NUMERICAL SIMULATIONS OF AIR ENTRAINING CHARACTERISTICS OVER HIGH HEAD CHUTE SPILLWAY AERATOR

PRAJAKTA P. GADGE
Scientist B, Central water and power research station, Pune, India

M. R. BHAJANTRI,
Scientist E, Central water and power research station, Pune, India

V. V. BHOSEKAR
Director, Central water and power research station, Pune, India

ABSTRACT

Aeration on the spillway surface is one of the most reliable and economic measure used at present world over for mitigating cavitation damage. Aerators have been installed on spillways worldwide following their success at various dams. The design of aeration system for high head spillway is a challenging task. Literature reveals that the physical model studies provide a good first-hand information and insight in the hydrodynamic characteristics of aerator with the help of sophisticated instrumentation facility. Due to recent advances in computer technology, Computational Fluid Dynamic (CFD) technique has been used widely for modeling the air-water characteristics of spillway flow. The CFD software Flow 3D was used for simulating the flow over spillway aerator. Aeration system is provided in the form of step, ramp and two air vents on either side of spillway span. Studies were carried out to assess the performance of spillway in terms of pressures, water surface profile, air entrainment coefficient, jet length and air concentration throughout the length of long chute. Air entraining characteristics were simulated well in numerical model that helped in determining the efficiency of first aerator downstream of gate seat. Need of second aerator was identified with the help of pressure distribution and air concentration along the chute surface computed in numerical model.

1. INTRODUCTION

Spillway is an important structure of the dam. They are usually designed to discharge large floods with a considerable head. High-velocity flow often occurs on spillways, particularly for high dams, which can cause severe cavitation damage to the hydraulic structures. Some measures, such as optimizing the structure body, smoothening the concrete surface, and applying anti-cavitation materials are commonly implemented to prevent the cavitation, but the potential damage cannot be completely eliminated. Aeration is the most effective method to mitigate cavitation damage. Natural aeration of the flow on the spillway may not be sufficient for this purpose. Therefore, aerators are provided to supply the air underneath the flow along the spillway surface. The design of an aerator system for high head chute spillway is of a complex manner due to the many parameters such as the channel slope, ramp angle, Froude number, flow velocity etc.

Physical scale modeling has been used in the design and investigation of design of aerator for over 100 years in spite of various scale effects associated with them. Advances in high-performance computations and the development of computational fluid dynamics (CFD) general purpose software have made it possible to investigate the physical reliability of simulations of complex flows measured in reduced-scale models and prototype spillways. Literature search on numerical modelling of spillways has revealed that it began as an investigative tool at research institutions (Kjellesvig 1996, Savage & Johnson 2001) and was gradually being accepted by hydraulic/dam engineering community (Cederstrom et al. 2000, Channel & Doering2007, Gessler 2005, Higgs 1997, Teklemariam et al. 2002, Yang and Johannson 1998).

The design of aerator on overflow spillways has been studied so far on physical models and numerical models have been sparsely used due to complex two-phase air-water flow. Very few studies Ozturk et al. (2008), Ozturk & Aydin (2009) and Aydin & Ozturk (2009) have proved that the availability of high-performance computing machines and efficient fluid dynamic software has made it possible to study the hydraulics of aerator numerically. Hydraulic characteristics of overflow spillway are entirely different than orifice spillway. Jothiprakash et al. (2014) studied the flow characteristics of orifice spillway aerator in the form of air concentration, pressure and velocity profiles in the vicinity of aerator using numerical model studies. Bhosekar et al. (2012) developed equations for jet length and air entrainment coefficient for orifice spillway aerator.

The present study aims at investigating the air entraining characteristics on high head chute aerator for deep-seated orifice spillway using both physical and numerical models. Physical model results were used for validation of numerical model. Studies were carried out for spillway operated at gated conditions i.e. 10% and 50% of orifice opening for design head 60 m. The results in terms of pressures, water surface profile, jet length, cavity pressure and air concentration profiles across the depth and along the bed of spillway profile are discussed in present paper. Based on the results, efficacy of first aerator along long chute designed for high head was studied and need of second aerator was identified.

2. AIR ENTRAINMENT MECHANISM OVER SPILLWAY AERATORS

The mechanism of an aeration device has been described by Falvey & Ervine (1988), Bruschin (1987), Pinto et al. (1982), Volkart & Rutschmann (1986) and Chanson (1989). Basically, aeration develops through four zones in the vicinity of an aerator as shown in Figure 1. These are: the approach zone, transition zone, aeration zone, and de-aeration zone.

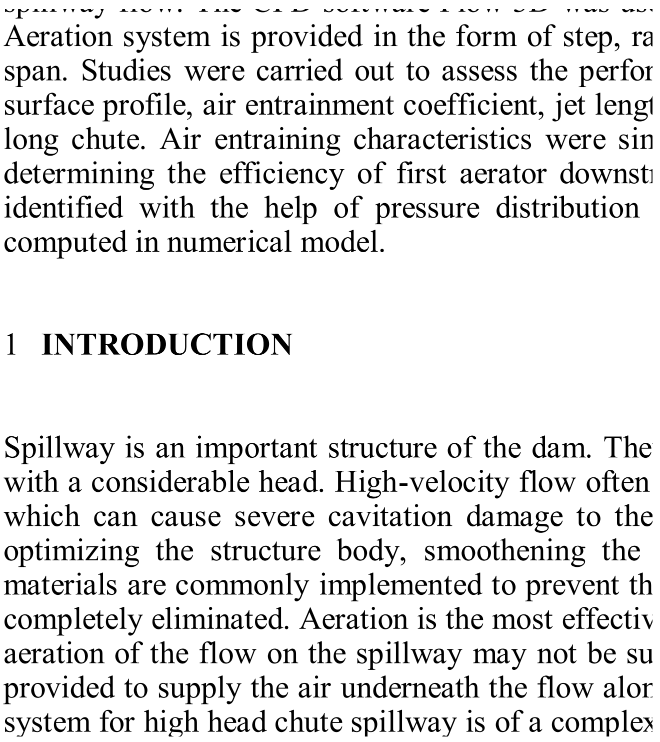

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Fig. 1 : Air entraining mechanism over spillway aerator (Volkart and Rutschmann, 1984)

In the approach and transition zones, the flow is in contact with the boundary, so natural aeration in the top layers of the flow may or may not take place. In the aeration zone, the top and bottom layers of the flow are detached from the boundary in the form of a high velocity jet. Local pressures in the bottom layers suddenly drop from a high value at the end of the transition zone to nearly atmospheric values at the beginning of the aeration zone. The zone of reattachment is a mixing region and a region in which the pressure gradient is greater than hydrostatic. The high pressure gradient in this region causes rapid changes in air distribution. In the de-aeration zone, the pressure gradient returns to hydrostatic and air concentration in the vicinity of the chute bottom diminishes as air bubbles rise to the flow surface. When this redistribution has lowered the concentration to an unacceptable level, another aerator device is required.

3. PHYSICAL MODEL

Physical model studies were conducted in 15 cm wide and 7 m long flume. The spillway chute is designed for 60 m head for height of orifice opening 14m. Free surface flows are usually modeled with the Froude similitude, correctly representing the ratio of gravitational and inertia forces. However, the modeling of free-surface aeration is impossible with geometrically similar models because the internal flow turbulence, represented by the Reynolds number, is underestimated, while surface tension, represented by the Weber number, is overestimated. Considering this criterion, scale of physical model for the present problem was selected as 1:25 and one third span of spillway was reproduced. The values of Reynolds number (Re) and Weber number (We) ($Re = 6.72\times106$ and $We = 841$) in the model have been observed in the relevant limits as discussed by various researchers (Pan & Shao 1984, Pfister & Hager 2010) for minimizing the scale effects.

The aerator is provided at 27 m downstream of dam axis. The aerator geometry consists of 2.5 m offset with ramp of height 0.56 m and angle 40. Cross section of spillway with details of aerator is shown in Figure 2. Two air vents of size 0.8 m were provided on either side of spillway spans to introduce air into spillway flows. Orifice spillway is generally operated at gated conditions. Hence, present study was carried out for head over the crest of 60 m with gated operation of spillway. Gate opening is considered as 10% of total height of orifice. The performance of aerator was evaluated in respect of pressure and water surface profiles over spillway profile, flow conditions in the vicinity of the aerator, jet lengths and cavity pressures. However, air concentration along spillway surface could not be measured on the physical model due to lack of instrumentation facility. Hence, numerical model studies were carried out to determine air concentration profiles along the chute and across the depth of spillway. Results from physical model were considered for validation of numerical model.

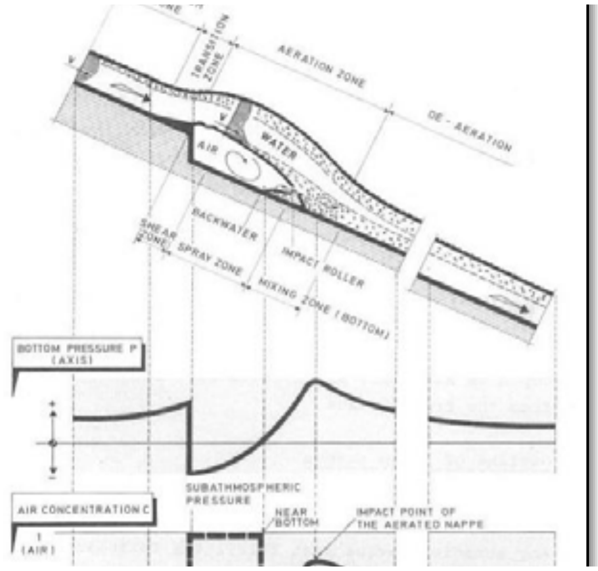


Fig. 2 : Cross section of spillway and details of aeration system.

4. NUMERICAL MODEL

The computational fluid dynamic (CFD) software, Flow-3D was used to simulate the flow over high head chute aerator for the geometry same as studied in physical model. Simulations were carried out for design head 60 m and gate openings 10% and 50% of total height of orifice.

4.1 CFD software

CFD software, Flow 3D numerically solves the Navier–Stokes equation by finite volume method and capable of solving a wide range of fluid flow problems. It allows either one or two fluid flow, with or without a free surface, and a multitude of available physics options to suit the specific application. It enables highly accurate simulations of free-surface flows using TruVOF, the original and true form of the Volume-of-Fluid technique. Various meshing and geometry options are available including multi-block grids and the ability to draw simple objects in the software or import different forms of more complex geometry or topographic files. A large selection of boundary conditions is also available to properly model each specific application. Simulation of highly turbulent flow over the spillway structure is very difficult task. The turbulence models such as RNG k-ε, k-ω and large eddy are available in the FLOW 3D software.

4.2 Model set up

In the present problem, 3-D model geometry was reproduced in Design software ‘AutoCAD 2016’ same as studied in the physical model. The geometry of the model consisted of an upstream tank (reservoir) and spillway channel with aerators and two air shafts on either side of spillway span. Once the geometry was prepared in AutoCAD software, it was then exported in CFD software ‘FLOW 3D’.Mesh generation was required to be assessed carefully. Structured hexahedral mesh with the mesh count of about 25 Lakh was generated throughout the domain. The fine grid was used throughout the length of the spillway to reproduce the air concentration accurately. Coarser mesh was generated in the upstream tank and downstream of spillway which was an area of less interest.

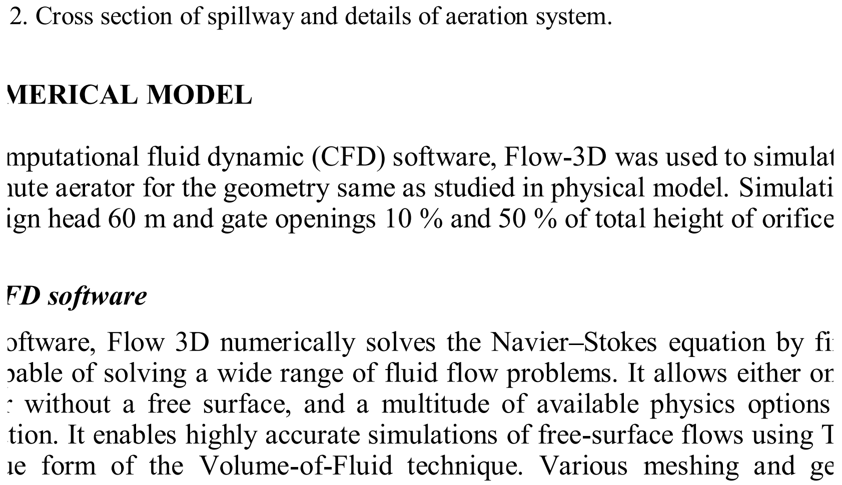
The boundary conditions were selected carefully, since it can have a significant impact on the solution. The main boundary conditions in the discretized equations of the finite volume method are inlet, outlet, wall, prescribed pressure, symmetry etc. The inlet of the domain was defined as a “specified pressure” boundary condition specifying the head over the crest of 60 m. Side and bottom of the domain was specified with the wall boundary condition and inter-connecting faces of the mesh bocks were defined as symmetry boundary conditions. The top faces of the mesh blocks of the domain were specified as “specified pressure” boundary condition with fluid fraction ‘0’ for maintaining atmospheric condition. Outlet of the domain was specified as “specified pressure” boundary condition.

RNG k-ε was used to simulate turbulent flows. Air entrainment model was used to compute volume fraction of entrained air over spillway flows. The simulations were run on desktop PC with Intel Xeon CPU @ 2.4 GHz, 12 GB RAM and 64 bit operating system. Simulations were run for 40 seconds to reach the convergence criteria. Once the solution was converged, data was extracted to study the air entraining characteristics of spillway aerator.

4.3 Validation of Numerical Model

Validation is the primary step for building and quantifying the confidence between modeling and simulation. It is the assessment of the accuracy of a computational simulation by comparison with experimental data. Validation of numerical model is very much essential for making it a complementary tool for design. In the present study, numerical model was validated in terms of pressures and water surface profile by comparing the results with physical model for 10% gated operation of spillway. Figure 3 shows the comparison of physical and numerical model in respect of pressures and water surface profile.

The trend and the values of pressures and water surface profile obtained in physical model are found closer to the values computed in numerical model. However, the results may be improved by refining the mesh over the complete spillway profile.



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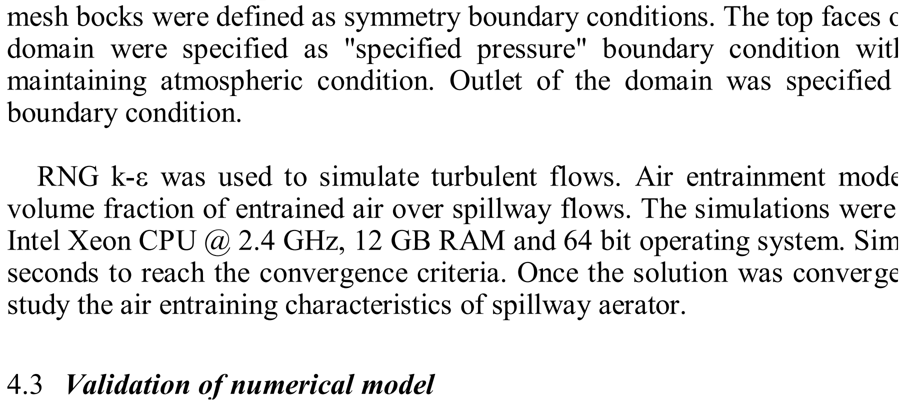
5 RESULTS

Further studies were carried out on numerical model to simulate air entrainment characteristics for 10% and 50% gated operation of spillway. Results obtained from the study are discussed in following subsections.

5.1 Pressures on spillway profile

Pressure profiles were plotted to study the pressure field throughout the length of spillway and in the vicinity of aerator. The pressures were high near the crest of the spillway and dropped rapidly as the flow accelerate downstream of dam axis. Pressure further dropped in the downstream of the offset and increased after the impact of jet. Figure 4 shows pressure distribution along spillway surface for 10% and 50% gate openings.



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4.3 ***Validation of numerical model***

Fig. 4 : Comparison of pressures and water surface profiles between physical and numerical model.

The pressure underneath the jet in the vicinity of aerator was calculated by averaging the readings of number of pressure points below the jet. The average cavity pressure for 10% and 50% gate opening was observed as 0.02 m and 0.17 m respectively. However, pressures were found to be positive throughout the length of spillway after reattachment of jet downstream of aerator.

5.2 Jet length

The length of trajectory is an important aspect for assessing the performance of aerator. The jet length was determined by subtracting the distance of point of impact from the distance of the offset from dam axis. The extent of cavity below the lower nappe of water downstream of aerator was determined by locating point of impact from pressure profile, water profile and visually observing the flow condition. The jet lengths for 10% and 50% gate opening were observed as 34 m (Chainage 61 m) and 29 m (Chainage 56 m) respectively. The jet reattachment point is farthest for the lowest gate opening and decreases for the increasing gate openings for a given head over the crest. This was because the increased thickness of jet for increasing gate openings increased the weight of jet and the jet fall down under gravitational force causing early reattachment.

5.3 Air entrainment

The chute aerator efficiency was normally described with the global air entrainment coefficient β, the ratio of the air supply discharge through the ducts provided on either side of spillway spans and the water discharge. The coefficient β was computed as 38% and 12 % for lower and higher gate opening respectively. For lower gate openings i.e. 10%, air entrainment was more at the top and bottom of jet up to the impact of jet. These two aeration layers were meeting at the downstream and the full depth was seen aerated after the impact of jet. However, for higher gate openings transparent central core of the water was visible up to the impact of jet. After this location, entrained air was carried by the water flow and got distributed across the depth of flow. Air entrainment was found to be more at the top as compared to the bottom of spillway. Figures 5a & 5b show the phase diagram for the volume of fraction of entrained air throughout the length of spillway profiles for gate openings 10 & 50% respectively.

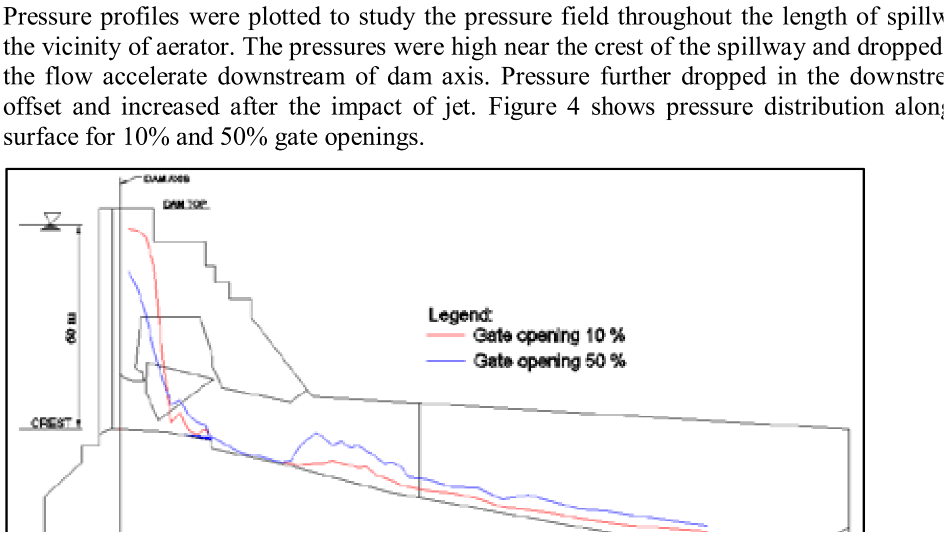

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Fig. 5a : Volume fraction of entrained air for 10% gate opening

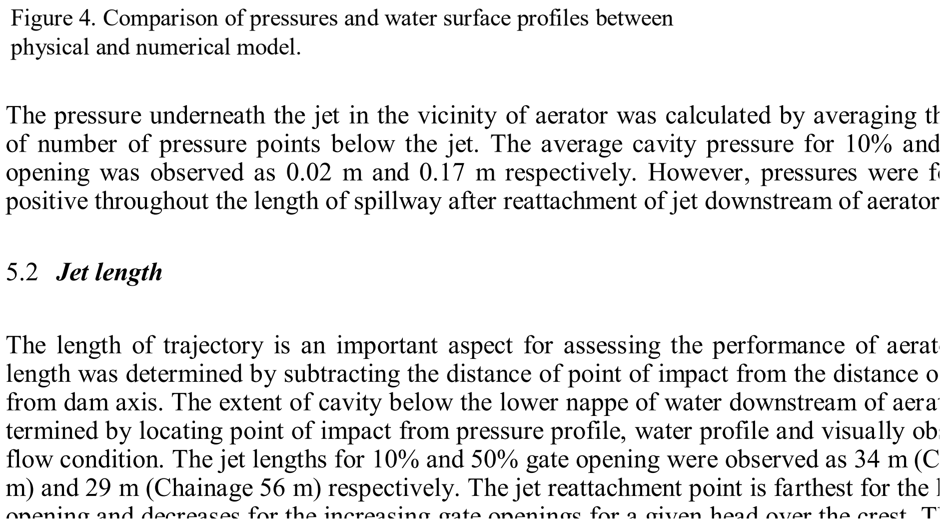

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Fig. 5b : Volume fraction of entrained air for 50% gate opening

5.4 Air concentration across depth of spillway

Air concentration was computed throughout the depth of flow at the downstream of the point of reattachment of the jet at three chainages viz. 75 m, 110 m and 150 m downstream of dam axis. The air concentration measurements revealed interesting information about the flow field downstream of the aerator as shown in Figure 6.

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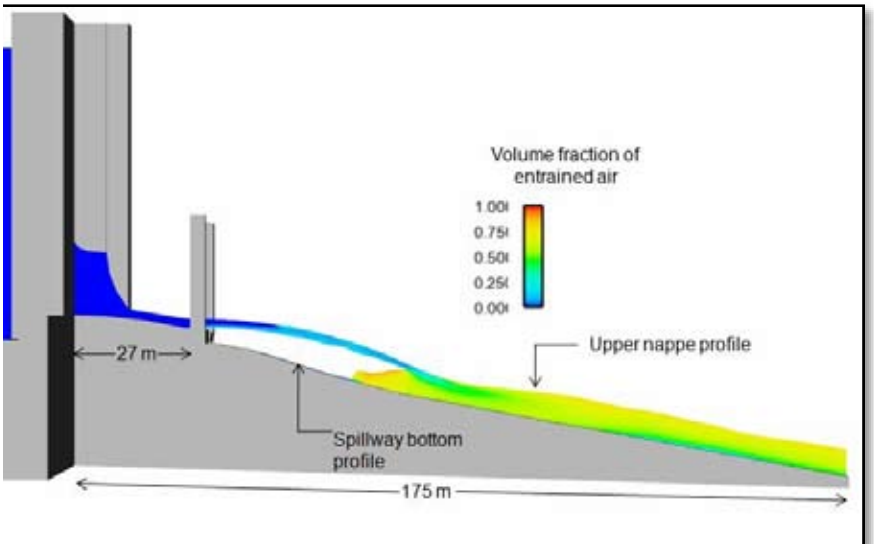

Fig. 6 : Air concentration profiles across the depth of spillway.

The air concentration was maximum at the bottom and minimum at the top at location 75 m from dam axis for gate opening 10% and 50%. This location was nearer to zone where impact of jet was observed. The air concentration was about 52% at the bed and increased up to75% at about 2.5 m from the bed for gate opening 10%. However, the bed concentration was 18 % at the bed and increased upto 30% at about1.5 m from the bed for gate opening 50%. The air concentration was found to be minimum i.e about 20% and 2% for gate opening 10% and 50% respectively at the top of the surface.

The air concentration was maximum at the top and minimum at the bed at locations 110 m and 150 m respectively for gate opening 10% and 50%. For low gate opening, air concentration was found in the range of about 30 to 75% as entire depth of flow was fully aerated. However, for high gate opening, air concentration was found in the range of about 1 to 50%.

5.5 Air concentration along spillway bed

Air concentration profiles along the bed are important as they show the extent of protection provided along the spillway surface by the aerator. Figure 7 shows the plot for the volume of fraction of entrained air along the bottom profile of spillway for gate openings 10% & 50%. Figure shows that after the impact of jet full depth was aerated for high Froude numbers i.e. smaller gate openings. Air concentration was found to be more throughout the length of spillway. This air-water mixture is useful in absorbing the pressure shocks created by cavitation and thus there is no possibility of serious cavitation damage after aerators are introduced. However, the air concentration was much less throughout the length of spillway for low Froude numbers i.e. larger gate openings as compared to high Froude number. Numerical model studies indicated that the air concentration dropped to less than 10% at chainage 80 m & subsequently reducing to zero asymptotically along remaining length of spillway for higher gate openings.

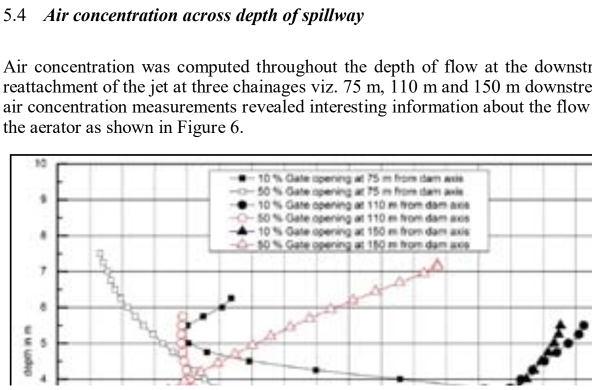
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Fig. 7 : Air concentration profiles along spillway bed

5.6 Need of second aerator

Air concentration near the spillway surface is of real significance and not the average air concentration for cavitation mitigation. The studies indicated a very low air concentration near the spillway bed for higher gate openings after chainage of 80 m from dam axis. Air entrained by the aerator does not travel with the flow throughout spillway length. The tendency of air bubbles is to travel upward due to buoyancy resulting in reduced air concentration along the spillway surface. This may cause cavitation along spillway surface. Due to large length of the spillway, the second aerator was recommended to provide at chainage of 88 m from dam axis so as to minimize the possibility of cavitation along spillway surface. Provision of second aerator would increase the air concentration through the length of spillway.

5.7 Air velocity in the duct

Velocity observed in the air vent was in the range of 26 to 149 m/s for one third span of spillway. The maximum velocity was higher than the permissible limit of air velocity i.e. 60 m/s. Hence, size of air vent was increased from 0.8 m to 1.5 m to reduce the air velocity in the duct. For full span of spillway, air demand will be increased due to increase in cavity area beneath the spillway jet. Hence, it is required to increase either the numbers or size of air vents for adequate air supply to the jet. Based on the study, it is suggested to provide two air vents of size 1.5 m X 1.5 m on both the sides of spillway span. The air vents may be provided in the form of square duct instead of circular cross section due to ease of construction at site.

6. CONCLUSION

Air entrainment is an important phenomenon in mitigating the cavitation damage. In the present study, numerical simulations were carried out to determine the air entraining parameters over chute aerator for high head orifice spillway. Studies were carried out for design head 60 m with 10% and 50% gated operation of spillway. Numerical model was validated with the physical model data by comparing pressure and water surface profile along spillway surface. The results were found in good agreement. The numerical model data was further analysed in determining the air entraining parameters over the chute aerator aerator in term of pressure distribution over spillway surface, jet lengths, cavity pressures beneath the jet, air entrainment and air concentration across the depth and along the length of spillway profile. The results are discussed as below:

- All the parameters were simulated well in numerical model that helped in determining the efficiency of first aerator located at 27 m downstream of dam axis.
- The pressures were found to be positive throughout the length of spillway.
- The jet reattachment point is farthest for the lowest gate opening and decreases for the increasing gate openings for a given head over the crest. There was no back water observed in the cavity for both gate openings.
- The coefficient β was computed as 38% and 12% for lower and higher gate opening respectively.
- Studies indicated adequate air concentration near the spillway bed for small gate openings as the full depth was aerated after impact of jet. However, inadequate air concentration was observed nearer to spillway bed for high gate opening after the impact of jet i.e. after 80 m downstream of dam axis. There may be possibility of occurrence of cavitation damage of the spillway surface. Hence, it is needed to provide second aerator at 88 m downstream of dam axis. Provision of second aerator would enhance the air concentration throughout the length of spillway so as to minimize the possibility of cavitation of spillway surface.
- Based on the study, it was also identified that two air vents of size 1.5 m x1.5 m are required to be provided on both the side of spillway spans to supply air in the cavity beneath the jet so as to make the nappe ventilated for all the discharges.
- Numerical model can be used as a complementary tool for modeling the complicated air-water interface phenomena.

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