Uses of Stepped Chutes and Cascades

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ABSTRACT

Stepped chutes and cascades have become a subject of renewed interest in the last two decades. Their use is commonly related to dams but they are also used for environmental and for aesthetic applications, and these applications are often forgotten. This paper reviews the different applications of stepped chutes and provides general guidelines in their applicability and design.

RÉSUMÉ

Au cours des dernières années, un intérêt accru a été accordé à l'application des chutes en escalier. Ces ouvrages sont souvent associés aux évacuateurs de crues de barrage, mais ils sont également utilisés pour des raisons écologiques et esthétiques, bien que ces types d'applications soient moins connus. Le présent article examine les différentes utilisations des chutes en escalier et offre des recommandations relatives à leur conception et à leur exploitation.

INTRODUCTION

The hydraulics of stepped chutes is a field that has evolved in the last 20 years in direct connection with new construction techniques and the use of new materials in hydroelectric projects. Therefore, they are commonly associated with dams. Nevertheless, stepped chutes and cascades have been used for a long time not only in hydropower but also for environmental and aesthetic purposes. This

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paper presents a review of the different applications and provides general guidelines for their design and use.

CHARACTERISTICS OF STEPPED CHUTES

The key characteristic of a stepped chute is the presence of steps, from near the top to the bottom. These steps can be horizontal, inclined (downward or upward) or pooled as Figure 1 illustrates. Previous studies (Chanson, 1995, 2001) have shown that in a stepped chute three flow regimes can occur: nappe, transition and skimming. In the nappe flow regime, the water flows over each step, drops as a jet hitting the next step, and then continues flowing until it drops again (Fig. 2a); an air pocket is present in the step cavity. In the transition flow regime, a pool of recirculating water replaces the air pocket in some steps whilst others still have air under the jet. In the skimming flow regime (Fig. 2b), the water flows over a pseudo bottom formed by the water trapped in the step cavity. Large amounts of air are entrained and it is therefore considered to be a two-phase flow. According to Chanson (2001), the nappe flow regime occurs when

$$\frac{y_c}{h} \leq 0.89 - 0.4\frac{h}{l}, \qquad (1)$$

where y_c is the critical depth of the flow, h is the step height and l is the step length; whilst the skimming flow regime occurs when

$$\frac{y_c}{h} \geq 1.2 - 0.325\frac{h}{l}. \qquad (2)$$

The transition flow regime occurs between the nappe flow and skimming flow regimes defined by (1) and (2), respectively. Equations (1) and (2) were deduced for flat horizontal steps with $0.05 \leq h/l \leq 1.7$ and uniform flow conditions. Finally, within the nappe flow regime, three sub-regimes can be distinguished: the subcritical, the mixed and the supercritical. Murillo and Doering (2002) give a procedure to classify them.

APPLICATIONS OF STEPPED CHUTES AND CASCADES

The use of stepped chutes and cascades goes back more than 2000 years. Examples of dams, channels, and fountains are present in many ancient civilizations as well as in modern times (Chanson, 1995, 1998). Broadly speaking, the use of these chutes can be divided into three general categories: dam, environmental, and aesthetic applications. Considerations on each application are given henceforth.

Dam applications

Stepped chutes were often used in dams built prior to the 1920's, before developments in stilling basin design were achieved and they were put aside. However, during the last two decades, stepped chutes have again become a popular method for handling flood releases. On embankment dams, the need to increase the discharge capacity during floods motivated Soviet engineers to use precast concreted stepped block on top of an existing embankment. These blocks are placed over a filter and erosion protection layer. The USBR has designed and patented one type of these blocks (Frizell et al., 2000), whilst Baker (2000a) described one application of precast stepped blocks in U.K.

On concrete gravity dams, the popularity of stepped chutes is based on its compatibility with roller compacted concreted (RCC) and slip-forming techniques. Stepped chutes made of RCC have been used to build new dams as well as to rehabilitate hydroelectric facilities with too small capacity. In this case, the RCC chute is placed on top of the existing spillway, thus increasing the discharge capacity during floods.

A well-known fact is the presence of steps on the spillway increases significantly the rate of energy dissipation taking place along the chute and therefore, it reduces the size and the cost of the downstream stilling basin. However, this dissipation is only effective if the dam is high enough. Mateos Iguacel and Elviro

(2000) mentioned that if the ratio of dam height to critical depth is less than 10, the energy dissipation is similar to that of a conventional smooth spillway. In this case, the cost reduction on the stilling basin would not be achieved, although the cost of the chute may be reduced due to the construction technique, e.g., RCC or slip-forming. Furthermore, the experiences of some South African dams have shown (Stephenson, 1991) that the energy dissipation can be increased until the stage when the water depth on the spillway is approximately one third of the critical depth, beyond which it is very difficult to increase the energy dissipation further. Matos and Quintela (1995) as well as Matos (2000) indicated that the optimum step height (h_{opt}) for energy dissipation purposes can be estimated by $h_{opt} / y_c \approx 0.3$.

Regarding the maximum unit discharge ($q_{\max}$) several criteria are available. The Spanish Hydraulic Laboratory (CEDEX) recommends a $q_{\max}$ of only 10 m^3/s/m (Mateos Iguacel and Elviro, 1995), whilst Minor (2000) mentioned that the $q_{\max}$ commonly accepted is about 25 to 30 m^3/s/m. Boes and Minor (2000) analyzed the influence of local air concentrations on the flow and they concluded that higher steps allow a considerably larger $q_{\max}$ than small steps. The $q_{\max}$ that can safely flow on a stepped chute according to Boes and Minor (2000) are indicated in Table 1.

Stepped spillways are usually designed with horizontal steps and for the skimming flow regime. Chanson (1995) and the UK Construction Industry Research and Information Association (CIRIA) (Baker, 2000b), provided detailed design guidelines for the use of precast stepped blocks. Detailed design guidelines for conventional stepped chutes are provided by Chanson (1995), Boes and Minor (2000) and Matos (2000).

Environmental applications

Environmental applications of stepped chutes and cascades are numerous. Generally speaking, cascades are utilized to help the re-oxygenation of polluted waters, the cooling of surrounding areas and of warm waters as well as the masking of undesirable ambient noises among other uses. An example of the re-oxygenation effect is the Sidestream Elevated Pool Aeration (SEPA) in Chicago (Macaitis, 1990; Robinson, 1994). In this project, five cascades where introduced along a stream and the surrounding areas transformed into parks. According to Butts et al. (2000), since its introduction, the SEPA project has been successfully keeping DO concentrations above the required standards.

Environmental applications are usually designed for nappe flow regime. Especially attractive is the use of pooled steps where the cascade is formed by a succession of weirs. Aigner (2001) presented a methodology for its design. The use of fine nappes will have the greatest cooling capacity and the splashing will mask undesirable noises. A preliminary estimate of the oxygen transfer process can be obtained using the expression developed by Avery and Novak (1978) or by Kim and Walters (2000).

The USACE has also been studying the use of stepped chutes as a gas abatement alternative for hydroelectric projects on the Lower Snake and Columbia Rivers. According to Ahmann and Zapel (2000), stepped chutes provide a reasonable improvement in the gas abatement process. Hence, the use of these structures can reduce gas concentrations in the water and therefore the mortality due to gas bubble trauma of juvenile salmonids or any other species in the river could be reduced. Besides the beneficial effects associate with reducing gas levels, Ahmann and Zappel (2000) also found that fillets added to the steps reduce or eliminate the re-circulation of flow within the step cavity. They suggested that this fact may improve fish passage survival without significantly reducing the stepped spillway's ability to dissipate energy. The design of stepped chutes for gas abatement is similar to a dam application and further information on the use as a potential fish ladder is still needed (Ahmann and Zappel, 2000).

Aesthetic applications

Water performs numerous functions as an aesthetic element: it may provide a visual experience, create a mood, reinforce or direct circulation paths, and modify the environment by introducing the dimension of time. These effects are created by taking advantage of the forever-changing effect that flowing water produces, on the fascination that humans have with water as well as the water's capacity to energize a static surrounding. As a result of all this, it is not uncommon to find applications of stepped chutes and cascades in the architecture of old as well as modern cities (Chanson, 1995, 1998).

In using cascades as an aesthetic element, the performance of the water itself and the different effects that can be achieved become the main attraction. For example, the clear water region of the skimming flow, may introduce serenity into an otherwise congested area or densely developed site, serenity that could be enhanced by the use of small slopes in order to introduce the additional effect of a wavy pattern. In addition, the kinetic effect of the water would be an invitation for people to dabble their fingers in the water. In the nappe flow regime, the use of many small jets will also produce a tranquility effect.

On the other hand, the use of large step heights would produce the necessary sound effect to mask surrounding noises. A similar sound effect, but different aesthetic one, would be achieved with the use of skimming flow with white water. Nevertheless, the sound effect may become a problem if it is not used properly, especially in confine spaces. As a general rule, small steps will produce gentle sounds whilst large steps will have the opposite effect. In any case, the step cavity in nappe flow should be well ventilated in order to avoid nappe oscillations and annoying noises.

Aesthetic applications are easily combined with an environmental application (e.g., the SEPA project) and they could be designed for nappe or skimming flow regime, depending on the desire aesthetic effect. In nappe flow regime, cascades with horizontal or inclined steps are designed according to the concept of a drop structure and Chanson (1995) provided guidelines for this. Pooled steps cascades are designed as a succession of weirs. The use of weirs in a cantilever position, with a small notch on its underside, is recommended in order to facilitate the aeration of the step cavity and to achieve a free fall from the lip. Furthermore, to get smooth water sheets in still air, a head of at least 6 mm is necessary. Depths greater than 9 to 13 mm, however, may produce turbulence, while water depths of less than 6 mm may fail to sustain a continuous sheet of water (Friedberg and Rice, 1982). A smooth water sheet is usually produced by the use of sharp-crested weir(s). Additionally, the ratio of downstream basin length to the depth of fall is generally about 3 to 2, but this proportion will vary according to the volume and velocity of the flow. The lowest basin should be containing enough space to hold the water under the static condition as well as provide enough depth for all electro mechanic equipment. If skimming flow is the desired condition, guidelines provided by Chanson (1995), Boes and Minor (2000) or Matos (2000) should be followed.

Finally, in northern climates aesthetic applications may require a long period of winter shutdown. Therefore the design of the structure and its appearance are of equal importance to the performance of the water itself. Alternatively, when frozen, the structure might become a skating rink. In such a case, the system must accommodate the expansion of the water as it freezes, as does a pond with shallow, sloping sides.

FINAL REMARKS

Stepped chutes have been traditionally associated with dams. However, their applications go beyond this and there are many examples of environmental and of aesthetic applications. Stepped chutes and cascades offer many environmental benefits: re-oxygenation of polluted waters, cooling of warm water or surrounding areas and reduction of gas concentration to prevent bubble gas trauma in fishes, among other benefits. Cascades are also use with aesthetic purposes (i.e., fountains) in order to improve the quality of life.

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REFERENCES

Ahmann, M.L. and Zapel, E.T. (2000). "Stepped spillways, a dissolved gas abatement alternative". In: Minor, H.E. and W.H. Hager (eds.), *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 45-52.

Aigner, D. (2001). "Hydraulic design of pooled step cascades". In: Li, G.(ed.), *21^{st} Century: The new era for hydraulic research and its applications. Proc. 29^{th} IAHR Congress, Theme D, Vol. I.*, Beijing, China: 635-640.

Avery, S.T. and Novak, P. (1978). "Oxygen transfer at hydraulic structures". *Journal of Hydraulic Division*, *ASCE,* 104(HY11): 1521-1540.

Baker, R. (2000a). "Field testing of Brushes Clough stepped block spillway". In: Minor, H.E. and W.H. Hager (eds.), *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 13-20.

Baker, R. (2000b). "The CIRIA guide for the design of stepped-block spillways". In: Minor, H.E. and W.H. Hager (eds.), *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 155-161.

Butts, T.A., Shackleford, D.B. and Bergerhouse, T.R. (2000).

"Sidestream Elevated Pool Aeration (SEPA) Stations: Effects on In-stream Dissolved Oxygen": Report ISWS CR 2000-02. Illinois State Water Survey, Champaign, IL, U.S.A.

Boes, R.M. and Minor, H.E. (2000). "Guidelines for the hydraulic design of stepped spillways". In: Minor, H.E. and W.H. Hager (eds.), *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 163-170.

Chanson, H. (1995). *Hydraulic design of stepped cascades, channels, weirs and spillways*. Pergamon. Oxford, U.K.

Chanson, H. (1998). "Le développement historique des cascades et fontaines en gradins" (Historical development of stepped cascades and fountains). *La Houille blanche*, Revue de la Société Hydrotechnique de France, No 7: 76-84. (In French).

Chanson, H. (2001). "A transition flow regime on stepped spillway? The facts". In: Li, G. (ed.), *21^{st} Century: The new era for hydraulic research and its applications. Proc. 29^{th} IAHR Congress, Theme D, Vol. I.*, Beijing, China: 490-498.

Friedberg, M.P. and Rice, C. (1982). "Decorative pools and fountains". In: Alpern, A. (ed.), *Handbook of specialty elements in architecture*, McGraw-Hill, USA: 265-281.

Frizell, K.H.; Matos, J. and Pinheiro, A. (2000). "Design of concrete stepped overlay protection for embankment dams". In: Minor, H.E. and W.H. Hager (eds.), *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 179-186.

Kim, J. and Walters, R.W. (2001). "Oxygen transfer at low drop weirs". *Journal of Environmental Engineering, ASCE*, 127(7): 604-610.

Macaitis, B. (1990). "Sidestream elevated pool aeration station design". In: Wilhelms, S.C. and J.S. Guilliver (eds.), *Proc. 2nd Symp. On Gas transfer at water surfaces, air-water mass transfer*, ASCE, U.S.A.: 670-681.

Mateos Iguacel, C. and Elviro, V. (1995). "Stepped spillways. Design for the transition between the spillway crest and the steps". In: *Proc. 26th IAHR Congress, Hydra 2000, Vol. 1*, Thomas Telford, London, U.K.: 260-265

Mateos Iguacel, C. and Elviro, V. (2000). "Stepped spillway studies at CEDEX". In: Minor, H.E. and W.H. Hager (eds.), *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 87-94.

Matos, J. (2000). "Hydraulic design of stepped spillways over RCC dams". In: Minor, H.E. and W.H. Hager (eds.), *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 187-194.

Matos, J. and Quintela, A. (1995). "Flow resistance and energy dissipation in skimming flow over stepped spillways". In: W.H. Espey and P.G. Combs (eds.), *Proc. Water Res. Eng.*, San Antonio, Texas.

Minor, H.E. (2000). "Spillway for high velocities". In: Minor, H.E. and W.H. Hager (eds)., *Intl. Workshop on Hydraulics of stepped spillways*, Balkema Publ., Netherlands: 3-10.

Murillo, R. and Doering, J.C. (2002). "Nappe flow regimes in stepped spillways". *Journal of Hydraulic Engineering*, *ASCE*. (In review).

Robinson, R. (1994). "Chicago's waterfalls". *Civil Engineering*, *ASCE*, June: 36-39.

Stephenson, D. (1991). "Energy dissipation down stepped spillways". *Water Power & Dam Construction*, 43(9): 27-30.

Table 1. Maximum unit discharge in uniform flow on stepped spillways according to Boes and Minor (2000).

	Chute inclination		
	2H:1V (26.6°)	0.8H:1V (51.3°)	0.6H:1V (59°)
Step height	$q_{\max}$ (m³/s/m)	$q_{\max}$ (m³/s/m)	$q_{\max}$ (m³/s/m)
h = 0.3 m	10.0	13.2	13.8
h = 0.6 m	37.3	49.3	51.6
h = 0.9 m	68.5	90.5	94.9
h = 1.2 m	105.5	139.4	146.0

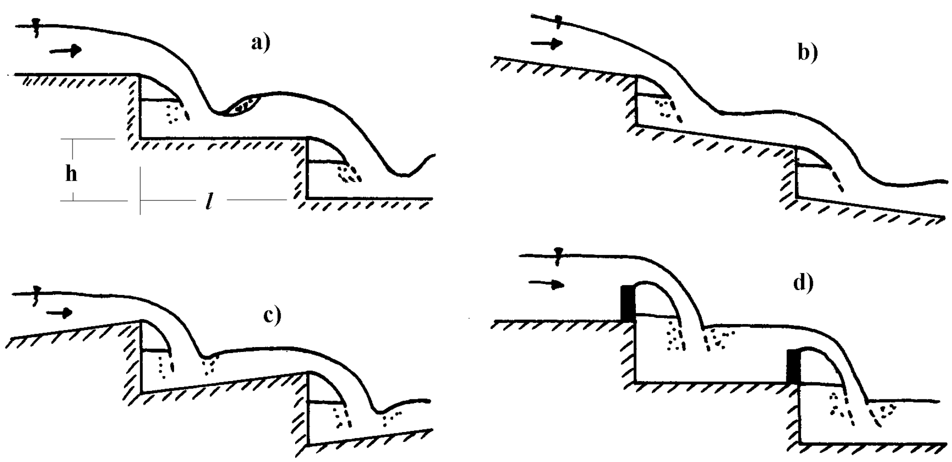

Figure 1. Different step types: a) horizontal steps, b) downward steps, c) upward steps and d) pooled steps.

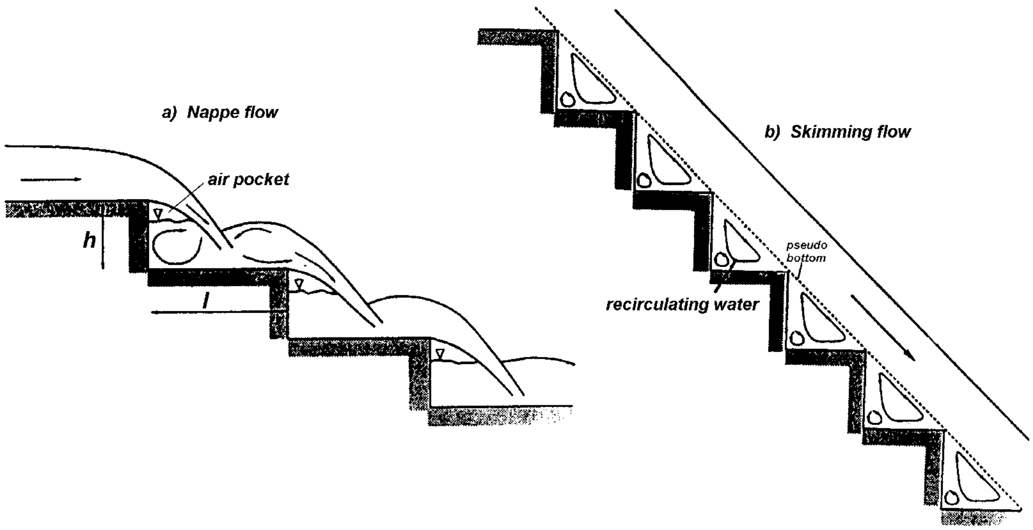

Figure 2. Flow regimes in a stepped chute: a) nappe flow regime, b) skimming flow regime.