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Analysis of Air Concentration in a Physical Model of the Bottom of a Spillway Chute with Aerators

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Abstract: *Given the inherent difficulties and constraints of taking measurements on a prototype and representing the behavior of air in a physical model, this paper presents comparative analysis results from air content measurements in a spillway bottom model with aerators. This was done using model measurements and an analytical model to define the accuracy and credibility of extrapolating results to the prototype. The numerical criterion used allows calculation of air concentration decay along the chute at the same point where the physical model measurements were made. Since air concentration can only be measured at the bottom of the prototype, it can be concluded that the analytical approach works well, and with some adjustments, the results can be extrapolated to measure other points on the prototype Air content at the bottom chute is the most important understanding for the protection spillway.*

Keywords: *air concentration, cavitation, aerators, chute*

1. INTRODUCTION

The damage caused by chute cavitation at high speeds can be avoided if air is supplied to the flow water using aerators. One approach is to take air from the free surface to the bottom of the channel, however, this requires a channel with very large widths which is not always possible or desirable (Chanson, 1990, Chanson,1994). Another approach is to supply air using devices called aerators installed at certain cross sections. In the literature on the subject (Bhosekar et al 2012; Falvey, 1990; Sinniger & Hager, 1989; Wood 1991), criteria for dimensioning these devices are listed, but no information is given on a fundamental problem that is, precisely, where should the aerators be placed to achieve reliable and safe operation. In this situation it is convenient to perform measurements in prototypes as extrapolation of results from physical models is problematic.

The main difficulty in measurement of velocity and air concentration in a prototype, is their magnitude, as measuring at speeds between 30 and 40 m/s (as is the case here) is not a simple task. There are now tools to address the problem of designing aerators through numerical simulation based upon computational fluid dynamics (CFD). Among them are Flow-3D, Ansys Fluent (Chanel & Doering, 2008, Orturk et al 2008, Li et al 2011, Von Crabe et al (2013). However, access to these is not always easy for practical design purposes. Most of the tools are just beginning to address some aspects of this complex phenomenon, such as the air-water mixture flow. Prevailing methods for complex phenomenon comprehension such as air-water flows, had been specified duo instrumental development, and make it possible focus on complex problems as aerators separation that have been difficult to study (Kramer et al 2006). In many cases, a lot of time, technical and financial effort is required, and yet the main problem is still that there are no comparisons with prototype results (Chanson, 2013). Practical measurement of the air reliably presents major challenges. In general, access to suitable instrumentation is difficult and most of it is still at an experimental stage.

More than two decades ago the Huites Dam was built in Mexico in the State of Sinaloa. This dam has a spillway with two aerators and has worked well since its construction. It has been proposed to install air measurement sensors at some points to determine air concentrations at the bottom of the chute and compare these with those from a physical model. Due to the difficulty in performing measurements they are restricted to the bottom of the chute which is probably the only place where such measurements can be performed reliably. The bottom of the chute is also the most important place to consider for protection of the concrete structure (Kramer et al 2006).

2. BACKGROUND

Aerators are devices that exploit the ability of flows at high speed to suck air. These devices have two vertical jacks located on their sides through which air comes in. The ducts that start at the jacks are curved to become horizontal such that a camera can be placed under the insole. From this chamber, air entering into the bottom of the channel is distributed. Upstream, the aerator has a small ramp that facilitates the task of the aerator. In Figure 1 a picture of the H P Huites model is shown, corresponding to the description given above (scale 1:21). The details of the physical model are presented in the work of Rodal (1996).

As indicated in Wood (1991) in well finished concrete channels (smooth and without irregularities), cavitation damage is not presented if the mean velocity does not exceed 28 m/s. To prevent damage occurring when this limit is exceeded, requires that the concentration of air in the vicinity of the bottom, is not less than 8%. As air/water concentration is usually between 2% and 4% it is necessary to introduce additional air. This is the problem being addressed in this work. It is often considered that the average concentration in the stream is representative. However, the main problem is the need to increase air concentration at the bottom to prevent cavitation damage.

Figure 1- View of the H P Huites physical model.

2.1. Criterion for evaluating the air concentration at the bottom of the spillway

Kramer (2004) presented a methodology to evaluate the concentration profile behavior with aerators. Kramer showed, air output is generated exponentially and depends on the air content upstream, Froude number and chute slope. For high air concentration on relative flat chute for small inflow Froude numbers the maximum detrainment is obtained and vice versa. In this work we have taken the following equations to determine the air behavior at the bottom of the chute.

$$C_b = C_{b,o} \; e^{-\left((7.2)\,0.006^{S_o} + 6.6\right) F_o^{-2.80} X_{90u}^{2}} \qquad (1)$$

where C_b is the bottom air concentration, $C_{b,0}$ is upstream bottom air concentration, S_o is the chute slope, F_0 Froude Number, X_{90u} is a dimensionless flow distance $X_{90u}=x/h_{90u}$, h_{90u} is the uniform mixture flow depth where $C=90\%$ (m), C is the local air concentration by volume. As can be seen the bottom air concentration determination depends amongst other factors upon $C_{b,o}$. Use of a value between 4% and 5% is normally recommended but to measure it in a physical model is preferable.

2.2. Air concentration measuring device

We are working for develop an instrument to get air content on biphasic flow with high velocity, based on impedance probes. Actually it is in process for getting amplified signal in order to tune up air content. To measure the concentration of air in the flow a conductivity/resistivity probe was manufactured by an expert in the area. Air measurements were performed at 5 mm from the bottom of the chute. The device (at present) allows 1000 samples/second to be taken to determine air presence. Figure 2, shows an example of the conductivity/resistivity probe equipment measurement output. The development of this equipment is still in progress. In Figure 3, the position of the measurement device used in the physical model is shown.

The physical model where testing has been made is an spillway with 4.13m high, 11.77m effective length, 2.2 m³/s as a maximum volume that is obtained by 2 pumps. All along the slope there are 2 aerators, the first has been located at 4.69m from crest and the second 8.6 m from same structure, each one with 0.000121 m² total area. A general model view is show in figure 3.

Figure 2 - Air presence at the chute bottom, measured on the physical model.

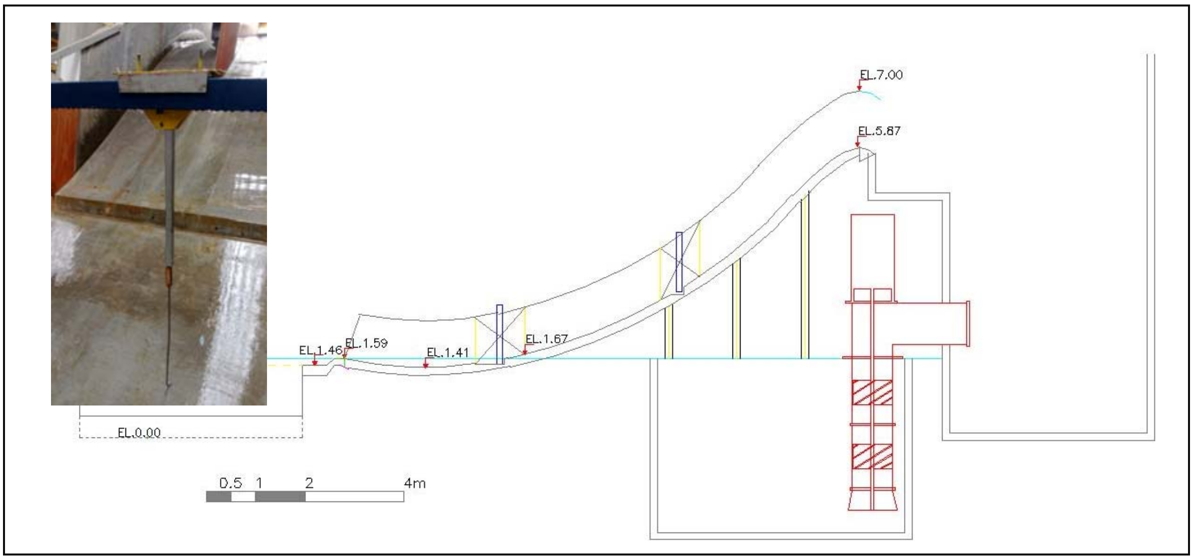

Figure 3 - physical model and Installation of the air probe.

3. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS FOR AIR CONCENTRATION

The cases presented here correspond to the parameters shown in Table No.1, for the prototype and model.

A summary of the results of the measurement and calculation of the air content in the bottom of the chute is presented in Table 2, these data were obtained of Rodal (1996). The calculation was performed for the same measurement sites in the physical model using the equation 1, and de results are presented in the Figure 3.

The main conclusion is that, in general, there is good agreement between the measurements and the calculated values. However, it should be noted that in the last station the difference is consistently substantial and this is very important as it is the zone where one must decide if another aerator should be installed or not.

Table 1 Tests

	Model	**Model**	**Model**	**Prototype**
Discharge (m^3/s)	0.5	1	1.4	1009
Chute width (m)	1.72	1.72	1.72	36.12
velocity	4.3	5.6	6.4	21.8
Froude Number	5.35	5.6	5.71	6.96
Reynolds Number	290 000	580 000	809 000	28 000 000
Weber Number	1731	44 900	70 800	9 080 000
Morton Number	2.5E-11	2.5E-11	2.5E-11	2.5E-11
Depth (m)	0.067	0.103	0.127	1
Cavitation index	8.11	4.84	3.79	0.36

Table 2 Measurements and calculation of air concentrations (%) in the bottom at the physical model chute.

Q = 0.5 m^3/s

Position (X90u)	**0.00**	**4.627**	**19.552**	**43.881**
Physical model (%)	9.0	5.0	2.0	1.0
Computation (%)	-	4.26	0.38	0.075

Q = 1.0 m^3/s

Position (X90u)	**0.00**	**3.01**	**12.72**	**28.54**
Physical model (%)	15.0	8.0	3.0	2.0
Computation (%)	-	9.72	2.40	0.25

Q = 1.4 m^3/s

Position (X90u)	**0.00**	**2.441**	**10.32**	**23.15**
Physical model (%)	15.0	9.0	3.0	2.0
Computation (%)	-	10.73	3.63	0.62

Note. Position is referred to the non-dimensional distance from the jet site impact on the floor.

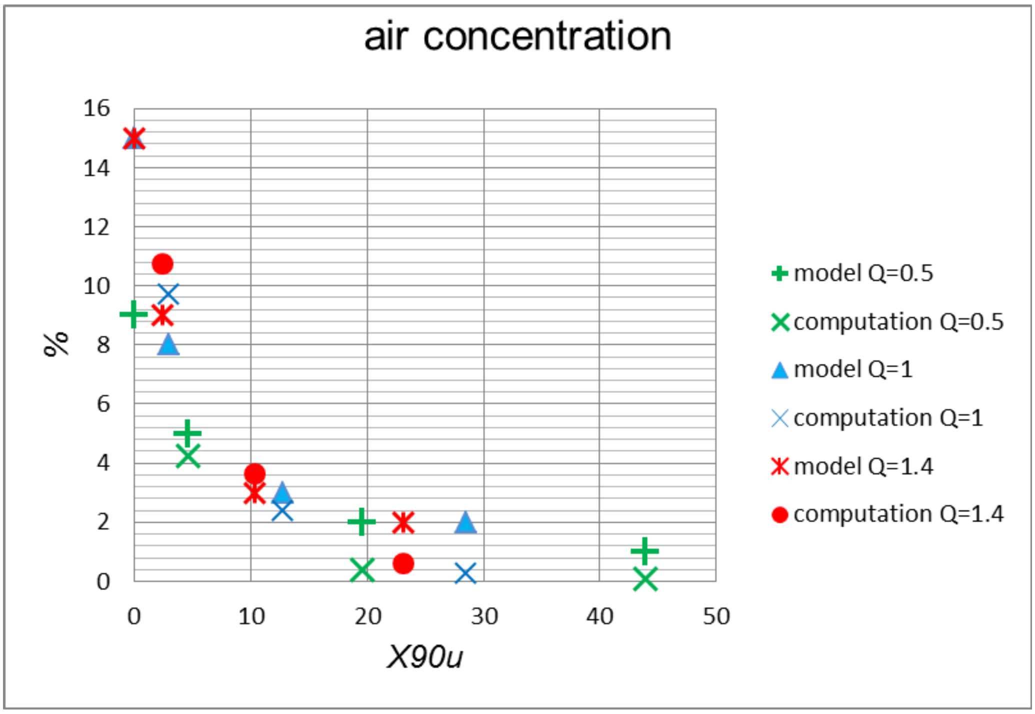

Figure 4. Air concentration for different discharges and locations

4. EXTRAPOLATION OF AIR RESULTS FOR THE BOTTOM OF THE PROTOTYPE CHUTE

From the results in the preceding paragraph, it is clear that the theory employed represents the physical behavior of air with some considerations; however the question remains whether it is valid to extrapolate this for the prototype. Table 3 shows the calculated air concentration values for the bottom of the prototype chute.

Table 3 Concentrations of air (%) computed for prototype

Position (X90u)	**0.00**	**5.517**	**34.888**	**53.322**
Computation (%)	9.0	5.67	1.28	0.11

Q = 1000 m^3/s (0.5 m^3/s at model)

For the prototype data, if the air content at the last two positions is under 1 % it is unacceptable, but considering the model results this does not seem correct. The next step is to find out how long these conditions prevail, as it is well known that cavitation also depends on time exposure. This can be done by taking measurements and comparing results from the prototype with the numerical results produced by the model, especially considering the amount and fluctuation of the air content.

The physical modeling of air-water two-phase flows in hydraulic engineering would require the Froude number F, Weber number W and Reynolds number Re to be identical in the prototype and laboratory, however, this is physically impossible (Pfister & Chanson, 2013). A re-arrangement of the dimensionless numbers results in the introduction of the Morton number M. Combining these considerations together with published limits to minimize scale effects in terms of air concentration, the outcome indicated that values of $W^{0.5} > 140$ and $Re > 2{\times}10^5$ to $3{\times}10^5$ should be respected to avoid relevant scale effects in terms of air concentrations within $5 \le Fr \le 15$. As in this case the dimensionless numbers are within desirable limits, it is considered that the results are trustworthy and suitable for the extrapolation of the prototype.

5. CONCLUSION

In this work a calculation methodology was applied and measurements of air content were performed at the invert of the spillway physical model of the PH Huites dam. The findings suggest that it is possible to extrapolate results to a prototype, using a combination of a theoretical approach and typical model theory. The fluctuation of air content at the bottom of the chute is highly important, The variations with time have direct impact on cavitation damage. In studies to date, the fluctuation of the air content at the bottom of the chute has not been given enough importance, although it seems to be the most important location where knowledge of the air content is indispensable to avoid cavitation. It is proposed to employ the methodology of this work for air measurements on the prototype and verify the theoretical approach. Finally, the present study emphasizes the need for full-scale prototype data of two-phase air-water flows typically observed in prototype hydraulic structures. Differences between results obtained with Kramer equation and measurements were probably caused by some measurement quality results. It is necessary to go deeper into the study of these phenomena in order to decrease spillway impacts, because the air content at the bottom chute is the most important knowledge for the spillway protection. An accurate instrumentation will impact in a refinement of the phenomena research.

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