Journal of Hydrology 508 (2014) 254–265

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Modeling energy dissipation over stepped spillways using machine learning approaches

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ARTICLE INFO

Article history:
Received 23 September 2013
Accepted 30 October 2013
Available online 7 November 2013
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Energy dissipation
Genetic programming
Neural network
Sensitivity analysis

SUMMARY

Study of the energy dissipation over the stepped spillways is necessary in flood control-related studies. The aim of this study is to apply different methods to modeling energy dissipation in nappe and skimming flow regimes over stepped spillway by using original experimental dataset through the artificial networks (ANNs) and Genetic Expression Programming (GEP) techniques. Subsequently, three kinds of data including the napped and skimming regimes data as well as combination of them are applied as models input–output variables. A preliminary investigation on various GEP operators is also carried out for selecting the proper operators. The obtained results indicate that applied machine learning techniques have reliable performance in predicting energy dissipation over stepped spillways.
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1. Introduction

Spillway is a major part of a dam for disposing the flood flows. Energy dissipation over dam's spillway is usually achieved by (i) a standard stilling basin at downstream of the spillway to dissipate a large amount of flow energy with formatting a hydraulic jump, (ii) a high velocity water jet taking off from a flip bucket and impinging into a downstream plunge pool, and (iii) the construction of steps on the spillway to assist in energy dissipation.

The steps act as roughness elements to reduce flow acceleration and hence terminal velocity. A stepped spillway has a stepped ogee-profile spillway instead of the traditional smooth ogee-profile spillway, where a series of drops are made in the invert from the vicinity of the crest to the toe. Stepped spillway can reduce dimension construction of especial energy dissipaters because of its special shape, thus reduces construction cost and time of the project. Flow over a stepped spillway can be divided into three separate flow regimes, namely, nappe, skimming and transition flows. Nappe flow usually corresponds to relatively low discharges values and skimming flow corresponds to high discharges values while the intermediate discharges have transition flow regimes. 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. Schematic representations of nappe and skimming flow regime are shown in Fig. 1. There are three types of nappe flows:

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

The skimming flow is characterized by a complete submersion of the totality of the steps which form the spillway. No diving was observed.

1.1. Literature review

So far, considerable physical models have been developed for modeling stepped spillways. However, the obtained results are case-sensitive and could only be used as a preliminary guide for other similar cases. Young (1982) studied the feasibility of a stepped spillway for the upper Stillwater dam and managed a 75% energy reduction. Sorensen (1985) performed a physical model investigation for stepped spillways, where he found that adding a few steps to the face of the spillway eliminated the deflecting water jet. Christodoulou (1993) found that energy loss due to the steps depends primarily on the ratio of the critical depth to the height of the step, as well as on the number of steps. Sorensen (1985) studied the design of steps and their spacing on the spill-

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http://dx.doi.org/10.1016/j.jhydrol.2013.10.053

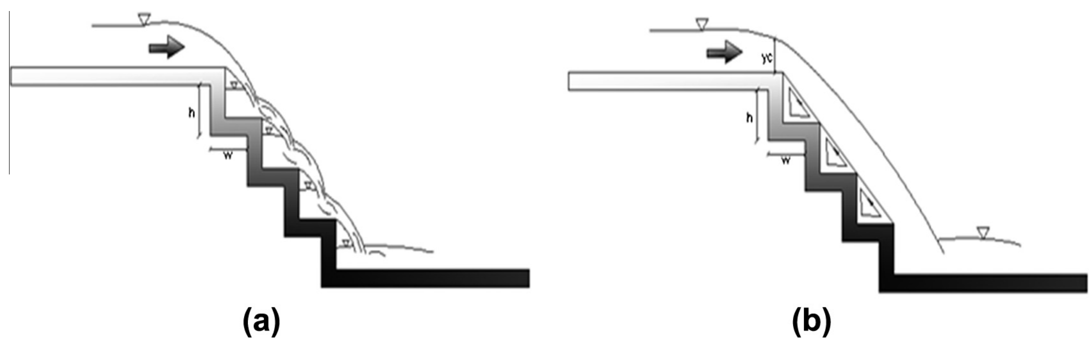

Fig. 1. Flow regim above a stepped spillway: (a) nappe flow and (b) skimming flow.

way face in order to optimize the energy dissipation. Sorensen (1985), Bayat (1991), Diez-Cascon et al. (1991) Bindo et al. (1993), and Christodoulou (1993) measured the depth of the flow at the toe or along the length of stepped spillway models. Relative energy loss over stepped spillways, calculated based on these depths, ranged from 50% to 97%.

Christodoulou (1993) proposed an approximated method of estimating the energy loss including the number of steps. Rajaratnam (1990) used the idea of a fully developed region with a Reynolds shear stress between the skimming flow and the recirculating region on the steps, and developed an expression for the relative energy loss over a stepped spillway in terms of that on a smooth spillway and showed that significant energy losses could occur on a stepped spillway. Tozzi (1994) evaluated the variation of the friction factor. Based on experimental observations, the Darcy friction factor "*f*" was described by the equation:

$$\frac{1}{\sqrt{f}} = 2.16 + 1.24\log(Y/k) \tag{1}$$

where Y is depth of flow, and k is roughness produced by the step.

Chanson (1994) has presented the following equations for the energy dissipation, for the nappe and skimming flow regimes, respectively:

$$\frac{E}{E_{\max}} = 1 - \frac{0.54\left(\frac{y_c}{h}\right)^{0.275} + 1.715\left(\frac{y_c}{h}\right)^{-0.55}}{\frac{3}{2} + \frac{H_{\mathrm{dam}}}{y_c}} \tag{2}$$

$$\frac{E}{E_{\max}} = 1 - \frac{\left(\frac{f}{8\sin\alpha}\right)^{\frac{1}{3}}\cos\alpha + \frac{1}{2}\left(\frac{f}{8\sin\alpha}\right)^{-\frac{2}{3}}}{\frac{3}{2} + \frac{H_{\mathrm{dam}}}{y_c}} \tag{3}$$

where $\frac{E}{E_t}$ is energy-loss ratio, ΔE is energy loss, H_{dam} is dam height ($H_{\mathrm{dam}} = Nh$), E_t is maximum head available, N is step number, h is height of step and y_c is critical flow depth, f is friction factor, and α is spillway slope.

Chamani and Rajaratnam (1994) studied jet flow on stepped spillways and based on it presented an equation that is given below:

$$\frac{E}{E_t} = 1 - \frac{\left\{(1-\alpha)^N\left[1 + 1.5\left(\frac{y_c}{h}\right)\right] + \sum_{i=1}^{N-1}(1-\alpha)^i\right\}}{N + 1.5\left(\frac{y_c}{h}\right)} \tag{4}$$

$$\alpha = a - b\log\left(\frac{y_c}{h}\right) \tag{4a}$$

$$a = 0.3 - 0.35\left(\frac{h}{l}\right) \tag{4b}$$

$$b = 0.54 + 0.27\left(\frac{h}{l}\right) \tag{4c}$$

where α is equal proportion of energy loss per steps. h, l and N are height, length and number of steps respectively, y_c is equal critical depth, $\frac{E}{E_t}$ is energy-loss ratio, ΔE is energy loss, E_t is equal specific energy at bottom of spillway.

Kells (1995) compared energy dissipation between nappe and skimming flow regimes on stepped chutes. Barani et al. (2005) obtained optimization of dimensions of stepped spillway and investigated flow energy dissipation over a physical model. Tabbora et al. (2005) analyzed flow over stepped spillway with finite element method. Kavianpour and Masoumi (2008) studied two physical models of the Siah Bisheh stepped spillway in Iran to determine the energy dissipation over stepped spillways and Naderi Rad and Teimouri (2010) studied simple stepped spillways to evaluate energy dissipation on them by numerical method.

In the recent years, application of Machine Learning (ML) [e.g. Artificial Neural Networks (ANNs), Neuro-Fuzzy models (NF) and Genetic Programming (GP)] in water resources engineering has become viable leading to numerous publications in this field. A complete review of all the applications is beyond the scope of this paper and only some literatures are mentioned here. Among others, ANNs have been applied for predicting the friction factor of open channel flow (Yuhong and Wenxin, 2009), determining flow discharge in straight compound channels (Zahiri and Dehghani, 2009), long term prediction of river discharge (Cheng et al., 2005), simulating groundwater levels (Taormina, 2012), and estimating daily pan evaporation values at different climatic zones (Kim et al., 2012).

Shiri et al. (2013) applied Genetic Expression Programming (GEP) for estimating daily evaporation through spatial and temporal data scanning. Kisi and Shiri (2012) estimated river suspended sediment by climatic variables implication by using of GEP and ANN. Shiri and Kisi (2012) estimated daily suspended sediment load using the hybrid wavelet-AI models. Shiri et al. (2012) compared various AI techniques for forecasting daily stream flow and found GEP as the superior model in this field. Kisi et al. (2013) introduced GEP as the best model of rainfall-runoff modeling among soft computing techniques.

To the best of the authors' knowledge, only few studies have been carried out for evaluation of energy dissipation using machine learning approaches. Musavi and salmasi (2008) applied neuro-fuzzy (NF) technique to simulate the experimental data of energy dissipation over stepped spillways. The present work aims at application of GP technique for modeling energy dissipation over stepped spillways and comparing the results with those of ANN models. Consequently, GP (i.e. GEP) and ANN models are developed and tested using the experimental data set from laboratory and their performances are compared.

1.2. Methodological structure

1.2.1. Machine learning approaches

Machine learning, a branch of artificial intelligence, deals with the representation and generalization using data learning

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