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FORUM ARTICLE

Hydraulics of stepped spillways : current status

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Stepped-channel spillways, staircase waste waterways, stepped spillways, or stepped chutes have been used for more than 3,000 years (Fig. 1). In recent years they are experiencing renewed attention. The present forum article discusses briefly the current status of stepped spillways, and it draws attention to a recent workshop on the subject.

A significant number of dams were built with overflow stepped spillways during the 19th century and early 20th century, before such spillways became outdated by progresses in hydraulic jump stilling basins (Fig. 2). Recent advances in technology (e.g. RCC, polymer-coated gabion wire) have however triggered a regain of interest for stepped spillways. Unfortunately, though, much expertise had been lost in the past 60 years. Research on stepped spillway hydraulics has been active for the past ten years (Fig. 3). During the period 1985-2000, the international database Science Citation Index (The Web of Science) lists fourteen papers and twenty-one discussions and closures on stepped spillway, or stepped chute, hydraulics, all but two were published between 1990 and 2000. A 1985 paper (*Jl Hyd Engrg*) was cited seventeen times during the period, and two papers published in 1994 (*Jl of Hyd Res*) were cited twenty-two times altogether. The database Global Books in Print lists further one book (Chanson 1995).

An international workshop on hydraulics of stepped spillways was held recently at the Eidgenössische Technischen Hochschule (ETH) in Zürich, Switzerland in March 2000. The workshop was organised by

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Drs Minor and Hager and it attracted over forty participants from Europe, North America, Iran, and Australia. The participants were professionals, academics and researchers involved in stepped spillway design. Sponsorship by the ASCE, IAHR and Swiss national committee on large dams demonstrated the workshop's professional importance. The workshop was organised into five sections : (1) case studies, (2) aeration characteristics and cavitation risk, (3) energy dissipation, (4) internal flow features and (5) design. Altogether twenty-two papers were presented, plus one introductory and one invited lectures. The lectures covered nine papers on skimming flows, and two on nappe flows. Two papers discussed the gas-transfer process (or mass transfer) at stepped spillways and chutes, and seven articles dealt with design experience.

Overall the workshop presentations and the associated discussions were an useful exercise. They showed a general agreement on a number of issues. It is acknowledged that the waters flow as a succession of free-falling nappes at low flow rates and as a skimming flow at larger discharges for a given stepped chute geometry. Yet there are some arguments about a transition flow region between nappe and skimming flow regimes, a theory supported by some researchers. All the workshop participants agree that air entrainment is significant on stepped chutes. In nappe flow, one paper highlighted the complexity of the air-water flow while several papers demonstrated that air entrainment in skimming flow is similar to the self-aeration process observed on smooth-invert chutes (Fig. 3). In skimming flow, it is generally agreed that the cavity recirculation contributes to significant form drag and that the dimensionless friction coefficient f (or Darcy friction factor) is about 0.1 to 0.3, with one analytical development implying f = 0.2. Yet different research facilities yield different results and the researchers agree to disagree on the reasons for these differences ! Experimental studies suggest that cavitation is not an issue on stepped spillways because the flow velocities remain low. Step damage caused by pressure fluctuations in the step cavities may however be a problem. It is understood that scale effects may be significant when the geometric scaling ratio of prototype to model dimensions is greater than 10 to 20.

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The discussions held during the workshop highlighted some questions. Is an Ogee crest the most suitable crest design ? What is the order of magnitude of the pressure fluctuations on the step faces ? Is there a drag reduction process induced by air entrainment as observed on smooth-invert chutes ? How much mass transfer occurs along a stepped cascade ? Is there an optimum stepped design for re-oxygenation purposes?

The writer attended the workshop and he was surprised by the absence of two topics : failures and education. No paper discussed accidents and failures with stepped spillways although over twenty-one major accidents have been documented (e.g. Chanson 1955). The writer is concerned that too few engineers are willing to share their engineering failure experience with peers. Yet this would be of a great service to the community. The teaching of stepped channel hydraulics is another issue. Of the over two hundred RCC dams built to date in North-America, only sixty were equipped with a stepped spillway. Why ? It is believed that most engineers, young and senior, have never been exposed to the complexity of the stepped spillway design. The writer has lectured stepped spillway hydraulics at postgraduate and undergraduate levels since 1992 in Australia (e.g. Chanson 1999, pp. 313-363) and overseas (e.g. Nihon University 1998). Could it be that some researchers and engineers do not fully appreciate the needs for continuing education and undergraduate teaching of quality in hydraulic structures ?

In summary, the research on stepped spillway hydraulics is very active. Although progresses were achieved in the last decade, more research is needed to gain a sound understanding of the complex flow patterns. The organisers of the recent workshop did a service to the society in attracting both professionals and researchers actively involved in stepped spillway design. A review of the proceedings book resulting from the workshop will be forthcoming in an later issue of JHE. The writer, as a participant in the

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workshop, has two minor criticisms of the proceedings. Readers of the proceedings may not entirely grasp the number of issues for which there is incomplete consensus. Secondly as frequently happens with good meetings, the informal discussions held during the workshop added substantially to the understanding of the subject of stepped spillways but the discussions are not included in the book. The hydraulic design of stepped spillways and chutes is an illustration a loss of hydraulic expertise by professional engineers during the 20th century. It is hoped that a lesson will be learned and that the profession will not "re-discover the wheel" every sixty years.

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Fig. 1 - Old stepped weir in Akarnania, Greece B.C. 1,300 (Courtesy of Professor KNAUSS)

Dam : 10.5-m height, weir crest length : about 25 m, earthfill structure, about 14 steps, mean stepped slope : about 45º (from 39º down to 73º), step height : 0.6 to 0.9-m

(A) Three-quarter view with watermill in foreground and new road ramp over the weir

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(B) Details of the steps

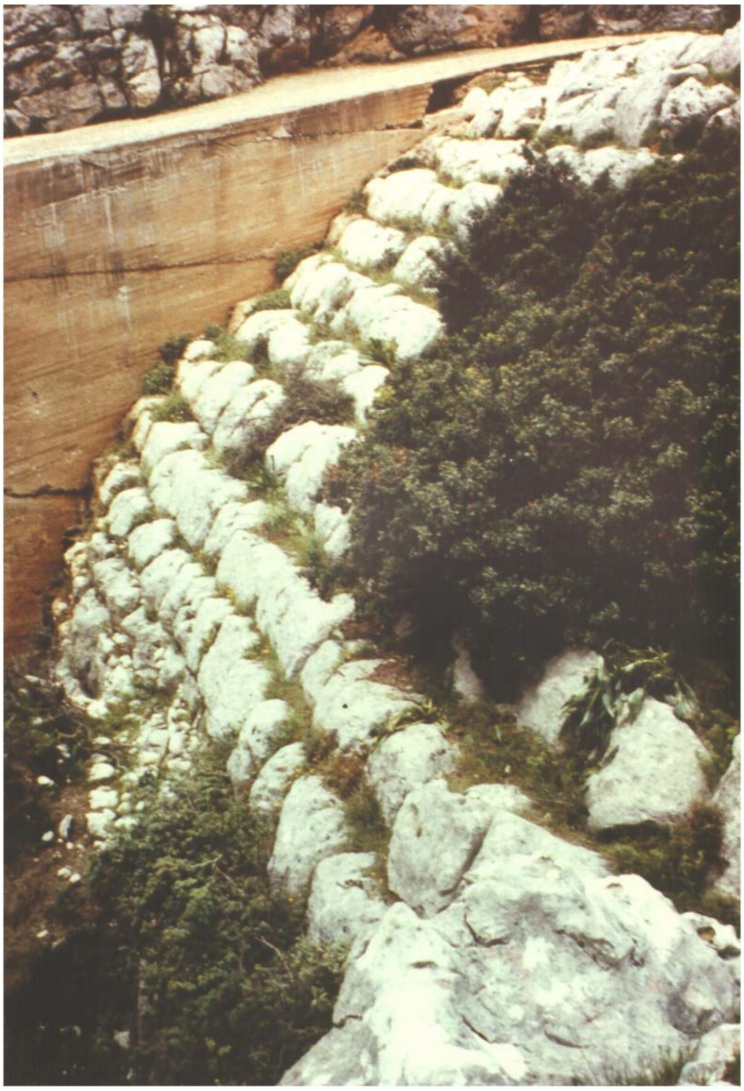

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Figure 2 - Claerwen dam spillway (Wales 1952) in operation (Courtesy of Mr L. Stuart DAVIES, Welsh Water). Dam height : 67 m, step height : 1.5 m

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Figure 3 - Skimming flow at Nihon University spillway model in November 1998

Slope: 30º, step height : 0.05 m