FORUM ARTICLE

HYDRAULICS OF STEPPED SPILLWAYS: CURRENT STATUS

Stepped-channel spillways, stepped spillways, staircase waste waterways, 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 international 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were built with overflow stepped spillways during the 19th century and early 20th century, before such spillways became outdated by progresses in hydraulic jump stilling basins (Fig. 2).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., roller-compacted concrete, polymer-coated gabion wire), however, have triggered a renewal of interest in stepped spillways. Unfortunately, though, much expertise has been lost in the past 60 years. Research on stepped-spillway hydraulics has been active for the past 10 years (Fig. 3). During the period 1985–2000, the international database Science Citation Index (The Web of Science) lists 14 papers and 21 discussions and closures on stepped-spillway, or stepped-chute, hydraulics, all but two having been published between 1990 and 2000. A 1985 paper (*Journal of Hydraulic Engineering*) was cited 17 times during the period, and two papers published in 1994 (*Journal of Hydraulic Research*) were cited 22 times altogether. The database Global Books in Print lists 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 organized by Drs. H. Minor and W. Hager, and it attracted over 40 participants from Europe, North America, Iran, and Australia. The participants were professionals, academics, and researchers involved in stepped-spillway design. Sponsorship by ASCE, IAHR, and the Swiss national committee on large dams demonstrated the workshop's professional importance. The workshop was organized into five sections: (1) case studies; (2) aeration characteristics and cavitation risk; (3) energy dissipation; (4) internal flow features; and (5) design. Altogether 22 papers were presented, plus an introductory and an invited lecture. There were 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. One analytical development implied $f = 0.2$. Yet different research facilities yield different results, and people agreed 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, however, may be a problem. It is understood that scale effects may be significant when the geometric scaling ratio relating prototype and model dimensions is greater than 10 to 20.

Discussions during the workshop highlighted some important 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 reoxygenation purposes?

The writer attended the workshop and was surprised by the absence of two topics: failures and education. No paper discussed accidents and failures with stepped spillways, although over 21 major accidents have been documented (e.g., Chanson 1955). The writer is concerned that too few engineers are willing to share their engineering-failure experiences with peers. Yet doing so would be a great service to the profession. The teaching of stepped-channel hydraulics is another issue. Of the over 200 RCC dams built to date in North-America, only 60 were equipped with a stepped spillway. Why? It is believed that most engineers, young and senior, have never been ex-

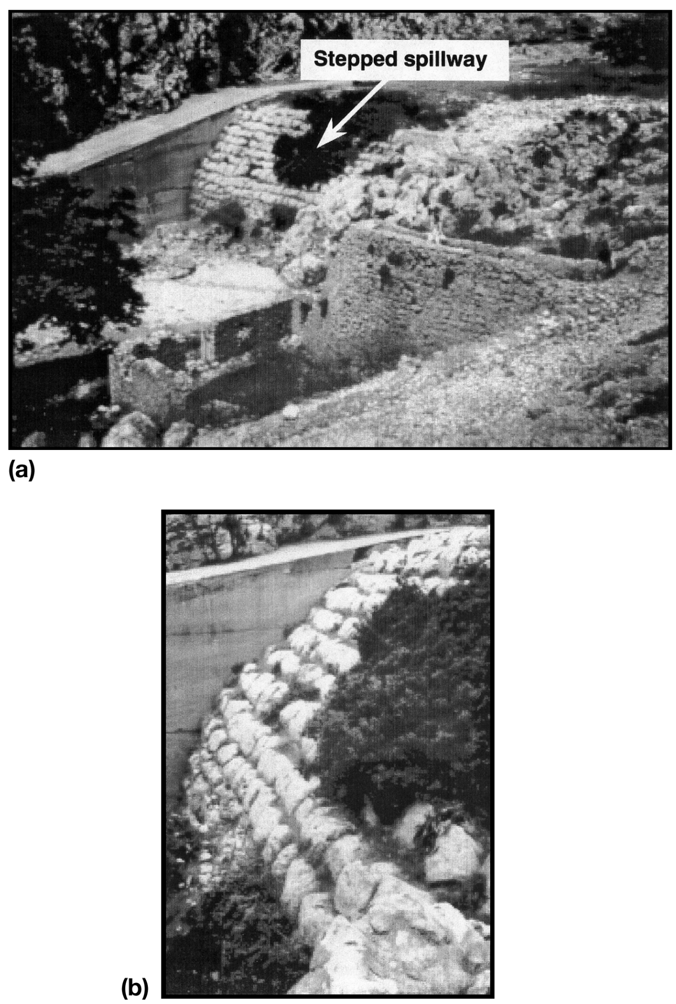

FIG. 1. (a) Old Stepped Spillway in Akarnania, Greece, Built around 1300 BCE, Having Height of 10.5 m and Crest Length of about 25 m; It Comprises Earth-Fill Structure Encased with 14 Steps of Stone; Mean Stepped Slope Is about 45 (From 39° Down to 73°); Step Height Is 0.6 to 0.9 m (Photo Courtesy of Prof. J. Knauss); (b) Close-Up View of Spillway Steps

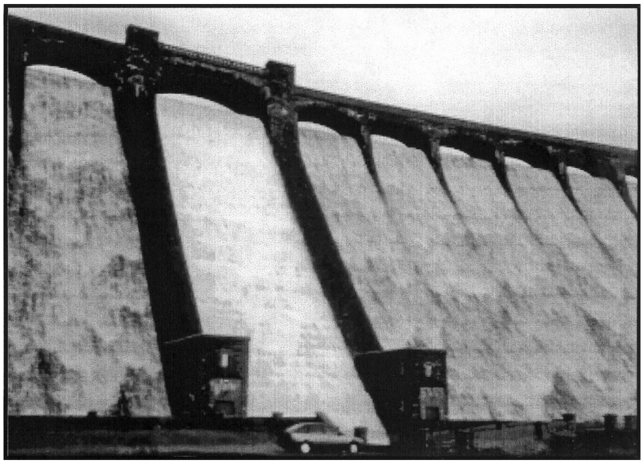

FIG. 2. Stepped Spillway in Operation, Claerwen Dam, Wales (Dam Height 67 m, Step Height 1.5 m; Photo Courtesy of L. Stuart Davies)

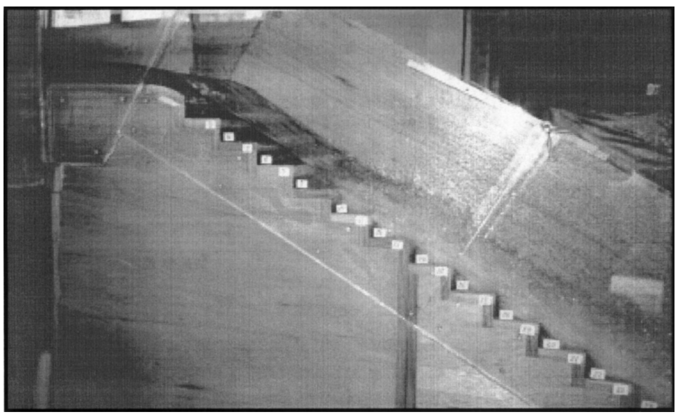

FIG. 3. Skimming Flow in Spillway Model (Nihon University); Spillway Slope Is 30°; Model-Scale Step Height Is 0.05 m

posed 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) and overseas (e.g., Ohtsu and Yasuda 1998). Could it be that some researchers and engineers do not fully appreciate the need for continuing education and undergraduate teaching of quality in hydraulic structures?

In summary, research on stepped-spillway hydraulics is very active. Although progress has been achieved in the past decade, more research is needed to gain a sound understanding of the complex flow patterns. The organizers of the recent workshop did a service to the profession by attracting a diverse group of professionals and researchers actively involved in stepped-spillway design. A review of the proceedings book (Minor and Hager 2000) resulting from the workshop will be forthcoming in an later issue of the *Journal of Hydraulic Engineering*. The writer, as a participant in the 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. Second, 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 of 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 ''rediscover the wheel'' every 60 years.

APPENDIX. REFERENCES

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