Ecological Engineering 83 (2015) 208–217

Contents lists available at ScienceDirect

Ecological Engineering

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

Derivation and application of the energy dissipation factor in the design of fishways☆

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ARTICLE INFO

Article history:
Received 28 August 2014
Received in revised form 2 June 2015
Accepted 8 June 2015
Available online 8 July 2015

Keywords:
Fishway
Fish passage
Fish ladder
EDF
Energy dissipation
Turbulence

ABSTRACT

Reducing turbulence and associated air entrainment is generally considered advantageous in the engineering design of fish passage facilities. The well-known energy dissipation factor, or EDF, correlates with observations of the phenomena. However, inconsistencies in EDF forms exist and the bases for volumetric energy dissipation rate criteria are often misunderstood. A comprehensive survey of EDF criteria is presented. Clarity in the application of the EDF and resolutions to these inconsistencies are provided through formal derivations; it is demonstrated that kinetic energy represents only 1/3 of the total energy input for the special case of a broad-crested weir. Specific errors in published design manuals are identified and resolved. New, fundamentally sound, design equations for culvert outlet pools and standard Denil Fishway resting pools are developed. The findings underscore the utility of EDF equations, demonstrate the transferability of volumetric energy dissipation rates, and provide a foundation for future refinement of component-, species-, and life-stage-specific EDF criteria.

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1. Introduction

Fishways, or fish passes, are hydraulic structures and devices that provide routes for fish to move, volitionally or non-volitionally, over otherwise impassable stream barriers. Fishways have been employed in many parts of the world and over a wide range of hydrologic scales in the form of roughened culverts on minor tributaries to large fish lifts at hydroelectric facilities on main-stem rivers. Recognized as a field of hydraulic engineering since the mid-1800's (McLeod and Nemenyi 1941), fish passage design has evolved to integrate many constraints, but "swimming ability and behavior of the specie [*sic*] are the key factors" (Yagci 2010).

Turbulence has been shown to influence both swimming behavior and performance of fish (Lupandin, 2005; Enders et al., 2003; Pavlov et al., 2000). A phenomenon common to the natural river environment, turbulence is often exacerbated by the dissipation of energy that is characteristic of dams and other anthropogenic in-stream structures. In many cases, the dissipation is the result of a rapid conversion of potential energy to kinetic energy (e.g., high velocity flow over a spillway impounding a quiescent reservoir). Fishways overcome these barriers by providing continuous hydraulic pathways over or around dams. Kinetic energy in these pathways must be dissipated to ensure flow velocities do not exceed the swimming ability of fish. Dissipation can be effected through increased roughness (form or surface) or through the momentum exchange that occurs when high speed jets discharge into larger quiescent pools. However, excessive power dissipation or energy dissipation rates can also lead to unwanted turbulence and air entrainment. Thus, the engineering challenge is to design a fishway that simultaneously reduces flow velocities to speeds below maximum fish swimming speeds while maintaining acceptably low levels of turbulence.

The energy dissipation factor or EDF is a common, albeit indirect, metric of turbulence in fishways. Historically applied to pool-type fishways (e.g., pool-and-weir, vertical slot, Ice Harbor), the concept has been extrapolated to baffled-chute resting pools, nature-like channels, culverts, pre-barrages, and auxiliary water systems. The wide acceptance of the EDF and its suitability as an engineering design parameter has generated numerous component-, species-, and life-stage-specific values. For clarity, the volumetric energy dissipation rate (EDF) values found in resource agency guidelines, peer-reviewed literature, and design manuals are collectively termed "EDF criteria"; this avoids confusion with the EDF equation and its many forms. Many EDF criteria are based

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http://dx.doi.org/10.1016/j.ecoleng.2015.06.014
0925-8574/Published by Elsevier B.V.

on the best professional judgment offered by practitioners (Hotchkiss and Frei 2007) and are not the result of controlled experiments. Consequently, a need exists for additional research into the relationship between EDF and fishway performance. However, the authors are not aware of any fundamental derivations of this important parameter or comprehensive inventories of its many forms and values. This has contributed to several significant misunderstandings that pervade the practice. A comprehensive review of the EDF, its derivation, and a survey of published EDF criteria are presented with the intent of clarifying the use of this parameter in the design and evaluation of fishways.

2. Energy dissipation factor in pool-type fishways

As the name implies, the EDF represents energy dissipation in a fishway. More specifically, it is a measure of the volumetric energy dissipation rate. While the dissipation of energy cannot be measured directly, application of the conservation of energy allows for the resolution of this loss rate.

The conservation of energy, otherwise known as the energy principle, couples the first law of thermodynamics with the Reynolds Transport Theorem (RTT) to develop the energy equation for fluid flow with respect to a control volume (CV). The energy form of the RTT, Eq. (1), equates the rate of change of energy within a system of fluid particles with the rate of change of energy within the CV and the amount of energy entering/leaving the CV in a specified time interval:

$$\frac{dE_{sys}}{dt} = \frac{d}{dt}\int_{CV} e\rho d\forall + \int_{CS} e\rho u \times dA \tag{1}$$

where E_{sys} is the extensive energy of the fluid in the system representing kinetic, potential, and internal energy, e is the intensive energy of the fluid independent of system mass, ρ is the density of water, $\forall$ is the volume of water in the CV, CS is the control surface, u is the velocity of water with respect to the CS, t is time, and A is the area of the CS.

The first law of thermodynamics, Eq. (2), states that for a given system or quantity of matter, the change in energy is equal to the heat transferred to the system in a given time minus the work done by the system on its surroundings in the same time interval.

$$\Delta E_{sys} = Q - W \tag{2}$$

where ΔE_{sys} is the change in energy in the system, Q is the heat transferred to the system, and W is the work performed on the system. Taking the derivative of Eq. (2) with respect to time and recognizing there is no shaft work (e.g., work associated with pumps and turbines) within the fishway, the equation becomes:

$$\frac{dE_{sys}}{dt} = \dot{Q} - \dot{W} \tag{3}$$

where

$$\dot{W} = \dot{W}_f = \int_{CS} \frac{p}{\rho}\rho u \times dA \tag{4}$$

where W_f is the flow work, and p is the pressure force acting on the surrounding fluid.

Combining Eqs. (2) and (3), rearranging terms, dividing by the mass flux, $\dot{m}$, introducing the dimensionless Coriolis coefficient, α, as a kinetic energy correction factor, and simplifying by the following assumptions: the flow enters at section 1 and exits at section 2; there is no acceleration at each section (streamlines are parallel); the internal energy component is constant across each section; flow is steady; and water is incompressible, then the following form of the energy equation between any two sections in a fishway can be derived:

$$\frac{p_1}{\rho} + \alpha_1\frac{V_1^2}{2} + gz_1 = \frac{p_2}{\rho} + \alpha_2\frac{V_2^2}{2} + gz_2 + \text{loss}_{1\to2} \tag{5}$$

where p, V, and z represent the average pressure, mean velocity, and elevation of the inlet and outlet sections in lbf/ft^2, ft/s, and ft respectively, ρ is the density of water in slugs/ft^3, g is the gravitational acceleration (32.17 ft/s^2), $\text{loss}_{1\geq2}$ represents the time rate of decrease in stored energy in ft-lbf/slug, and α is the Coriolis coefficient determined by the following:

$$\alpha = \frac{1}{A}\int_A \left(\frac{u}{V}\right)^3 dA \tag{6}$$

where an α value of 1 indicates a uniform velocity distribution at the cross section of interest. Greater values of α can be incorporated into one-dimensional forms of the energy equation to account for the increased kinetic contributions of non-uniform velocity distributions.

Eq. (5) is a representation of total mechanical energy per unit mass, it assembles pressure, kinetic and potential energy components and includes a loss term for the energy dissipated through viscous effects. The loss term is an indirect measure of turbulence, and can be manipulated to quantify an energy dissipation rate for fishways. Isolating the loss term yields:

$$\text{loss}_{1\to2} = \frac{p_1 - p_2}{\rho} + \frac{\alpha_1 V_1^2 - \alpha_2 V_2^2}{2} + g(z_1 - z_2) \tag{7}$$

Additional refinement of Eq. (7) necessitates discussion of an important simplifying assumption. Volitional fishways may be categorized as baffled-chute-type, pool-type, or as a hybrid of the two. Baffled chutes include the Alaska Steeppass (Ziemer, 1962) and the standard Denil Fishways. Ignoring the effect of flow development in the upper reach of baffled chutes and conceptualizing the energy-dissipating baffles in steeppasses and Denil fishways as roughness elements, one may treat flow in baffled chutes as essentially uniform between any two sections. However, pool-type fishways (e.g., Ice Harbor fishways) are instead comprised of a series of pools separated by weir walls and the flow through these fishways is not uniform per se. Alternatively, a “uniform-in-the-mean” argument can be made by prescribing sections 1 and 2 in Eq. (5) at the weir crests as shown in Fig. 1. Indeed, most pool-type fishways are designed for uniform-in-the-mean conditions. That is, each successive pool maintains the same hydraulic characteristics at the inlet and outlet. Accordingly, the contributions to the energy per unit mass resulting from the pressure and velocity components (the first and second terms, respectively) in Eq. (7) are balanced and the loss reduces to:

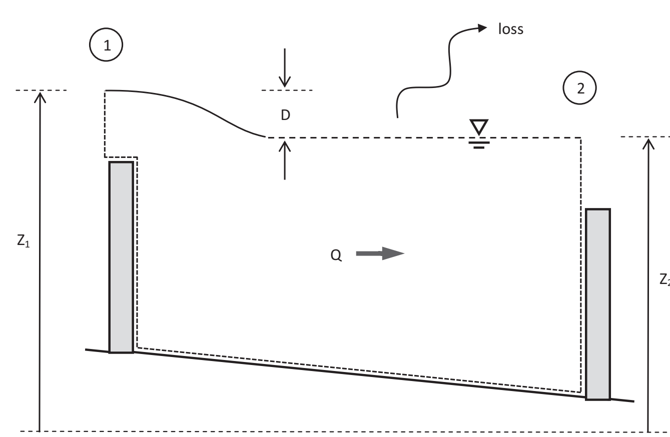

Fig. 1. Step pools in a fish ladder. Sections 1 and 2 are located at the (water) entrance and exit sections.