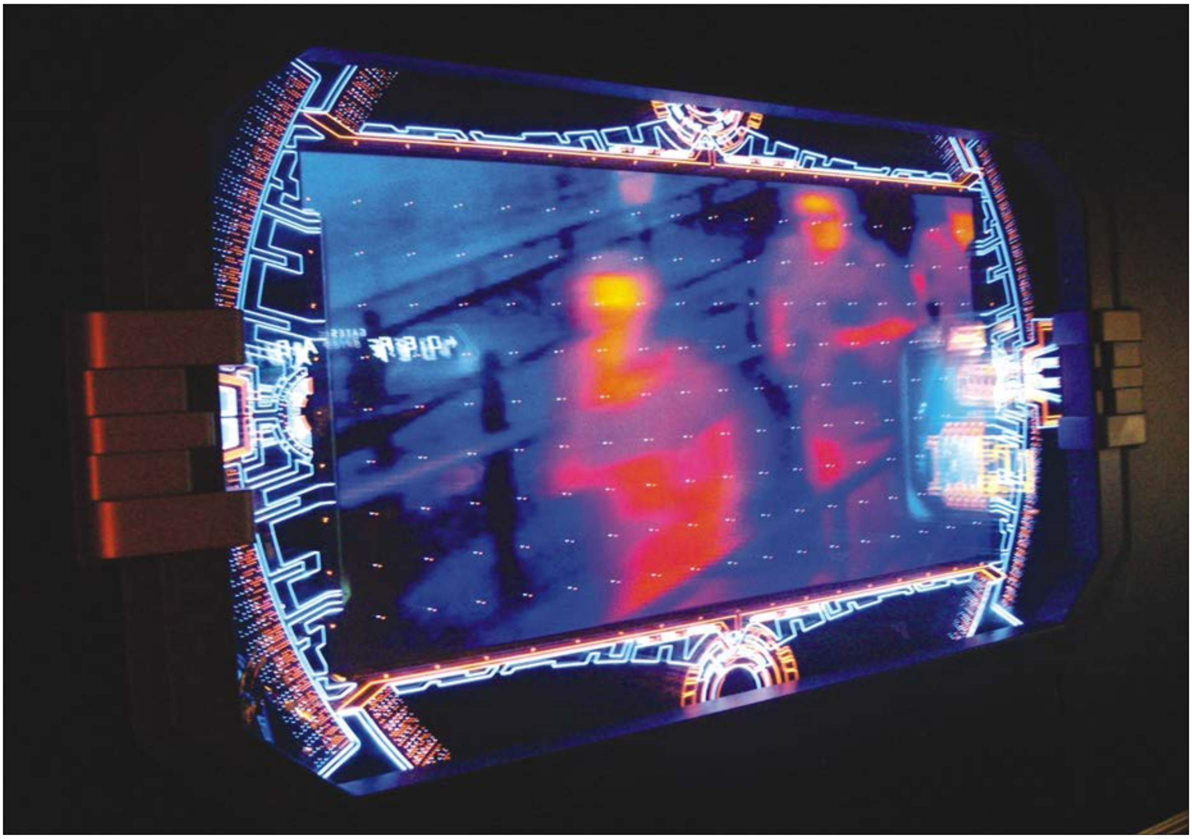

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Experimental Investigation of Flow Aeration on Chute Spillway

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ABSTRACT

Spillways are one of the most important structures which are responsible to carry out the high capacity flood discharging into the reservoirs. Due to the combination of high velocity flows and low pressure occurs over these structures and especially close to the rigid boundaries, the potential for cavitation is also raised. Scaled model study of aerators is a common way to investigate the effects of geometries and flow conditions on aeration mechanism. However, these studies are usually concentrated on specific geometry of aerators and flow conditions. In this study, experimental investigation of flow aeration through aerators in chute spillways is investigated. Experiments were performed on different hydraulic models including of Azad, Karkhe, Godar, Shafarood and Nazloochay spillways, in Iran. The study focused on derivation of relationships by using a wide range of geometries and flow conditions to estimate the coefficient of air entrainment. The results show acceptable data, compared with the previous investigation.

Key words: Aeration, cavitation, chute spillway, experimental investigation

INTRODUCTION

Spillways of high dams are expected to carry a large quantity of water discharging into the reservoir. Therefore, with raising the height of dams, the flow discharge and high velocity also intensify which may endanger the structure. In outlet conduits and tunnel spillways, high velocity flows and pressure reduction provide situation favorable for cavitations erosion. Studies of cavitation on open channels and chute spillways show that flow aeration is a accurately practical, cheap and economic way to eliminate cavitation damages (Chanson, 1988). Upto now, extensive research have been performed on two phase air water mixture and a number of relationships are recommended to estimate the aeration ratio (quantity of air into water discharge). However, due to the complexity of this phenomenon, these relations may introduce excessive errors for different situations. Therefore, more investigation are required to understand the process and its impact of that which lead to more accurate correlations and formulas. In this studies, extensive experimental investigations on physical models of chute spillways and aerators of Azad, Karkheh, Godar, Shafaroud and Nazlouchay dams are presented. Experiments include about 100 tests to cover a wide range of parameters which impact the process of aeration.

Studies have shown that in the presence of air, caviatation damages are eliminated. According to Vischer (1933), when the velocity is exceeded from 25-35 m sec^{-1}, caution taking to protect the structure against cavitation. Peterka (1953) performed experiments in a venturi and measured the weight of the demolished concrete pieces. He realized that 2% air concentration considerably reduced cavitation damages. In the presence of 5-7% air concentration, no damages were measured. So, with the flow velocity of 30 m sec^{-1}, 5-7% air concentration would be enough to stop the damages to the concrete (28 days strength of 17 MPa). Mussalli and Carstens (1969) and Russmussen (1956) demonstrated the effect of aeration on cavitation damages. Based on field measurements in a chute spillway with the velocity of 45 m sec^{-1}, Zhang (1991) showed that 4-8% air concentration completely removed the damages.

Many studies have tried to derive relationships between the quantity of air based on aerator and spillway geometries and hydraulic conditions. Pinto (1984) presented a relation for aeration ratio (**β**) based on the field measurements of Foz dam do Ariea, Emborcacao, Colbun and Tarbela dams as follows:

$$ß = 0.29(Fr - 1)^{0.62}\left(\frac{D}{h}\right)^{0.59} \tag{1}$$

where, D = τA/B, Fr is the Froude number of flow, $\bar{c}$ is the loss concentration, A is the cross sectional area of air vent, h is the depth of water and b is the half weidth of the chute.

Wood (1991) showed that **β** is a function of underpressure, ramp geometry and Froude number of flow. Based on the data of Foz dam do Ariea, he derived the following equation:

$$\beta = 0.0079(Fr - 4.3) - 0.16\left(\frac{B}{d}\right)\left(\frac{\Delta P}{\rho_w g d}\right) \tag{2}$$

where, B is the height of the ramp and d is the flow depth.

Kobus (1980) expressed the aeration ratio (**β**) as a function of Froude difference ($\Delta F_r = F_r - F_{rc}$) and nappe underpressure in the form of $P_r = \Delta P/\rho gd$ or pressure gradient. The F_{rc} is also the critical Froude number. The results lead to the following equation:

$$\beta = C_1.\Delta_3^{1.5}.(1 - C_2 P_2) \tag{3}$$

where, C_1 and C_2 are coefficients related to the chute geometry.

Using the data of Tan (1984), Koschitzky (1987) and Rutschmann (1988) recognized that $0.02<C_1<0.1$, $0<C_2<0.5$ and Frc~3.5±1.

EXPERIMENTAL PHYSICAL MODELING

In this study various range of physical models of chute spillway dams have been studied. Dimensional analysis and dynamic similarity considerations highlighted the potential for scale effects in small-size laboratory studies. Herein a physical study is performed on a relatively large size stepped spillway channel. Several stepped chute configurations are tested. Detailed air-water flow measurements are conducted systematically for a range of flow conditions at large Reynolds The relationship between rate of energy dissipation and turbulence levels is investigated. Azad dam spillway, including the reservoir, dam, entrance channel, gates, flip bucket and spillway with the scale of 1:33.33 was constructed. Two aerators were fixed at low pressure locations along the spillway to prevent cavitation. Physical model of Shafaroud with the scale of 1:40 and one aerator, Nazlouzhay Dam with the scale of 1:40 and one aerator, GodarLandar hydropower and chute spillway with the scale of 1:66.67 and four aerators along its spillway were also constructed and used for our study. Physical model of Karkheh dam with the scale of 1:64 and two conduits (each of them with three aerators) was the last model used for this study (WRII, 1985, 1988, 2007, 2008, 2009).

Air bubble entrainment is defined as the entrapment of air bubbles and pockets that are advected within the turbulent flow. The entrainment of air packets can be localised or continuous along the air-water interface. Interfacial aeration is defined as the air entrainment process along an air-water interface, usually parallel to the flow direction. Various effective parameters on aeration can be characterized in two classes of hydraulics and geometry. Some of these parameters such as discharge (Q_W), air vent velocity (V_{air}), depth of water (d), flow velocity (V) and underneath pressure (Δp) can be directly determined by experimental measurements. Some of them like spillway slope (α), slope of ramp (φ), length (L_{ramp}) and height (t_r) of the ramp reflect the geometry. Dimensional analyses and ignoring of the insignificant parameters lead to a non-dimensional mathematical description in the form of:

$$\beta^{inlet} = f\left(Re, We,\ Fr,\ \alpha,\ \frac{t_r}{d},\ Tu,\ \frac{L_{ramp}}{d},\ P_n,\ \frac{\rho_{air}}{\rho_w}\right) \tag{4}$$

Based on the results of Laali and Michel (1984), the effect of Weber number can be eliminated for We>400:

$$We = \frac{v}{\sqrt{\frac{\sigma}{\rho_w \times d}}}$$

Less information is available on the importance of turbulence intensity, so it is usually eliminated in the mathematical process. Also, assuming a nearly constant temperature, lead to ignore the effect of density ratio (p_{air}/p_w). Therefore, we have:

$$\beta^{inlet} = f\left(Re,\ Fr,\ \alpha,\ \frac{t_r}{d},\ \frac{L_{ramp}}{d},\ P_n\right) \tag{5}$$

where, the aeration ratio is:

$$\beta = \frac{Q_{air}}{Q_w}$$

Reynolds number is:

$$R_e = \frac{\rho_w \times V \times d}{\mu}$$

Froude number is:

$$F_r = \frac{V}{\sqrt{g \times d}}$$

Pressure gradient is:

$$P_n = \frac{\Delta P}{\rho_w gh}$$

Assuming constant values of C_0, A_i, n_i in a power expression of **β** lead to the following relationship:

$$\beta = C\left(Fr \pm A_1\right)^{n_1}\left(\frac{L_{ramp}}{d} \pm A_3\right)^{n_3}\left(\tan\alpha \pm A_4\right)^{n_4}\left(P_n \pm A_5\right)^{n_5}\left(\frac{t_r}{d} \pm A_6\right)^{n_6}\left(Re\right)^{n_7} \quad (6)$$

The experimental data was used by statistical approach which is based on regression analyses R^2 to determine these constant values.

EXPERIMENTAL DATA ANALYSIS

In this study about 100 experiment's data from 5 different physical models were used. Figure 1 shows the variation of aeration ratio (**β**) with Froude number of flow (Fr). It is observed that although the ratio **β** increases with Fr but its rate of change varies for every model. For example, for Fr = 8, the ratio **β** varies in a wide range from 0.08-0.27 which reflects the complex behavior of aeration process. Therefore, care should be taken in introducing a single and unique relationship to exactly describe the aeration coefficient for different geometries and flow conditions (Koschitzky, 1987). As a result, further investigation was projected to reach a more accurate equation to describe the quantity of air demand downstream of aerators of chute spillways.

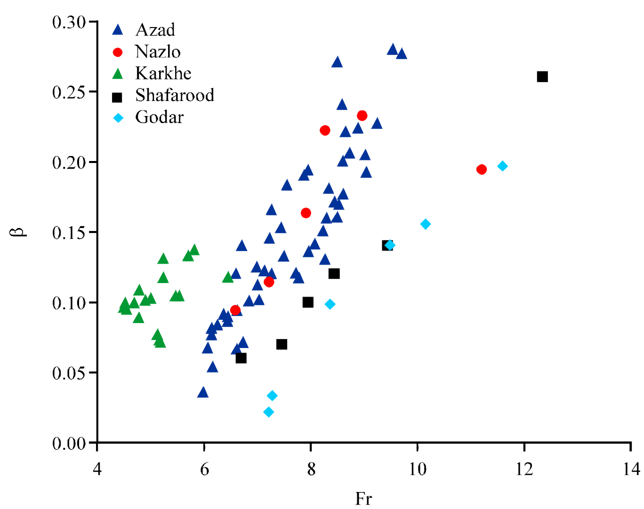

Fig. 1: Variation of **β** against Fr for different models of present study

Table 1: Results of parameters in statistical approch of the present study

Parameters		R^2	Adj R^2
$\beta^* = 9.9046(\tan\varphi + 0.47)^{-5.575}(\tan\alpha)^{0.04}\left(\frac{L_{ramp}}{d} + 7.3\right)^{-1.514}\left(\frac{t}{d}\right)^{1.241}(Pn)^{0.509}(Fr - 2.7)^{-0.285}$	6	0.881	0.872
$\beta^* = 8.8729(\tan\varphi + 0.47)^{-5.658}\left(\frac{L_{ramp}}{d} + 7.3\right)^{-1.59}\left(\frac{t}{d}\right)^{1.224}(Pn)^{1.224}(Fr - 2.7)^{-0.207}$	5	0.879	0.872
$\beta^* = 10.4437(Re)^{-0.004}(\tan\varphi + 0.47)^{-5.568}(\tan\alpha)^{0.04}\left(\frac{L_{ramp}}{d} + 7.3\right)^{-1.515}\left(\frac{t}{d}\right)^{1.44}(Pn)^{0.509}(Fr - 2.7)^{-0.288}$	7	0.881	0.870
$\beta^* = 9.9046\left(\frac{L_{ramp}}{d}\right)^{0.983}\left(\frac{\tau}{d} + 0.6\right)^{-0.456}(Pn)^{0.439}(Fr - 4.4)^{-0.026}$	4	0.872	0.866
$\beta^* = 0.2772\left(\frac{L_{ramp}}{d}\right)^{0.969}\left(\frac{\tau}{d} + 0.6\right)^{-0.482}(Pn)^{0.431}$	3	0.870	0.865
$\beta^* = 9.07797\times10^{-10}(Re)^{0.668}(\tan\varphi + 0.75)^{3.215}(\tan\alpha)^{-0.174}\left(\frac{L_{ramp}}{d}\right)^{1.618}\left(\frac{t}{d} + 0.09\right)$	6	0.770	0.753
$\beta^* = 8.556\times10^{-10}(Re)^{0.71}(\tan\alpha)^{-0.178}\left(\frac{L_{ramp}}{d}\right)^{1.223}\left(\frac{\tau}{d} + 0.35\right)^{-0.762}(Fr)^{2.412}$	5	0.764	0.750
$\beta^* = 3.82\times10^{-9}(Re)^{0.675}(\tan\varphi)^{0.678}\left(\frac{L_{ramp}}{d}\right)^{1.809}\left(\frac{\tau}{d} + 0.05\right)^{-1.145}(Fr)^{2.109}$	5	0.733	0.717
$\beta^* = 6.248\times10^{-9}(Re)^{0.809}\left(\frac{L_{ramp}}{d}\right)^{1.199}\left(\frac{\tau}{d} + 3\right)^{-2.221}(Fr)^{2.133}$	4	0.725	0.712
$\beta^* = 2.8541\times10^{-3}(\tan\varphi)^{0.85}(\tan\alpha)^{-0.177}\left(\frac{L_{ramp}}{d}\right)^{1.539}\left(\frac{\tau}{d} + 0.05\right)^{-1.379}(Fr)^{1.41}$	5	0.712	0.694
$\beta^* = 0.0181(\tan\alpha + 0.18)^{-0.397}\left(\frac{L_{ramp}}{d}\right)^{0.702}\left(\frac{\tau}{d} + 1.8\right)^{-1.7}(Fr)^{1.245}$	4	0.699	0.685
$\beta^* = 0.3791\left(\frac{L_{ramp}}{d}\right)^{0.665}(Fr)^{0.646}\left(\frac{\tau}{d} + 3.9\right)^{-1.975}$	3	0.623	0.610

Extensive investigations lead to the following expressions which describe the aeration ratio as a function of various non dimensional parameters. Based on statistical approach on data and using the non-dimensional parameters in Eq. 6, regression coefficient $R^2 = 0.881$ was achieved. The statistical results of this study have been summarized in Table 1. The results are sorted based on adjusted R^2 (adj R^2) in column 5. Column 3 also shows the number used parameters in our expression for aeration ratio. It is observed that amongst all descriptions of this table, the relationship in the fifth row with 3 parameters and $R^2 = 0.87$ provides the best expression for aeration ratio. To determine the effect of different parameters on **β**, first Lramp/d was considered and then the remaining parameters were included and the results are presented in the forms of Eq. 7-9. Figure 2 also shows the dispersion of calculated aeration ration ***β** from Eq. 9 and measured value **β** along the 45° line **β* = β**:

$$\beta^* = 0.07879\left(\frac{L_{ramp}}{d}\right)^{0.643} \qquad (R^2 = 0.553) \tag{7}$$

$$\beta^* = 0.14912\left(\frac{L_{ramp}}{d}\right)^{0.736}\left(\frac{t}{d} + 3.9\right)^{-0.741} \qquad (R^2 = 0.558) \tag{8}$$

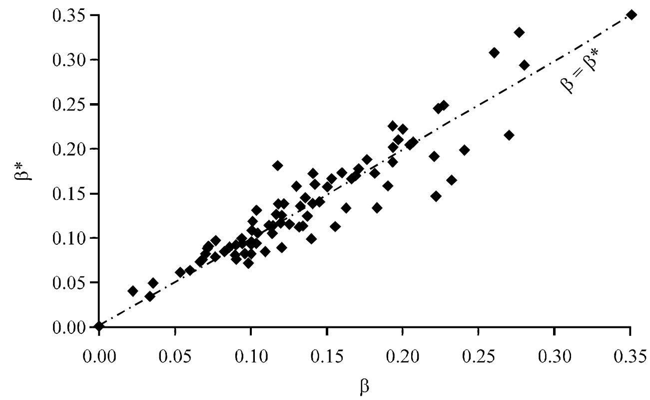

Fig. 2: Variation of measured **β** vs. calculated ***β**

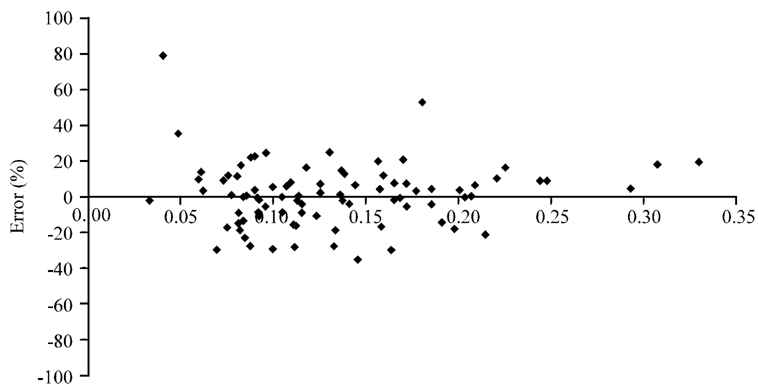

Fig. 3: Distribution of percentage error due to calculated ***β**

$$ß^* = 0.2772\left(\frac{L_{ramp}}{d}\right)^{0.969}\left(\frac{t}{d}+0.6\right)^{-0.482}(Pn)^{0.431} \qquad (R^2 = 0.870) \tag{9}$$

Figure 3 shows the percentage errors of calculated results from Eq. 9, compared to those of measured values. According the Fig. 3, 29% of errors lied in a range of ±5, 50% in a range of ±10, 88% in a range of ±25, 98% in a range of ±35 and 100% in a range of 80%. Also, about 57% are positive and 43% are negative. Further analysis of the whole data showed the Absolute Mean Error, AME = 1.63%, Sum of Square Error, SSE = 4.74%, Root Mean Square Error, RMSE = 0.26% and the absolute maximum and minimum errors to be 7.6 and 0%, respectively.

The results were also compared with the suggested expressions by Kobus (1980). They expressed the aeration ration **β** as a function of Froude difference:

$$\Delta Fr = Fr\text{-}Frc$$

and relative sub pressure Pn, in the form of Eq. 3. Based on the available data, they realized that $0.02<C1<0.1$, $0<C2<0.5$ and $Frc\sim3.5\pm1$. According to these limitations, the upper and lower limit of this equation may be determined as follows:

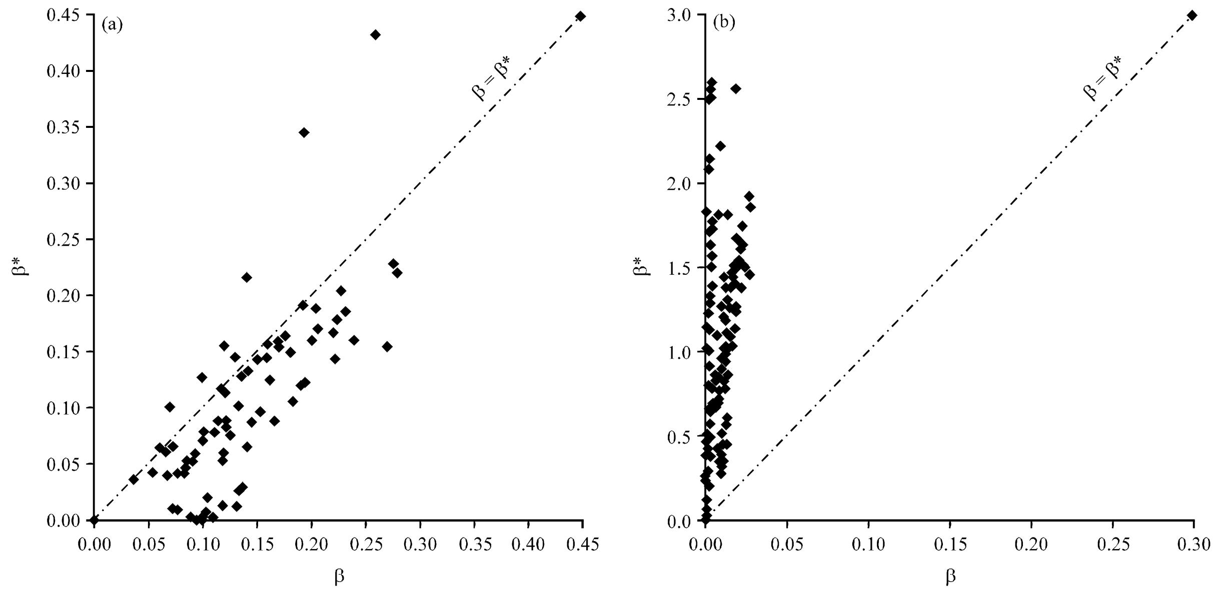

Fig. 4(a-b): Comparison of with experimental results of aeration ratio with predicted (a) Upper limit and (b) Lower limit values by Kobus and Koschitzky

$$\text{Upper limit} \qquad \boldsymbol{\beta^*} = 0.7(\mathrm{Fr}-2.5)^{1.5} \tag{10}$$

$$\text{Lower limit} \qquad \boldsymbol{\beta^*} = 0.02(\mathrm{Fr}-4.5)^{1.5}\,(1-1.5\mathrm{Pn}) \tag{11}$$

The comparison of results for upper and lower limit calculated from Eq. 10 and 11 are shown in Fig. 4 in comparison with the present data. It is observed that the suggested equation by Kobus (1980) introduces a wide range of error and it is difficult to make a decision in applying the above mentioned expressions to predict the air demand downstream of aerators on chute spillways.

In this study a sensitivity analyses was also performed to determine the main effective parameters in Eq. 9. Based on the data, the pressure gradient, relative height of the ramps and relative length of the ramps are, respectively in the range of:

$$0.00866 \le \mathrm{Pn} \le 0.215383$$

$$0.0375 \le \frac{\tau}{d} \le 1.755$$

and:

$$0.3 \le \frac{L_{ramp}}{d} \le 8.801$$

where, d is the depth of water. The results showed that L_{ramp}/d, P_n and t/d, respectively rank the 1st, 2nd and 3rd effective parameters on aeration ratio.

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