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The Prediction of Relative Energy Dissipation Using Linear Regression Equations in Adverse-Sloped Stepped Spillways

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ABSTRACT

Background: Energy dissipation downstream of hydraulic structures is required phenomena in order to increase of structure safety. Different approaches are used for reducing the flow energy which adverse-slope stepped spillways are one of the efficient one. This structure not only has more efficiency in energy dissipation but also decreases the cost of construction. **Objective:** The effect of adverse-slope stepped spillway on energy dissipation has been studied in this paper using physical and numerical modeling. Using Buckingham theory, five dimensionless parameters were derived to predict energy dissipation using numerical model. Four linear regression equations were applied to simulate energy dissipation as: linear, pairwise interaction, quadratic, and purequadratic equations. **Results:** The results showed that the effect of adverse-slope steps on energy dissipation is significant as the ration of energy loss to upstream energy varies 0.83 to 0.983. **Conclusion:** Also, using different statistical criteria and scatter plots illustrated that quadratic regression model has good agreement with measured data.

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INTRODUCTION

The use of stepped spillways is not a new technology. The ancient Romans first designed low head structures where water flowed down steps. Also early masonry dams (circa 1900) in the USA featured stepped spillways. Reemergence of stepped spillways is attributed to the RCC horizontal lift placement of which a stepped surface is a nature outcome. Usually the secondary reason is the potential for dissipation of the flow energy as it travels down the steps to the toe of the dam. Energy dissipation also provides a cost benefit due to the reduce stilling basin length or entire elimination of the required basin. The step shape has been obtained in many ways. Steps have been shaped from unformed or formed RCC, and standard formed or slope-formed conventional concrete with or without reinforcement. The problem with using stepped spillways has been, and continues to be, the lack of general design criteria that quantifies the energy dissipation characteristics of the steps for a given unit discharge, flow depth, and hydraulic dam height. Steps have proven for effective for small unit discharges, where the steps height clearly influences the flow. The need to pass larger flows has pushed designs beyond the limitations of the present data base (Kavianpour et al, 2008).

As mentioned, the design of stepped spillways has been known for at least 3,500 years, but at the beginning of the 20th century, breakthroughs in the design of hydraulic jump-stilling basins led to the disuse of stepped spillways (Chanson, 1994). With the development of new, more efficient construction techniques [(e.g., roller-compacted concrete (RCC)], the design of stepped spillways regained interest in the 1980s (Chanson, 1994). This was associated with a substantial amount of physical modeling research (Chamani, and Rajaratnam, 1999), (Fratino, 2000). Most experiments were conducted on stepped spillways with uniform flat steps to quantify the energy dissipation and to provide some design guidelines. But some prototype spillways are equipped with nonuniform step heights (Malmsbury and Upper Coliban) and their long operation indicates that the design is sound (Chanson, 1994). However, some flow instabilities and shock waves might occur for the nonuniform step heights, as reported by Toombes and Chanson (2008) in the nappe flow regime and by Thorwarth and Köngeter (2008) for pooled stepped spillways.

On uniform stepped configurations, a napped flow regime was observed for the smallest flow rates. For some intermediate flows, a transition flow was seen with some strong spray, splashing, and flow instabilities. For the largest flow rates, the waters skimmed over the pseudo bottom formed by the stepped edges. For all

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stepped spillway configurations, the flow patterns were observed for the full set of discharges. Figure 1 shows three regimes on a stepped spillway. Several research studies have been done to derivate equation for determining energy dissipation through stepped spillways under different flow conditions. Chanson (1994) developed the following expression valid for free flow spillways and napped flow with fully developed hydraulic jump (Chanson, 1994):

$$\frac{\Delta E}{E_U} = \frac{0.54 \left(\frac{N}{h}\right)^{0.275} + 1.715 \left(\frac{N}{h}\right)^{-0.55}}{1.5 + \frac{P}{y_c}}$$

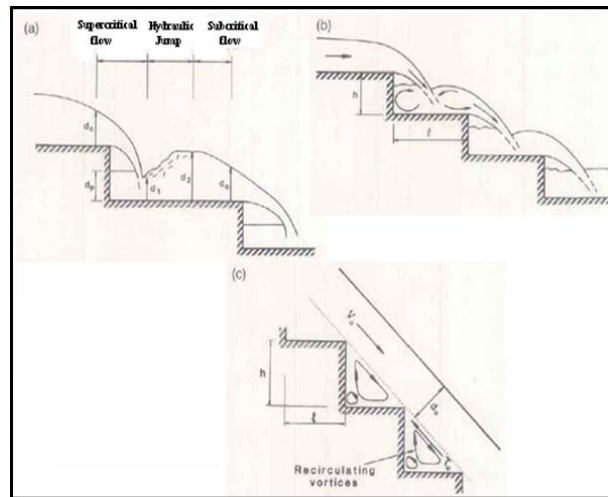


Fig. 1: Flow regimes above a stepped.

Fratino *et al.*(2000) analyzed energy dissipation at the base of a stepped spillway under nappe flow as follows:

$$\frac{\Delta E}{E_U} = 1 - \frac{\lambda + 0.5\lambda^2}{1.5 + \frac{P}{y_c}} \quad (2)$$

$$\lambda = \frac{\sqrt{2}}{\frac{3}{2\sqrt{2}} + \sqrt{1.5 + \frac{h}{y_c}}} \quad (3)$$

Chamani and Rajaratnam(1999) investigated energy dissipation for nappe flow on inclined steps. Their relationship is as following:

$$\frac{\Delta E}{E_U} = 1 - \frac{[(1-\alpha)(1+1.5\frac{h}{y_c}) + \sum_{i=1}^{N-1} (1-\alpha)^i]}{N+1.5\frac{y_c}{h}} \quad (4)$$

$$\alpha = -0.746 \log\left(\frac{y_c}{h}\right) - 0.548 \log\left(\frac{h}{L}\right) - 0.0455 \quad (5)$$

Yashuda *et al.* (2001) have derived a general expression for the energy loss at the base of a stepped spillway with skimming flow, regardless of whether the flow is uniform or not:

$$\frac{\Delta E}{E_U} = 1 - \frac{\left(\frac{y_m}{y_c}\right)^2 + 2\left(\frac{y_m}{y_c}\right)\cos\theta}{3 + 2\left(\frac{y_m}{y_c}\right)} \quad (6)$$

Boes and Minor(2000) suggest the following equation for the non-uniform flow in skimming regime:

$$\frac{\Delta E}{E_U} = \exp\left[\left(-0.045\left[\frac{k}{D_h}\right]^{0.1}(\sin\theta)^{-0.8}\right)\frac{P}{y_c}\right] \quad (7)$$

Boes and Hager(2003) introduced a relationship for the rate of energy dissipation in skimming regime as following:

$$\frac{\Delta E}{E_U} = 1 - \frac{\left(\frac{f}{8 \sin \theta}\right)^{\frac{1}{3}} \cos \theta + \frac{\Phi}{2} \left(\frac{f}{8 \sin \theta}\right)^{\frac{2}{3}}}{1.5 + \frac{P}{y_c}} \quad (8)$$

Yazdani(1994) assumed uniform flow all over the spillway and the rate of energy dissipation was suggested as a function of this drag coefficient as follow

$$\frac{\Delta E}{E_U} = 104.33 \left(\frac{P}{h \cos \theta}\right)^{-0.105} C_D^{0.054} \quad (9)$$

$$C_D = \frac{2.02}{\left(\frac{D_h}{h \cos \theta}\right)^{0.067} Fr^{1.96}} \quad (10)$$

Kavianpour and Masoumi(2008) presented the following relationship for C_D :

$$C_D = \frac{3.285 \left(\frac{D_h}{h \cos \theta}\right)^{0.015} (\tan \theta)^{0.547}}{(Re)^{0.013} Fr^{1.021}} \quad (11)$$

Kavianpour and Masoumi(2008) developed an expression was derived to determine the rate of energy dissipation for non-uniform flow regime as follow:

$$\frac{\Delta E}{E_U} = 0.2047 \left(\frac{k_s}{D_h}\right)^{0.4708} Re^{0.2115} Fr^{-0.4970} \times (\tan \theta)^{0.1615} \left(\frac{L_s}{L_1}\right)^{-0.0834} \quad (12)$$

Fuladipanah and Jafarinia(2010) developed the following equation to estimate energy dissipation on a adverse-sloped stepped spillway:

$$\frac{\Delta E}{E_U} = 0.83 n^{0.05} \Phi^{0.0027} \alpha^{0.088} \left(\frac{y_c}{h}\right)^{0.024} \left(\frac{h}{L}\right)^{-0.016} \quad (13)$$

Hunt and Kadavy(2010) studied the effect of spillway slope on energy dissipation. They found that many of researches studies were performed on steeper (2(H):1(V) or steeper) stepped spillways, but a few researchers, including Peyras *et al.*(1992), Rice and Kadavy(1996), Yasuda and Ohtsu(1999), Chanson and Toombes(2002), Boes and Hager(2003b), Gonzalez(2005), Takahashi *et al.*(2006), and Hunt and Kadavy(2009,2010) have examined flat-sloped (2(H):1(V) or flatter) stepped spillways. As it clear, all above mentioned equations are nonlinear . In this research work, linear regression equations will be derived to evaluate energy dissipation on an adverse-sloped stepped spillways which will be compared to nonlinear regression relationships. The best choice will cause appropriate hydraulic and structural designing.

Spillways (a) Nappe flow with fully developed hydraulic jump. (b) Nappe flow with partially developed hydraulic jump. (c) Skimming flow above a stepped spillway

MATERIALS AND METHODS

In this paper, it has been attempted to derive multiple linear regression (MLR) equations to evaluate energy dissipation on adverse-sloped stepped. MLR is a method used to model the linear relationship between a dependent variable and one or more independent variables. The dependent variable is sometimes also called the predictand (y), and the independent variables (x) the predictors. MLR is based on least squares: the model is fit such that the sum-of-squares of differences of observed and predicted values is minimized. On the other words, the objective in trying to find the "best equation" will be to find the simplest model that adequately fits the data. This will not necessarily be the model the explains the most variance in the dependent variable "y". This equation will be the equation with all of the independent variables in the equation. The objective will be to find the equation with the least number of variables that still explain a percentage of variance in the dependent variable that is comparable to the percentage. Five dimensionless parameters (independent variables, X vector) were determined using Buckingham theory as: number of steps (n), step slope(Φ), energy dissipation coefficient per step (a), the ratio of critical depth on spillway crest to step height ($\frac{y_c}{h}$), and the ration of step height to step length ($\frac{h}{L}$). the dependent variable is ($\frac{\Delta E}{E_U}$), the ration of energy loss between upstream and downstream of spillway to energy amount in the upstream of spillway. In statistics, linear regression models often take the form of the following equation:

$$y = \beta_1 f_1(x) + \beta_2 f_2(x) + \dots + \beta_p f_p(x) + \varepsilon \quad (14)$$

Which y is dependent variable, β_j ($j=1,2, \dots, p$) is model coefficients, $f_j(x)$ ($j=1,2, \dots, p$) is model terms, and ε is random error. In this paper, four different linear regression type have been used to derive regression equations based on N independent variables $X(x_1, x_2, \dots, x_N)$:

1. Linear additive model, which the terms are $f_1(x)=1, f_{k+1}(x)=x_k, k=1,2,\dots,N$
2. Pairwise interaction models, which the terms are linear additive terms plus $g_{k_1 k_2}(x)=x_{k_1} x_{k_2}, (k_1, k_2=1, \dots, N)$. Note that $k_1 \neq k_2$.
3. Quadratic models, which the terms are pairwise interaction terms plus $h_k(x)=x_k^2, (k=1,2,\dots,N)$.
4. Pure quadratic models, which the terms are quadratic terms minus the $g_{k_1 k_2}(x)$ terms.

Experimental setup:

All measurements were done on a model which was made from plexiglass. The model was installed in a rectangular glass flume with 20.0 (m) length and 1.5 (m) width. Figure 1 illustrates installation of experiments. Total number of experiments was 353. Table 1 shows the range of the parameters which were measured in this case.

RESULTS AND DISCUSSION

In this paper, the effect of adverse-slope on energy dissipation was considered. Four linear equations, according to Eq. (14), were derived. The coefficients of regression equations, β_i , are listed in table 2. The results of regression equations are presented in table 3. Using the regression equations with coefficients in table 2, predicted values of relative energy dissipation were calculated which, their properties are presented in table 3. Figure 2 illustrates the agreement criteria in table 2, graphically. As it seen in table 3, the minimum and maximum amount of relative energy dissipation are 0.831 and 0.989, respectively. In the other words, the adverse-slope steps causes significant dissipation of flow. Not only the maximum correlation coefficients are corresponding to quadratic, pairwise interaction, purequadratic and linear regression equations, but also the minimum root mean square error are corresponded to them, respectively. According to the fourth row of table 3, the maximum amount of predicted relative energy dissipation for pairwise interaction and quadratic equations are more than one, which is not acceptable. This error have mathematical base and according to the calculation, only one value more than one was seen. The quadratic is one that can be selected according to numerical criteria. Figure 3 shows the linear equation output in scatter plot form of predicted vs. measured values of relative energy dissipation. As it clear, there is a gap between data. On the other words, this equation has not been predicted some cases which has been caused poor agreement between measured and predicted values. In the figure 4, scatter of points around 1:1 line is significant for low values. However, there is acceptable fitting for high values. According to figure 5, predicted values have comparable ranges to those measured. Thus, they have scattered firmly about 1:1 agreement line. In the figure 6, the scatter of points are more than to other figures. Thus, it can be concluded that among mentioned regression equations, quadratic model has acceptable results than the others.

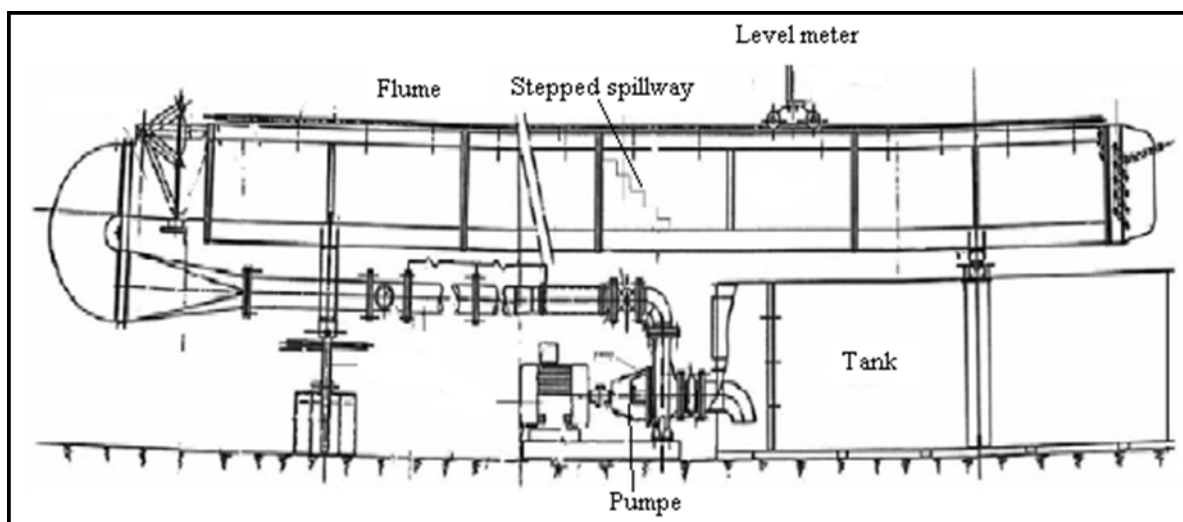


Fig. 2: Installation of experiments.

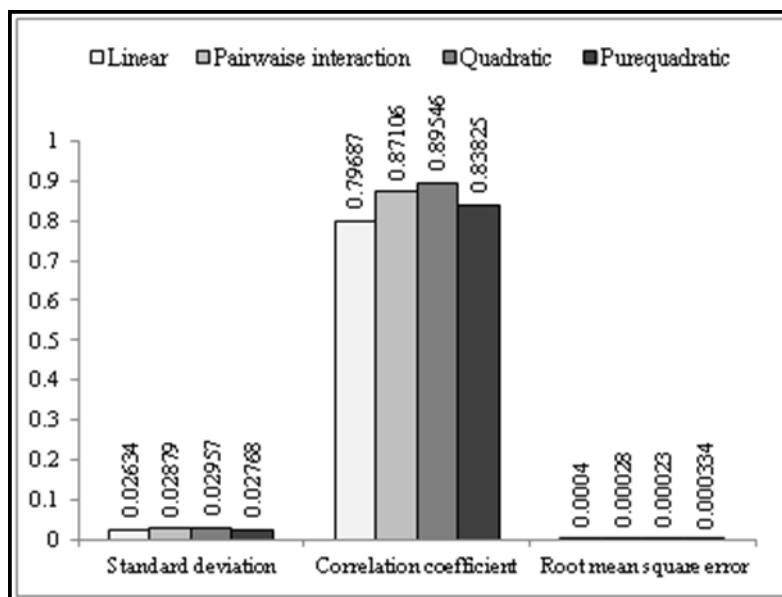


Fig. 3: The graphical presentation of agreement criteria for mentioned linear regression equations.

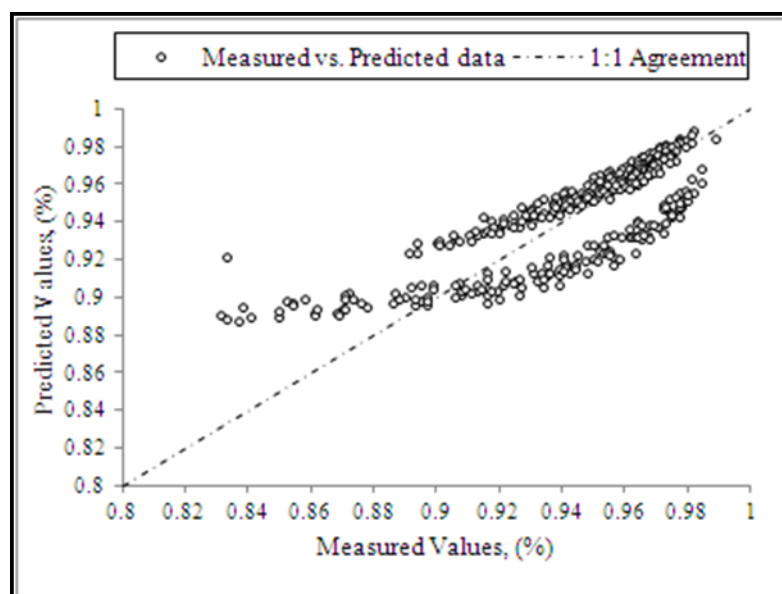


Fig. 4: The scatter plot of predicted vs. measured values of relative energy dissipation (Linear regression equation).

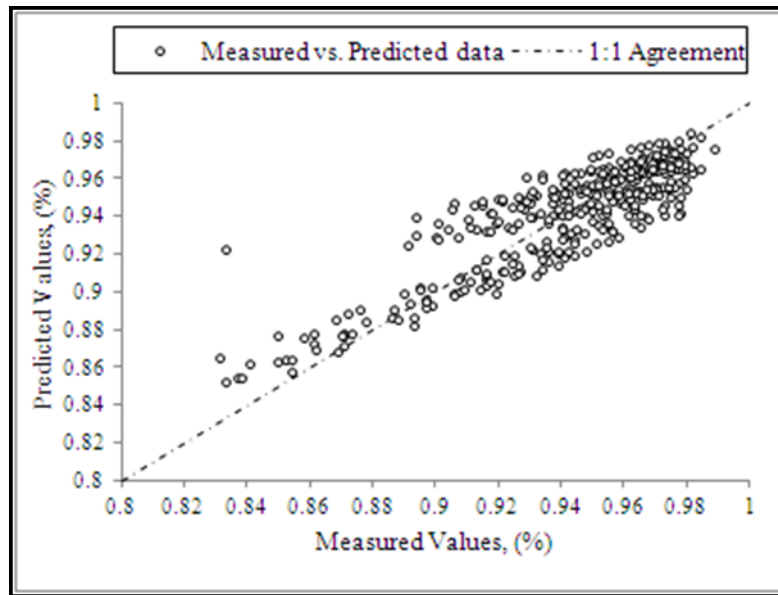


Fig. 5: The scatter plot of predicted vs. measured values of relative energy dissipation (pairwise interaction regression equation).

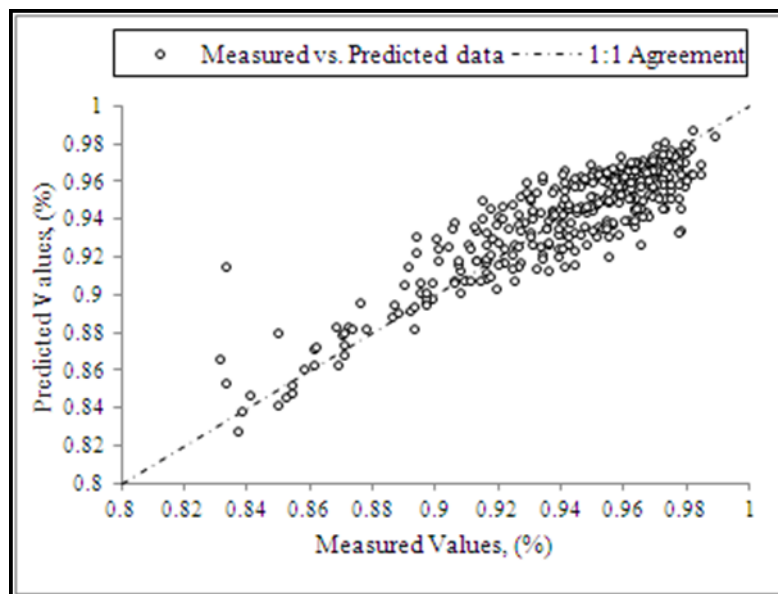


Fig. 6: The scatter plot of predicted vs. measured values of relative energy dissipation (quadratic regression equation).

Conclusion:

In this paper, the effect of adverse-sloped steps on energy dissipation were studied through mathematical modeling. Four linear regression equations were considered as following: linear equation, pairwise interaction equation, quadratic equation, and purequadratic equation. Statistical numeric criteria and scatter plot were used to evaluate the application of each model. The results showed that quadratic model has the most accurate, the least error, and the best scatter around the 1:1 agreement line.

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