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Hydraulic Design of Headrace and Tailrace Channel for a Low-Head Hydro Power Plant Using Partial Analysis

M. Karthikeyan[1]
Centre for Water Resources
Anna University
E-mail: karthi_k2k@yahoo.co.in

B.V. Mudgal[2]**, G. Ravikumar and K. Karunakaran**
Centre for Water Resources
Anna University
E-mail: [2]bvmudgal@annauniv.edu

ABSTRACT: An undistorted physical model of a low head hydropower plant of scale 1:100 was constructed to achieve the designated head through model studies by designing the tailrace and headrace channels. In order to minimize the number of modifications and thereby time consumption, design and analysis were carried out using HEC-RAS software and the results were implemented in the physical model. Rationale for deviations between the two results was analyzed and suitable modifications in the physical model were implemented. From the experiments it has been concluded that use of hybrid model is an effective and efficient way to achieve optimum channel alignment and design for the low head installations within short time horizon.

INTRODUCTION

The need for additional energy production in the India has resulted in increased interest in the development of remaining hydropower resources. Much of the undeveloped capacity is in the low-head range. Many hydraulic phenomena which occur in nature are too complex to be described by rigorous mathematical techniques alone and models are used as an alternative means of obtaining the information necessary to complete efficient and satisfactory design. In addition to that the nature and pattern of hydraulic phenomena differs widely depending on the existing site conditions and boundary conditions. Scale models permit visual observation of the flow and make it possible to obtain certain desired numerical data. The increasing use of mathematical techniques and computers during the past two decades have led to increasing use of hybrid models combining the advantages of both physical and mathematical model.

The main objective of this study was to achieve the required head of 6.5 m and 9.0 m for maximum and minimum discharges respectively through hybrid model studies. In addition, hydraulic performance of various components of the barrage was assessed and velocity profile in the tailrace channel for maximum discharge was obtained.

STUDY AREA DETAILS

Series of barrages are put in place for every 9 m fall of head below the Mettur dam in the river Cauvery in Tamil Nadu to utilize the irrigation discharges for production of hydropower. The sixth in this series called Bhavani Kattalai Barrage-2 is the scope of this study. Elevation data was collected for every 10 m interval for 500 m upstream and 1000 m downstream of the proposed barrage along with dimensions and levels of the powerhouse and barrage from Tamil Nadu Electricity Board (TNEB).

EXPERIMENTAL SETUP

Since the flow is predominantly gravity, Froude number was used to achieve the similarity between the model and the prototype. A 1:100 undistorted physical model was constructed using the collected spot levels, details of the barrage and the powerhouse. The schematic representation of the experimental setup is shown in Figure 1. A Rectangular notch and V-notch were used to measure the discharges delivered into the model.

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[1] Conference speaker

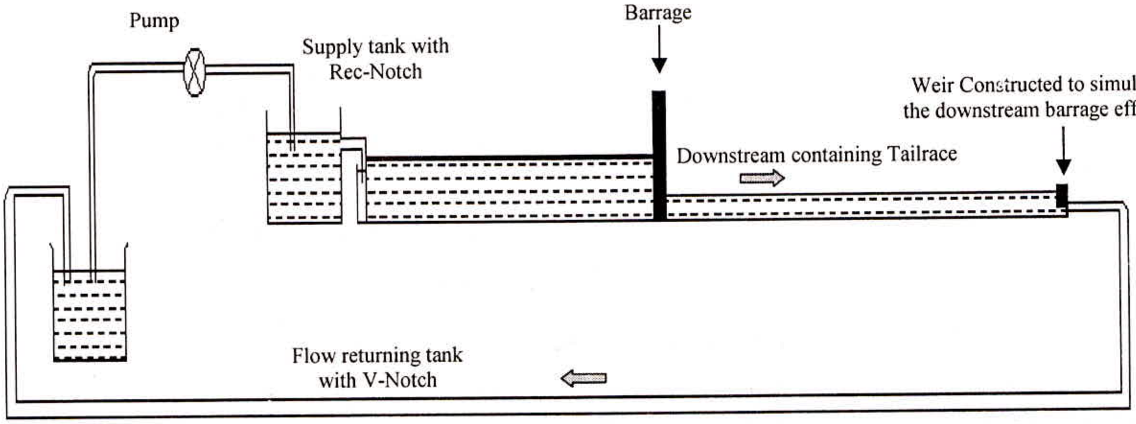

Fig. 1: Schematic diagram showing Experimental Setup

Once the required model discharge is delivered, the gates in the powerhouse were adjusted to maintain the Full Reservoir Level (F.R.L.). The head across the turbine is the difference between F.R.L. and tail water level, which was measured using the gauge fixed at the outlet of the draft tube.

PHYSICAL MODEL RUN FOR THE EXISTING CONDITION

Table 1 shows the three trial runs conducted in the physical model for the existing site conditions. The constructed model produced the head of 6.1 m for maximum discharge (Q_{max}= 540 m^3/s) and 8.0 m for minimum discharge (Q_{min} = 85 m^3/s) instead of the required 6.5 m for Q_{max} and 9.0 m for Q_{min}. This means that the downstream water level has to be lowered to achieve 6.5 m for Q_{max} and 9.0 m for Q_{min}. The only way to achieve the required head by lowering the water level is to carry out channel modification.

Table 1: Physical Model Output for Existing Condition

Sl. No.	*Discharge (m^3/s)*	*Head (m)*			*Required Head (m)*
		Run 1	*Run 2*	*Run 3*	
1.	Q_{min} = 85	8.0	8.0	8.0	9.0
2.	200	7.5	7.5	7.5	–
3.	300	7.2	7.2	7.2	
4.	400	6.8	6.8	6.7	
5.	500	6.5	6.5	6.5	
6.	Q_{max} = 540	6.0	6.1	6.0	6.5

DIMENSIONS OF THE DRAFT TUBE OUTLET

Dimensions of the entrance of the tailrace channel depend on dimensions of the draft tube outlet. Divergent sidewalls of the draft tube, length of the side wall along the flow direction, width of the draft tube outlet are the components shaping the dimensions of the tailrace channel. The dimensions of the draft tube outlet constructed in the physical model are shown in the Figure 2. Based on the angle of inclination of the side walls and its length along the course of the stream, the width was fixed as 60 m in length excluding the thickness of the side walls. So for the initial trials the width of the tailrace channel has been fixed as the same 60 m to provide the flow a smooth transition from the draft tube.

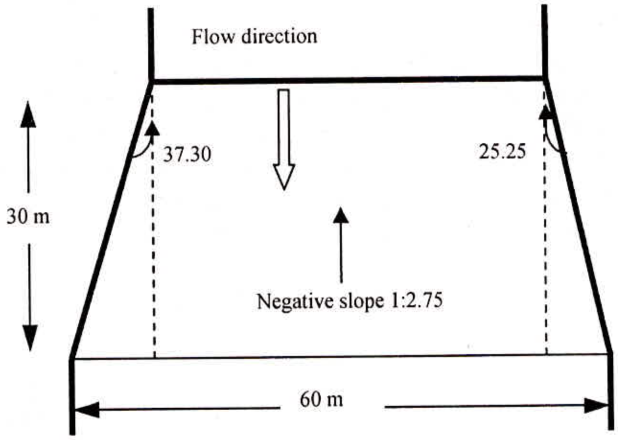

Fig. 2: Dimensions of the draft tube

MODELING OF TAILRACE CHANNEL USING HEC-RAS

In order to reduce the number of modifications and trail runs in the physical model, the computations were carried out using steady flow component of HEC-RAS (Hydrologic Engineering Center-River Analysis System), developed by the U.S. Army Corps of Engineers. The basic computational procedure is based on the solution of the one-dimensional energy equation. Contour maps and Digital Elevation Model (DEM) of the study area

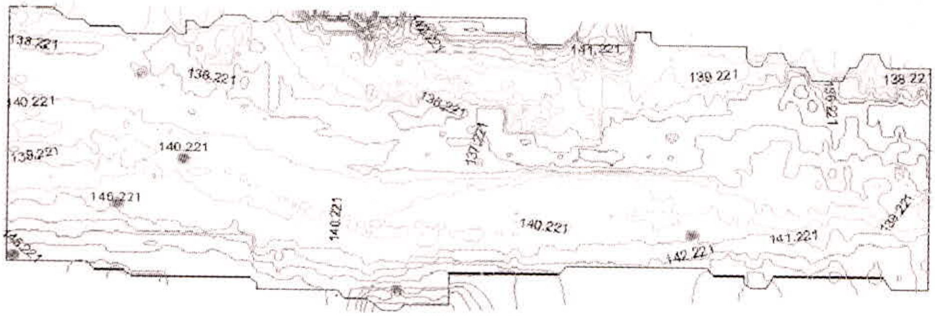

Fig. 3: 1 m Contour map of the study area

were prepared using the MapInfo software's vertical mapper module. Figure 3 shows the 1 m contour map of the study area Observations in the DEM, contour map and the physical model revealed the existence of low levels in patches below the outlet of the draft tube. These patches were made use for aligning and constructing the tailrace channel to minimize the quantum of excavation.

Once the geometry, steady flow data and boundary conditions has been established, the model can be used to calculate the steady flow water surface which in turn provides the water level at the outlet of the draft tube for the corresponding discharge, from that the head available for that discharge can be found. Table 2 shows the HEC-RAS output for the existing condition after providing the necessary geometry, steady flow data and boundary conditions.

The design of the tailrace channel encompasses the introduction of guiding walls on the either side to confine the flow in designed channel and to avoid the disturbances caused by the surges. Figure 4 shows the encompassed guide walls of the tailrace channel to confine the flow from the draft tube outlet.

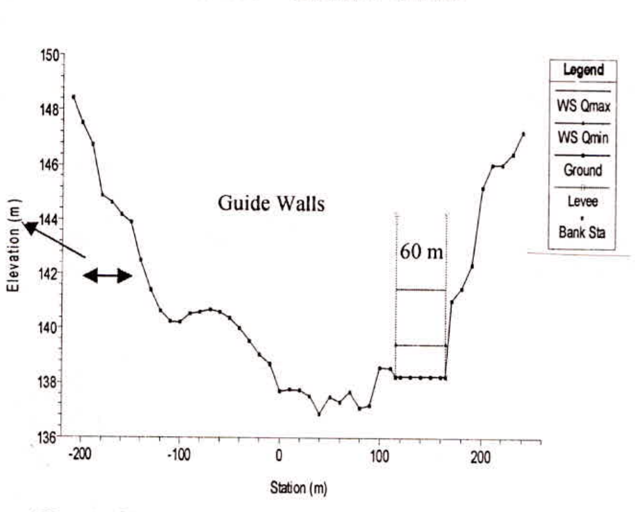

Fig. 4: Simulated cross section in HEC-RAS with guide walls

Table 2: HEC-RAS Output for the Existing Condition

Sl. No	Discharge m^3/s	Head (m)
1.	$Q_{Max} = 540$	6.22
2.	$Q_{Min} = 85$	8.17

DESIGN AND IMPLEMENTATION OF THE TAILRACE CHANNEL

Alignment-1

Trail and error method was used for designing the tailrace channel in HEC-RAS. From the obtained dimensions of the draft tube outlet, the width of the tailrace channel inlet was fixed as 60 m. So it is necessary to compute the water surface profiles for various the bed elevations, width and lengths of the tailrace channel. Steady flow profiles for both maximum and minimum discharge were simulated in HEC-RAS for the various combinations of depth, width and length of the channel.

From the results obtained using HEC-RAS, combination of channel bed elevation of +138.25 m and length of 100 m for 60 m width of the channel was selected to be implemented in the physical model. HEC-RAS and Physical model results for the selected alignment are given in Table 3. From Table 3, it can be seen that the required head of 6.5 m for maximum discharge has been successfully achieved while the head for the minimum discharge is deficit by 0.9 m.

Table 3: HEC-RAS and Physical Model Output for Alignment-1

Sl. No.	Discharge (m^3/s)	Head (m)	
		Physical Model Output	HEC-RAS Output
1.	540	6.6	6.66
2.	85	8.1	8.88

Observation of tailrace channel in the physical model showed the presence of hump for the entire width of tailrace which in turn caused substantial stagnation of water in the tailrace channel thus decreasing the head across the turbine. Figure 5 shows the hump in Alignment-1.

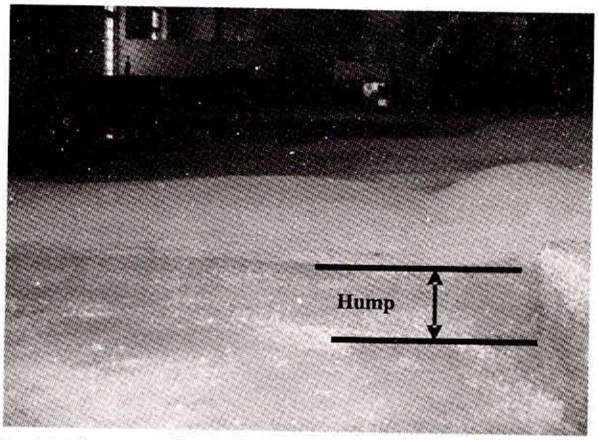

Fig. 5: Hump at the intersection of tailrace channel with main stream bank channel

Alignment-2

So a modification in the existing alignment was planned to reduce the hump and to retrieve the deficit head. The length of the channel has been increased by 1 m for each trial in the HEC-RAS; after analyzing the HEC-RAS output, tailrace channel in the physical model was further extended to 15 m downstream where the bed level is significantly lower then the hump. Table 4 shows the HEC-RAS and physical model output for Alignment-2. Though there is no appreciable change in the net head for minimum discharge, the net head for maximum discharge has been increased significantly. Comparison of the cross sectional data at 100 m and 115 m confirmed existence of comparatively reduced bed levels, which lowers the height of hump upon construction up to the point of 115 m. The increase in the head can be attributed to the reduced backwater effect because of smaller hump.

Table 4: HEC-RAS and Physical Model Output for Alignment-2

Sl. No.	*Discharge (m^3/s)*	*Head (m)*	
		Physical Model Output	*HEC-RAS Output*
1.	540	7.5	7
2.	85	8.9	8.89

Alignment-3

Even after the implementation of Alignment-2, still there is still deficit of 0.1 m head for minimum discharge. So it was decided to go for one more modification. Instead of varying the length of the channel alone, the width of channel was varied by making the left guide wall inclined at angle of 8° with the flow direction. From the results obtained in HEC-RAS the tailrace channel in the physical model was further extended to 5 m. The available elevation at the intersection point of the tailrace channel with the main stream is almost same as that of the tailrace channel, resulting in smooth transition of flow with virtually no hump. Table 5 shows the physical model and HEC-RAS output for Alignment-3. Since the required head for both maximum and minimum discharge has been obtained, the dimensions employed in alignment-3 were suggested as the final to be implemented on site.

Table 5: HEC-RAS and Physical Model Output for Alignment-3

Sl. No.	*Discharge (m^3/s)*	*Head (m)*	
		Physical Model Output	*HEC-RAS Output*
1.	540	8.1	7.68
2.	85	9	8.99

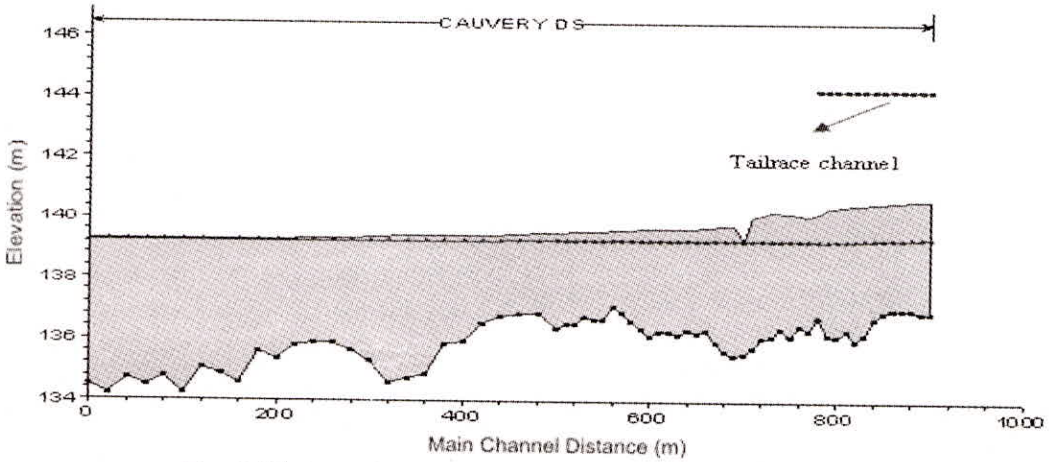

Fig. 6: Water surface profile plot for the existing condition

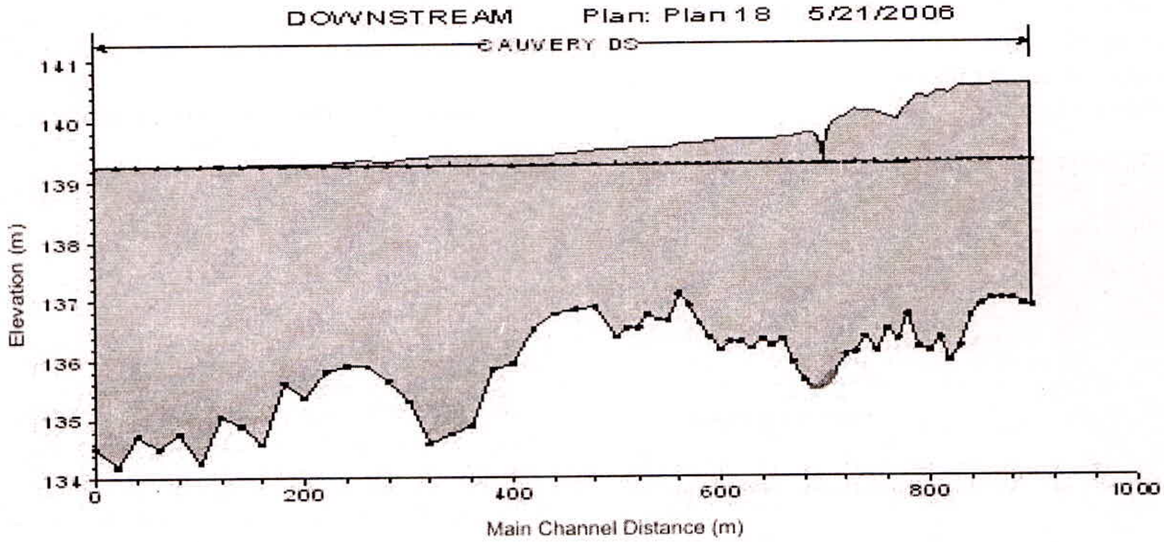

Fig. 7: Water surface profile plot for the final alignment-3

COMPARISON OF WATER SURFACE PROFILE FOR THE EXISTING WITH THE MODIFIED CROSS SECTION

By comparing both the profiles, it can be inferred that the water surface in Figure 7 varies gradually and smoothens because of the implemented tailrace channel in the cross sections.

ASSESSMENT OF HYDRAULIC PERFORMANCE OF INTAKES

Intakes are evaluated for the availability of adequate submergence to avoid the formation of vortex using the formula provided by Gordon [6],

$$\rightarrow \quad S = 0.3V\,(d)^{1/2} \qquad \ldots (1)$$

Where, S = Submergence, V = Velocity through the inlet, and d = depth of the intake.

In this case d = 15.3 m, V_{max} = 1.4077 m/s, V_{min} = 0.2146 m/s.

Applying the above values in Equation (1), the required submergence are, S = 1.42 m for maximum discharge and S = 0.252 m for minimum discharge.

The available submergence is 148.25 – 141.375 = 6.875 m for both minimum and maximum discharge, which is more than the value specified by the criteria. As suggested by Gordon [6], Physical model was operated at velocities higher than model velocities of the order of 1.538 m/s and 1.798 m/s. The flow visualization experiment were carried out, it was found that there is no vortex formation or swirl at the inlet or at the outlet. This can be attributed to availability of adequate submergence and streamlined flow at the inlet of water into the model.

SUBMERGENCE AT THE OUTLET OF THE DRAFT TUBE

Gordon [6] suggested having a minimum submergence of 0.75 m–1.0 m at low tailwater. But the available submergence at the outlet is 139.25 – 139.10 = 0.15 m. The main reason for providing the submergence of 0.75 m–1.0 m is to avoid the power swings due to surges and turbulence caused by the rise of channel bottom. Since the tailrace channel in this barrage is designed to avoid such surges and disturbances, it will be sufficient, if the available submergence at the outlet of the draft tube is maintained. So the care is taken during the trials in the model study to keep the tailwater level at the prescribed +138.25 m for minimum discharge.

COMPARISON OF VELOCITY PROFILES

Tailrace channel was divided into grids of the size 10 cm × 10 cm and the velocities at each point of the grid were measured using Nortek acoustic Doppler velocity meter. Figure 8 shows the actual velocities measured in the tailrace channel, once the hump is reduced in the model velocity increases substantially. The pronounced effects of the hump was well depicted from the velocity measurements taken in alignment-2 and alignment-3 shows the changes in velocity readings once the hump is removed from the model. From Figure 9, it can be observed that the HEC-RAS tend to overestimate the velocity in the tailrace channel. At the end of tailrace the velocity tends to increase suddenly due to the low elevation values lying immediately below the tailrace channel. Once the hump is removed

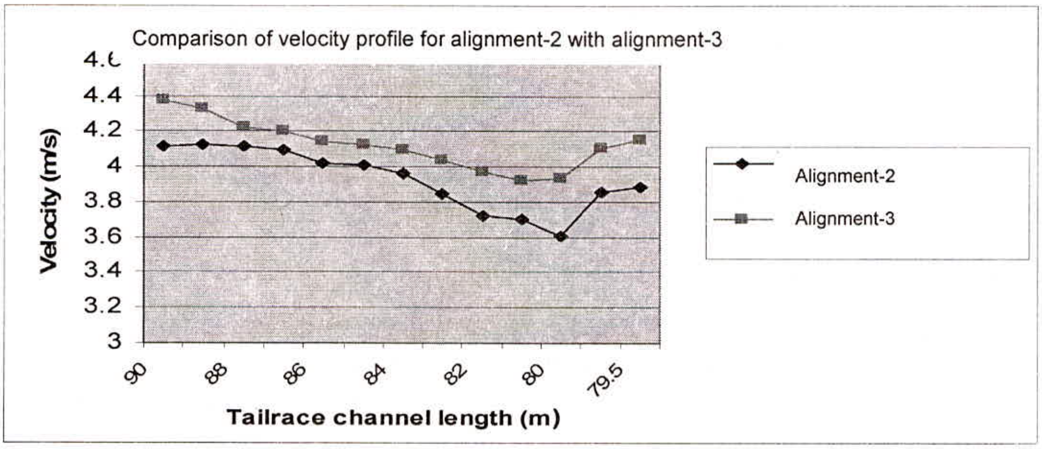

Fig. 8: Comparison of the velocity profile in the tailrace channel for Alignment-2 with Alignment-3

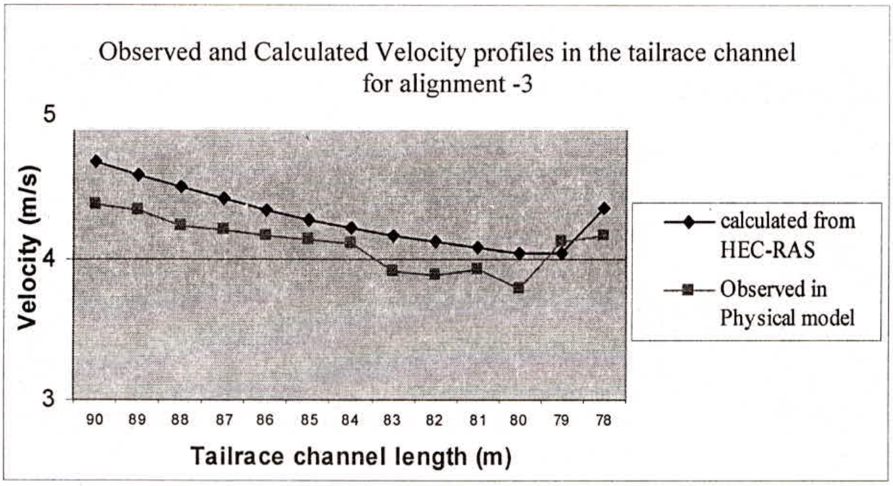

Fig. 9: Calculated and observed velocity profile in the tailrace channel for Alignment-3 (final alignment)

through the river training work, the velocity improved significantly. HEC-RAS computed velocities are reasonably closer to the observed values in the physical model, and this can be authenticated from the Figure 9.

RESULTS AND DISCUSSIONS

For the existing condition, the results from the both models for the two critical model discharges matched with only slight deviation. But it is not the same in case of Alignment-1 where the observed output for the maximum discharge matched with the computed one while there is 0.78 m deviation for minimum discharge. The difference occurred because of the inability of HEC-RAS to simulate the hump shown in Figure 5 located at the critical interface of tailrace channel with the main channel. Figure 10 shows the interface of tailrace channel with the main channel simulated by HEC-RAS; it is clearly evident that there is no hump.

The inverse case happens incase of third and fourth trial runs i.e. Alignment-2 and Alignment-3, where the observed values of minimum discharge matches with the predicted one. This can be attributed to the absence of the hump in both physical and HEC-RAS simulated model. After reviewing the analytical methodology employed by HEC-RAS for calculating the backwater profile, it was found that, the HEC-RAS uses only the designated tailrace width of 60 m between the guide walls for calculating the backwater effect, while the physical model employs the entire main channel cross section in accounting the backwater effect. This can evident from the Figures 11 and 12.

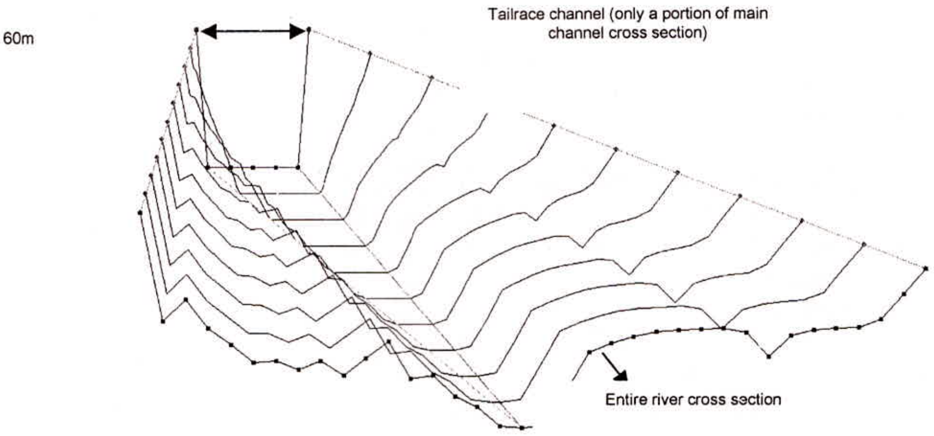

Fig. 10: HEC modeled interface between the tailrace channel and main channel

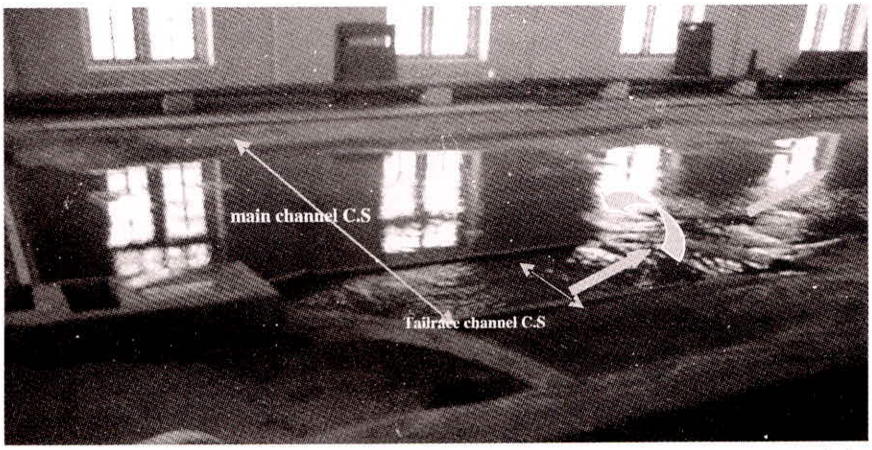

Fig. 11: Backwater effect alongside the tailrace channel in Physical model

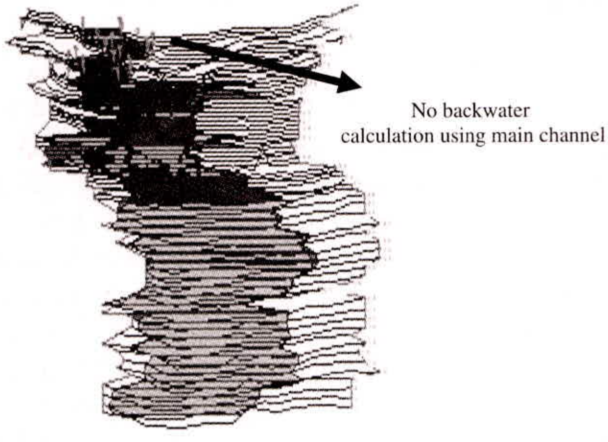

Fig. 12: Three dimensional plot of the down stream cross sections with tailrace channel and guide walls

SUMMARY

The combined HEC-RAS and physical model experimental investigation substantiates the following conclusions:

The required head of 6.5 m and 9.0 m for maximum and minimum discharge have been successfully achieved by designing a tailrace channel of length 120 m from the outlet of the draft tube. For maximum discharge, the achieved head is 24.5% more than the required head of 6.5 m. The principal reason for the observed deviation in the results between the HEC-RAS and the physical model is due to the inability of HEC-RAS to consider the 3-dimensional surfaces into account. To overcome this effect, providing additional cross sectional data for HEC-RAS in the region of sudden change in the elevation levels within short distance will yield closer results.

From the experimental results it was concluded that deviation between Physical model and HEC-RAS ranged from 9% in initial trials to < 5% in the final trials, so the HEC-RAS can be productively used in designing the tailrace channel of a low-head power plant to achieve the required head with acceptable standards of accuracy.

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