Study of Flow and Energy Dissipation in Stepped Spillways

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ABSTRACT

We present in this work the quantitative and qualitative study of the flow in the stepped spillways. The experimental measurement is realized on the reduced model. Different flow configurations on a spillway are described. New experimental results linked to the flow aspect and to the energy dissipation after the passage over the spillway are presented. The experimental results relative to the energy dissipation are analysed. They are compared thereafter to the results of the experiences and models found in other research works.
KEYWORDS: Energy, Dissipation, Stepped cascade, Flow, Configurations.

RÉSUMÉ

Dans ce travail, on décrit les différentes configurations de l'écoulement sur un coursier en gradins. De nouveaux résultats expérimentaux liés surtout à l'aspect de l'écoulement et à la dissipation de l'énergie après le passage sur le coursier sont présentés. Les résultats expérimentaux relatifs à la dissipation de l'énergie sont analysés. Ils sont comparés aux résultats des expériences et ceux des modèles trouvés dans d'autres travaux de recherche.

INTRODUCTION

The dams composed of stepped spillways are often considered as the adapted structures for the passage of sludge. The stepped channels conception does not relieve of a new idea, since structures of such a type existed a long time before.

We note that among the hydraulic structures realized in the years ago in USA and in South Africa, we find numerous structures realized on the base of this concept. Recently, and with the introduction of new construction materials and the technology modernization, the interest for the stepped spillways has considerably increased.

The synthesis of recent studies shows that the concrete steps or gabion hydraulic structures are used in the engineering technologies. This discharging structure presents a high mechanical stability and a good resistance to break flood "swelling".

The adaptation of this kind of technique in the hydraulic structures is of a great interest to both the structure and the environment. The spillways present in addition to good structure stability, water aeration during its passage over the spillway. The spillway technique became mainly an economical mean. The gain on the project cost is about 20% compared to other techniques (e.g., inclined spillways, vertical full spillways), (Peyras et al., 1992).

Indeed, the steps increase considerably the energy dissipation along the spillway and reduce the size of structures annexed to the main hydraulic structure.

The analysis of the published results shows that despite the many available results for specific cases, only few relevant results concerning the general case are obtained, because only particular and isolated cases are modelled. The modelling of this kind of flow using the classical equations of the fluid mechanics is approximate if the flow behavior change characteristics are not taken into consideration.

During the past years, authors such as Chanson (1994a) and Rajaratnam (1990) have systematically

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studied flows on spillways of complex forms. The work of Chanson concerns particularly certain fundamental aspects of the problem. The most important was the energy dissipation. The reactions to the Chanson paper (Chanson, 1994a) show on one hand the divergence about some points of view and on the other hand the complexity of the problem.

A global study of the subject requires new data. These data have to be either compared to the results of existing models or used to propose other models giving better representation of the flow structure.

The results concerning the flow configuration change and those in relation with the energy dissipation are presented and analyzed.

EXPERIMENTATION

The experiments are realized by means of the complex fluid measurement installation in the hydraulic institute of Ain el Hadjar (Saida, Algeria). It concerns an installation allowing fluid circulation in a variable slope glass channel. The installation allows mainly observing the different flow regimes.

a) Nappe flow **b) Skimming flow**

Figure 1: Flow Regimes above a Stepped Spillway

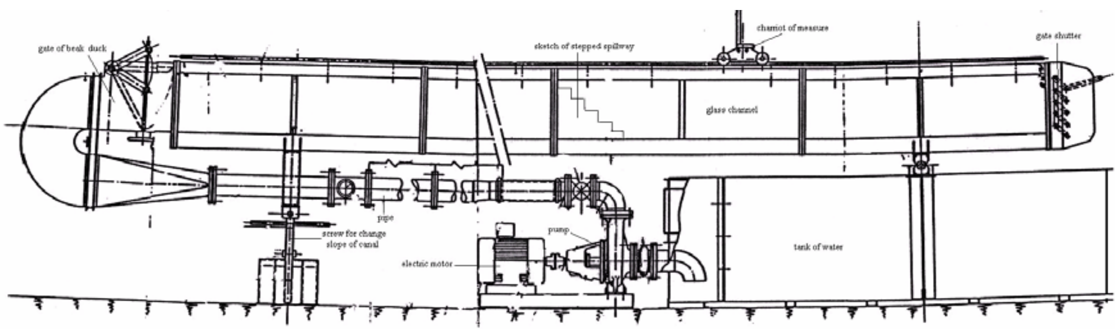


Figure 2: Installation of experimentation

A detailed description of this installation and different methods of measurement are presented by Chafi (1998).

The measurement canal part is a reduced model of a spillway. The latter is composed of (seven) 7 equally sized steps as:

- Height : h = 7 cm.
- Width : l = 11.5 cm.
- Length : L = 24 cm.

The spillway slope value α (tgα = 7/11.5 = 0.6087 hence α ≈ 32°) is greater than the critical value defined by Chanson (1994) which is α = 27°.

The author presented a study which indicated that a change flow mechanism and recirculation were observed for the spillway slope values which ranged [25°, 30°]. Skimming flows on slope (α < 27°) are characterized by friction factors less than for turbulent flows on spillways with a slope greater than 27°.

It is admitted that the spillways of a slope of 27° show certain effects of appropriate recirculation mechanism.

For the slope of 27°, the flow way is more or less characterized by the interference of the movement with the following one.

The area of each step was prepared to be smooth. In this way, the influence of the step surface roughness may be neglected compared to the relative roughness defined by the ratio K_S / D_H ,

where $K_S = h \cos \alpha$ and D_H is the hydraulic diameter.

The spillway elements form a compact set. Strong special glue was used in order to obtain a stable and compact spillway and to limit the infiltration phenomenon to the maximum.

In fact, certain studies have shown the importance of infiltration phenomenon in flow studies on stepped spillways.

Kells (1994) has also studied the influence of two reduced models of spillways with four steps and different shapes (Chanson, 1994). He has also studied the influence of the downstream and facial infiltration on the measurements. From the author's conclusions, it is shown that the spillway downstream infiltration is more important than that of the facial part.

The author's results indicate that there is a noticeable difference between the energy dissipation data of a spillway without downstream infiltration and that with downstream infiltration. The same results indicate that this difference depends on flow rate and may attain a percentage of 30%.

In order to mainly eliminate the influence of this infiltration type, we proceed to the installation of a barrier plate fixed in the channel. This plate was fixed by means of glue on the downstream spillway.

Our observations on preliminary test measurement series have permitted to observe that no infiltration is possible neither at the downstream spillway nor at the facial part. In addition to the advantage of eliminating downstream infiltration in the spillway flow, the barrier plate contributes to calm the flow before its circulation in the measurement spillway.

The prototype is placed to a sufficient distance so that perturbations due to the flow passage in the divergent are damped down.

This idea is inspired from the measurement cases in the ducts. In fact, appropriate values must be considered to determine the measurement points in order to guarantee the establishment of the flow regime in the duct.

For the measurement cases in the latter, the experimental estimations show that the entrance length value necessary for the regime establishment must be 25 times greater than the duct diameter (Scrivener et al., 1986).

RESULTS

Flow Description

Our experiment allowed considering two flow regimes. The first regime is that of the nappe flow and the second is that of the skimming flow.

The study of experimental results shows that the nappe flow appears for lesser discharge $30\, l/s.ml$ ($7.2\, l/s \big/ 0.24\, m = 30\, l/s.m$) for our case.

However, the skimming flows are observed for high discharge ($\rangle\, 30\, l/s/m$).

Surely, the shape characteristic and the step surface quality affect the flow regime change. It is evident that the unity discharge of 30 is specific to the structure of our experiment.

The conceptions of weak channel slopes contribute to the appearance of nappe regime (Essery and Horner, 1978).

The synthesis of the works of specialized authors in the field shows that the classification by flow regime is the most used (Peyras et al., 1991; Christodoulou, 1993; Chanson, 1995; Chanson, 1996).

In the nappe flow regime, water undergoes a succession of free-falling nappes. In the edge of each step, water becomes a jet of a free descent before it permeates the following step. Different configurations corresponding to this regime are observed. Our observations confirm those of Peyras et al. (1992). The works of authors have permitted to distinguish three types of nappe flow:

- Nappe flow with fully-developed hydraulic jump for low flow rate and small depth.
- Nappe flow with partially developed hydraulic jump.
- Nappe flow without hydraulic jump.

The skimming flow is characterized by a complete submersion of the totality of the steps which form the spillway. No diving was observed. Our observations agree with the description presented in the report BaCaRa (1996).

So, the flow, in skimming regime, on the spillway is divided into 3 parts:

The first part consists of a few steps at the entrance of the spillway. In this part, the flow presents a configuration characterized by a regulator free surface.

Also, it was observed that there was no air entrainment in this part. The induced fall (waterfall) by the spillway slope accelerates the flow and the water depth decreases.

The entrance to the second part occurs by the air injection point (point of inception of air entrainment) in the flow. In fact, concerning conditions related to the spillway shape and the flow discharge, it was observed that the air begins to be drifted in the flow.

Because of its presence and its advantages in the engineering applications (structure damage reduction, friction decrease, aeration process...), this phenomenon was of great interest in the research works on the use and the optimization of the evacuation process (Wood et al., 1983; Chanson, 1993).

The air entrainment process in the flow is complex. The water jumps above the step surface and falls under the gravity influence. During this process, the water aerates the flow. The air bubbles introduced will be taken in the rolls formed at the cavity beneath the free-falling nappes and steps. The association of these air bubbles and the moving water forms a two-phase flow (water + air) called white water. A transition zone formed by a few steps is also observed. In this zone, the depth of water corresponds to flowing water, which increases progressively by more and more pronounced aeration. The third part is formed by the remaining steps of the spillway. In this part, the flow appears under an emulsion form. The thickness of the flowing water tends to remain constant. It is to be noted that in case of skimming regime described, the flow does not appear to separate in parts as in the case of nappe flow.

A global observation permits to notice that the skimming flow, from a hydraulic point of view, presents a configuration which seems to be coherent over the whole spillway.

Furthermore, in skimming flows down stepped chutes, the flow is non-aerated at the upstream end and the free-surface is relatively smooth and glassy. Turbulence is generated however at the invert and a bottom boundary layer develops (Chanson, 2006).

Limit Between Nappe and Skimming Regimes

The flow regime change in a spillway was observed and analyzed. The conditions linked to the flow configuration changes have been quantitatively studied. The parameters which have been considered to quantify this change are the parameter related to flow critical depth (d_c) and to the spillway shape, which are the non-dimensional ratios d_c/h and h/l.

These parameters have been considered in other studies, especially by the authors (Chanson, 1994b; Chanson, 1995; Chanson, 1996; Chanson, 2004; Sorenson et al., 1985; Stephenson, 1988).

The exploitation of our results as a correlation of d_c/h and h/l permits to compare them with the results found in the bibliography.

During the experiment, we have noticed the existence of a transition zone. In this zone, the distinction between the two regimes is not possible. Similar observations have been noticed by other authors (Chanson, 1996).

The works of some authors put in evidence the appearance of this transition zone. It is to be noted that in this zone, the flow is unsteady. It is sometimes nappe and sometimes skimming.

Chanson (1996) emphasizes that the regime instability may be a source of fluctuations, which are of hydrodynamic origin. These fluctuations present a real risk affecting the concerned hydraulic structures.

In fact, the flow behavior presented that way generates additional oscillating charges to the efforts of the fluid flow on the structures.

Table 1: Values of d_c/h

Author	(Essery et al., 1978)	(Degoutte, 1990)	(Rajaratnam, 1990)	(Chanson, 1994)	(Kells, 1995)	(Moacyr et al., 1995)	Present study
d_c/h	0.81	0.69	0.80	0.77	0.50	0.83	0.67

The oscillations due to this phenomenon may be the cause of damage of a part or of the whole hydraulic structure. The author gives two examples for the damage of the hydraulic structure: the dam weir of Arizona (1905) and the dam weir of New Croton (1955).

The study of our experimental results shows that the regime change (nappe flow and skimming) is observed for a unit rate of 32.05 $l/s.m$ which corresponds to a calculated value of the critical depth $d_c = 4.7cm$.

The corresponding critical non-dimensional value is $d_c/h = 0.67$.

The bibliographic study shows that many propositions have been done to predict the regime change (nappe/skimming).

Rajaratnam (1990) takes into account the non-dimensional parameters d_c/h and h/l. The author has noticed that for several results linked to regime change conditions, the appearance of skimming regime is observed for a constant value of $d_c/h = 0.8$. He proposes the adoption of this value as the beginning of the skimming flow whatever the geometric specifications of the structure are.

Several authors have taken this proposition into account in their research work (Christodoulou, 1993).

Comparison of results shows that the value found in our experiment is less than the one proposed by Rajaratnam (1990); that is $0.67 \langle 0.8$.

Degoutte et al. (1992) have observed that for the flow on gabion spillways the critical value of the regime change defined by Rajaratnam is systematically less than 0.8.

Also, they have shown that the critical value decreases with the increase of the parameter h/l. For the flows on the same channel type, they have proposed a plot to predict the change of the flow nature (from the nappe flow to the skimming flow).

The application of the relation deduced from the authors' work to the geometric data of our spillway gives the value of 0.69. This value is almost the same as the one deduced from our experiment 0.67.

Kells (1995) had also noticed that the critical value of the parameter (d_c/h) corresponding to the flow regime change is highly less than 0.8. The result found in our experiment is different form the value preconized by Rajaratnam (1990). Our results give a value, which is close to those found by the work of Kells (1995).

It is admitted that the recommended conditions to predict the flow regime change for the case of concrete steps are different from those in gabions.

The infiltration, which is present for the case of steps with gabions and also the structure roughness seems to affect the flow regime change (Kells, 1995).

Essery et al. (1978) have studied the change of the flow nature, for concrete structure, as a function of the flow discharge and the step form. The relation deduced from the works of the authors applied to the geometric data of our spillway gives a value which is close to the one deduced from our experiment.

Table 2: Values of d_c/h with respect to number of steps

Number of steps	8	10	20	30
d_c/h	0.15	0.18	0.34	0.47

The exploration of the obtained data shows that the majority of values of the factor d_c/h corresponding to the flow regime change are less than 0.8.

In his results, Chanson (1994a) also takes into account the analysis of Essery and Horner (1978). The author proposes, for the prediction of the flow regime change, the following empirical relation:

$$\left(\frac{d_c}{h}\right)_c = 1.06 - 0.465\frac{h}{l} \qquad (1)$$

Also, Chanson (2004) re-analyzed previous experimental observations using the same nappe, transition and skimming flows. For the limit of transition flows, the author proposed a relation for this:

$$\frac{d_c}{h} \rangle\, 0.9174 - 0.381 * \frac{h}{l} \quad \text{for} \quad (0 \langle h/l \langle 1.7) \qquad (2)$$

The use of equations (1) and (2) for the data of our experiment, i.e. for $h/l = 0.608$, gives :

$$\left(\frac{d_c}{h}\right)_c = 0.77 \quad \text{and} \quad \frac{d_c}{h} \rangle\, 0.686 \qquad (3)$$

Concerning the non-dimensional values, relative to the critical depth of the regime change, calculated from equations (1) and (2), which are equal to 0.77 and 0.686, respectively, the first value is greater than that deduced from our experiment, 0.67, but the second value is near.

The exploitation of the relation results shows that the values of $(d_c/h)_c$ decrease when h/l increases. The difference between the two extreme values is about 50%.

Also, we notice that except the values of $h/l \leq 0.5$, the values of $(d_c/h)_c$ corresponding to the regime change are systematically less than that given by Rajaratnam (1990) :

$$\left(\frac{d_c}{h}\right)_c = 0.8\,. \qquad (4)$$

Chanson (1996) recalled the conditions of the development of his relation to predict the flow change nature. He gives also the limits and the precision of the appliance of his relation. Also, he suggests, developing an eventual correction of the proposed empirical relation, to take newer experimental data into account.

In terms of this analysis, we deduce that the results obtained by the application of different approaches are different from one another. These results are not all compatible with the results of our experiment.

Chanson (1996) admits that the application of his relation may give an estimation of the critical value of the regime change with a 20% error. If we take our experimental value into account, the error in relation to the obtained results by relation (1) is of the order of 13%.

Energy Dissipation Study

Figures 3a and 3b illustrate the data of the energy dissipation measurement for the smooth and stepped spillway.

Concerning the smooth spillway, the relative energy dissipation increases as a function of the discharge till an optimal value is reached. Above this value, the plot shapes become inversely proportional with less flow discharge.

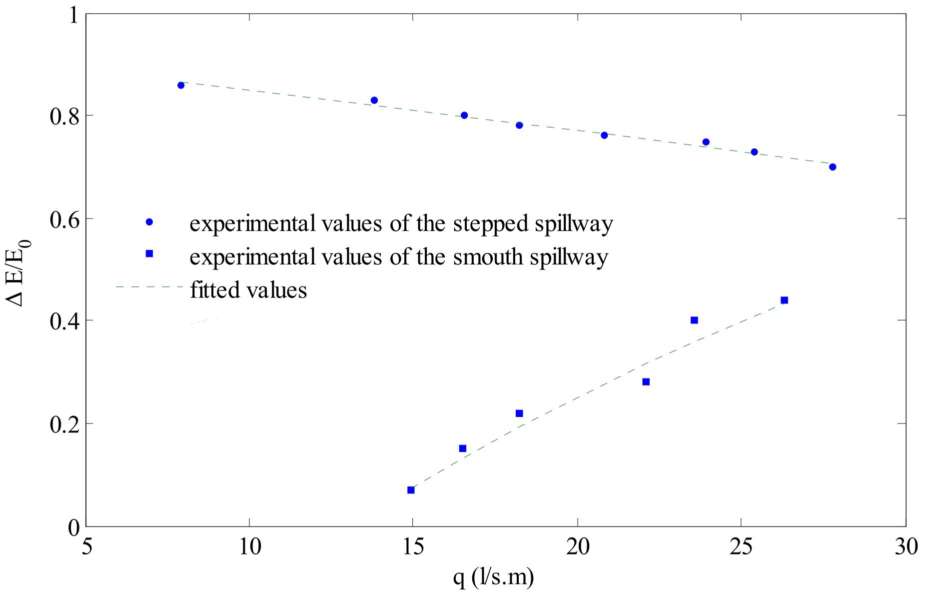
The examination of the results, for this spillway type, indicates that the variation of the energy at the spillway entrance between each two consecutive experiences is almost constant.

However, in the case of the energy at the stem spillway, it has been noticed that the energy variation is clearly significant for flow discharge values, which are greater at the point of the change of the plot shape (optimal value).

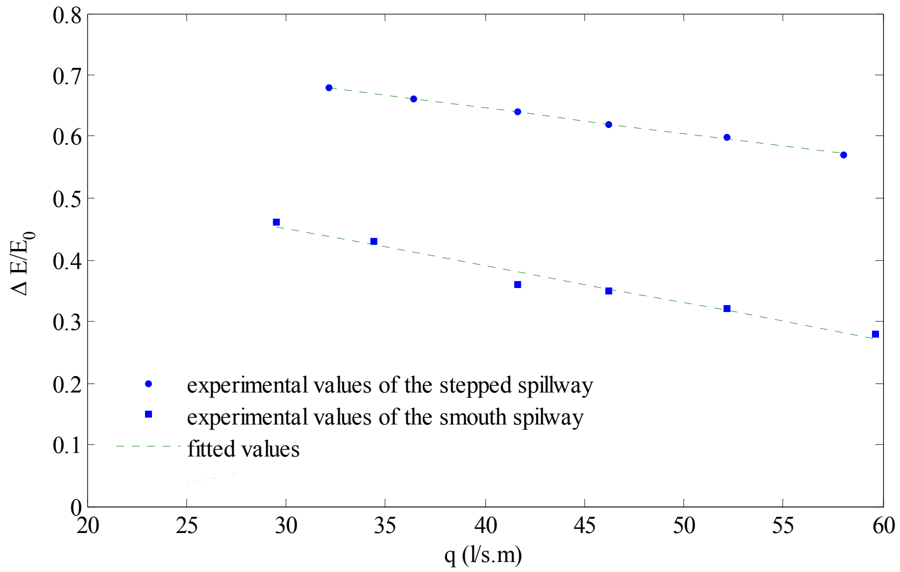
For flow discharges less than the optimal value, the shape of the two spillways (smooth and stepped), is different. The shape of this plot becomes similar in the range of discharge greater than the optimal value. This may be explained by the flow nature in this discharge values' range.

A noticeable difference of the energy dissipation values is observed for the case of steps' spillway relative to the case of smooth spillway. This difference may attain for less flow discharge the value of 90% (see Figure 3a).

The exploration of the result relative to the step spillway indicates that the energy dissipation value decreases frequently as the discharge increases or implicitly as the critical depth d_c increases.



(a)



(b)

Figure 3: Comparison values of energy dissipation, (a) Energy dissipation for nappe flow regime, (b) Energy dissipation for skimming flow regime

Stephenson (1988, 1991) has also noted that the energy dissipation is inversely proportional to the discharge values. These results have been confirmed later by other authors, especially by Chanson (1994a) and Kells (1994).

The results obtained also show that there is more energy dissipation in the case of nappe flow regime than in the case of skimming flow regime. The results of Peyras et al. (1991, 1992) show for a gabion spillway, that the energy dissipation of skimming flows is clearly less than that which is realized during nappe flows. Chanson (1994a, 1995) indicated that, for small structures for which the non-dimensional ratio linked to the structure height H_d is less than 35, i.e. the non-dimensional parameter $H_d/d_c \langle 35$, the nappe flow dissipates more than the skimming flow. The maximum of the ratio value H_d/d_c which corresponds to the structure of our experiment is equal to 22.1. This value is remarkably less than the limit value of ($H_d/d_c \langle 35$). The results indicate also that the maximum of the energy dissipation value is observed for a specific value of a normal depth of the flow d_0 ,

$$d_0/d_c = 0.36\,. \qquad (5)$$

In this part of the analysis, we note that certain authors take the ratio d_0/d_c into account to characterize the energy dissipation maximum value.

Stephenson (1991) indicated that the maximum energy dissipation is observed for a value of non-dimensional ratio $d_0/d_c = 1/3$.

The results of Tozzi (1992) give for this ratio the value of 0.29.

The exploration of other works indicates that some authors use the ratio d_0/d_c to specify and characterize the maximum energy dissipation. Tozzi (1992) indicates that the maximum energy dissipation is observed for a value of the ratio $d_0/d_c = 0.27$.

In their analysis, Matos and Quintela (1995) have obtained a ratio value $d_0/d_c = 0.3$.

The analysis of our results indicates that the maximum energy dissipation is observed for a value of the non-dimensional ratio of $d_0/d_c = 0.27$.

Analysis of the Energy Dissipation in the Case of Nappe Flow Regime

Figure 4 represents our experimental results concerning the energy dissipation in nappe flow regime versus the discharge and those of Horner for spillways of different numbers of steps.

The examination of the results shows that since the equipment of our laboratory could not permit us to obtain eight (Christodoulou, 1993) steps spillway results, we are obliged to do only a qualitative comparison.

The qualitative comparison is limited to our value, which offers this possibility. The extension to other values is possible only if we take the exploration of values taken from the extrapolation into account.

We point out that for values of flow discharge, which are near to each other, the values linked to the energy dissipation seem confusing. The comparison with the results of Horner indicates that the data of our experiment are less than those obtained by the author for spillways of 10, 20 and 30 steps.

In view of our analysis, we notice that the variation of the spillway slope α from which the results are utilized in this first part of comparison work seems to affect less the energy dissipation results.

The results' analysis of Matos and Quintela (1995) indicates that for less values of the discharge ($d_0/d_c \langle 0.3$), the inclination does not influence the energy dissipation. The discharge values, which are taken into consideration in this comparison, are all less than the critical value of 0.3.

These conclusions agree with those of Kells (1995) and Peyras et al. (1991). For higher discharge values, the slope influences significantly the energy dissipation.

Taking into account the influence of the number of spillway steps, the results found confirm with those found by Chamani and Rajaratnam (1994).

Analysis of the Results of Energy Dissipation in the Case of Skimming Flow Regime

Figure 5 represents our experimental results concerning the energy dissipation of skimming flow versus the discharge (d_c) and those of Peyras et al. (1991) and Iwao and Youichi (1995) for different spillway slopes.

The results are presented versus available data in the bibliography. We present then, in this part of analysis and comparison work, the parameters linked to the energy dissipation versus the non-dimensional parameter reported to the discharge value (critical depth) H_d/d_c . From this analysis, the global tendency of the energy dissipation variation versus the non-dimensional parameter H_d/d_c is obtained.

The analysis of the data of the figure indicates that the energy dissipation values obtained in our experiments are greater than those of Peyras et al. in which the spillway slope is 18° and those of Iwao and Youichi (1995) with a spillway slope of 30°. We note also that our results are less than those of Iwao and Youichi (1995) which correspond to a spillway slope of 55°.

The analysis shows that the discharge and the spillway slope have significant influences on the energy dissipation variation.

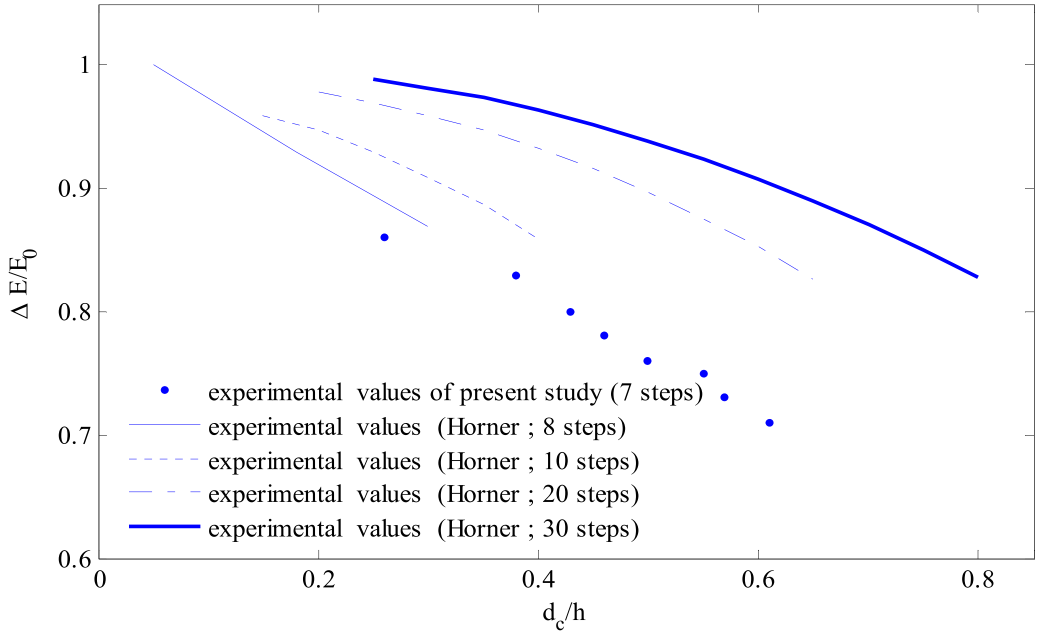


Figure 4: Energy dissipation in nappe flow regime

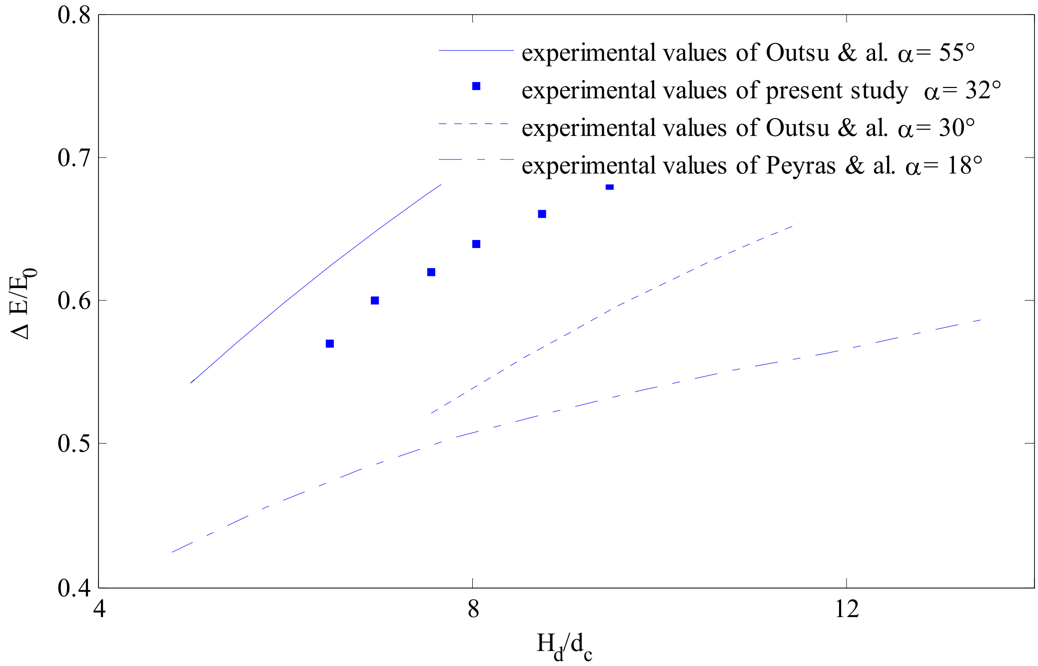


Figure 5: Energy dissipation in skimming flow regime

The results presented by Chanson (1994a) and Sorenson (1985) indicate that the energy dissipation value depends on the spillway slope.

No significant influence for the number of spillway steps on the energy dissipation value in the case of skimming flow was indicated in the work of these authors. Only Christodoulou (1993) evoked the dependency of the energy dissipation on the variation of the number of spillway steps. These results don't seem to be confirmed in any other investigation.

The energy dissipation values change around a value of 63%. This value is greater than that of the experimental results of Christodoulou (Scrivener et al., 1986) which is equal to 50%. The bibliographic analysis shows that the energy dissipation in the case of skimming flow depends strongly on the value of the friction coefficient.

A study of bibliography reveals that the average of the friction factor for this type of structure is in the order of 0.30 (Rajaratnam, 1990; Christodoulou, 1993; Chanson, 1995, 2006). For our study, we have obtained 0.24; this value is certainly near to the average value of 0.30.

CONCLUSIONS

The experimental results presented have permitted to describe flow configurations on the stepped spillway. They also indicate that:

- The stepped spillway dissipates the energy flow better than the spillway of a smooth profile.
- The energy dissipation is inversely proportional to the flow discharge, $30\, l/s.m$, for our case.
- For the exploration data of our experiment, the nappe flow dissipates better than that of skimming regime.
- The energy dissipation, in the case of a nappe flow, depends on the number of spillway steps and on the discharge.
- In the case of skimming flow, the energy dissipation depends on the spillway slope and on the discharge.
- The friction factor has a strong influence on the energy dissipation, the mean value of which is 0.24.

List of Symbols

A_w	flow area (m^2)
d	depth of water measured perpendicular to a flow (m)
d_0	depth of water in uniform flow (m)
d_c	critical depth of water (m) $d_c = \sqrt[3]{q^2/g}$
$(d_c)_c$	characteristic depth of water (m)
D_H	Hydraulic diameter (m) $D_H = \frac{A_w}{\chi_w}$
E_0	energy at the crest of the dam (m)
E	energy (m) $E = d + V^2/2g$
ΔE	energy loss (m)
H_d	height of dam (m) $H_d = n.h$
h	height of step (m) (measured vertically)
K_s	height of roughness (m) $K_s = h.\cos\alpha$
L	width of channel (m)
L_d	length of dam (m)
l	width of step (m)
n	number of steps
q	rate per unit (discharge) ($m^3/s.m$)
χ_w	wetted perimeter
α	angle $\alpha = \frac{n.h}{L_d}$

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