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EXPERIMENTAL INVESTIGATION OF FLOW AND ENERGY DISSIPATION IN STEPPED SPILLWAYS

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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 novel idea, since structures of such a type existed a long time before. We note that among the hydraulic structures realised at the beginning of the century in USA and in South Africa, we find numerous structures realised on the base of this concept. Recently, and with the introduction of novel construction materials and the technology modernisation, the interest for the stepped spillways has increased considerably to the sludge on the dams.
The synthesis of recent studies show that the concrete steps or gabion hydraulic structures are used utilised in the engineering appliances. 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 on the spillway. The spillway technique became mainly an economical mean, the gain on the project cost is about 20% compared to the other techniques (e.g.: inclined spillways, vertical full spillways (Peyras and al. 1992).
In effect, 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 show that despite of the many results available for specific cases, only few relevant results concerning the general case are obtained, only particular and isolated cases are modelled. The modelisation of this kind of flow using the classical equation of the fluid mechanics is approximate if the flow behaviour change characteristics are not taken into consideration.
During the latest years, authors such as Chanson and Rajaratnam have studied

systematically flows on spillways complex forms. The works of Chanson concerns particularly certain fundamental aspects of the problem. Essentially the most concern was the energy dissipation. The reactions to the Chanson paper (Chanson, 1994) show in 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 availability of 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 analysed.

EXPERIMENTATION

The experiments are realised by means of measurement installation of the complex fluid laboratory of 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 detailed description of this installation and different means of measurement are presented by Chafi (1998).
The measurement canal part is a spillway in a reduced model. This later is composed by 7 steps equally sized as: height: h= 7cm, width b=11.5cm, length L=24cm. The spillway slope value α [$tg(\alpha) = 7/11.5 = 0.6087 \Rightarrow \alpha \cong 32°$] is greater than the critical value defined by Chanson (1994) which is $\alpha = 27°$.
The author presented study indicated that a change flow mechanism and recirculation is observed for the spillway slope values ranged in [25°, 30°]. Turbulent flows on slope ($\alpha < 27°$) are characterised by friction factors less than for turbulent flows on spillways slope greater than 27°.
It is admitted that 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 characterised by the interference of the movement with the following one.
The surface (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 to the best the infiltration phenomenon.
In fact, certain studies have shown the importance of infiltration phenomenon in flow studies on stepped spillway.
Kells (1994) has studied also the influence on two reduced models of spillways with four (Chanson, 1994) steps and different shapes. He's also studied the influence of the downstream and facial infiltration on the measurements. From the author conclusions it is shown that the spillway downstream infiltration is

more important than that of the facial part.
The author results indicate that there is 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 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 conduits. In fact, appropriate values must be considered to determine the measurement points and this in order to guarantee the establishment of the flow regime in the conduit.
For the measurement cases in the later, the experimentators estimate that the entrance length value necessary for the regime establishment must be greater that 25 times the conduit diameter (Scrivener and al., 1986).

RESULTS

Flow description

The indications of our experiment have permitted to consider two flows regimes. The first regime is that of the nappe flow, the second is that of the turbulent flow. This study of experimental results shows that the nappe flow appear for lesser discharge 30 *l/s.ml* (7.2/0.24 = 30 *l/s.ml*) for our case. However, the turbulent flows are observed for high discharge $(> 30\, l/s.m)$.
Surly, 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 specialised authors in the field, shows that the classification by flow regime is the most used (Peyras al., 1991; Christodoulou, 1993; Chanson, 1995; 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 and *al*. (1992).
The works of authors have permitted to distinguish three types of nappe flow:

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

The skimming flow is characterised 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:

i. The first part consists of a few steps at the entrance of the spillway. The flow presents in this part a configuration characterised by a regulator free surface.
Also, it was observed that in this part, there is no air entrainment. The induced fall (waterfall) by the spillway slope accelerates the flow and the depth water decreases.
ii. The entrance of the second part regime by the air injection point (point of inception of air entertainment) in the flow. In fact, from conditions related to the spillway shape and the flow discharge, it was observed that the air begins to be drifted in the flow. This phenomenon, because of its presence and its advantages in the engineering applications (structure damage reduction, friction decrease, aeration process...) was of great interest in the research works on the appliance and the optimisation of the evacuate process (Wood and al., 1983; Chanson, 1993).
The entrainment air process in the flow is complex. The amount of water jump above the step surface and fall under the gravity influence. During this process, the water amounts aerate 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 diphasic flow (water + air) called white water. 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.
iii. The third part is formed by the remaining steps of the spillway. In this part, the flow is 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 thus described, the flow does not appear to separate in parts as in the case of nappe flow.

A globally observation permits to note that the skimming flow presents from an hydraulic point of view, a configuration which seems to be coherent over all the spillway.

Limit between nappe and skimming regimes

The flow regime change in a spillway was observed and analysed, the conditions linked to the flow configuration changes have been studied quantitatively. 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 non dimensional ratio d_c/h and h/l. These parameters have been considered in other studies, especially by Chanson (1994; 1995; 1996), Sorenson and al. (1985) and 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 have been permitted to make in evidence the appearance of this transition zone. It is to be noted that in this zone, the flow is unsteady. It is sometime nappe and sometime skimming.
Chanson (1996) emphasises 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 behaviour presented that way; generate additional oscillating charges to the efforts of the fluid flow on the structures. The oscillations due to this phenomenon may be the cause of damage to a part or to the whole hydraulic structure. The author gives two examples for the damage of the hydraulic structure. It concerns the dam weir of Arizona (1905), and that of the dam of New Croton (1955).
The study of our experimental results show 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 $d_c = 4.7$ *cm*. 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 in account the non dimensional parameters d_c/h and h/l. The author has noted 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 are the geometric specifications of the structure.
Several authors have taken into account this proposition 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 that is $0.67 < 0.8$.
Degoutte and 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*. They propose, for the flows on the same channel type, 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 give the value of 0.69. This value is almost the same of that deduced from our experiment 0.67.
Kells (1995) had also noted that the critical value of the parameter d_c/h, corresponding to the flow regime, change is highly less than 0.8. It is to be noted that the result found in our experiment is different form the value preconized by Rajaratnam. Our results give a value which is near it those found by the work of Kells. The values of d_c/h given by many authors are reported in table 1. Also indicated is our result.

Table 1: Values of d_c/h

Author	Essery and al. 1978	Degoutte 1990	Rajaratnam 1990	Chanson 1994	Kells 1994	Moacyr and al. 1995	Our result 1998
d_c/h	0.81	0.69	0.80	0.77	0.50	0.83	0.67

It is admitted that the recommended conditions to predict the flow regime change are different form the case of steps concrete than form those in gabions. The infiltration which is present for the case of steps with gabions and also the structure roughness seem affecting the recommended data for the flow regime change (Kells, 1995). Essery and al. (1978) have studied the change of the flow nature, for concrete structure, in function of the flow discharge and the step form. The appliance of the relation deduced from the works of the authors to the geometric data of our spillway gives a value which is near to that deduced from our experiment. Table 2 gives the values of d_c/h with respect to number of steps.

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 factors value d_c/h corresponding to the flow regime change are lesser than 0.8.
Chanson takes in account also in his results analysis of Essery and Horner (1978). The author proposes, for the prediction of the flow regime change, the following empirical relation:

$$(d_c / h)_c = 1.06 - 0.465 \frac{h}{l} \tag{1}$$

The appliance of this relation for the data of our experiments (h/l = 0.608) gives a value of $(d_c/h)_c$ = 0.77.

The non dimensional value, relative to the critical depth of the regime change, calculated from the relation (1) is equal to 0.77 and it is greater than that deduced from our experiment (0.67).
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 of the order of 50%.
Also, we note that except the values of $h/l \leq 0.5$, the values of $(d_c/h)_c$ corresponding to the regime change are systematically lesser than that given by Rajaratnam$(d_c/h)_c = 0.8$.
Chanson (1996) recalled the conditions of the development of his relation to predict the flow nature change. 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 in account newer experimental data.
In terms of this analysis, we deduce that the results, obtained by the appliance of different approaches are different from one another. These results are not all compatible with that of our experiment.
Chanson admits that the appliance of his relation may give an estimation of the critical value of the regime change with a 20% of error. If we take in account our experimental value, the error in relation to the obtained results by the relation (1) is of the order of 13%.

Energy dissipation study

Figures 1a and 1b illustrate the data of the energy dissipation measurement for the smooth and stepped spillway.
Concerning the smooth spillway, the relative energy dissipation increases in function of the discharge till an optimal value is reached, above this value, the plot shapes become inversely proportional with lesser 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, the case of the energy at the stem spillway, it was been noted 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).

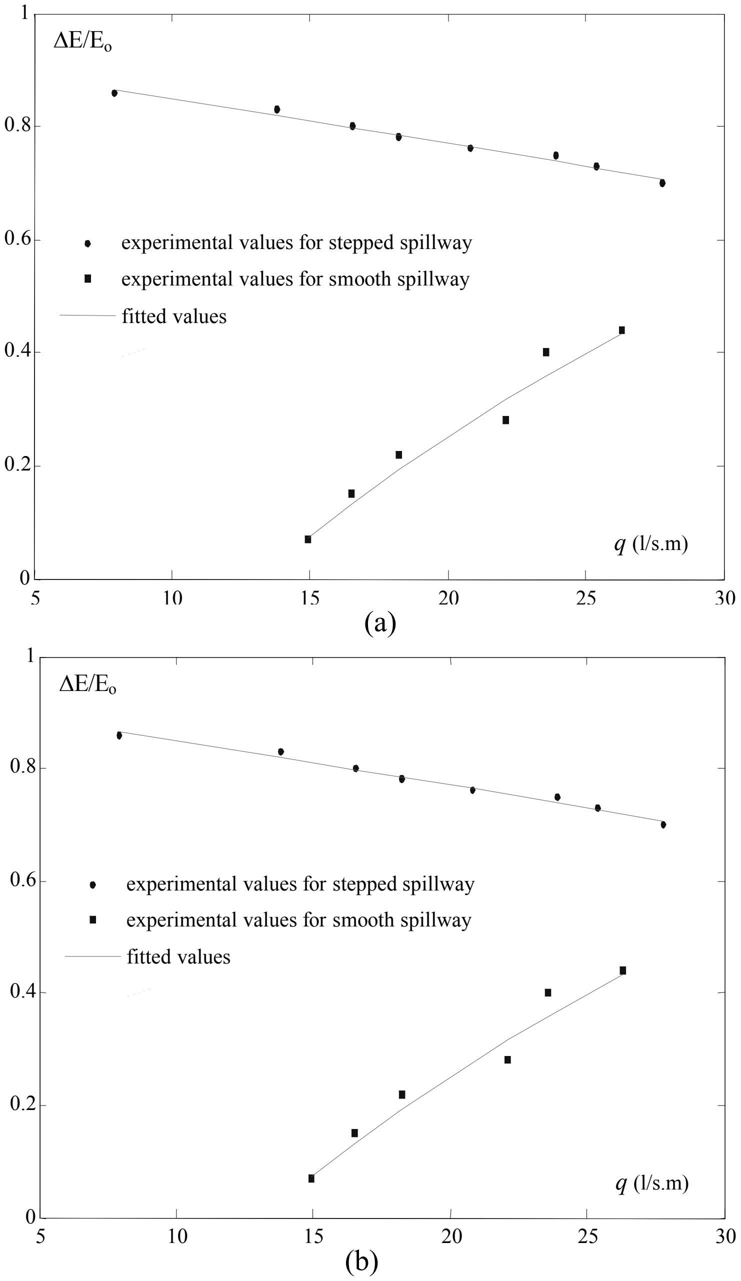

Figure 1: Comparison values of energy dissipation. (a) Energy dissipation for nappe flow regime, (b) Energy dissipation for skimming flow regime

For flow discharges lesser 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.
In effect, the flow is in this case of skimming type and the two spillways are totally submerged, from which the similarity of the shape of the two plots.
The results indicate also clearly that a great amount of flow energy may be dissipated in a stepped spillway.
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 lesser flow discharge the value of 90% (see Figure 1a).
The exploration of results 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.
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 (1994) and by Kells (1994).
The results obtained show also that there is more energy dissipation in the case of nappe flow regime than in the case of skimming flow. The results of Peyras and al. (1992; 1991) show, for a gabion spillway, that the energy dissipation of skimming flows is clearly lesser than that which is realised during nappe flows.
Chanson (1994; 1995) had indicated that, for small structures for which the non dimensional ratio linked to the structure height H_d is lesser than 35, i.e. the non dimensional parameter $H_d/d_c < 35$ the nappe flow dissipates more than the skimming flow. The maximum value of the ratio H_d/d_c which corresponds to the structure of our experiment is equal to 22.1. This value is highly lesser than the limit value of $H_d/d_c < 35$. 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_o i.e. $d_o/d_c = 0.36$. We note in this part of analysis that some authors take in account the ratio d_o/d_c to characterize the energy dissipation maximum value. Stephenson (1988) had indicated that the maximum energy dissipation is observed for a value of non dimensional ratio $d_o/d_c = 1/3$. The results of Tozzi give for this ratio the value of 0.29. The exploration of other works indicates that some authors use the ratio d_o/d_c to specify and characterize the maximum energy dissipation. Tozzi indicates that the maximum energy dissipation is observed for a value of the ratio $d_o/d_c = 0.27$. In their analysis Matos and Quintela (1995) have obtained a ratio value $d_o/d_c = 0.3$.
The analysis of our results indicates that the maximum energy dissipation is observed for a value of the non dimensional ratio of $d_o/d_c = 0.27$.

Analysis of the energy dissipation in the case of nappe flow regime

Figure (2) presents our experimental results concerning the energy dissipation in nappe flow regime versus the discharge and those of Horner for spillways of different number of steps.

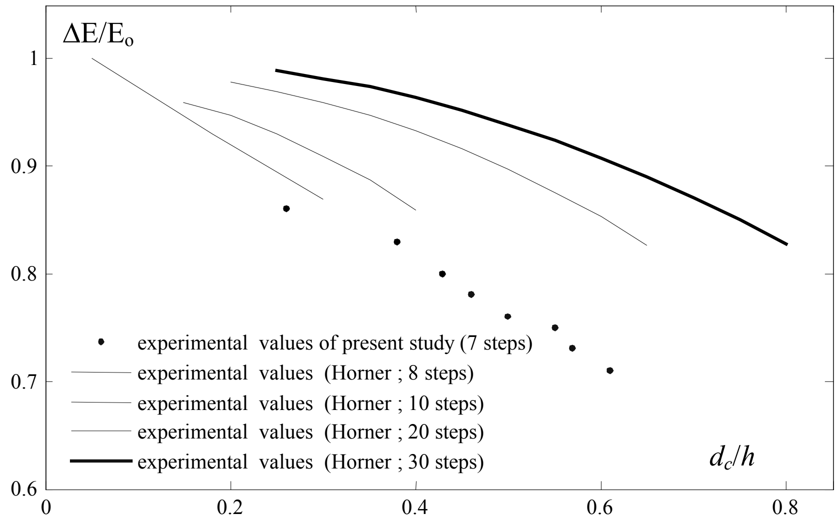

Figure 2: Energy dissipation in nappe flow regime

The examination of the results shows that since the equipment of our laboratory could not permit us to obtain eight (Christodoulou G.C. 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 in account to exploration of values taken from the extrapolation.

We point out then 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 lesser than those obtained by the author for spillway of 10, 20 and 30 steps.

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

The results analysis of Matos and Quintela indicate that for lesser values of the discharge i.e. d_o/d_c < 0.3, the inclination does not influence the energy dissipation. The discharge values, which are taken in consideration in this comparison, are all lesser than the critical value of 0.3.

We note also that these conclusions agree with those of Kells (1995) and Peyras and al. (1991). For higher discharge values the slope influences significantly the energy dissipation.

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

Analysis of the results of energy dissipation in the case of skimming flow regime

On figure 3, we have presented our experimental results concerning the energy dissipation of skimming flow versus the discharge (i.e. d_c) and those of Peyras and al. (1991) and Iwao O. and Youichi (1995) for different spillway slopes.

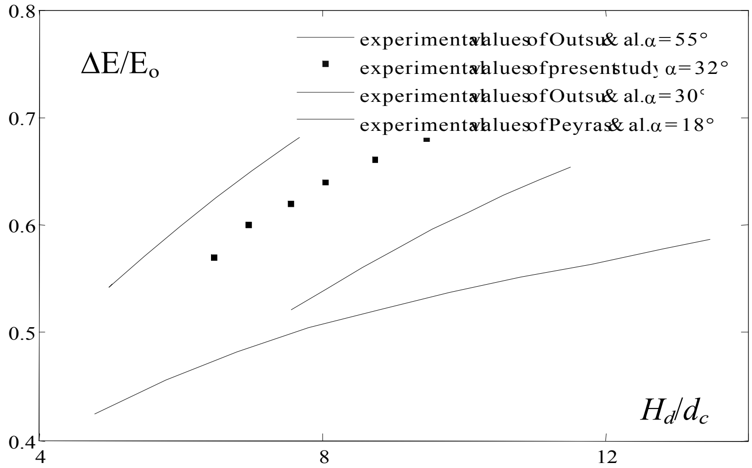

Figure 3: Energy dissipation in turbulent flow regime

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 (i.e. critical depth) H_d/d_c. It is obtained from the analysis that the global tendency of the energy dissipation variation versus the non dimensional parameter H_d/d_c. The analysis of the data of figure 3 indicates that the energy dissipation values obtained in our experiments are greater than those of Peyras and al. in which the spillway slope is 18° and of Iwao and Youichi (1995) whith a spillway slope of 30°. We note also that our results are lesser 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 a significant influence on the energy dissipation variation. The results presented by Chanson (1994) and Sorenson (1985) indicate all that the energy dissipation value depends on the spillway slope. No significant influence of the number of spillway steps on the energy dissipation value in the case of skimming flow is indicated in the work of these authors. Only Christodoulou (1993) evokes the dependency of the energy dissipation to 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 equal to 63%. This value is greater than that of the experimental results of Christodoulou (Scrivener and 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. Study of bibliography reveals that the average value of the friction factor for this type of structure is in order of 0.30 (Rajaratnam, 1990; Christodoulou, 1993; Chanson, 1995). For our student, we have obtained 0.24 which is near certainly of the average value of 0.30.

CONCLUSION

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

i. stepped spillway dissipates the flow energy better than those of smooth profile.

ii. The energy dissipation is inversely proportional to the flow discharge which is equal to 30 *l/s.m* for our case.

iii. For the exploration data of our experiment, the nappe flow dissipates better than that of skimming regime.

iv. Also, our results indicate that the energy dissipation, in the case of a nappe flow, depends on the number of spillway steps and on the discharge.

v. In the case of skimming flow, the energy dissipation depends on the spillway slope and the discharge.

vi. The friction factor has a strong influence on the energy dissipation whose mean value is 0.24.

NOTATION

A_w water area
b width of channel
d depth of water measure perpendicular to a flow
d_o depth of water in uniform flow
d_c critical depth of water equal to $(q^2/g)^{1/3}$
$(d_c)_c$ depth characteristic of water
D_H hydraulic diameter equal to $(4A_w/\chi_w)$
E_o energy at the crest of dam
E total head equal to $[d + V^2/(2g)]$
ΔE energy loss
H_d height of dam equal to (nh)
h height of step
K_s height of roughness equal to $[h\cos(\alpha)]$
L_d length of dam
l width of step
n number of steps
q discharge per unit width
χ_w wetted perimeter
α angle equal to (nh/L_d)

REFERENCES

BACARA (1996). Projet National BaCaRa, Les barrages en B.C.R, Presses de l'Ecole National des Ponts et Chaussées, 200 p.

CHAFI, C. (1998). Etude de l'écoulement d'un fluide sur un profil complexe de type marche d'escalier, *Thèse de Magister*, Centre Universitaire de Mascara.

CHAMANI, M.R, RAJARATNAM, N. (1994). Jet Flow on Stepped Spillways, *J. Hydraul. Engng.*, *ASCE* 120 (2), 254-259.

CHANSON, H. (1996). Prediction of the Transition Nappe / Skimming Flow on a Stepped Channel, *J. Hydraul. Res.*, *IAHR* 34(3), 421-429.

CHANSON, H. (1995). *Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways*, Pergamon, Elsevier Science, Oxford, U.K.

CHANSON, H. (1994). Comparison of Energy Dissipation Nappe and Skimming Flow Regime on Stepped Chutes. *J. Hydraul. Res.*, *IAHR* 32(2), 213-218.

CHANSON, H. (1994). Hydraulics of Skimming Flows Over Stepped Channels and Spillways, *J. Hydraul. Res.*, *IAHR* 32(3), 445-460.

CHANSON, H. (1993). Stepped Spillway Flows and Air Entrainment, *Canadian Journal of Civil Engng.*, 117(3), 371-389.

CHRISTODOULOU, G.C. (1993). Energy Dissipation on Stepped Spillways, *J. Hydraul. Engng., ASCE*. 119(5), 644-650.

DEGOUTTE, G., PEYRAS, L. and ROYET, P. (1992). Skimming flow in stepped spillways, *Discussion*, *J. hydraul. Engng.*, *ASCE*.118(1),.111-114.

ESSERY, I.T.S. and HORNER, M.W. (1978). The Hydraulic Design of Stepped Spillways, CIRIA Report N°33, 3rd edition, January, London, UK.

IWAO, O. and YOUICHI., Y. (1995). Comparison of Energy Dissipation between Nappe and Skimming Flow on Stepped Chutes, *Discussion*, *J. Hydraul. Res.*, *IAHR* 32(02), 115-119.

KELLS, J.A. (1995). Comparison of Energy Dissipation between Nappe and Skimming Flow Regimes on stepped Chutes, Private communication, *J. Hydraul. Res.*, *IAHR* 33(1), 128-134.

KELLS, J.A. (1994). Energy Dissipation at a Gabion Weir with Through flow and Overflow, Canadian Society for Civil Engng., Annual Conference, Winnipeg, MB.

MATOS, G. and QUINTELA, A. (1995). Flow Resistance and Energy Dissipation in Skimming Flow over Stepped Spillways, *J. Hydraul. Res.*, *IAHR* 33(1), 115-119, 135-139.

PEYRAS, L., ROYET, P. and DEGOUTTE, G.(1992). Flow and Energy Dissipation Over Stepped Gabion Weirs, *J. Hydraul. Engng.*, *ASCE* 118(5), 707-717.

PEYRAS, L., ROYET, P. et DEGOUTTE, G. (1991). Ecoulement et Dissipation sur les Déversoirs en Gradins de Gabion, *La Houille Blanche*, n°1, 37-47.

RAJARATNAM, N. (1990). Skimming flow in stepped spillways, *J. Hydraul. Engng.*, *ASCE* 116(4), 587-591.

SCRIVENER, O., REITZER, H., HAZZAB, A. and IDRISSI, A. (1986). Optical and ultrasonic instruments for mixture flow investigation, Hydrotransport, 10th international conference on transport of solid in pipes, paper H2, 275- 282, Insbruck, Austria, 29 - 31 oct 1986, Ed. A. B. Burns.

SORENSEN, R.M. (1985). Stepped Spillway Hydraulic Model Investigation. *J. Hydraul. Engng.*, *ASCE* 113(12), 1461-1472.

STEPHENSON, D. (1991). Energy Dissipation down Stepped Spillways. Intl. Water Power and Dam Construction, 43(9),.27-30.

STEPHENSON, D. (1988). Stepped Energy Dissipation, Proc. Intl. Symp. On Hydraulics for High Dams. *IAHR*, Beijing, China, 1228-1235.

TOZZI, M.J. (1994). Residual energy in stepped spillways, *Int. Water Power and Dam Construction*, 74(2), 32-34.

WOOD, I.R., ACKERS, P. and LOVELESS, J. (1983). General Method for Critical Point on Spillways, *J. Hydraul. Engng.*, *ASCE* 109(2), 308-312.