# Comparison of energy dissipation between nappe and skimming flow regimes on stepped chutes

# Comparaison de la dissipation d'énergie pour des écoulements en nappe et extrémement turbulents sur des évacuateurs de crue en marches d'escaliers

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**SUMMARY**
For the last decades, stepped spillways have become a popular method for handling flood releases. The flow regime over a stepped chute can be either a nappe flow or skimming flow regime. The energy dissipation of both flow regimes are analysed. The results are compared with experimental data. For long chutes where uniform flow conditions are reached, higher energy dissipation takes place in a skimming flow regime. But, for short channels, nappe flows would dissipate more kinetic energy than skimming flows.

**RÉSUMÉ**
Durant les dernières décennies, l'utilisation d'évacuateurs de crues en marches d'escalier est devenue courante. Le régime d'écoulement, dans un canal en marches d'escalier, peut être en nappe ou extrémement turbulent. Le taux de dissipation d'énergie pour ces deux régimes est analysé. Les résultats sont comparés avec des mesures expérimentales. Si un écoulement uniforme est obtenu en fin de canal, le régime d'écoulement extrémement turbulent permet une meilleure dissipation d'énergie. Par contre, un écoulement en nappe dissipera plus d'energie cinétique pour des coursiers de petite longueur.

## 1 Introduction

### 1.1 *Presentation*

Water flowing over a stepped chute can dissipate a major proportion of its energy. On a spillway chute, the steps increase substantially the energy dissipation taking place on the spillway face, and lead to a reduction in the depth and dimensions needed for the stilling basin at the toe of the chute. The behaviour of flow over a stepped chute can be classified into two types of flow: nappe flow regime and skimming flow regime (Fig. 1).

Nappe flow is characterised by a succession of free-fall jets impinging the next step and followed by a fully developed or partially developed hydraulic jump (Fig. 1a). A nappe flow regime requires relatively large steps. This situation may apply to small discharges or relatively flat spillways. In the skimming flow regime, the water flows as a coherent stream skimming over the steps (Fig. 1b). Stable recirculating vortices develop between the steps. These vortices are maintained through the transmission of shear stress from the fluid flowing past the edges of the steps (Rajaratnam 1990).

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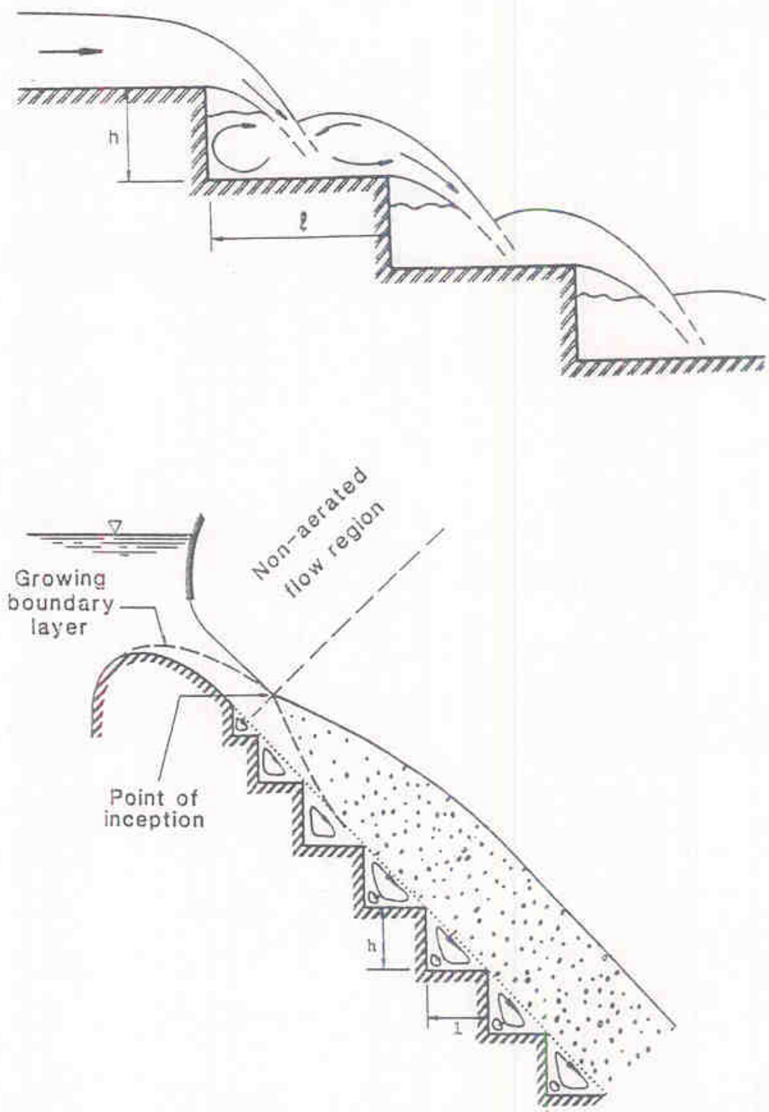


Fig. 1. Flow regimes above stepped channel: (a) nappe flow; (b) skimming flow.

Ellis (1989) and Peyras et al. (1991) suggested that there is much higher energy dissipation in nappe flows than in skimming flow situations. In this note, head loss calculations for nappe flow and skimming flow regimes are developed. The results are discussed and compared with experimental data (Table 1).

### 1.2 *Onset of skimming flows*

For small discharges and flat slopes, the flow regime is a nappe flow regime. An increase of discharge or of channel slope may induce the appearance of a skimming flow regime. A re-analysis of experimental data (Table 2) indicates that skimming flow regime occurs for discharges larger than a critical value. The characteristic discharge for the onset of skimming flow can be defined in term of a critical depth, which is correlated for the data presented in Table 2 as:

$$\frac{(d_c)_{onset}}{h} = 1.057 - 0.465 * \frac{h}{l} \tag{1}$$

where $h$ is the step height, $l$ is the step length and $(d_c)_{onset}$ is the characteristic critical depth.

Table 1. Characteristics of model studies

| reference | slope (deg.) | $q_w$ ($m^2/s$) | step height $h$ (m) | Nb of steps | comments |
|---|---|---|---|---|---|
| Essery and Horner (1978) | 11 to 40 | | 0.03 to 0.05 | 4 to 18 | CIRIA tests |
| Noori (1984) | 5.7<br>11.3 | 0.007 to 0.09<br>0.027 to 0.2 | 0.004<br>0.013 | 100<br>70 | $W = 0.5$ m |
| Sorensen (1985) | 52.05 | 0.005 to 0.235<br>0.006 to 0.11 | 0.061<br>0.024 | 11<br>59 | Monksville dam spillway model $W = 0.305$ m |
| Diez-Cascon et al. (1990) | 53.1 | 0.025 to 0.2 | 0.03-0.06 | 50 to 100 | $H_{dam} = 3.8$ m<br>$W = 0.8$ m |
| Peyras et al. (1991) | 18.4, 26.6, 45 | 0.045 to 0.268 | 0.20 | 3, 4, 5 | Gabion stepped chute $W = 0.8$ m |
| Stephenson (1991) | 54.5 | | | | Kennedy's vale model |
| Beitz and Lawless (1992) | 51.3 and 48.0 | 0.0013 to 0.093 | 0.02 | 10 | Burton Gorge dam spillway model |
| Frizell (1992) | 26.6 | 0.58 | 0.051 | 47 | $W = 0.457$ m |
| Bindo et al. (1993) | 51.34 | 0.02 to 0.152<br>0.007 to 0.036 | 0.038<br>0.019 | 31-43<br>43 | M'Bali spillway model<br>$W = 0.9$ m |
| Christodoulou (1993) | 55.0 | 0.02 to 0.09 | 0.025 | 15 | $W = 0.5$ m |

Table 2. Onset of skimming flows - experimental data

| $d_c/h$ | $h/l$ | reference |
|---|---|---|
| 0.20 | 1.15 | Essery and Horner (1978) |
| 0.42 | 0.81 | |
| 0.53 | 0.82 | |
| 0.74 | 0.82 | |
| 0.84 | 0.80 | |
| 0.33 | 0.74 | Peyras et al. (1991) |
| 0.5 | 0.67 | |
| 1.0 | 0.61 | |
| 1.25 | 0.40 | Beitz and Lawless (1992) |

## 2 Energy dissipation for nappe flow regime

A stepped chute with nappe flow regime is a succession of drop structures. The energy dissipation occurs by jet breakup in the air, jet impact and jet mixing on the step, with the formation of a fully developed or partial hydraulic jump on the step (Fig. 1a). The total head loss equals the difference between the maximum head available $H_{max}$ and the residual head at the bottom of the spillway. The residual energy is dissipated by hydraulic jump in a dissipation basin at the spillway toe. Combining the definition of the head loss with the momentum equation applied to the base of an overfall (White 1943) and with the correlations obtained by Rand (1955), it yields (Chanson 1993):

$$\frac{\Delta H}{H_{max}} = 1 - \frac{0.54 * \left(\frac{d_c}{h}\right)^{0.275} + 1.715 * \left(\frac{d_c}{h}\right)^{-0.55}}{\frac{3}{2} + \frac{H_{dam}}{d_c}} \quad \text{Un-gated spillway} \tag{2a}$$

$$\frac{\Delta H}{H_{max}} = 1 - \frac{0.54 * \left(\frac{d_c}{h}\right)^{0.275} + 1.715 * \left(\frac{d_c}{h}\right)^{-0.55}}{\frac{H_{dam} + H_0}{d_c}} \quad \text{Gated spillway} \tag{2b}$$

where $H_{dam}$ is the dam head crest above the downstream toe and $H_0$ is the free-surface elevation above the spillway crest. For an un-gated spillway, the maximum head available and the dam height are related by: $H_{max} = H_{dam} + 1.5 * d_c$. For a gated spillway: $H_{max} = H_{dam} + H_0$.

On Fig. 2, the energy dissipation (equation (2a)) is plotted as a function of the relative dam height $H_{dam}/d_c$ for various number of steps. The results indicate that the energy dissipation increases with the dam height. Further, for a given dam height, the rate of energy dissipation decreases when the discharge increases.

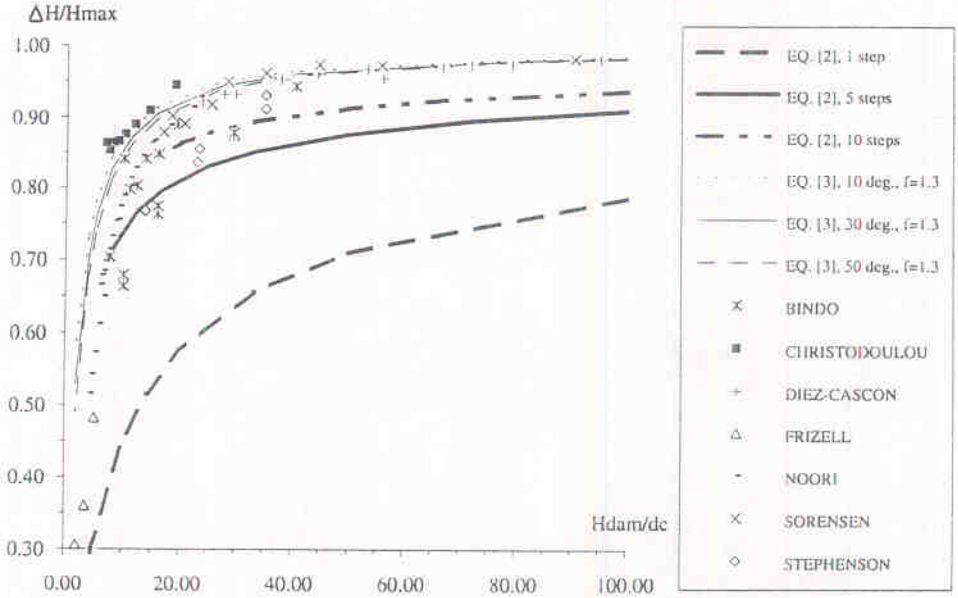


Fig. 2. Comparison of the energy dissipation between nappe flow and skimming flow regime.

## 3 Energy dissipation for skimming flow regime

In a skimming flow regime, the steps act as large roughness. Most of the energy is dissipated to maintain stable horizontal vortices beneath the pseudo-bottom formed by the external edges of the steps. The vortices are maintained through the transmission of turbulent shear stress between the skimming stream and the recirculating fluid underneath (Fig. 1b).

Assuming that uniform flow conditions are reached before the end of the spillway, the depth of flow and the flow velocity can be deduced from the momentum equation (Chanson 1993). And the energy loss can be estimated as:

$$\frac{\Delta H}{H_{\max}} = 1 - \frac{\left(\frac{f}{8*\sin\alpha}\right)^{1/3} * \cos\alpha + \frac{1}{2} * \left(\frac{f}{8*\sin\alpha}\right)^{-2/3}}{\frac{2}{3} + \frac{H_{\text{dam}}}{d_c}} \quad \text{Un-gated spillway} \quad (3a)$$

$$\frac{\Delta H}{H_{\max}} = 1 - \frac{\left(\frac{f}{8*\sin\alpha}\right)^{1/3} * \cos\alpha + \frac{1}{2} * \left(\frac{f}{8*\sin\alpha}\right)^{-2/3}}{\frac{H_{\text{dam}} + H_0}{d_c}} \quad \text{Gated spillway} \quad (3b)$$

where $f$ is the friction factor, $\alpha$ is the channel slope.

A recent analysis of experimental data (Chanson 1993) indicated skimming flow situations exhibiting friction factors between 0.5 and 4 with a mean value of about 1.3. For that value (i.e. $f = 1.3$), equation (3a) is presented on Fig. 2 for several channel slopes. Fig. 2 shows little effects of the channel slope on the rate of energy dissipation for $f = 1.3$. The results are compared also with experimental data (Table 1). They show a reasonable agreement between the data and equation (3) computed assuming $f = 1.3$. Note that all the data presented on Fig. 2 were obtained in a skimming flow regime.

It must be noted that equation (3) depends critically upon the estimation of the friction factor. Further equation (3) and the present analysis neglect the effects of air entrainment. Indeed the friction factor and hence the energy dissipation are affected significantly by the rate of free-surface aeration (Chanson 1993).

## 4 Discussion

Experimental data presented on Fig. 2 indicate that high energy dissipation takes place on a stepped chute. Although the mechanisms of energy loss are quite different between nappe flow and skimming flow regime, both flow situations can dissipate a major proportion of the flow energy (equation (2) and (3)).

Fig. 2 compares the rate of energy dissipation in nappe flows (equation (2)) and skimming flows (equation (3)). Equation (2) is plotted for 1, 5 and 10 steps, and equation (3) is presented for slopes ranging from 10 to 50 degrees, assuming $f = 1.3$. For large dams (i.e. $H_{\text{dam}}/d_c > 35$), Fig. 2 indicates that a skimming flow regime (equation (3) and data) can dissipate higher flow energy than nappe flow regime (equation (2)).

For short spillway channels, the uniform flow conditions are not obtained at the toe of the spillway. Equation (3) becomes inaccurate and overestimates the energy dissipation in skimming flows. In a nappe flow regime, energy dissipation takes place at each step. It is believed that nappe flow situations can dissipate higher energy than skimming flow regime on short chutes. It must be noted however that, for a given discharge, a nappe flow regime requires flatter slope and larger steps (equation (1)) than a skimming flow regime. In some cases, such requirements might increase the cost of the structure or are not possible.

## 5 Conclusion

In this study, calculations of energy dissipation on stepped chutes are summarised. The results are compared with skimming flow data. For long chutes, uniform flow conditions are obtained at the toe of the spillway and a skimming flow regime enables higher energy dissipation than a nappe flow regime. For short channels, it is believed that nappe flow situations would dissipate higher flow energy. In both flow regimes, the rate of energy dissipation can be as high as 95% on a spillway (Fig. 2).

This analysis indicates that the results depend greatly upon the estimation of the flow resistance. Further all the data presented on Fig. 2 were obtained on model. Additional prototype data is required.

## Notations

| | |
|---|---|
| $d_c$ | critical flow depth (m) |
| $(d_c)_{onset}$ | critical flow depth (m) at the onset of skimming flows |
| $d_0$ | uniform flow depth (m) measured normal to the channel slope at the edge of a step |
| $f$ | friction factor of non-aerated flow |
| $H_{max}$ | total head (m) |
| $H_{dam}$ | dam head crest above downstream toe (m) |
| $H_0$ | free-surface elevation (m) above the spillway crest |
| $h$ | height of steps (m) |
| $l$ | horizontal length of steps (m) |
| $q_w$ | water discharge per unit width ($m^2/s$) |
| $W$ | channel width (m) |
| $\alpha$ | spillway slope |
| $\Delta H$ | head loss (m) |

## References / Bibliographie


Beitz, E. and Lawless, M. (1992), Hydraulic Model Study for dam on GHFL 3791 Isaac River at Burton Gorge, Water Resources Commission Report, Ref. No. REP/24.1, Sept., Brisbane, Australia.

Bindo, M., Gautier, J. and Lacroix, F. (1993), The Stepped Spillway of M'Bali Dam, Intl Water Power & Dam Construction, Vol. 45, No. 1, pp. 35-36.

Chanson, H. (1993). Stepped Spillway Flows and Air Entrainment, Can. J. of Civil Eng., June, Vol. 20, No. 3, pp. 422-435.

Christodoulou, G. C. (1993), Energy Dissipation on Stepped Spillways, J. of Hyd. Engrg., ASCE, Vol. 119, No. 5, pp. 644-650.

Diez-Cascon, J., Blanco, J.L., Revilla, J. and Garcia, R. (1991), Studies on the Hydraulic Behaviour of Stepped Spillways, Intl Water Power & Dam Construction, Sept., pp. 22-26.

Ellis, J. (1989), Guide to Analysis of Open-Channel Spillway Flow, CIRIA Technical Note No. 134, 2nd edition, London, UK.

Essery, I. T. S. and Horner, M. W. (1978), The Hydraulic Design of Stepped Spillways, CIRIA Report No. 33, 2nd edition, Jan., London, UK.

Frizell, K. H. (1992), Hydraulics of Stepped Spillways for RCC Dams and Dam Rehabilitations, Proc. of the 3rd Specialty Conf. on Roller Compacted Concrete, ASCE, San Diego CA, USA, pp. 423-439.

Noori, B. M. A. (1984), Form Drag Resistance of Two Dimensional Stepped Steep Open Channels, Proc. of the 1st Intl Conf. on Hyd. Design in Water Resources Engineering, Channels and Channel Control Structures, Southampton, UK, K. V. H. Smith ed., Springer-Verlag Publ., pp. 1.133-1.147.

Peyras, L., Royet, P. and Degoutte, G. (1991), Ecoulement et Dissipation sur les Déversoirs en Gradins de Gabions, (Flows and Dissipation of Energy on Gabion Weirs), J. La Houille Blanche, No. 1, pp. 37-47 (in French).

Rajaratnam, N. (1990), Skimming Flow in Stepped Spillways, J. of Hyd. Engrg., ASCE, Vol. 116, No. 4, pp. 587-591.

Rand, W. (1955), Flow Geometry at Straight Drop Spillways, Proceedings, ASCE, Vol. 81, No. 791, Sept., pp. pp. 1-13.

Sorensen, R. M. (1985), Stepped Spillway Hydraulic Model Investigation, J. of Hyd. Engrg., ASCE, Vol. 111, No. 12, pp. 1461-1472.

Stephenson, D. (1991), Energy Dissipation down Stepped Spillways, Intl Water Power & Dam Construction, Sept., pp. 27-30.

White, M. P. (1943), Ergy Loss at the Base of a Free Overfall - Discussion, Transactions, ASCE, Vol. 108, pp. 1361-1364.

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