Conference Paper, Published Version

**Bhosekar, V. V.; Jothiprakash, V.; Deolalikar, P. B.; Chavan, A. R.**

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*Proceedings of ninth International Conference on Hydro-Science and Engineering (ICHE 2010), IIT Madras, Chennai, India.*
*2 - 5 August 2010*

# NUMERICAL MODELLING OF FLOW OVER AERATOR OF ORIFICE SPILLWAY

Mrs. V. V. Bhosekar [1], V. Jothiprakash[2], P.B.Deolalikar[3], A. R. Chavan[4]

***Abstract:*** *For reservoirs located in the mountainous regions of Himalayas large size (8-15 m (W)) X (10-23 m (H)) submerged orifice spillways as near the river bed as possible are designed to perform the dual function of flood disposal and flushing of sediment. Negative pressures occur on the spillway crest profile making the spillway profile susceptible to cavitation damage as the cavitation index falls below the critical cavitation index of 0.2. Provision of aerator helps to keep the spillway profile free from cavitation damage. Considerable research has been carried out by various researchers worldwide on physical models in development of design of aerators of overflow spillways. However, no work has been reported for the design of aerator for orifice spillways. Physical model studies are expensive and time consuming for studying number of alternatives as compared to numerical models. In view of this background, both physical and numerical model studies have been taken up for design of offset aerator for a typical orifice spillway in the present study. The flow on the orifice spillway has been modeled using the Computational Fluid Dynamics (CFD) software FLUENT for gated and ungated operation of the spillway without aerator using a 2D model to establish the necessity of aerator and for gated operation of spillway at 50% gate opening with aerator using 3 D model. The results in respect of pressures over the crest profile, cavity sub pressures, air discharge and length of jet obtained from the numerical model are compared with the results of the physical model studies. It is found that the resulted aerator parameters are similar to those resulted from physical model study.*

***Keywords***: *Orifice spillway; Aerator; physical modeling; numerical modeling*

## INTRODUCTION

Large hydro power potential is available in the north and north eastern part of India due to perennial rivers and mount ainous region. Out of an estimated total hydroelectric potential of 84,044 MW; 65,623 MW lies in these regions. Narrow gorges, fragile geology , high level of seismicity and steep bed slopes are a few characteristics of the Himalayan terrain. Of major concern is the siltation in front of the power intakes and the consequent damage to the

1. Chief Research Officer , Central Water & Power Research Station, Pune -411024, and Research Scholar, Department of Civil Engineering, IIT Bombay, Mumbai- 400 076, vvbhosekar@yahoo.co.in , (Member, ISH)
2. Associate Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai- 400 076, vprakash@iitb.ac.in, (Fellow, ISH)
3. Former Joint Director, Central Water & Power Research Stati on, Pune -411 024, pbdeolalikar@yahoo.com, (Fellow, ISH)
4. Joint Director, Central Water & Power Research Station, Pune - 411 024,ashokc_2003@yahoo.co.in, (Member, ISH)

equipments or the generating units of the hydropower plants. The highly abrasive silt particles cause cavitation followed by erosion of the under water parts of the water conductor system. Many incidents of damages caused by sediments have been reported from projects like Baira-Siul, Maneri Bhali, Chilla, Salal etc. Removal of sediment in the vicinity of power intakes becomes essential to overcome the problems caused due to sediments. The obvious solution is to provide a facility in the dam to dispose the deposited sediments at regular intervals. Orifice spillways are increasingly being used for flushing of sediment as well as disposal of flood . The hydraulics of orifice spillway changes with the varying reservoir levels. The flow is free flow for reservoir water levels below the top of the roof of the sluice. For higher water levels the flow is orifice flow. Studies conducted for more than 20 projects at Central Water and Power research Station (CWPRS), Pune, India; indicated that the spillway glacis is susceptible to cavitation damage when the head over the spillway is more than 50 m. Negative pressures are observed over the crest profile and the cavitation index drops below critical cavitaion index of 0.2. Aeration is the most effective method to mitigate cavitation damage. The width of spillway is restricted due to narrow gorge in mountainous regions leading to high discharge intensity and depth. Thus, natural aeration of the flow near spillway surface is ruled out. Therefore, provision of aerator becomes necessary.

Review of literature indicated that considerable experimental work in laboratory and field has been done for evolving design of aerators for the overflow spillways. Researchers (Falvey (1990), Rutschmann and Hager (1990), Volkart and Rutschmann (1991), Pinto and Neidert (1982), Pinto (1989) and Kokpinar and Mustafa (2002 )) have attempted to develop empirical equations for jet length, sub-atmospheric pressure under the nappe and quantity of air entrainment through the lower nappe of the jet using physical hydraulic models. However, no work has been reported for the design of aerator for the orifice spillway (Bhosekar et. al. 2009). Hydraulic models are expensive, time consuming and there are many difficulties associated with scale effects. Nowadays, with the use of high performance computers and more efficient computational fluid dynamics software, it is possible to investigate the hydraulic performance of spillway numerically. A literature search on numerical modeling of spillways has revealed that it began as an investigative tool at research institutions (Kjellesvig 1996, Savage and Johnson 2001), and was gradually being accepted by the hydraulic/dam engineering community (Higgs 1997, Yang and Johnson 1998, Cederstrom et al. 2000, Teklemariam et al 2002, Gessler 2005). Modeling of flow over aerator would be further step.

In view of this background, both physical and numerical model studies were taken up for design of offset aerator for a typical orifice spillway located 60 m below the maximum reservoir water level. This paper presents the numerical model studies conducted for simulating the flow over an orifice spillway with and without aerator and validation of the model using the data available from the physical model studies conducted at CWPRS for a typical orifice spillway.

## EXPERIMENTAL SET UP

### Physical model

Model studies were conducted for design of offset aerator for an orifice spillway located 60 m below the maximum reservoir water level. The equation of the crest profile is $X^2 = 220 \ Y$. The design discharge is 35000 $m^3$/s corresponding to a discharge intensity of 330 $m^3$/s/m and velocity of about 30 m/s. Experiments were conducted on 1: 90 scale comprehensive model to assess the pressures on the crest profile without aerator. Negative pressures were prevailing on the crest profile for the entire range of discharges for the gated operation of the spillway. The cavitation index was below 0.2 indicating susceptibility of the crest profile for cavitation damage (Bhosekar et al (2008)). Several alternative designs of crest profile were studied however the magnitude of negative pressures on the crest profile did not reduce. Since the spillway length was only 88 m from the crest, limiting the aerator jet length up to the start of the ski jump bucket was necessary.

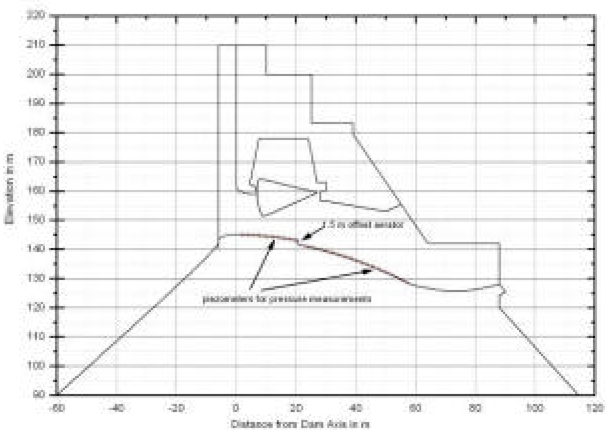


**Fig.1. Cross section of spillway with aerator**

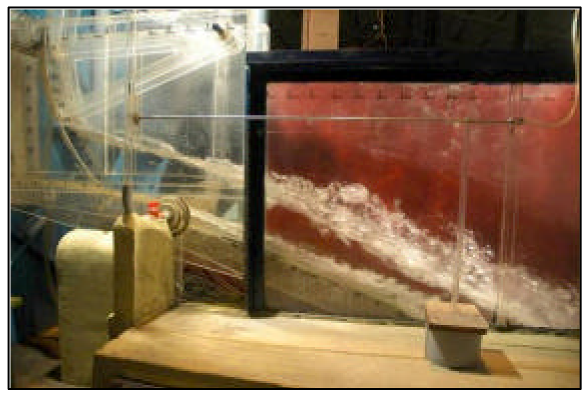

**Fig. 2. View of the spillway aerator model**

Figures 1 and 2 show cross section of the spillway with aerator and view of the running model. The model of one third span of the spillway to a scale of 1:25 was constructed in a 14 cm wide glass sided flume connected to a 3 m (L) X 3 m (W) X 3.8 m (H) steel tank.

## NUMERICAL MODEL

Computational Fluid Dynamics ( CFD) can be a very useful tool to minimize the efforts and expenses of physical modeling as it consumes less time and gives accurate results once the CFD code is validated. CFD software FLUENT was used for the numerical modeling. A licensed copy of the soft ware is available with Indian Institute of Technology Bombay, Mumbai. The equation of conservation of mass or continuity equation and the Navier -Stocks equations form the basis of the continuum model of the fluid flow. The equation for conservation of mass, or continuity equation for incompressible as well as compressible flows, can be written as follows:

$$\frac{\partial \rho}{\partial t} + \ . \rho v = S_m \tag{1}$$

The source $S_m$ is the mass added to the continuous phase from the dispersed second phase, $\rho$ is the fluid density and $v$ is the fluid velocity. Conservation of momentum in an inertial (non-accelerating) reference frame is described

$$\frac{\partial}{\partial t}(\rho v) + \nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot (\tau) + \rho g + F \tag{2}$$

where $p$ is the static pressure, $\tau$ is the stress tensor (described below), and $\rho g$ and $F$ are the gravitational body force and external body forces (e.g., that arise from interaction with the dispersed phase) The stress tensor $\tau$ is given by

$$\tau = \mu\left[\left(\nabla v + \nabla v^{T}\right) - \frac{2}{3}\nabla \cdot v I\right] \tag{3}$$

where $\mu$ is the molecular viscosity, $I$ is the unit tensor, and the second term on the right hand side is the effect of volume dilation. Volume of fluids (VOF) method was used as it relies on the fact that two or more fluids (or phases) are not interpenetrating. Realizable k-e viscous model with Eulerian multiphase solver was used. In the present study two dimensional grid was used for simulating the flow on the spillway without aerator, whereas a three dimensional geometry for simulating flow with aerator. A length of abou t 54 m of the reservoir was reproduced on the upstream and 250 m of the downstream portion was reproduced for the formation of the ski jump jet. GAMBIT program was used to create the geometry and the grid. The upstream end of the reservoir was treated as p ressure inlet with open channel flow option to maintain a reservoir water level. The boundary of the spillway profile, piers and breast wall were treated as wall. Gate opening of 25 and 50 % for the 2D simulation and 50% for the 3 D simulation were studied . The downstream boundary was treated as pressure out let. Figure 3 shows the grid of the orifice spillway domain with and without aerator.

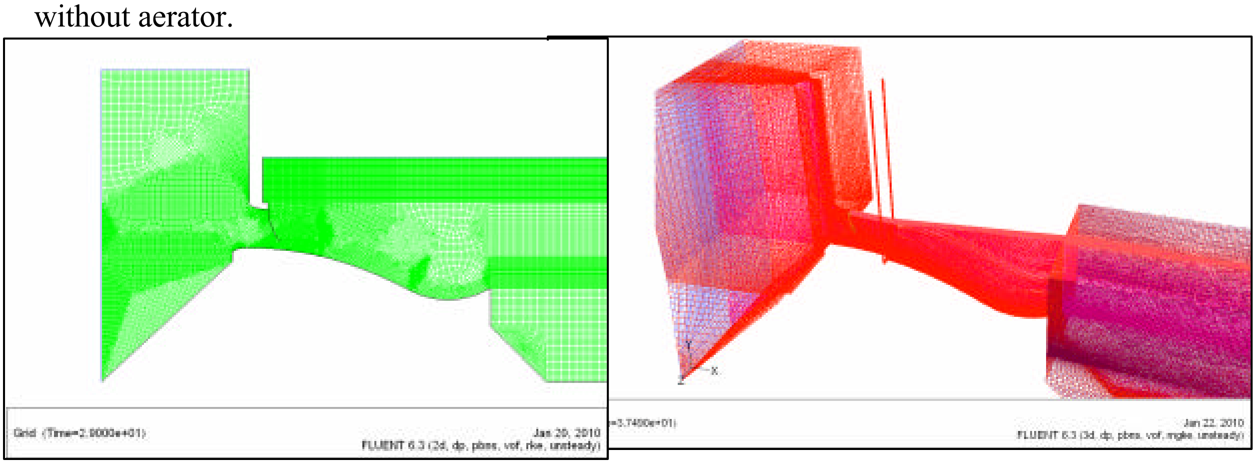


**Fig. 3. Two dimensional and 3-dimensional grid system created for orifice spillway**

## EXPERIMENTAL PROGRAM

The orifice spillway would be operated for ungated condition for flushing the sediment from the reservoir with low reservoir water levels. However, for flood disposal it would be operated with gated condition. The gate openings would vary from 10 to 80 % of the orifice opening. Studies (Table 1) were conducted on both hydraulic and numerical model of the spillway without aerator for the following conditions:

**Table 1. Conditions for experimental program**

| Sr. No. | Reservoir water level (m) | Operating condition of spillway |
|---|---|---|
| 1 | 159.2 | Ungated |
| 2 | 167.2 | Ungated |
| 3 | 180.2 | Ungated |
| 4 | 199.8 | Ungated |
| 5 | 205 | Ungated |
| 6 | 205 | Gated Operation<br>Opening: 7.3 m for passing 50% of design discharge |
| 7 | 205 | Gated Operation<br>Opening: 3.6 m for passing 25% of design discharge |

For validation simulations were made for two reservoir water levels viz. FRL El 205 m and MDDL El. 181 m for a single gate opening of 50% (7. 3 m) on a 3D model with aerator.

## RESULTS AND DISCUSSIONS

The hydraulic parameters such as discharge, pressure profile, jet length etc resulted from numerical and physical model without aerators are compared.

### Discharging capacity of spillway

Discharging capacity of spillway is the most important aspect as it has direct impact on the safety of the structure. Assessment of coefficient of discharge analytically is very difficult for a designer as it depends on various factors such as the approach flow conditions, the upstream depth of the spillway crest from the river bed, size and shape of the orifice opening, its location with respect to the maximum reservoir water level, inlet transition shapes of the orifice opening etc. Therefore, hydraulic model studies is the only means to assess it. Hydraulic model studies were conducted on 1:90 scale model for assessing the discharging capacity, pressures on the spillway crest profile and flow conditions. Similar studies were conducted on the 2D numerical model for various reservoir water levels and the results are summarizes in the following Table 2.

As seen from the table, the difference in discharging capacity of the spillway between the CFD and hydraulic model is within 5% for the higher water levels for both gated and ungated operation of the spillway. However, this difference increased as the water levels are reduced. This difference is marginal and due to the fact that approach flow conditions due to 800 m

**Table 2. Comparison of discharges of physical and 2D numerical model**

| Sr. No. | RWL m | Q physical model $m^3/s$ | Q numerical model $m^3/s$ | % difference |
|---|---|---|---|---|
| 1 | 159.2 Ungated | 84.5 | 90.7 | 7.34 |
| 2 | 167.2 Ungated | 169.1 | 180 | 6.45 |
| 3 | 180.2 Ungated | 253.62 | 255.1 | 5.83 |
| 4 | 199.8 Ungated | 338.16 | 339.5 | 3.96 |
| 5 | 205 Ungated | 358.45 | 359.7 | 3.48 |
| 6 | 205 GO 7.3 m | 169.08 | 174 | 2.9 |
| 7 | 205 GO 3.6 m | 84.54 | 88.5 | 4.68 |

long river portion and interaction of the flow passing throug h 9 spans was not reproduced in the numerical model. Overall these results are in good agreement with typical CFD results found in literature for overflow spillway (Chanel and Doering (2007)) and are well within hydraulic model accuracy of 5%as stated by G essler (2005).

**Pressures on the spillway profile**

With the satisfactory comparison of discharging capacity a further comparison of pressure profiles was obtained which is more important for assessing the cavitation potential of the flow. Figures 4 and 5 show the pressure profiles for the condition of RWL El.180.2 m with ungated operation of spillway and FRL El.205 m with 7.3 m gate opening passing a discharge of 17500 $m^3/s$ (5 0 % of design discharge). It can be seen that the pressures are positive through out the spillway profile for the ungated operation. However, for the partial gate operation of the spillway at high reservoir water level the pressures are negative downstream of the gate up to the start of the bucket. Thus, this portion is susceptible to cavitation damage. Results of both hydraulic and numerical modeling are superimposed. The general trend and the magnitude are in good agreement with the observed data on the hydraulic model. Some variations are seen which are probably due to local mesh ge ometry. The variations for the condition of FRL El. 205 m Gate opening 7.3 m is more than for the condition of RWL El. 180.2 m ungated due to several factors such as increase in turbulence level with increase in discharge intensity and head, interaction of flow downstream of piers and formation of cross waves and rooster tails in hydraulic model. Figures 6 and 7 show the Cavitation index curves for the condition of RWL El.180.2 m ungated operation of spillway and FRL 205 m with 7.3 m gate opening passing a discharge of 17500 $m^3/s$ (50% of design discharge). The curves clearly indicate that the cavitation index is above 0.2 for ungated operation of the spillway and below 0.2 for the gated operation. The flow simulation on the numerical model is shown in Figure 8. The general trend of flow and the formation of ski jump is well simulated.

Another striking feature is the absence of air along the spillway surface without aerator which could be clearly seen in the inset . It is difficult to observe this in the hydrau lic model as the upper nappe aeration covers it and it can only be speculated. Thus, necessity of the aeration groove is confirmed.

**3D simulations for spillway with aerator**

Design of aerator for the orifice spillway is a grey area where no literature is reported so far except a few scanty references (Zhou 2005). No systematic guidelines are available even for preliminary design. Design of aerator is more complex due to change of regime from free flow to orifice flow , wide variation of upstream water leve ls, Froude number 6 for the entire range of discharges due to high discharge intensity . For the present case design of aerator was very sensitive to the ramp/step height as the spillway length is only 88 m. A 1.5 m offset aerator was designed as the spillway slope is very flat i.e. about 10 degrees. Two air vents of diameter 0.625 m were provided downstream of offset. A 3 D simulation was performed for a typical case of partial gate operation of spillway at 50% gate opening i.e. 7.3 m . Two reservoir water levels viz. FRL El. 205 m and MDDL El181 m were simulated for validation of the model with the data obtained from physical model. Table 3 shows the comparison of results for various parameters.

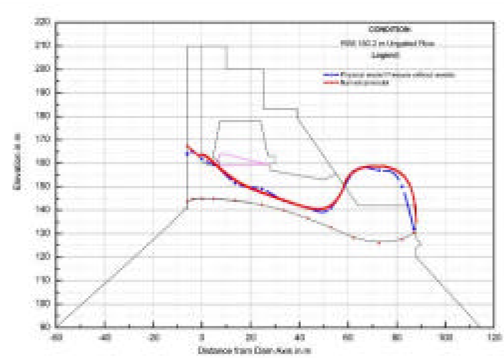

**Fig. 4.Pressure profile for RWL El.180.2 m Ungated operation of spillway**

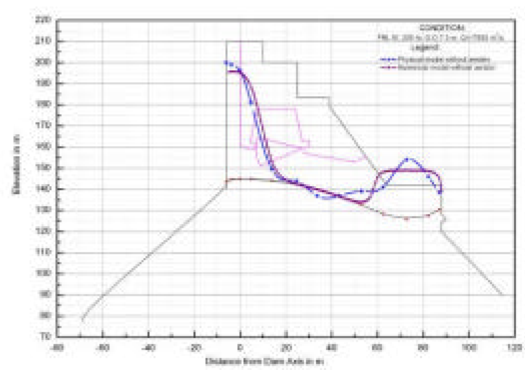

**Fig. 5. Pressure profile for FRL El.205 m GO 7.3 m**

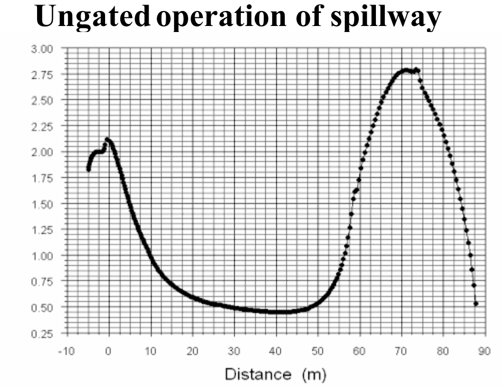


**Fig. 6 Cavitation index profile for RWL 180.2 m Ungated operation of spillway**

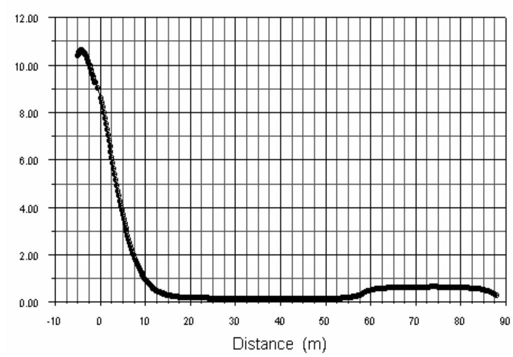


**Fig. 7.Cavitation index profile for FRL EL.205 m GO 7.3 m**

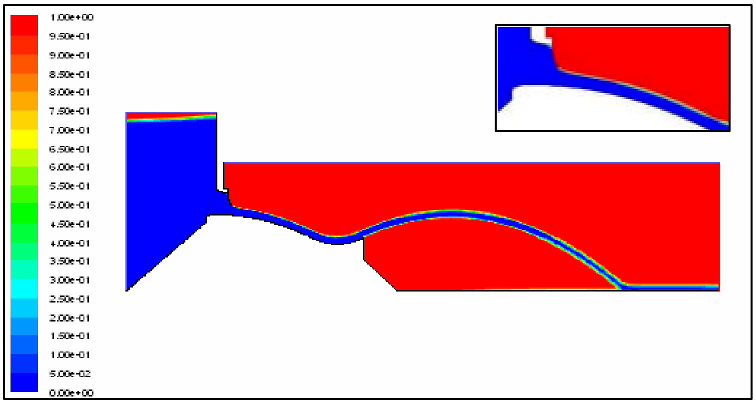


**Fig. 8 Flow simulations over spillway without aerator**

**Table 3.Comparison of results of physical and 3-D numerical model**

| **Sr. No.** | **Hydraulic parameter** | **Physical model** | | **Numerical model** | |
|---|---|---|---|---|---|
| | | **FRL EL. 205 m GO 50%** | **MDDL El. 181 m GO 50%** | **FRL EL. 205 m GO 50%** | **MDDL El. 181 m GO 50%** |
| 1. | $Q_{water}$ $m^3/s$ through spillway | 545 | 390.3 | 561 | 419.94 |
| 2. | $Q_{air}$ $m^3/s$ through air vent | 37.4 | 19.77 | 35.5 | 17.36 |
| 3. | Jet length in m | 22.5 | 18.3 | 28.3 | 17.93 |
| 4. | Cavity sub pressure ‘m’ of water | -0.53 | -0.02 | -0.77 | -0.08 |

It can be seen from the table that the various parameters like water discharge through the spillway gate, air discharge entrained through the air vents, the jet length and cavity sub pressures calculated by the numerical simulation are in good agreement with the hydraulic model data for both the reservoir water levels. Figure 9 shows the flow simulation over the spillway aerator and a closer view of the same respectively. It may be mentioned here that no air was seen at the spillway surface without aerator and entrainment of air with the aerator is clearly seen in Figure 9.

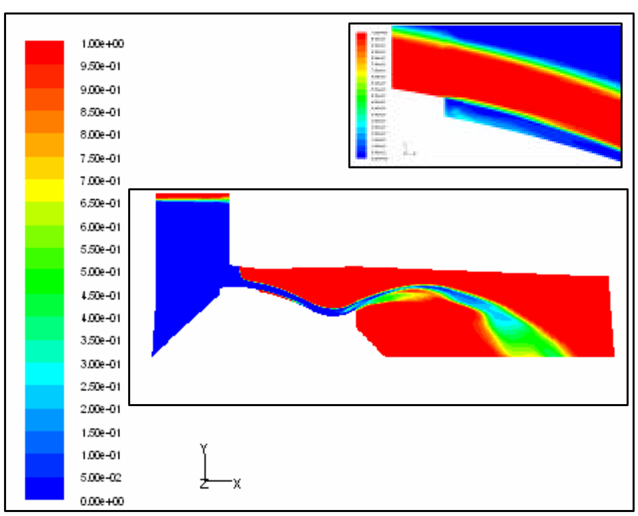


**Fig. 9 Flow simulations over spillway aerator and closer view near the aerator**

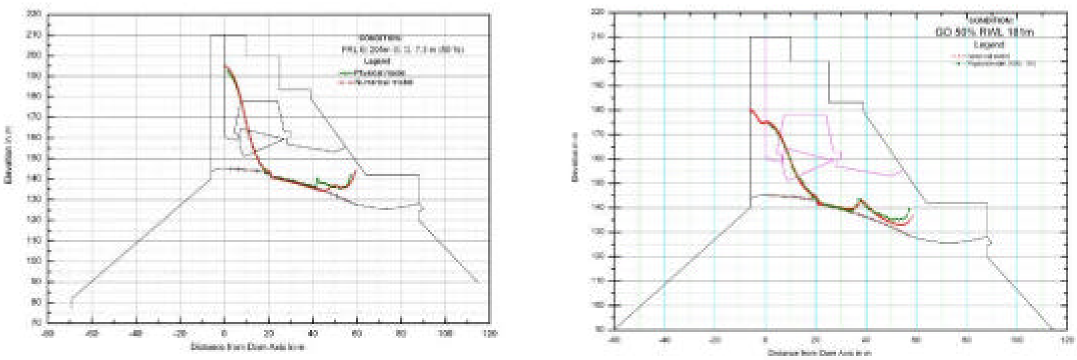

**Fig. 10 Comparison of Pressure profiles of physical and numerical model for RWL El.205 m and El. 181 m, G. O. 50%**

Figure 10 shows the pressure profiles of hydraulic and numerical model simulation superimposed for the condition of FRL El. 205 m and El. 181 m. The agreement between the two results is excellent. Thus the 3D numerical model has been fully validated and can be used for the parametric studies with variation in gate openings, air vent diameters and height of offset.

## CONCLUSIONS

Design of aerator for the orifice spillway is complex, scanty literature has been reported so far and no guidelines are available. Physical hydraulic models have been used so far by the researchers for the design of aerators of overflow spillway. Attempts had been made in past to simulate the flow over spillway using numerical models with several limitations. With the advent of high performance computing facilities it is now possible to model the flow over spillway numerically. Numerical modeling of flow over orifice spillway has been done using the CFD software FLUENT and compared with the data of physical model. The results are in good agreement. Flow over the spillway aerator has been simulated in a 3D numerical model. Results in respect of water discharge through the spillway, air discharge entrained through the air vents, jet length and cavity sub pressures compared well with the data of physical model. Thus, the present studies revealed that numerical modeling of spillway aerators is a new tool complementing the physical hydraulic model studies being used traditionally so far.

## ACKNOWLEDGEMENT

The first and last authors are grateful to Dr. I. D. Gupta, Director-in-charge, CWPRS for the consent to publish this paper.

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