Physical and Numerical Model Studies for Hydraulic Design of Stilling Basin as an Energy Dissipator of a Spillway - A Case Study

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Physical and Numerical model studies for Hydraulic design of Stilling basin as an Energy dissipator of a Spillway - A Case study

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Abstract: The design of the stilling basin for a dam spillway is site specific and hydraulic model studies are required to be carried out for evolving the best possible design. A properly designed hydraulic jump stilling basin can ensure 60-70% dissipation of energy in the basin itself. Supported by hydraulic model studies and prototype experience, a suitable stilling basin caters to a variety of conditions covering discharge intensity, head, tail water variation, and topographical conditions. The most serious problem with hydraulic jump type dissipator is more structural strength rather than hydraulic efficiency. Experience in recent years gives many examples of stilling basins having damages due to uplift, vibration, cavitation and abrasion, all having their origin in the internal structure of hydraulic jump. Model studies play an important role in optimizing the length of the stilling basin, elevation of the stilling basin floor level for a high head spillway and height of the end sill and hydraulic jump characteristics. This paper discusses hydraulic model studies conducted at Central water and Power Research Station (CWPRS), Pune, India, for the hydraulic jump stilling basin as energy dissipator for Kotlibhel dam spillway stage 1-B, Uttarakhand, India, at the conceptual stage, which played an important role in enhancing the overall performance of spillway and energy dissipator by incorporating modifications such as lowering of stilling basin floor level and modifying the height of the end sill. Through recent advances in computing power and modeling software capabilities, it is now feasible to undertake complex three-dimensional analysis using Numerical/Computational Fluid Dynamics (CFD) modeling techniques. Numerical model studies were carried out to assess the performance of the stilling basin using Computational fluid dynamics software, FLOW-3D. The major benefit of the CFD modeling is that it allows early identification of problematic flow features and modifications to the design/layout could be tried rapidly and cost-effectively. The results obtained from the numerical model were compared with the results of the physical model studies. Comparison of the results from the two modeling approaches has provided a very good insight into the design process to optimize the stilling basin design. This use of physical and Numerical modeling (CFD modeling) techniques has provided invaluable insight and greater confidence for future use of standalone CFD analysis in spillway/energy dissipator design as complementary tool for physical model studies. After studying the performance of the stilling basin for Kotlibhel stage 1-B Hydro electric project, both through the physical and numerical techniques, it is found that CFD modeling can be used as a valuable tool to test the preliminary empirical design and in the optimization phase of the stilling basin design prior to conducting physical model studies. The details of physical and numerical model studies conducted for improving the overall performance of stilling basin are described in the paper.

Keywords: Hydraulic jump, Numerical modeling physical modelling, Spillway, Stilling basin, Tailwater level.

1. Introduction

The design of energy dissipators below a spillway of a dam occupies a vital role in the design construction and safe operation of the dam. The problem while designing energy dissipator is one essentially reducing the high velocity flow to a velocity low enough to minimize erosion of natural river bed. Otherwise, it would damage not just the downstream river reach but also cause local scour of the spillway or dam, which if significant and able to progress could present a dam safety issue. This reduction in velocity is accomplished by providing suitable energy dissipator at the base/downstream of the spillway depending upon the head, discharge intensity, tailwater conditions and type of bed rock or bed material downstream of the spillway. For spillways on weak bed rock, hydraulic jump type stilling basins are recommended. When the tailwater rating curve approximately follows the jump height curve or is slightly above or below it, then hydraulic jump type stilling basin with horizontal apron provides the best solution for energy dissipation. A well-formed stable and strong hydraulic jump contained within the stilling basin is an indication of proper energy dissipation downstream of the spillway.

Criteria recommended by Bureau of Indian Standards (BIS) code IS 4997-1968 for stilling basins of rectangular cross-section with horizontal apron hold good provided that the jet entering the basin is reasonably uniform in regard to both velocity and depth. Though the criteria are applicable for all cases, yet for heads greater than 15 m, discharge intensities greater than 30 m³/s/m and possible asymmetry of flow, the specific design should be tested on a
hydraulic model. Extensive studies of stilling basin have been carried out by Peterka (1984), Higgs, (1996), (Johnson et al. 2006), (Amorim et al. 2015) through physical as well as numerical models.

The present paper describes the physical model studies conducted for optimizing the performance of the stilling basin for Kotlibhel Stage-1B Hydroelectric Project, Uttarakhand, India on a 1:80 scale 3-D comprehensive model and the results were compared with the results obtained from the numerical model studies. Numerical model studies were carried out using Computational Fluid Dynamics, FLOW-3D Software.

1.1 Case Study / Project Details

Kotlibhel H.E. Project, Stage -1B, Uttarakhand, India, is located on river Alaknanda in the Pauri and TehriGarhwal district of Uttarakhand. The project envisages construction of a 90 m high and 348.2 m long concrete gravity dam 2.2 km upstream of Devprayag at the confluence of river Alakananda with Bhagirathi. The spillway consists of six spans each with an opening size of 15 m (W) x 21.2 m (H) with breast walls and has been designed to pass the design discharge of 26,615 m³/s at Maximum Water Level (MWL) at EL 522 m. The Full Reservoir Level (FRL)/ Minimum Draw Down level (MDDL) is at EL 521 m. The right training wall in the form of cellular wall has been provided between spillway and power house. Figures 1 and 2 show the general layout plan and section of the spillway, respectively. The energy dissipator is provided in the form of a stilling basin with floor level at EL 460.8 m. A surface powerhouse on the right bank has been provided with an installed capacity of 320 MW (4 units of 80 MW each) with a design discharge of 587.4 m³/s. A 230 m long tail race channel has been provided downstream of the power house.

Figure 1. General layout plan
2. Physical Model Studies

A 1:80 geometrically similar scale 3-D comprehensive model was constructed after duly incorporating all the design features such as upstream & downstream river reach, spillway, stilling basin, piers, training walls and radial gates. Necessary arrangements were made for measurement of discharge, reservoir water levels and pressures. The accepted equations for similitude, based on Froudian similitude were used to express the mathematical relationship between the dimensions and hydraulic parameters of the model and the prototype. Figures 3 and 4 show the stilling basin with original and modified design of stilling basin constructed at CWPRS respectively.

Hydraulic model studies were conducted to assess the performance of stilling basin in respect of pressure distribution along the bottom profile of the spillway for various operating conditions, water surface profiles and to observe the flow conditions in the stilling basin for entire range of discharges to assess its efficacy.

2.1 Performance of Stilling Basin with Original Design (Stilling Basin Floor Level at El. 460.8 m)

Hydraulic model studies were conducted for the original design of the stilling basin with floor level at El. 460.8 m for both the gated and ungated operation of the spillway for the entire range of discharges. Studies revealed that the performance of stilling basin was unsatisfactory as the hydraulic jump was sweeping out of the basin for the discharges of 12,000 m³/s and below for gated operation of the spillway. It was seen that the tail water level was deficient for the formation of hydraulic jump for the discharges of 12,000 m³/s and below. Figure 5 shows the sweep out condition for the discharge of 6653.75 m³/s at FRL for gated operation of spillway.
2.2 Tailwater and Jump height analysis

The tailwater rating curve supplied by the project authorities as shown in Figure 6 was maintained at 200 m downstream of dam axis while conducting the model studies. Based on the analytical calculations for Froude number and sequent depth, it was found that by lowering the stilling basin by 5 m may a yield a sequent depth \( D_2 \) which would match with the tail water requirements to form a stable and strong hydraulic jump. Jump height analysis was carried out by computing sequent depth with stilling basin floor levels at EL 460.8 m and EL 455.8 m for entire range of discharges with gated and ungated operation of spillway and the same have been superimposed for comparison as shown in Figure 6. For the stilling basin with floor level EL 460.8 m, it was noticed that the tail water rating curve was less than the sequent depth for lower discharges for gated and ungated operation of the spillway due to which sweeping out condition was taking place in the stilling basin. But with the lowering of the stilling basin floor level by 5m i.e. at EL 455.8 m, the tail water level was higher for entire range of discharges. Therefore, it was suggested to lower the stilling basin floor level by 5 m i.e. at EL 455.8 m so that the performance of the stilling basin could be improved.

![Figure 6](image)

Figure 6. Tail water rating curve and sequent depth curves with stilling basin level at EL 460.8 m & EL 455.8 m for ungated and gated operation of the spillway
2.3 Performance of the Stilling basin with Modified design (Stilling Basin Floor Level at El. 455.8 m)

Hydraulic model studies were carried out for the modified design of the stilling basin with floor level at El. 455.8 m to assess the performance of the stilling basin. It was observed that a stable and strong hydraulic jump was forming in the stilling basin for the entire range of discharges with gated and ungated operation of spillway as the tail water level was sufficient to form the hydraulic jump. Thus, the performance of the stilling basin was found to be satisfactory. Figure 7 shows the flow conditions in the stilling basin with stable and strong hydraulic jump formation for the discharge of 6653.75 m$^3$/s for gated operation of the spillway.

3. Numerical Model Studies

In recent years, the computational fluid dynamics (CFD) method, through turbulence models, has become a useful tool to study complex environmental fluid-mechanics problems. The numerical modelling of a hydraulic jump, which involves fluctuating boundaries as well as a multiphase flow, is still challenging, considering its complexity. Furthermore, whereas most of the experiments provide measurements at a point or on a plane, the complete three-dimensional (3D) flow field supplied by a CFD simulation would enable us to have a deeper understanding of the dynamics of coherent structures that are responsible for free-surface fluctuations and aeration in hydraulic jumps. Several turbulence models have been proposed for solving the turbulent flow. In this regard, the K-epsilon, RNG K-epsilon, and large eddy simulation (LES) are the advanced turbulence models that recently have been widely used in hydraulic engineering (H.K. Versteeg, 2007). Several commercial software and open-source codes have been proposed for the comfortable use of numerical modelling in hydraulic engineering studies. In this regard, the commercial software Flow-3D is used for numerical model studies.

3.1 Numerical Model set up

The commercial software Flow-3D, developed by Flow Science, uses the finite-volume method to solve the Reynolds-averaged Navier–Stokes (RANS) equations over the computational domain (Amorim et al, 2004). The equations resulting from the time-averaging of Navier-Stokes equations are known as Reynolds-Averaged Navier-Stokes (RANS) equations and the numerical modeling based on these equations is known as RANS-based turbulence modeling. Tracking of the free surface is performed using the Volume-of-Fluid method. To represent the flow characteristics of the flow over the stilling basin, the Re-normalized Group (RNG) turbulence model was used before starting the solution, initial guesses like geometrical information of all grid points, the meshing of the geometry, the initial upstream boundary condition, and the number of time steps to achieve the steady-state solution have to be provided for the solution flow field. The numerical model studies were carried out to observe the...
performance of stilling basin for the original and modified design of the stilling basin. Therefore two geometries were generated with the help of AutoCAD software in the geometrically similar physical model scale of 1:80. The numerical simulations were carried out for the prototype discharge of 6653.7 m$^3$/s (25 percent of the design discharge 26615 m$^3$/s) which in the model scale comes out as 0.116 m$^3$/sec for gated condition by maintaining the tailwater level at El. 476.74 m. The geometry of the spillway profile including stilling basin is embedded in the computational grid by the pre-processor using the FAVOR concept (Hirt, C.W., 1985). In Flow 3D, grid generation is the most important issue for an accurate solution. Flow 3D uses a grid system of orthogonal meshes in the Cartesian or cylindrical coordinates. The Cartesian coordinate system is selected for this investigation. The flow region is subdivided into a mesh of fixed rectangular cells. The grid generation does not depend on geometry. The geometry in the domain is represented simply and properly without requiring a body-fitted grid system so that the geometry and grid generation are independent of each other. A uniform mesh is used for the first simulation trial, as it took more computational time non-uniform mesh system was generated for other trials to provide more grid refinement close to the block of the spillway. For non-uniform mesh systems, Flow 3D users manual advices to generate an appropriate grid. The most significant issue is to avoid large differences in sizes between adjacent cells. The size ratio between adjacent cells should be as close to unity as possible, and not exceed 1.25 for efficient results. Hence, in the upstream domain, cell size of 0.02 (total cell count of 2 million) was provided whereas in the spillway domain, fine mesh with a cell size of 0.01 (total cell count of 4 million) was provided and in the downstream, coarse mesh with a cell size of 0.02 (total cell count 1 million) were provided to optimize the use of computational resources and time. In this paper, input data to set the boundary conditions were used from the physical model data to study the performance and location of hydraulic jump in the stilling basin. Figures 8 and 9 show the numerical model showing boundary conditions and grid distribution for the computational domain of the model respectively.

3.2 Boundary Conditions

Boundary conditions were set for the upstream and downstream of the domain and the interface between the fluid and solid boundary was considered a closed boundary. The upstream face of the geometry was set as the inlet discharge of 6653.7 m$^3$/s (0.116 m$^3$/s in the model scale) with gated condition which is recognized as Volume Flow Rate in the Flow 3D. In the downstream, the exit of the domain was set as a pressure outlet. The extent of the mesh in the upstream X-direction was adjusted until any further increases had a negligible effect on the discharge. Numbers of probes were provided at different locations on the surface of the spillway and stilling basin floor level for observing the performance of stilling basin and free surface elevation. Baffles were provided at the inlet and outlet boundary of the domain to observe the discharge passed through the spillway. For iterative convergence, it is generally stated that the normalized residuals for each equation in the numerical solutions must drop under at least 0.001. If the computed values within a time step exhibit variations over a distance comparable to cell width or time comparable to the time increment, the accuracy of the computed results is not reliable. It is said that the solution has not converged. Hence for accuracy mesh increments were chosen small enough to resolve the spatial variation in all dependent variables and finer grids were provided near the wall boundaries. The duration of the simulation was decided by running a typical simulation for a longer time of about 80 seconds. It was found that the inlet and outflow discharge was reaching steady-state condition after about 50 seconds. Therefore, a simulation time of 50 seconds was adopted for the remaining runs.

![Figure 8](image)
4. Comparison of results of Physical and Numerical Models

The prototype size of the spillway of the Kotlibhel H.E. Project is 138 m wide, 195 m long and 90 m high and the numerical model study for this large size prototype spillway is not possible with the available computational facility. Hence for the numerical model study physical model scale i.e., 1:80 was chosen. The numerical model study was carried out for the gated operation of the spillway for 6653.75 m$^3$/s (0.116 m$^3$/s model scale) for the original and revised design of stilling basin. Numerical Model results were validated with physical model results of the water surface profile and the pressures on the spillway. To correlate the model study results with the prototype, the results obtained from both the physical and numerical model study were converted into the prototype dimensions.

4.1 Water Surface Profiles

In the numerical model studies water surface profiles were obtained for a discharge of 6653.75 m$^3$/sec (0.116 m$^3$/s model scale) at FRL for the gated operation of the spillway for the revised design of the stilling basin with floor level at EL 455.8 m. Water surface profiles observed along the centre line of spillway, for a discharge of 6653.75 m$^3$/s at FRL for gated operation of the spillway from both the model studies were converted to prototype dimensions to compare the results as shown in figure 10. It could be observed from the figure that the hydraulic jump formed is contained well within the stilling basin. Comparison of the numerical model profile with the physical model, it was observed the numerical model profile almost follow the trend of physical model profile. However, there was around 1.8 % to 13% error in observed water surface elevations of the profiles. As the numerical model study was done on the 1:80 scale, in the simulation 0.1 m error stands for 8 m in the prototype result. Hence, a slight difference could be seen in the water profiles. The reasons for the error generation in the numerical model studies are primarily caused by the grid density, especially in the regions close to the interface. The errors can be reduced with a denser grid, but the computing time will be increased accordingly.

![Figure 9. Grid distribution for computational domain of model](image)

![Figure 10. Comparison of water surface profile for the discharge of 6653.75 m$^3$/s for gated operation of spillway (Modified Design)](image)
4.2 Pressure Profiles

Pressure observations on the physical model were made along the center line of the spillway up to the end of stilling basin with revised design for different discharges viz. 26615, 19961.25, 13307.5, 6653.75 m$^3$/s for ungated as well as for the gated operation of the spillway. The pressure profiles on the surface of the spillway and over the stilling basin indicated that the pressures were positive for the entire range of discharges except at very few locations for the discharge of 6653.75 m$^3$/sec passing under the gated operation of the spillway. However, the corresponding cavitation index works out to be above the critical cavitation index of 0.2, therefore, the pressures were found to be acceptable. As such the performance of the spillway profile along with the stilling basin in respect of pressures was considered to be satisfactory. The pressure profiles obtained from the modified design of stilling basin with floor level at El. 455.8 m, for a discharge of 6653.75 m$^3$/s for the gated operation of the spillway from the physical and numerical studies are depicted in figure 11. It could be seen from the figure that the pressure profiles are matching very well.

![Figure 11. Comparison of pressure profiles for the discharge of 6653.75 m$^3$/s for gated operation of spillway (modified design)](image)

4.3 Performance of the Stilling Basin with Original and Modified Design

Figure 12 shows the phase diagram of sweep out of hydraulic jump in the stilling basin for a discharge of 6653.75 m$^3$/s for gated operation of the spillway in the Numerical simulation for the original design of the stilling basin. Figure 13 shows the phase diagram showing the formation of strong and stable hydraulic jump in the stilling basin for discharge of 6653.75 m$^3$/s for the gated operation of the spillway in the Numerical simulation for the revised design of the stilling basin. It shows that the performance of the modified design of stilling basin is satisfactory as a stable and strong hydraulic jump is forming in the stilling basin.

![Figure 12. Phase diagram showing sweep out of hydraulic jump in the stilling basin for discharge of 6653.75 m$^3$/s for gated operation of the spillway by Numerical simulation (original design)](image)
5. Results and Discussions

Performance of the stilling basin of the spillway of proposed Kotlibhel H.E. Project stage 1-B was assessed by conducting hydraulic model studies for flow conditions in the stilling basin for the original and revised design of the stilling basin. The results of the water surface profiles and pressures over the spillway profile obtained by numerical studies are compared with the physical model studies. Flow conditions observed in the stilling basin from numerical model studies were compared with that of physical model studies to assess its performance for the original and modified design from both techniques. The following observations are made.

- Results showed that water surface profiles of the numerical model and physical model are in reasonably good agreement with one another. However, for the gated operation of the spillway, water surface profiles obtained from numerical modelling are slightly lower than that obtained by physical modelling. The difference in water surface profiles may be attributed to the formation of the Rooster tail in the 3D physical model, and lesser grid density in the numerical model.

- Pressures observed over the spillway profile and stilling basin were positive for the entire range of discharges with the gated and un-gated operation of the spillway in both physical as well as numerical models except at very few locations for the discharge of 6653.75 m$^3$/sec passing under the gated operation of the spillway. However, the corresponding cavitation index works out to be above the critical cavitation index of 0.2, therefore, the pressures were found to be acceptable. As such the performance of the spillway profile in respect of pressure was considered to be satisfactory. The pressures obtained from the numerical simulation are in good agreement with the physical model studies.

- Phase diagrams show that flow conditions/features observed on the physical model have been captured exactly in the numerical simulation. Sweep out of hydraulic jump due to deficient tail water level as observed in the physical model (shown in the photo, Figure 5), and formation of hydraulic jump with the lowering of the stilling basin floor with sufficient tail water level as observed in the physical model (shown in the photo, Figure 7), have been exactly simulated through the numerical model studies (Phase diagrams in figures 12 and 13). This highlights that the flow conditions observed in the physical model are very well simulated in the numerical model.

- The formation of the stable and strong hydraulic jump was seen in the stilling basin with the revised stilling basin floor level at El. 455.8 m, both in the physical and numerical model study results and hence it was concluded that its performance was satisfactory.

6. Conclusions

In the present study, the performance of stilling basin as an energy dissipator for the proposed Kotlibhel 1-B Dam spillway, Uttarakhand, India, was evaluated by physical and numerical model studies. The results of both the model studies are compared. It is concluded that the performance of the stilling basin with revised floor elevation at El. 455.8 m is satisfactory. It is to highlight that the flow conditions in the stilling basin are very well simulated in the numerical model studies when compared with the flow conditions in the physical model for both the original and modified design of the stilling basin. The results for pressure measurements and water level elevations obtained from numerical model studies are well corroborated with the physical model results. It is found that Numerical / CFD modelling software Flow-3D could effectively simulate the flow conditions over the spillway and in the stilling basin.
basin. A comparison of the results from the two modelling approaches has provided a very good insight into the design process to optimize the design of stilling basin. The numerical modelling technique has provided invaluable insight and greater confidence for future use of standalone CFD analysis as a complementary tool for physical model studies in optimizing the design of stilling basin as an energy dissipator for the spillway. After studying the performance of the stilling basin both through physical and numerical techniques, it is found that numerical / CFD modelling can generally be used as a valuable tool to test the preliminary design and in the optimization phase of the spillway/stilling basin design prior to taking up the physical model study. This will save time and cost involved in the physical model construction and studies at the conceptual stage of the project.

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