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Modeling Aeration of Sharp Crested Weirs by Using Support Vector Machines

Arun Goel

***Abstract*—**The present paper attempts to investigate the prediction of air entrainment rate and aeration efficiency of a free overfall jets issuing from a triangular sharp crested weir by using regression based modelling. The empirical equations, Support vector machine (polynomial and radial basis function) models and the linear regression techniques were applied on the triangular sharp crested weirs relating the air entrainment rate and the aeration efficiency to the input parameters namely drop height, discharge, and vertex angle. It was observed that there exists a good agreement between the measured values and the values obtained using empirical equations, Support vector machine (Polynomial and rbf) models and the linear regression techniques. The test results demonstrated that the SVM based (Poly & rbf) model also provided acceptable prediction of the measured values with reasonable accuracy along with empirical equations and linear regression techniques in modelling the air entrainment rate and the aeration efficiency of a free overfall jets issuing from triangular sharp crested weir. Further sensitivity analysis has also been performed to study the impact of input parameter on the output in terms of air entrainment rate and aeration efficiency.

***Keywords*—**Air entrainment rate, dissolved oxygen, regression, SVM, weir.

I. Introduction

DISSOLVED OXYGEN (DO) is one of the most cited water quality parameters in the surface water such as rivers, lakes, and reservoirs. The dissolved oxygen concentration in surface water is a prime indicator of quality of water needed for human use and by the aquatic life. Aeration is a natural process of oxygen transfer from the atmosphere to replenish the used oxygen. A sharp crested weir can be used in the rivers for oxygen absorption/transfer in the form of a large number of bubbles by creating turbulence in water which helps in oxygen transfer (Fig. 1). The weir in a river system assists in increase in dissolved oxygen, even though water remains in contact with the structure for only a short time. The oxygen transfer is caused by a rapid flow transition from sub critical to supercritical flow and again back to the sub critical flow. However, same quantity of oxygen transfer may occur in a longer river reach which would otherwise may occur at a single weir provided in a river. The oxygen transfer in a weir is accomplished during the breaking of the jet of water and subsequent collision of jet at the bottom of the channel. Thus air entrainment due to turbulent mixing will contribute greatly towards oxygen transfer and subsequently aeration efficiency of the system is enhanced [1]-[3].

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Earlier studies by investigators [4]-[7] had reviewed air entrainment and aeration efficiency of hydraulic structures. Recently, [8]-[14] investigated sharp crested weirs having different cross section geometry and demonstrated that the air entrainment rate and the aeration efficiency of weirs changed depending on weir. References [5], [13], [15]-[19] studied on air-demand ratio (ratio of volume flow rate of air to that of water) and aeration efficiency in weirs. In recent years, the developments in the intelligent methods make them possible to use in the complex systems modeling in a useful manner as suggested by [1]-[3].

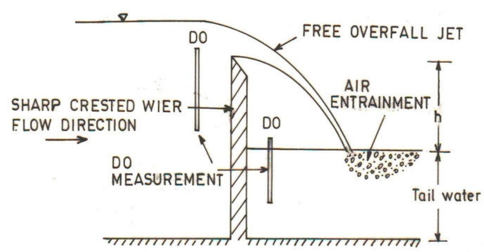

Fig. 1 Aeration of sharp crested weir

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II. Aeration Efficiency of Weirs

The change in oxygen concentration over a period of time in a parcel of water as it travels through a hydraulic structure such as weir can be expressed by:

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

where, K_L = bulk liquid fill coefficient, Cs and C are the saturation concentration of oxygen in water at prevailing conditions and actual concentration of oxygen in water at time t, A is air water contact area, V is volume of water associated with (1). The mechanisms by which air is entrained and transferred into water because of a free overfall jet are several

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and complex.

The predictive relations assume that C_S is constant and determined by the water atmosphere partitioning. If that assumption is made, C_S is constant with respect to time, and the oxygen transfer efficiency (aeration efficiency), E may be defined by [20]: major source of air supply is visualized as a thin layer surrounding the jet and carried into the water upon impact, and therefore air entrainment capacity is given by:

$$E = \frac{C_d - C_u}{C_s - C_u} \tag{2}$$

A value of E > 1 means the downstream water has become supersaturated (when $C_d > C_S$). A transfer efficiency value of 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, the most often used temperature correction factor has been that of [21], although some investigators have chosen to use an Arrhenius–type of water temperature correction. Gulliver et al. [20] applied the theories to mass transfer similitude and developed the relationship as:

$$1 - E_{20} = (1 - E)^{1/f} \tag{3}$$

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

$$f = 1.0 + 0.02103(T - 20) + 8.261x10^{-5}(T - 20)^2 \tag{4}$$

where T = water temperature.

$$Q = \left[0.17h^{-0.29}Q^{-0.158}\left(\cos\theta/2\right)^{-0.172}\right]^{-4.598} \tag{5}$$

$$E_{20} = 1 - \left[1 + 0.149h^{1.341}Q^{-0.280}\left(\sin\theta/2\right)^{-0.206}\right]^{-1} \tag{6}$$

where Q = discharge, h = head over weir, θ = vertex angle. Baylar et al. [3] and [19] have applied AI methods and soft computing techniques for prediction of oxygen transfer efficiency successfully. However, literature review indicates that no one has applied SVM (Poly & rbf) on these data sets as mentioned by [3]. In this paper, Support vector machine (Polynomial and rbf) models, linear regression equations and empirical regressions suggested by [3] were tested and compared in order to determine the air entrainment rate and the aeration efficiency of the triangular sharp crested weirs.

III. Support Vector Machines (SVM) and Data Set Used

The data used in this study were taken from the study conducted by [3]. Support vector machines (SVMs) are classification and regression methods, which have been derived from statistical learning theory [22]. The SVMs classification methods are based on the principle of optimal separation of classes. If the classes are separable - this method selects, from among the infinite number of linear classifiers, the one that minimize the generalization error, or at least an upper bound on this error, derived from structural risk minimization. Thus, the selected hyper plane will be one that leaves the maximum margin between the two classes, where margin is defined as the sum of the distances of the hyper plane from the closest point of the two classes [22]. The modelling techniques like support vector machines have the capability to reproduce the unknown relationship present between a set of input variables and the output of the system. Support vector machines performance was found to be better due to its use of the structural risk minimization principle in formulating cost functions and of quadratic programming during model optimisation. These advantages lead to a unique optimal and global solution as compared to conventional neural network models. The support vector machines can be applied to regression problems and can be formulated as in (7)-(11).

Investigator [22] proposed ε-support vector regression (SVR) by introducing an alternative ε-insensitive loss function. The purpose of the SVR is to find a function having at most ε deviation from the actual target vectors (y_i) for all given training data and have to be as flat as possible [23]. This can be put in other words as the error on any training data has to less than ε. For a given training data with k number of samples, represented by $(x_1, y_1), \ldots\ldots\ldots, (x_k, y_k)$ and a linear function.

$$f(x) = \langle w, x \rangle + d \tag{7}$$

where $w \in R^N$, and d ∈ R. $\langle w, x \rangle$ represents the dot product in space R^N and N is the dimension of input space. A smaller value of w indicates the flatness of (7), which can be achieved by minimizing the Euclidean norm as defined by $\|w\|^2$ [23]. Thus, an optimization problem for this can be written as: minimize $\frac{1}{2}\|w\|^2$ subject to:

$$\begin{cases} y_i - \langle \mathbf{w}, \mathbf{x}_i \rangle - d \le \varepsilon \\ \langle \mathbf{w}, \mathbf{x}_i \rangle + d - y_i \le \varepsilon \end{cases} \tag{8}$$

The optimization problem in (8) is based on the assumption that there exists a function that provides an error on all training pairs which is less than ε. In real life problems, there may be a situation like one defined for classification by [24]. So, to allow some more error slack variables ξ, ξ' can be introduced and the optimization problem defined in Equation 1 can be written as:

$$\text{minimize } \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{k}\left(\xi_i + \xi_i'\right)$$

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Subject to $y_i - \langle w, x_i \rangle - d \leq \varepsilon + \xi_i$

$$\langle w, x_i \rangle + d - y_i \leq \varepsilon + \xi_i^{'} \tag{9}$$

and ξ_i, $\xi_i^{'} \geq 0$ for all i = 1, 2,……, k.

The parameter C is determined by the user and it determines the trade-off between the flatness of the function and the amount by which the deviations to the error more than ε can be tolerated. The optimization problem in (9) can be solved by replacing the inequalities with a simpler form determined by transforming the problem to a dual space representation using Lagrange multipliers λ_i, $\lambda_i^{'}$, η_i, $\eta_i^{'}$ i = 1,….,k [25]. The prediction problem can finally be written as:

$$f(x, \alpha) = \sum_{i=1}^{k} \left(\lambda_i^{'} - \lambda_i\right)\langle x_i, x \rangle + d \tag{10}$$

This technique can be extended to allow for non-linear support vector regression by introducing the concept of the kernel function [22]. This is achieved by mapping the data into a higher dimensional feature space, thus performing linear regression in feature space. The regression problem in feature space can be written by replacing $x_i \cdot x_j$ with $\Phi(x_i) \cdot \Phi(x_j)$ where $K(x_i, x_j) \equiv \Phi(x_i) \cdot \Phi(x_j)$. The regression function for this can be written as:

$$f(x, \alpha) = \sum_{i=1}^{k} \left(\lambda_i^{'} - \lambda_i\right) K(x_i, x) + d \tag{11}$$

IV. Material and Methods

In this paper modeling techniques such as SVM (poly & rbf), empirical equations and linear regression are being applied to the problems in prediction of air entrainment rate and aeration efficiency for a sharp crested weir. The SVM (poly & rbf) based technique requires setting up of the few user-defined parameters. The SVMs, in addition to the choice of kernel, require setting up of kernel specific parameters. The optimum values of the regularization parameter C and the size of the error-insensitive zone ε need to be determined. To select user-defined parameters i.e. (C, γ and d*) a large number of trials were carried out by using different combination of these parameters on each of the data sets. For quantitative comparison of results, an error measure, a correlation coefficient (r) and RMSE, which presents the degree of linear regression association between predicted and true values has been considered, which is preferred to, in many iterative prediction and optimization scheme. To reach at a suitable choice of these parameters, the correlation coefficients (CC) and Root Mean Square Error (RMSE) were compared and a combination of parameters providing smallest value of RMSE and the highest value of correlation coefficient was selected for the final results. Similarly, a number of trials were also carried out to find a suitable value of ε (error-insensitive zone) with a fixed value of C and kernel specific parameters. A number of trials were carried out with different data set to select a suitable value of regularization parameter C. Variation in the error-insensitive zone ε as was observed, have no effect on the predicted air entrainment rate and aeration efficiency so a value of 0.0010 was chosen for all experiments. Due to the availability of small data sets, a cross validation was used to train and test the performance of the SVMs regression techniques. The cross-validation is a method of estimating the accuracy of a classification or regression model. The input data set is divided into several parts (a number defined by the user), with each part in turn used to test a model fitted to the remaining parts. In this study, the data sets of the laboratory and field data were used for both creating and testing the models. For example the data set was divided in to ten equal parts. 90% of data was used in model building and remaining 10% was used in testing. The model was run and next time another 90 % were used in training and remaining 10% was used in testing and again model was run and so on. The model giving maximum (r) and minimum (rmse) was chosen finally for the study.

V. Performance Evaluation Criteria

The parameters considered in the study are water discharge (Q), drop height (h), angle in triangular sharp crested weir (θ), air entrainment rate (Q_A) and aeration efficiency at 20°C (E_{20}). The parameters, Q, h, and θ were used as inputs to the SVM (poly & rbf) for the estimation of Q_A and E_{20}, respectively on 72 experimental data set. The model results were evaluated using the root mean square error (RMSE) and correlation coefficient (r) statistics.

The data sets mentioned in [3] are used in the present study for model building and validation to assess the potential of the empirical equations, linear regression, SVM (rbf & poly) modelling techniques in predicting of air entrainment rate and aeration efficiency for a sharp crested weir. The correlation coefficient (CC) and Root Mean Square Error (RMSE) values are used as shown in (12) and (13) mainly for the performance evaluation of models and comparison of the results for prediction air entrainment rate and aeration efficiency for a sharp crested weir. Higher value of a correlation coefficient and a smaller value RMSE mean a better performance of the model. Further, air entrainment rate and aeration efficiency for a sharp crested weir were plotted against the computed values obtained by empirical equations suggested by [3], linear regression, and SVM (rbf & poly). To study the scatter of line of perfect agreement (a line at 45°) along with +/- 10% line was plotted for data set.

A. Error Measure Criteria

1. Correlation Coefficient (R)

$$r = \frac{\sum xy}{\sqrt{\sum x^2 \sum y^2}} \tag{12}$$

where x = X - X', y = Y - Y' where X = observed values; X' = mean of X, Y = predicted values, Y' = mean of Y.

2. Root Mean Square Error

$$RMSE = \left[\frac{\sum (X - Y)^2}{n} \right]^{0.5} \quad (13)$$

VI. Prediction of Air-Entrainment Rate and Aeration Efficiency

The first set of analysis was carried out by using input parameters namely upstream head, discharge, vertex angle from the data sets [3] predicting the air entrainment rate and aeration efficiency. A number of trials were carried out to reach at the various user-defined parameters required for the SVM (Polynomial & rbf)) and linear regression based algorithms using WEKA software [26] by cross validation. Table I provides the values of parameters used for SVM (Polynomial & rbf)) modeling for the data set for prediction of air entrainment rate and aeration efficiency.

TABLE I
VALUES OF KERNEL SPECIFIC PARAMETERS OF SVMS MODELS

Type of parameter	SVM (rbf)		SVM (poly)	
	C	γ	C	Γ
QA	1	0.01	1	0.01
E20	1	0.01	1	0.01

The results for air entrainment rate and aeration efficiency in terms of correlation coefficient and root mean squared error, obtained by soft computing SVM (Polynomial & rbf), non-linear regression equations (5) and (6) and linear regression are shown in Tables II and III respectively.

TABLE II
VALUES OF PERFORMANCE PARAMETERS OF LINEAR, SVM, REGRESSION EQ FOR PREDICTION OF QA

Type of technique	Correlation coefficient (r)	Root mean squared error (RMSE)
Linear regression	0.9883	1.6529
SVM(POLY)	0.9869	1.7544
SVM(RBF)	0.9450	5.7935
Baylar regression equation (5)	0.9872	1.7380

TABLE III
VALUES OF PERFORMANCE PARAMETERS OF LINEAR, SVM, REGRESSION EQ FOR PREDICTION OF E_{20}

Type of technique	Correlation coefficient (r)	Root mean squared error (RMSE)
Linear regression	0.9822	0.0249
SVM(POLY)	0.9828	0.0245
SVM(RBF)	0.9656	0.0821
Baylar regression equation (6)	0.9830	0.0245

Measured versus calculated values of the air entrainment rate and aeration efficiency are shown as scatter plots as shown in Figs. 2 and 3 respectively. For air entrainment rate prediction (Q_A), a correlation coefficient and RMSE for polynomial based SVM (0.9869, 1.7544), rbf based SVM (0.9450, 5.7935), non-linear regression equation no 5 (0.9872, 1.738) and linear regression (0.9883, 1.6529) are obtained (Table II). A perusal of Fig. 2 indicates all three techniques are giving good performance on this data set. Also a scatter of 10% error was also plotted and most of the points are falling in this range. For aeration efficiency prediction (E_{20}), a correlation coefficient and RMSE for polynomial based SVM (0.9828, 0.0245), rbf based SVM (0.9656, 0.0821), non-linear regression equation no 6 (0.98304, 0.0244) and linear regression (0.9822, 0.02490) are obtained (Table III). Also a scatter of 10% error was plotted and majority of the points are falling in this range except a few points as predicted by SVM (Poly & rbf). It is evident from Fig. 3 that all three techniques are giving good performance on this data set. Further, SVM (Poly & rbf) is not performing at par for few data points as compared to non-linear regression equations (5) & (6) and linear regression techniques.

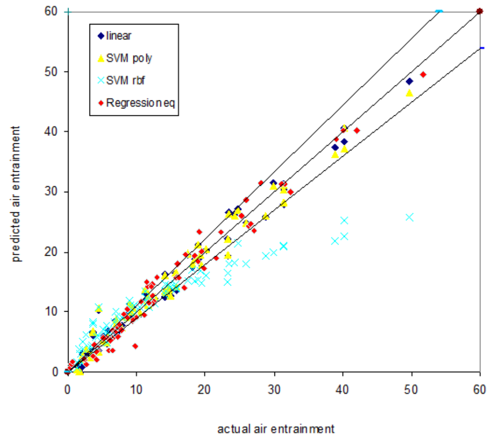

Fig. 2 Variation of Actual Air Entrainment with Predicted Air Entrainment (QA)

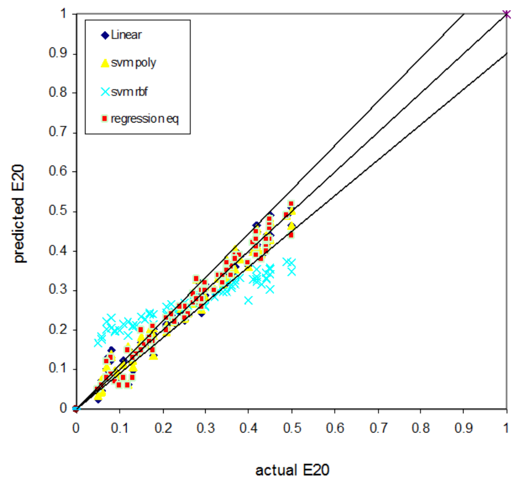

Fig. 3 Variation of Actual Aeration Efficiency with Predicted Aeration Efficiency (E20)

VII. Sensitivity Analysis

Sensitivity tests were conducted to determine the relative significance of each of the independent parameters (input neurons) on the air entrainment rate and aeration efficiency separately of a sharp crested weir (output). All parameter were considered one by one in the sensitivity analysis. The influence of each independent parameter was studied on

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dependent parameter in the present study as well. The functional relation as given by the equation is used in modeling of air entrainment rate i.e. QA = f (Q, h, θ). The Table IV indicates the results when one of the input parameter is removed. Each time the value of correlation coefficient and rmse values are calculated as given in Table IV.

TABLE IV
SENSITIVITY ANALYSIS OF INDEPENDENT PARAMETERS FOR QA CALCULATION

Type of model	Correlation coeff	RMSE
QA = f (Q, h, θ) All	0.7383	7.3284
QA = f (h,θ) No Q	0.7009	7.7419
QA = f (Q, θ) no h	0.3905	10.058
QA = f (Q, h) no θ	0.2077	10.698

It can be seen from Table IV that the value of QA is not changing much in case of Q and θ removed. However, QA is affected most when theta (θ) is not considered as an input parameter as shown by the minimum value of correlation coefficient and higher value of rmse in the model no 4. Similar exercise was done for aeration efficiency E20 = f (Q, h, θ). Table V compares the different models, with one of the independent parameters removed in each case.

TABLE V
SENSITIVITY ANALYSIS OF INDEPENDENT PARAMETERS FOR E20 CALCULATION

Type of model	Correlation coeff	RMSE
E20 = f (Q, h, θ) All	0.6697	0.0990
E20= f (h, θ) No Q	0.5685	0.1106
E20 = f (Q, θ) No h	-0.3160	0.1388
E20= f (Q, h) No θ	0.5539	0.1108

The results in Table V show that among the parameters, head over the weir (h) has the most significant effect on aeration efficiency as shown but negative value of correlation coefficient and higher rmse values in the model no 3.

VII. CONCLUSIONS

In this paper SVM (poly & rbf) based models, Baylar et al. [3] regression equations and linear regression equations are applied to determine the air entrainment rate and the aeration efficiency of the triangular sharp-crested weirs and were compared to each other. It was found that SVM (poly & rbf) models could be successfully used in computation of air entrainment rate and the aeration efficiency of weirs. The test results revealed that Support vector machine (polynomial and rbf) predicted the measured values nearly same accuracy than linear regression model. Extremely good agreement between the predicted and measured values confirms that the SVM (Poly & Rbf), linear regression and regression equation by [3] can be successfully used to predict air entrainment rate and the aeration efficiency of triangular sharp-crested weirs.

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