Aeration Performance Evaluation of Piano Key Weir using Linear Regression and Adaptive Neuro Fuzzy Inference System

Komal¹, Munish Kumar², Dr. N.K. Tiwari³ and Dr. Subodh Ranjan⁴
¹M.Tech Scholar, Department of Civil Engineering, NIT Kurukshetra, Haryana, India
²Ph.D. Scholar, Department of Civil Engineering, NIT Kurukshetra, Haryana, India
³Professor, Department of Civil Engineering, NIT Kurukshetra, Haryana, India
⁴Associate Professor, Department of Civil Engineering, NIT Kurukshetra, Haryana, India

Abstract—The paper investigates the modelling performance of experimentally observed aeration efficiency (E20) by free fall multiple plunging jets having piano key weir varying number of keys from 2.5 to 4.5. The output values of aeration efficiency were computed by using Linear Regression (LR) and Adaptive Neuro Fuzzy Inference System (ANFIS). The standard statistical performance evaluation measures, such as the Coefficient of Correlation (CC), Root mean square error (RMSE), $R^2$ and Nash-Sutcliffe (NS) have been utilized to compare the performance of modelling techniques. Linear Regression gives the best result and when ANFIS trimf, gbellmf and gaussmf is compared trimf gives the better results.

Keywords: Aeration Efficiency, Linear Regression (LR), ANFIS, Piano Key Weir

I. INTRODUCTION

Oxygen is vital to the life cycle common to water. It is essential to keep organisms living, to sustain species reproduction, and for the development of populations. Oxygen enters into the water by absorption directly from the atmosphere or by plant photosynthesis. The amount of oxygen in water is measured as (mg/L) dissolved oxygen (DO). The minimum level of DO in river should not be below 4 mg/L for survival of aquatic life. Total DO concentrations in water should not exceed 110 percent. The physical process of transfer of oxygen from the atmosphere acts to replenish the used oxygen. This process is known as aeration. Hydraulic structures increase amount of DO in a river system. Although the water is in touch with the structure for only a short time. The amount of oxygen transfer that usually would take place over several kilometres in a river can occur at a single hydraulic structure. Gameson (1957) was the first to report on the aeration potential of weirs in rivers. Since then a number of laboratory investigations into weir aeration have been carried out, notably by Van der Kroon and Schram (1969), Apted and Novak (1973), and Nakasone (1987). Investigations on the aeration performance of existing hydraulic structures were reviewed by Wilhelms et al. (1992) and Gulliver et al. (1998). McKeogh and Ervine (1981), Sene (1988), Evans et al. (1996), Cummings and Chanson. (1997) studied air entrainment by plunging water jets. Emiroglu and Baylar (2003) studied air entrainment rate of sharp-crested, broad crested and labyrinth weirs. Recently, Baylar and Bagatur (2006), Baylar and Hanbay (2008), Bagatur et al. (2003), Emiroglu and Baylar (2006), Baylar and Ozkan (2006, 2010, 2011), have conducted many studies to investigate air/water flow ratio (Qa/Qw) and aeration efficiency (E20) in different hydraulic structures. Wormleaton and Soufiani (1998) demonstrated that the aeration efficiency of labyrinth weirs generally is better than their equivalent-length linear weir. Here, our aim is to perform experiments to study the performance evaluation of piano key weir using LR and ANFIS Technique.

II. PIANO KEY WEIR

The Piano Key Weir (PKW) is a novel weir type developed by Blanc and Lemperiere (2001) and Lemperiere and Ouamane (2003) to combine the benefits of a labyrinth weir with overhangs to facilitate the weir location on a dam crest. The PKW has a particular geometry including up- and/or downstream overhangs of variable width, in- and outlet bottom slopes, involving a large set of geometric parameters (Fig. 1). The “PKW-unit” is the basic structure of a PKW, composed of two transversal walls, an inlet and two half outlets. Its main geometric parameters are weir height P, the number of PKW-units Nu, lateral crest length B, in- and outlet bottom slopes Wi and Wo, up-and downstream overhang lengths Bo and Bi and the wall thickness Ts (Pralong et al. 2011).

Fig. 1: 3-D Sketch of Piano Key Weir
III. OXYGEN TRANSFER PROCESS

Oxygen is a highly volatile compound with a gas–water transfer rate that is controlled entirely by the liquid phase. Thus, the change in oxygen concentration over time in a parcel of water as the parcel travels through a hydraulic structure can be expressed as:

$$\frac{dm}{dt} = V \frac{dC}{dt} = K_L (C_s - C)$$  (1)

Where; $dm/dt$ = mass transfer rate of gas molecules across an interface, $dC/dt$ = rate of change in concentration, and $K_L$ = bulk liquid film coefficient. $C_s$ is the saturation concentration of oxygen in water at prevailing ambient conditions.

The saturation concentration indistilled, deionized water may be obtained from charts or equations. This is an approximation because the saturation dissolved oxygen concentration for natural waters is often different from that of distilled, deionized water due to the impact of trace contaminants and salinity. $C$ is the actual concentration of oxygen in the water at time $t$ difference being proportional to the concentration gradient. The term $A$ is the air–water contact area and $V$ is the volume of water associated with this. Equation 1 does not consider sources and sinks of oxygen in the water body because their rates are relatively slow compared to the oxygen transfer that occurs at most hydraulic structures due to the increase in free-surface turbulence and the large quantity of air that is normally entrained into the flow. The predictive relations assume that $Cs$ is constant and determined by the water temperature and the aeration efficiency. $E$ may be defined as (Gulliver et al. 1990):

$$E = \frac{C_d - C_s}{C_d - C_u} = 1 - e^{-\frac{A}{K_L A_s}} = 1 - \frac{1}{r}$$  (2)

Where, $u$ and $d$ = subscripts indicating upstream and downstream locations, respectively; and $r$ = oxygen deficit ratio.

A value of $E=1$ means the down stream water has become supersaturated (i.e., $C_d>C_s$). $E=1.0$ means that the full transfer up to the saturation value has occurred at the structure. No transfer would correspond to $E=0$. Oxygen transfer efficiency is sensitive to water temperature, and investigators have typically employed a temperature correction factor. For hydraulic structures, Gulliver et al. (1990) developed a relationship for temperature correction factor:

$$1 - E_{20} = \left(1 - E\right)^{1/F}$$  (3)

Where, $E$ = aeration efficiency at the water temperature of measurement, $E_{20}$=aeration efficiency at the 20°C, and $f$ = the exponent described by:

$$f = 1 + 2.103 \times 10^{-2} (T - 20) + 8.261 \times 10^{-2} (T - 20)^2$$  (4)

Where, $T$ = water temperature in °C.

IV. METHODOLOGY AND DATASET

Tests were conducted in hydraulic laboratory of National Institute of Kurukshetra, having a rectangular rigid steel flume of 25 cm width, 30 cm height and 4 m length. The flume has transparent acrylic sheet in the middle on both sides of walls for 1.8m length. The flume is fed by 2 HP motor pump which delivers maximum discharge of 6 l/s. The discharge in the main channel is regulated by valve which is fitted in the water supply pipe an overhead water tank and discharge as well as the velocity is controlled in the main channel by regulating gate.

V. DATASET

Data set consisting of 36 observations were used and obtained from the laboratory experiments and used for testing the models. Input data set consists of discharge($D$), no. of keys($K$), head($h$); magnification factor($M$), height of weir($H$), length of jump ($L_j$), length of crest($L_c$), width at outlet($W_o$), shape factor($S$), whereas Aeration efficiency was considered as output.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Training</th>
<th>Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>E20</td>
<td>0.164</td>
<td>0.207</td>
</tr>
<tr>
<td>Discharge</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>Head</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>Mag. Factor</td>
<td>0.735</td>
<td>0.758</td>
</tr>
<tr>
<td>No of Keys</td>
<td>2.500</td>
<td>2.500</td>
</tr>
<tr>
<td>Length of Jump</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>Crest Length</td>
<td>1.250</td>
<td>1.250</td>
</tr>
<tr>
<td>Height of Weir</td>
<td>0.110</td>
<td>0.110</td>
</tr>
<tr>
<td>Outlet Width</td>
<td>0.023</td>
<td>0.023</td>
</tr>
<tr>
<td>Shape Factor</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Std. d.</th>
</tr>
</thead>
<tbody>
<tr>
<td>E20</td>
<td>0.164</td>
<td>0.770</td>
<td>0.425</td>
<td>0.165</td>
</tr>
<tr>
<td>Discharge</td>
<td>0.009</td>
<td>0.058</td>
<td>0.036</td>
<td>0.017</td>
</tr>
<tr>
<td>Head</td>
<td>0.009</td>
<td>0.024</td>
<td>0.016</td>
<td>0.004</td>
</tr>
<tr>
<td>Mag. Factor</td>
<td>0.735</td>
<td>1.910</td>
<td>1.197</td>
<td>0.342</td>
</tr>
<tr>
<td>No of Keys</td>
<td>2.500</td>
<td>4.500</td>
<td>3.462</td>
<td>0.824</td>
</tr>
<tr>
<td>Length of Jump</td>
<td>0.011</td>
<td>0.149</td>
<td>0.119</td>
<td>0.057</td>
</tr>
<tr>
<td>Crest Length</td>
<td>1.250</td>
<td>2.040</td>
<td>1.631</td>
<td>0.313</td>
</tr>
<tr>
<td>Height of Weir</td>
<td>0.110</td>
<td>0.150</td>
<td>0.129</td>
<td>0.016</td>
</tr>
<tr>
<td>Outlet Width</td>
<td>0.023</td>
<td>0.066</td>
<td>0.040</td>
<td>0.015</td>
</tr>
<tr>
<td>Shape Factor</td>
<td>1.000</td>
<td>1.500</td>
<td>1.250</td>
<td>0.255</td>
</tr>
</tbody>
</table>

VI. ANFIS (ADAPTIVE NEURO FUZZY INFERENCE SYSTEM)

ANFIS is a computer software based computing system (MATLAB 2013) which uses different inputs to give an output as result. Connecting all input through a layer of interface its gives a desired output value. Several methods for supplier selection have appeared in literature, including approaches based on fuzzy logic. The main reason for a fuzzy logic approach is the need to handle vagueness and ambiguity in the problem. Researchers try
to build effective models that not only consider quantitative aspects but also convert human judgments about qualitative criteria into meaningful results.

Baylar et al. (2008) used ANFIS to predict aeration entrainment rate and aeration efficiency of weirs by applying three inputs to two different ANFIS models. In a related study, model performance of multi-nonlinear and linear regression was compared; ANFIS produced better results than related regression models.

VII. CHOICE OF MEMBERSHIP FUNCTION

Membership function may be of many shapes: trapezoidal, triangular, generalized bell-shaped model, gaussian function and many more. In present study performance of triangular, generalized bell-shaped model, gaussian function are compared. All three MF’s are defined below.

**Trainangular:**

\[ \mu_X(a) = \frac{(a-x)}{(b-y)}, x \leq a \leq y \]

\[ = \frac{(z-a)}{(z-y)}, z \leq a \leq y \]

Gaussian:

\[ \mu_G(a) = \frac{1}{1 + \frac{(a-z)^2}{x}} \]

Bell Shaped:

\[ \mu_{b_i} = \frac{1}{1 + \frac{(a-z)^2}{x_i}} \]

\[ \mu_{b_j} = \frac{1}{1 + \frac{(a-z)^2}{x_j}} \]

i = 1, 2, 3...

j = 1, 2, 3...

In the current study ANFIS was used to model the relationship between input and output. Model was implementing using the fuzzy logic toolbox of MATLAB 2013. To construct ANFIS model data was divided into two groups training and testing. Training data set was composed of 25 data points and 11 data points in testing. There is no fixed rule for developing an ANFIS model (Cui et al., 2010). Trimf, gbellmf, and gaussmf membership functions for input are used for determination of best fit in the fuzzy model. The TRIMF membership functions were the best for each input.

Specifications of the developed ANFIS model are as follows:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Gauss mf</th>
<th>gbell mf</th>
<th>trimf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>1072</td>
<td>1072</td>
<td>1072</td>
</tr>
<tr>
<td>Number of linear parameters</td>
<td>512</td>
<td>512</td>
<td>512</td>
</tr>
<tr>
<td>Number of nonlinear parameters</td>
<td>36</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td>Total number of parameters</td>
<td>548</td>
<td>566</td>
<td>566</td>
</tr>
<tr>
<td>Number of training data pairs</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Number of fuzzy rules</td>
<td>512</td>
<td>512</td>
<td>512</td>
</tr>
</tbody>
</table>

VIII. LINEAR REGRESSION MODEL

In linear regression, the relationships are modelled using linear predictor functions whose unknown model parameters are estimated from the data. Such models are called linear models. Most commonly, the conditional mean of y given the value of X is assumed to be an affine function of X; less commonly, the median or some other quantile of the conditional distribution of y given X is expressed as a linear function of X. Like all forms of regression analysis, linear regression focuses on the conditional probability distribution of y given X, rather than on the joint probability distribution of y and X, which is the domain of multivariate analysis.

A typical linear regression model is developed by using regression analysis and is given by:

\[ Y = k_0 + k_1X \]

Where,

\[ Y = \text{Infiltration rate} \]

\[ X = \text{Time (t)} \]

\[ k_0 \text{ and } k_1 \text{ = Regression coefficients.} \]

In the current study, Linear Regression model was used consisting of training and testing data set. The equation obtained from training data set is:

\[ E = \frac{3.25004791059239E-02 + 14.9948359916943 \times D - 29.91625993119572 \times M + 0.13457817522464 \times K - 0.278180035706502 \times H - 0.167615074378671 \times Lj - 1.21138472717558 \times WO + 0.239607771049986 \times S}{0.024} \]

Where, E is the efficiency, D is the discharge, h is the head, M is the magnification factor, K is the no of keys, H is the height of weir, Lj is the length of jump, WO is the outlet width and S is the shape factor.

IX. ANALYSIS OF RESULTS

To evaluate the value of Linear Regression model and ANFIS model in predicting aeration efficiency Coefficient correlation (CC), R², Root mean square error (RMSE), NS are used. Table provides values of the parameters CC, R², RMSE, NS obtained from different modelling techniques.

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Training Data Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>R²</td>
</tr>
<tr>
<td>LR</td>
<td>0.998</td>
</tr>
<tr>
<td>trimf</td>
<td>0.999</td>
</tr>
<tr>
<td>gauss mf</td>
<td>0.999</td>
</tr>
<tr>
<td>gbell mf</td>
<td>0.999</td>
</tr>
</tbody>
</table>
From correlation coefficient value and root mean square value it was observed that out of Linear Regression (LR) and ANFIS, LR gives best result for aeration efficiency (E20) with CC value 0.9834. In ANFIS model out of the various techniques used (trimf, gaussmf, gbellmf) trimf gives better result having CC value 0.9593 and NS value 0.9361.

Following graph shows the Actual vs. Predicted Values obtained by different computing techniques.

![Fig. 2: Actual vs. Predicted Values using LR and ANFIS (trimf) for Training Data Set](image)

![Fig. 3: Actual vs. Predicted Values of Aeration Efficiency using LR, ANFIS (gbellmf, gaussmf, trimf) for Testing Data](image)

![Fig. 4: Variation of Error Values of Aeration Efficiency (E20) using Different Techniques](image)

**X. CONCLUSION**

This paper examines the potential of Linear Regression (LR) and ANFIS approaches in predicting the aeration efficiency. From the comparison of performance evaluation parameters, it has been observed out of LR and ANFIS (trimf), LR gives good results with CC 0.988. In ANFIS model trimf gives better results with CC 0.959. It can be successfully used in estimation of aeration efficiency of piano key weir with rectangular and trapezoidal geometry plunging into the water pool. LR and ANFIS (trimf) are concluded to be the most effective modelling technique in approximation of the volumetric oxygen transfer coefficient.

**REFERENCES**


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