1994), the compactness of a damping basin corresponds to its longitudinal extension, provided that the jump is entirely in the dissipater. The parameter characterizing compactness is naturally the length of the jump, but as this one is not very defined, because of the strong fluctuations of the profile of surface, we prefer to refer rather to the length of the roller (Ohtsu and Yasuda, 1991).

Hager and Bretz (1986), after conducting experiments on a reduced model, showed that the relative length $\lambda = L_r /h_2$ (negative step) and $\lambda = L_r (h2 +s)$ (positive step), did not vary systematically with F_1.

For the extreme positions, they found:

λ = 4.75 for the jump type A+.

λ = 3.50 for the jump type A-.

λ = 4.25 for the jump type B+.

λ = 4.25 for the jump type B-.

- for the jump type A, the end of the roller being by definition at the step (Walter, 1993).
- for the jump type B^+, the foot of the jump being at about $L_r /2$ from the upstream of the step.
- for the jump type B^-, the foot of the jump is at a distance equal to four times h_1 of the negative step.

In our study, we will try to determine the relative lengths $\lambda_1=L_r /h_1$ and $\lambda_1=L_r /h_2$ for all the types of jumps, for the case without step, then for the positive step and then for the negative step.

The study will be carried out for a fixed slope of 5% and a fixed step height of 5cm. The goal of our study is to proceed to a comparison between the types of jumps to be able to determine the longest of them and thus the least compact of them. The results of our experiments are shown in tables.

Determination of the Relative Length λ_1

a- Case of a channel with a slope of 5%, without step: s=0.

Table 5: Determination of relative length λ_1 for a channel with a slope of 5% without step

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2.1	16	1	16
2	4.2	65.1	2.1	31
3	5.0	120	3	40
4	6.1	195	3.9	50
5	8.3	286	4.4	65

b- Positive step with a height s=5cm for a slope of 5%:

• *Jump Type A^+*

Table 6: Determination of relative length λ_1 for a channel with a slope of 5% for a step height s=5cm, jump type A^+

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2.1	32.2	2	16.1
2	4.2	72.48	4.2	30.2
3	5.0	124	3.1	40
4	6.1	196.8	4.1	48
5	8.3	283.2	4.8	59

• *Jump Type B^+*

Table 7: Determination of relative length λ_1 for a channel with a slope of 5% for a step height s=5cm, jump type B^+

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2.1	33.6	1.6	21.0
2	4.2	61.74	2.1	29.4
3	5.0	93.42	2.7	34.6
4	6.1	124.74	3.3	37.8
5	8.3	176	4.0	44

c- Negative step with a height s=5cm for a slope of 5%:

• *Jump Type A^-*

Table 8: Determination of relative length λ_1 for a channel with a slope of 5% for a step height s=5cm, jump type A-

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2.1	32.25	1.5	21.5
2	4.2	60	2	30
3	5.0	98	2.8	35
4	6.1	130.9	3.4	38.5
5	8.3	185.5	4.1	45

• *Jump Type B-*

Table 9: Determination of relative length λ_1 for a channel with a slope of 5% for a step height s=5cm, jump type B-

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2.1	10.92	1.6	9.1
2	4.2	42.9	2.2	19.5
3	5.0	77.55	3.3	23.5
4	6.1	107.42	4.1	26.2
5	8.3	170.61	4.7	36.3

Determination of the Relative Length λ_2

a- Case of a channel with a slope of 5%, without step: s=0.

Table 10: Determination of relative length λ_2 for a channel with a slope of 5% without step

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2	38.22	9.8	3.9
2	3.9	46.2	11	4.2
3	6	58.75	12.5	4.7
4	7.1	70	14	5
5	8	84.15	16.5	5.1

b- Positive step with a height s=5cm for a slope of 5%:

• *Jump Type A+*

Table 11: Determination of relative length λ_2 for a channel with a slope of 5% with a step height s=5cm, jump type A+

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2	70.5	9.4	7.5
2	3.9	77.38	10.6	7.3
3	6	82.08	11.4	7.2
4	7.1	93.01	13.1	7.1
5	8	106.4	14	7.6

• *Jump Type B+*

Table 12: Determination of relative length λ_2 for a channel with a slope of 5% with a step height s=5cm, jump type B+

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2	37.6	8	4.7
2	3.9	45.5	9.1	5
3	6	54.59	10.3	5.3
4	7.1	61.56	11.4	5.4
5	8	73.08	12.6	5.8

c- Negative step with height s=5cm for a slope of 5%:

• *Jump Type A-*

Table 13: Determination of relative length λ_2 for a channel with a slope of 5% with a step height s=5cm, jump type A-

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2	31.85	9.1	3.5
2	3.9	37.37	10.1	3.7
3	6	37.76	11.8	3.2
4	7.1	37.5	12.5	3
5	8	38.08	13.6	2.8

• *Jump* Type B-

Table 14: Determination of relative length λ_2 for a channel with a slope of 5% with a step height s=5cm, jump type B-

N° of test	F_i	L_r(cm)	h_1(cm)	L_r / h_1
1	2	30.8	8.8	3.5
2	3.9	34.56	9.6	3.6
3	6	31.5	10.5	3
4	7.1	33.6	12	2.8
5	8	33.8	13	2.6

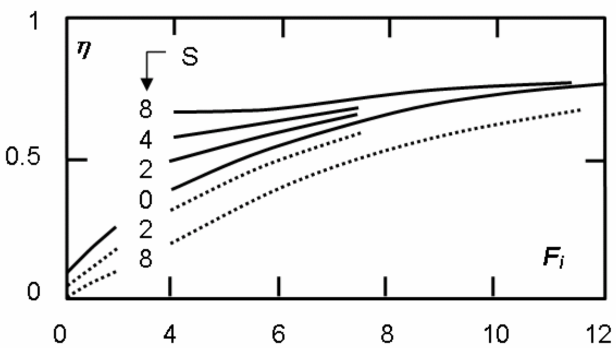

Figure 5: Efficiency η=ΔH/H$_1$ as a function of F$_1$ and S

(…) Jump of type A on a negative step.

(—) Jump of type B minimum on a negative step.

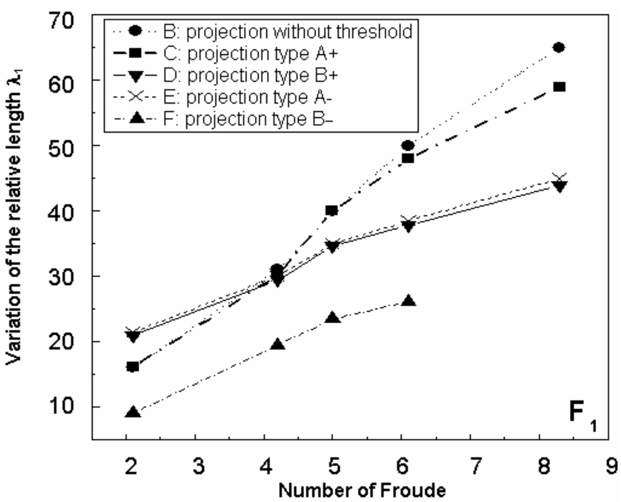

Figure 6: Variation of the Relative Length $\lambda_{1=}$ L_r /h_1 in Terms of Froude Number F_1 for s_0=5% and s=5cm

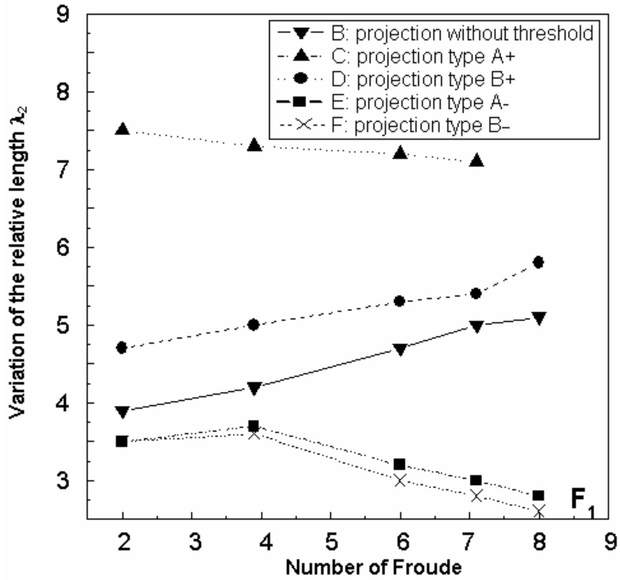

Figure 7: Variation of the Relative Length $\lambda_{2=}$ L_r /h_2 in Terms of Froude Number F_1 for s_0=5% and s=5cm

From the results of the tables, we can plot up the graphs shown in Figures (6 and 7), where the first includes all the types of jumps (the case without step is included) for a relative length $\lambda_1 = L_r / h_1$, while the second will correspond to $\lambda_2 = L_r / h_2$.

Figure 6 shows the variation in the relative length $\lambda_1 = L_r/h_1$ in terms of the number of Froude F_1, for a channel with a slope of 5% and a step height of 5cm.

It arises from the analysis of this figure, that the jump without step, or the classical jump, is characterized by a maximum variation of relative length compared with all the other types, showing the effect of the step in reducing the length of the roller and thus of the jump.

Figure 7 shows the variation in the relative length $\lambda_2 = L_r / h_2$ in terms of the number of Froude F_1, for a channel with a slope of 5% and a step height of 5cm. We notice-without sorrow-that the jump with a negative step presents a relative length λ_2 significantly lower compared to the jump with a positive step and also to that without step. This fact is probably due to the big augmentation of the draft, which compacts the length of the roller during the formation of the jump with a negative step.

Therefore, the advantage which characterizes the negative step is the insurance of compactness in a hydraulic jump in an inclined channel. Our results confirm perfectly the work of Hussain et al. (1994), but on the other hand they contradict with the consulted theory and the work of Hager and Bretz (1986), which found that the jumps of type A- and B- (with a negative step) are the longest.

The theory (Corquadale and Mohamed, 1994) goes even to define a length L_P as being the protected length of the bottom and recommends the following expressions for λ_p :

$$\lambda_p = \frac{L_p}{h_1} = 6\left(u - \frac{6s}{5}\right) \qquad \text{for the positive step.}$$

and

$$\lambda'_p = \frac{L_p}{h_1} = 7\left(u - \frac{3s}{8}\right) \qquad \text{for the negative step.}$$

with:

$$u = \sqrt{2}F_1 - \frac{1}{2}\,.$$

In our study, we used lengths of rollers for the ratios λ_1 and λ_2. In the theory, it acts the length of the protected bottom. It could be that the two sizes do not have the same significance.

Moreover, always in the ratios λ_1 and λ_2, we considered the height h_2 (the maximum height of combined heights), whereas for the theory it is the height h_1 which is used. It could be that this difference in the sizes leads to different results between experimental measurements and the theory. Those are only assumptions which would make it possible to explain the divergence between theoretical results and experimental ones.

CONCLUSION

The beginning of this work relates to the experimental analysis of stability. It resulted from it that a damping basin is more effective with a negative step than with a positive step to stabilize the jump.

The study of the effectiveness allowed classifying the various types of jumps through the two steps according to their efficiency. It was shown that the maximum efficiency is for the jump type B-, followed by the jump type B+, then by the jump type A-, and finally comes the jump type A+ with the minimum efficiency.

The end of work was devoted to the study of the compactness of the jump with a positive step and a negative step. It made it possible to show in experiments, through the comparison of relative lengths of the various types of jumps, that the jumps with negative steps were the least long and thus the most compact compared to those with positive steps.

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