MATHEMATICAL AND HYDRAULIC MODEL STUDIES FOR THE DESIGN OF TAILRACE CHANNEL FOR PUMPED STORAGE HYDROPOWER PLANT

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Abstract. The tailrace channel (TRC) in a pumped storage hydropower plant carries water from the turbines back to the lower reservoir and consequently pumped back to the upper reservoir. Its design plays an important role in evolving satisfactory flow conditions, optimizing the energy losses, and thereby increasing the overall efficiency of the system. Mathematical and physical hydraulic model studies were conducted for a tailrace channel having maximum discharge of 1820 cumec for generation mode and 1722 cumec for pumping mode. The studies were initially conducted using latest version of 2D Hec-RAS software, so as to have insight into the velocities, water levels and pressure distribution along the tailrace channel. Subsequently, 3D CFD studies were conducted covering intake structure, tailpool and part of TRC to assess the three-dimensional flow conditions. The results were analysed and the regions of circulatory flow conditions in the tailpool were noted. Further, in order to confirm the observations obtained from mathematical model studies, 3D hydraulic model to a geometrically similar scale of 1:50 was constructed. The studies were conducted to carrying out hydraulic design of tailrace channel for the off stream pumped storage plant having high discharge. The present paper describes the best possible design optimization to assess uniform flow conditions, velocities in the intake structure and the water surface profiles in the tailrace channel using 2D mathematical model, 3D CFD model and geometrically similar scale (1:50) physical model at Infraplan Hydraulic Laboratory, Pune. The integrated multi-modelling approach provided a reliable, optimized, and hydraulically efficient design solution for the TRC, tailpool, and lower intake structure.

Keywords: Tailrace Channel, Pumped Storage Project, Turbine Operation, Intake Structure, Reservoir.

1 Introduction

Pumped storage powerplant (PSP) represents the most mature and widely deployed form of large-scale energy storage technology. With the rapid global expansion of intermittent renewable energy sources such as solar and wind; the role of pumped storage powerplant in grid balancing and providing required power during peak hours has become increasingly vital. These plants operate reversibly, generating electricity during peak demand by releasing water from an upper reservoir to a lower reservoir through turbines and refilling the upper reservoir during off-peak hours by pumping water back against gravity.

A critical but often underappreciated component of a pumped storage powerplant is the tailrace channel (TRC). The TRC serves as the hydraulic link between the lower reservoir and the lower intake structure. During generation mode, it conveys turbine discharged water to the lower reservoir, while during pumping mode, it acts as an approach channel through which water is drawn into the intake structure by gravity and pumped to the upper reservoir. The hydraulic design of the TRC must satisfy stringent requirements including controlled approach velocities, uniform flow distribution across intake spans, absence of vortex formation and air entrainment, acceptable head losses, and stability under varying reservoir levels and asymmetric unit operations widely known as hydraulic short circuiting. This paper represented based on the multi modelling approach used to carrying out hydraulic design of tailrace channel conducted at the Infraplan Hydraulic Laboratory, Pune.

2 Hydraulic design of tailrace channel (TRC)

The design of the TRC for this off stream pumped storage plant presented several unique challenges. The lower intake structure is located inside the existing reservoir at EL. 361.0 m, well below the MDDL of EL. 381.0 m. To draw the maximum discharge at MDDL, a tailrace channel length of 2300-2350 m was found necessary. The existing reservoir bathymetry necessitated a horizontal curvature in the TRC alignment to reach the minimum ground levels within the reservoir. Furthermore, the exceptionally high design discharge of 1820 m^3/s demanded a channel width of at least 250 m to maintain acceptable approach velocities.

Considering these challenges approximately 50 Hec-RAS 2D trials were conducted to optimize the TRC geometry, alignment, longitudinal slopes, and channel width. The optimization process considered pumping rated discharge of 1512 m^3/s, pumping maximum discharge of 1721 m^3/s, and generation maximum discharge of 1819 m^3/s. The revised design adopted an inlet width of 400 m, gradually transitioning to narrower sections downstream. The final optimized TRC configuration comprises the following key features:

- Total channel length: 2350 m including a 60 m tailpool at El. 361.35 m
- Channel width varies from 400 m at the inlet (Ch. 2350 m), reducing to 300 m at Ch. 2006 m, and further to 250 m at Ch. 1506 m

- A bellmouth transition at the reservoir end for smooth entry flow
- Longitudinal profile with four slope segments: 1:22 (Ch. 60-300 m), 1:100 (Ch. 300-500 m), 1:745 (Ch. 500-2000 m, rising to EL. 377.0 m), and 1:175 (Ch. 2000-2350 m, rising from 377.0 to 379.0 m)
- Manning's roughness coefficient: 0.022 (shotcrete lining) and 0.040 (unlined channel)
- Three submersible divide walls of 150 m length with top at EL. 375.65 m upstream of the intake structure to ensure equal flow distribution near tailpool.

The tailpool length was assessed extensively. A length of 60 m was found to offer the most practical balance between hydraulic performance and construction feasibility. The 1:22 slope connecting the tailpool floor to the main TRC ensures adequate flow transitions in both operating modes.

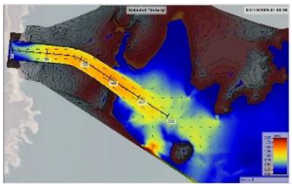
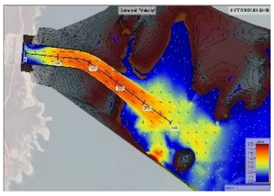
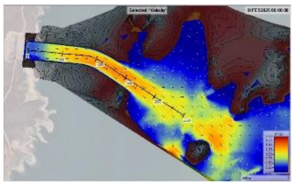
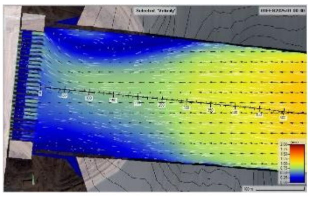
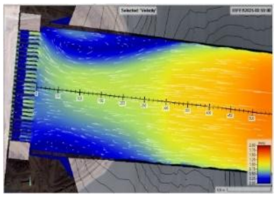
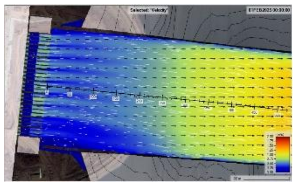
3 Hydraulic Model Studies

3.1 2D Mathematical studies

Initial design of tailrace channel was derived by using Hec-RAS 2D software having latest version. The bathymetric survey data of the existing reservoir, provided at 1 m contour intervals, was processed using QGIS to generate a Digital Elevation Model (DEM), which was subsequently imported into Hec-RAS 2D for terrain generation. The computational domain extended approximately 5 km into the reservoir from the TRC inlet to ensure accurate boundary conditions. The nine intake units were reproduced in the HEC-RAS model with their respective span configurations. Three primary simulation scenarios were evaluated: (i) pumping mode at rated discharge (1512.54 m^3/s), (ii) pumping mode at maximum discharge (1721.56 m^3/s), and (iii) generation mode at maximum and rated discharge (1819.45 m^3/s). For pumping mode simulations, reservoir water level was specified as the upstream boundary condition and unit discharges as the downstream boundary. For generation mode, the boundary conditions were reversed.

In pumping mode at rated discharge (1512.54 m^3/s), approach velocities in the reservoir ranged from 0.8 to 1.10 m/s near the start of the tailrace channel (Ch. 2000–2500 m), with a peak of about 1.35 m/s at Ch. 1500 m, gradually reducing to 0.4–0.7 m/s near the intake; localized circular return flows with velocities below 0.6 m/s were observed along the right bank, and stagnant zones developed near the tailpool edges due to flow concentration along the centre. At maximum pumping discharge (1721.56 m^3/s), velocities increased, reaching about 1.65 m/s at Ch. 1500 m and 1.0–1.4 m/s at the inlet, while similar circulatory patterns persisted, indicating the need for flow distribution measures. In generation mode at maximum discharge (1819.45 m^3/s), velocities near the intake ranged from 0.4–0.5 m/s up to Ch. 300 m and increased to 0.9–1.1 m/s between Ch. 300–2000 m, with a peak of about 1.40 m/s at Ch. 1400 m; the flow distribution was relatively uniform without significant return flows or stagnation, and the initial 1:22 longitudinal slope was found optimal despite minor acceptable turbulence associated with water level rise from EL 361.35 m to EL 375.0 m. The snapshots from Hec-RAS 2D are attached below for all these conditions. Here it may be mentioned that velocities obtained from the Hec-RAS 2D mathematical studies are depth averaged. To address this flow concentration towards centre of tailpool, three divide walls, each 150 m in length with top at EL. 375.65 m, was found to produce satisfactory velocity distribution across all nine intake spans. This arrangement of 3 divide walls is able to reduce maximum velocities at large intake spans to 0.5 m/s and at small intake spans to 0.3 m/s. Divide walls 1 and 3 were identified as the most critical for uniform flow distribution and hydraulic short-circuit mitigation, while divide wall 2 was found important for operational flexibility of intake units 3-7.

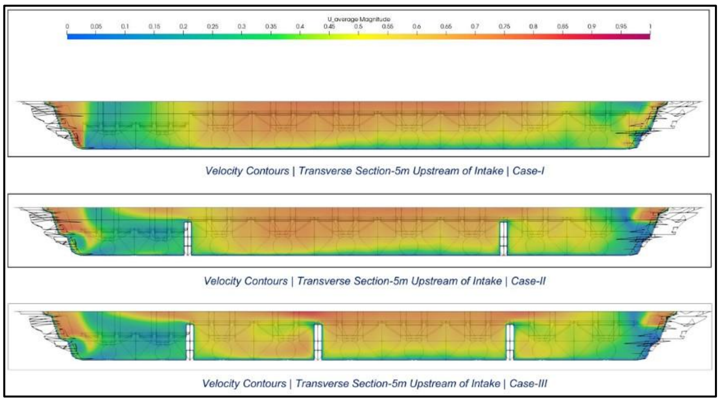
These results confirmed that the arrangement of three divide walls in the tailpool significantly improved flow distribution during all short-circuiting scenarios. Flow became stable with minimal turbulence near the intake. Overall velocities in the tailpool and TRC were below 1 m/s in all cases, confirming acceptability.

Velocities for pumping mode at rated discharge (1512.54 m³/s)	Velocities for pumping mode at Max discharge (1721.56 m³/s)	Velocities for generation mode at max discharge (1819.45 m³/s)
		
		

3.2 Mathematical Model Studies in 3D CFD

While HEC-RAS 2D gives depth-averaged velocities that are sufficient for overall tailrace channel design, it cannot capture detailed three-dimensional flow near the intake, which is important for studying vortices, swirl, and flow distribution. Therefore, 3D CFD studies were carried out using OpenFOAM for a region extending about 700 m upstream of the intake, including the tailpool and intake structure. The flow was simulated using Unsteady Reynolds-Averaged Navier-Stokes equations with the k-ω SST turbulence model, solved using the PimpleFoam solver in OpenFOAM suitable for unsteady flows. The model was meshed using blockMesh and snappyHexMesh with a base grid size of 1.25 m, refined to 0.625 m near the intake and 0.3125 m in critical zones like vortex breaker beams and diffuser regions, resulting in a total mesh size of less than 5 million cells. Three cases were analyzed: without divide walls (Case-I), with two divide walls (Case-II), and with three divide walls (Case-III), all under pumping mode at maximum discharge of 1721.56 m³/s and reservoir level at EL 381.0 m.

Streamline and velocity contour analysis showed that in Case-I (without divide walls), most of the flow was concentrated toward the central intakes, while the outer intakes received less discharge. Also, due to the internal geometry, the middle spans of each intake carried less flow than the outer spans, resulting in about 10–12% uneven distribution. In Case-II (with two divide walls), the flow distribution improved but was still not completely uniform. The best performance was observed in Case-III (with three divide walls), where flow was evenly distributed across all nine intakes. Velocity contours at different sections confirmed that Case-III achieved stable and well-balanced flow conditions.



Free surface and sub-surface vortex assessment was carried out based on the classification system of Alden Research Laboratory (Nakato, 1995) as per ANSI/HI 9.8-1998. In Case-I, small surface vortices were observed near one of the intakes, which were reduced significantly in Cases II and III after introducing divide walls, and no air-entraining vortices were found in any case, indicating that the submergence depth and channel geometry were adequate. Swirl angles were also evaluated in each tailrace tunnel and were found to be within the acceptable limit of ±5° as per standards, with maximum values of about 4.8° in Case-I, 3.9° in Case-II, and 3.2° in Case-III; among these, Case-III showed the best performance with the lowest swirl, confirming that the use of divide walls improves flow conditions inside the tunnels.

3.3 Physical hydraulic model studies

A 3D physical hydraulic model was developed at Infraplan Hydraulic Laboratory, Pune, using Froude similarity at a scale of 1:50 to correctly represent free-surface flow conditions. The model included part of the lower reservoir, the full tailrace channel, tailpool, intake structure with nine units, anti-vortex beams, and part of the tailrace tunnel. Scaling relationships ensured proper representation of velocity, discharge, time, and pressure. Flow was controlled using calibrated devices, while discharge, velocity, water levels, and pressure were measured using standard instruments, and flow patterns were observed using dye and sawdust. The experiments covered both pumping and generation modes under different reservoir levels and operating conditions, including unequal unit operation and hydraulic short-circuiting, with studies carried out for cases without and with divide walls to evaluate their effectiveness.

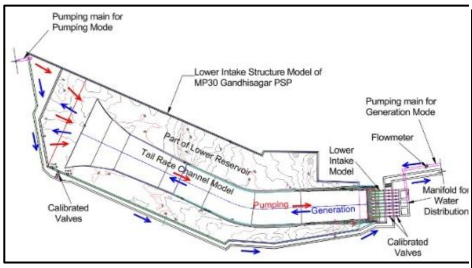
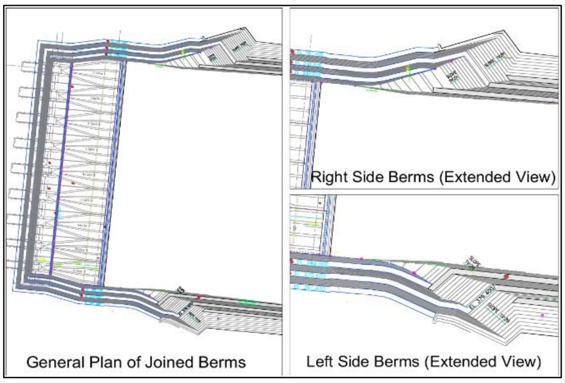


Fig. 1. General Layout of physical model

Fig. 2. Drone view of physical model

For both pumping and generation modes at MDDL (EL 381.0 m) with all units operating, the flow conditions in the tailrace channel and tailpool were generally satisfactory, with flow tending to move along the right bank due to channel curvature; only minor low-velocity circulations (<0.3 m/s) were observed near the ends of the tailpool, which were acceptable. In pumping mode, some flow concentration occurred upstream of the tailpool along the 1:22 slope, while in generation mode the flow was more uniform as it spread out from the intakes. Measured velocities in the channel ranged from 0.8 to 1.5 m/s, with lower values near the intake (0.4–0.9 m/s) and around 0.8–1.1 m/s at the trash rack, matching design expectations. Pressure measurements showed a drop of about 1.0–1.5 m from the trash rack to the tunnel, with no negative pressure observed. Water surface profiles indicated a gradual rise along the channel during generation mode, while in pumping mode a drawdown of about 0.8–1.3 m occurred between the reservoir and intake, which was consistent with model predictions.



The curvature of the tailrace channel created triangular spaces between the existing berms at site and the proposed channel alignment on both sides, for which a suitable connecting geometry was developed and tested; flow in these pockets was almost stagnant under all conditions, indicating that the design was acceptable. Additionally, a 2.5 m gap between the end spans of the intake and the side berms initially caused circulatory flow near the top right end during pumping mode; after filling this gap in the model, the circulations reduced significantly to about 0.3 m/s, which was within acceptable limits. Two layouts of divide wall arrangements were tested in the physical model. The first layout with two divide walls improved the flow distribution compared to the original condition but still showed some uneven flow, while the second layout with three divide walls (recommended) gave much better and uniform flow distribution. The results from the physical model matched well with CFD and HEC-RAS studies, confirming that three divide walls are effective and necessary. The top level of the divide walls is kept at EL 375.65 m, which remains below normal water levels (minimum about EL 380 m), so they do not obstruct the flow during operation. Hydraulic short-circuiting conditions were also tested for different scenarios with three divide walls at MDDL, where only minor surface circulations were observed, mainly near boundary units. The divide walls helped guide the flow properly towards the channel and reduced cross-flow between units operating in different modes. Even in short-circuiting cases involving smaller units, some circulation was observed near anti-vortex beams, but it remained within acceptable limits due to low discharge.

Fig. 3. Physical model with 3 divide walls

Fig. 4. Flow conditions during HSC with 3DW

4 Comparative Analysis of Results

A key objective of the multi-model approach was cross-validation between the three study methods. Table below represents a comparative summary of hydraulic parameters across all three methodologies.

Table 1. Comparative Summary of Key Results Across Three Study Methodologies

Sr. No.	Parameter	HEC-RAS 2D	CFD (Open-FOAM)	Physical Model
1	Max. velocity in TRC (pumping max.)	1.65 m/s	~1.5-1.8 m/s	1.3-1.5 m/s
2	Velocity at intake (pumping max.)	0.4-0.6 m/s	0.5-0.8 m/s	0.5-0.9 m/s
3	Head loss (reservoir to intake)	1.3 m (pump. max.)	N/A	1.0-1.5 m
4	Flow concentration without div. walls	Observed	Observed	Observed
5	Flow uniformity with 3 divide walls	Good	Good	Good
6	Swirl Angle	N/A	swirl -3.9° to 3.2°, acceptable	N/A

7	Vortex formation at MDDL	Circulations only	No air-entraining	Minor, acceptable

The results from all three methods were in close agreement for the key hydraulic parameters, providing high confidence in the final design. Minor quantitative differences are attributable to the inherent capabilities and limitations of each method: HEC-RAS provides depth-averaged velocities; CFD provides detailed 3D velocity fields but with simplified free-surface assumptions; physical models capture all real-world effects but are subject to scale effects and measurement uncertainties. The consistent identification of flow concentration and circulatory currents in the tailpool across all three methods underscores the importance of the divide wall solution. The equally consistent finding that three divide walls provide superior performance justified the final design recommendation.

5 Conclusion

The study demonstrates that the hydraulic design of the tailrace channel can be effectively optimized using an integrated multi-modelling approach involving HEC-RAS 2D, CFD (OpenFOAM), and physical hydraulic model studies. The 2D model established the channel geometry and alignment, while CFD provided detailed insights into three-dimensional flow behavior near the intake. These findings were validated through 1:50 scale physical model studies, confirming the reliability of the results. Flow concentration in the tailpool was mitigated by introducing three divide walls, improving flow uniformity and reducing swirl. The final design achieved controlled velocities, stable flow conditions, and acceptable head losses, proving the effectiveness of the combined modelling approach.

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