Hydraulic Design Aspects Of Pumped Storage Intakes For Reversible Turbines

Ashish A. Doshi[1], Pramod B. Deolalikar[2], Amruta S. Kale[3] and Karan H. Magadum[4]

[1] Infraplan Hydraulic Laboratory, Pune, India
[2] Senior Independent Hydraulic Consultant, Pune, India
[3] Infraplan Hydraulic Laboratory, Pune, India
[4] Infraplan Hydraulic Laboratory, Pune, India
ihl@infraplan.in

Abstract. The Pumped Storage Projects (PSPs) are essential elements of modern renewable power systems, providing large-scale energy storage. The efficiency of PSP operation depends on the hydraulic performance of intake structures, which must ensure uniform flow distribution during both generation and pumping modes. This study focuses on hydraulic design aspects of intake systems for reversible turbines, with emphasis on flow distribution, vortex control, and operational stability. Nowadays, horizontal diffuser-type intakes are commonly adopted in PSPs, comprising multiple spans subdivided by intermediate piers and divide walls. However, such configurations often create hydraulic challenges by reducing effective flow area, leading to increased velocities, higher frictional losses, and susceptibility to flow separation, vortex formation, and cavitation, especially under asymmetric operation and low reservoir water levels. To address these challenges, comprehensive physical and mathematical model studies were conducted at Infraplan Hydraulic Laboratory, Pune. Various design interventions, including flow-conditioning devices, optimized trash racks, and submersible divide walls, were evaluated to enhance flow uniformity and reduce turbulence. Additionally, an alternative bellmouth rectangular intake with a sloping trash rack was studied, offering reduced frictional losses and more stable flow conditions by eliminating the top slab and intermediate piers. The results demonstrate that the bellmouth intake provides more stable flow patterns and mitigates adverse hydraulic phenomena compared to diffuser-type structures. Improved flow conditions are observed during pumping operation, where frictional losses in diffuser-type intakes are higher. Overall, the study highlights the importance of tailored intake design strategies to improve efficiency, reliability, and safety in PSPs.

Keywords: Upper and Lower Reservoir, Diffuser Type Intakes, Horizontal Intakes, Pumped Storage Projects, Bellmouth Intakes.

1 Introduction

The rapid expansion of renewable energy has highlighted the critical role of large-scale energy storage systems in ensuring grid stability and reliability. Nowadays, among the various technologies available, pumped storage power plants (PSPs) have emerged as widely implemented solution for balancing renewable generation. Their ability to operate flexibly in both pumping and generating modes makes them indispensable for modern power systems transitioning toward higher shares of solar and wind energy. A critical component of such systems is the intake structure, which governs the interaction between the reservoir and reversible pump-turbines. Unlike conventional hydropower intakes, PSP intakes must accommodate two distinct and often conflicting hydraulic conditions such as high-velocity inflow during pumping and controlled outflow during generation. This dual functionality places stringent demands on intake design, requiring careful attention to flow stability, pressure distribution, and vortex suppression. The challenge is further compounded by fluctuating reservoir levels and the need for long-term operational reliability under repeated daily cycling. The hydraulic design of pumped storage intakes has therefore become an area of active research and innovation. This paper focuses on the hydraulic design aspects of pumped storage intakes, highlighting design recommendations, current practices, and observed challenges, that can enhance their efficiency and reliability. Various physical model studies and mathematical studies have been conducted at Infraplan Hydraulic Laboratory (IHL), Pune for achieving efficient design of the intake. These studies showed that the shape, position, and flow-control features of the intake are very important for keeping the system efficient, free from cavitation, and stable under different operating conditions.

2 Present Design Considerations

The current intake layout proposed for pumping operation, as illustrated in Fig. 1 and Fig. 2, features a configuration where the intake structure is divided into multiple spans. Each span is further subdivided by interposing divide walls extending across the width of the slab. Although such an arrangement is intended to manage flow distribution, it results in a highly construction-intensive design. Furthermore, this subdivision reduces the effective cross-sectional area available for flow, thereby accelerating the velocity from the upstream reservoir towards the intake structure.

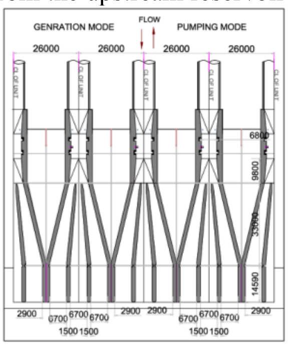


Fig. 1. Typical general layout of diffuser type intake structure in pumped storage project

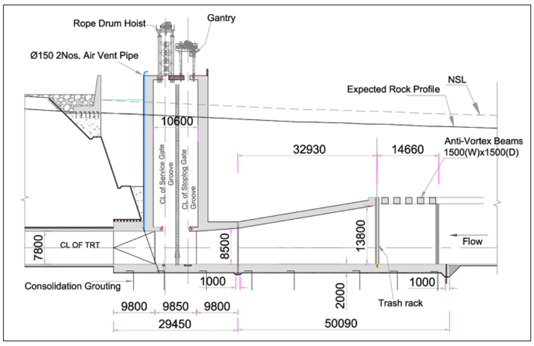


Fig. 2. Typical longitudinal section of Diffuser type intake structure in pumped storage project

A significant drawback of the current intake layout is the placement of the trash rack structure inside the intake barrels, downstream of the anti-vortex beams. This configuration presents considerable challenges for long-term maintenance and operational accessibility. Additionally, there exists a risk of debris accumulation and obstruction of the anti-vortex beams, particularly during fluctuating reservoir water levels associated with regular pumping and generation cycles. Although the upper reservoir is an artificially created impoundment where initially minimal debris ingress is expected, over time, the accumulation of organic material, sediments, and floating trash can become substantial. The current arrangement renders the intake structure highly susceptible to blockage, thereby posing risks to operational reliability.

Furthermore, the inclusion of a top slab over the bifurcated spans restricts the utilization of available submergence. The effective water depth above the intake is reduced, limiting the hydraulic advantages typically associated with deeper submergence, particularly in mitigating vortex formation. The rising slope of the intake top slab and the divide walls towards the reservoir further exacerbates this issue by reducing the effective flow depth, thereby increasing the likelihood of surface vortex formation and adversely impacting the intake performance during both operational modes.

3 Literature Review

Extensive global research has been conducted on intake hydraulics, particularly focusing on vortex formation, flow distribution, and intake geometry optimization.
Knauss (1987)[5] emphasized that swirling flows and vortices at intakes are strongly influenced by submergence and approach flow conditions. Similarly, studies by Gulliver and Rindels (1993) demonstrated that intake geometry plays a decisive role in minimizing flow separation and energy losses.

Hydraulic model studies by Cea et al. (2017)[6] on pumped storage systems showed that intake-outlet configurations significantly affect velocity distribution and turbulence characteristics. Guidelines from IAHR and ASCE[8] further highlight the importance of maintaining uniform approach flow and adequate submergence to prevent cavitation and vortex formation.

Case studies such as the Tehri PSP and Tala Hydroelectric Project illustrate practical challenges associated with multi-span intake configurations. These studies emphasize the importance of balanced flow distribution, optimized geometry, and proper flow alignment to ensure efficient and stable operation.

Hydraulic model studies for the Tehri Pumped Storage Plant focused on critical components such as the tailrace tunnel (TRT) outlet, upstream bifurcation, and downstream bifurcation under both turbine and pumping modes. The TRT outlet studies addressed oblique approach flow conditions that could induce circulatory currents and affect flow stability. Detailed investigations of upstream and downstream bifurcation systems were carried out using transparent physical models to simulate steady-state flow conditions with controlled head variations. Instrumentation including discharge measurement systems and pressure transducers was used to evaluate flow distribution and pressure characteristics. The studies emphasized the importance of balanced flow division and minimizing hydraulic losses in bifurcation zones. The results provided essential insights for optimizing intake and conveyance system design to ensure stable and efficient PSP operation.

Hydraulic model studies conducted at CWPRS for the Tala Hydroelectric Project involved comprehensive investigations on spillway, intake, and silt flushing systems under varying hydraulic conditions. The studies evaluated discharge characteristics, pressure distributions, and flow behavior for both original and modified designs using a large-scale physical model. Observations indicated issues such as negative pressures, overtopping of training walls, and highly turbulent flow conditions downstream of the ski-jump spillway. Modifications including changes in spillway geometry and introduction of divide walls were implemented to improve flow stability and reduce adverse hydraulic effects. Detailed intake studies demonstrated the importance of flow alignment and controlled approach conditions for efficient operation. The results highlighted that incorporation of divide walls significantly improved flow uniformity and reduced circulation near the intake region.

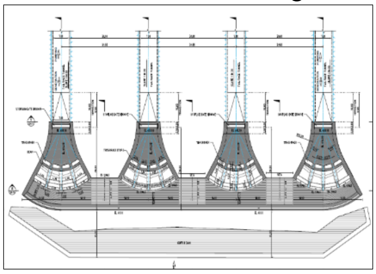


Fig. 3. Plan showing intake structure of Tehari PSP

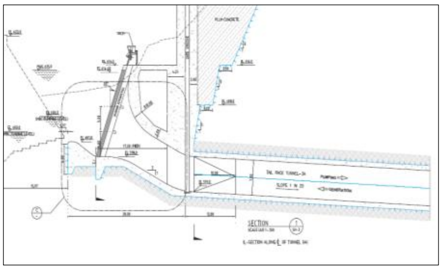


Fig. 4. Longitudinal section of intake structure of Tehari PSP

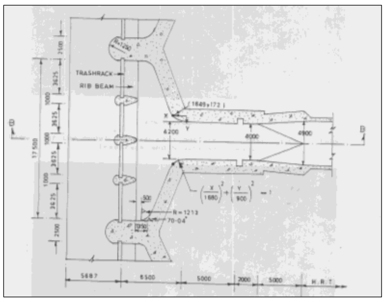


Fig. 5. Detailed plan view of intake structure in Tala HEP

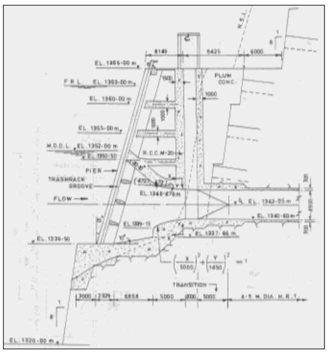


Fig. 6. Detailed plan view of intake structure in Tala HEP

4 Hydraulic Design Considerations

In such intake designs, the positioning of the intake structure is primarily influenced by vortex formation considerations. The required submergence depth for intake structures is clearly specified in the Bureau of Indian Standards (BIS) guidelines. In traditional hydroelectric projects, intakes are typically positioned at a right angle to the direction of water flow. However, in pumped storage power plants (PSPs), the intake is aligned with the direction of the water flow. As a result, it has been observed that the submergence requirements for PSP intakes are generally lower compared to those in conventional hydroelectric projects.

In hydroelectric projects, intakes are typically aligned at 90° to the flow direction due to the need for sediment flushing. However, in PSPs, sediment flushing is not a critical requirement. Despite this, provisions for sediment management should still be considered to enhance the performance and longevity of the intake structure. A key consideration in the current intake design is the placement of barrel structures in front of the intake. These barrel structures increase the likelihood of vortex formation at the upstream end, which can lead to inefficient flow conditions. (Ref: Gordon & Nagarkar – Fuentes, Turbulence).

5 Hydraulic Model Studies

A 1:40 scale hydraulic model of the lower and upper pumped storage intakes based on the Froudian similitude were constructed to investigate flow behaviour in the lower intake structure. The studies were carried out under steady-state conditions for both generation and pumping modes across multiple reservoir levels, including MDDL, MDDL+2 m, and MDDL–2 m, to capture the influence of varying submergence conditions. Key parameters such as velocity distribution, pressure variation, and flow patterns were systematically measured across lower intake spans and reservoir.

During generation mode, the approach flow from the reservoir towards the intake structure exhibited generally uniform and symmetrical characteristics under full-load operation; however, detailed observations indicate that the hydraulic performance cannot be considered fully optimal. While the inlet pool flow remained largely subcritical with absence of major vortex formation near the intake entrances, localized flow disturbances were evident under partial load conditions. Operation of non-central units resulted in noticeable surface circulations and mild asymmetry in flow patterns, indicating sensitivity of the intake system to operational variability. Furthermore, at reduced reservoir levels (MDDL–2 m), increased turbulence and circulatory flow were observed above the anti-vortex beams, highlighting the vulnerability of the intake system to reduced submergence and suboptimal approach flow conditions.

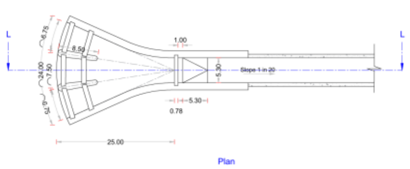
In pumping mode, the limitations of the intake configuration became more pronounced. Although the overall flow discharged from the penstocks into the inlet pool appeared macroscopically stable, persistent non-uniform flow distribution across the three spans of individual diffuser-type intake units was observed. One of the spans consistently exhibited reduced flow participation, indicating ineffective utilization of the available flow area. This non-uniformity, though random in occurrence, reflects inherent geometric and hydraulic inefficiencies within the intake configuration. Such asymmetric flow distribution can potentially lead to localized energy losses, uneven loading on structural components, and long-term operational concerns. While the anti-vortex beams were effective in preventing vortex formation, they did not address the issue of uneven flow distribution.

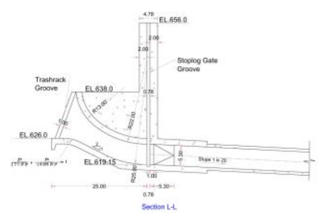
Velocity measurements further substantiate these observations. During generation mode, approach velocities ranged between 0.55 m/s and 0.68 m/s at the intake entrance, increasing to 0.75 m/s to 0.79 m/s near the trash rack, indicating localized acceleration and possible non-uniform flow contraction. In pumping mode, similar velocity trends were observed; however, variations across spans confirmed uneven flow distribution. Pressure measurements indicated a head loss of 1.5–1.6 m during generation mode and 0.6–0.7 m during pumping mode. Although these values fall within acceptable limits, they do not fully capture the localized inefficiencies arising from asymmetric flow conditions.

In view of the above hydraulic limitations, some geometric modifications were investigated to improve flow uniformity and overall intake performance. The primary modification involved the provision of a single divide wall (or optimized pier configuration) within the intake structure to guide the incoming flow and ensure more balanced distribution across the three spans. This intervention aims to reduce cross-flow interactions and minimize asymmetric flow patterns. Additionally, introduction of slight curvature along the side walls near the transition and trash rack regions was proposed to improve flow alignment, reduce boundary separation, and enhance streamline guidance into the intake barrels. These modifications are expected to mitigate the observed non-uniformity, improve hydraulic efficiency, and ensure more stable performance under varying operational conditions.

6 Design Recommendations for Pumped Storage Projects

In light of the findings and literature, it is recommended that intake designs similar to those shown below be considered for PSP studies. During the pumping mode of operation, the velocities exiting the intake structure could range from 4 to 5 m/s, with a depth and width varying between 8 to 14 meters. In this mode, water enters the reservoir with the minimum reservoir level at MDDL (Minimum Draw Down Level). During the generation (turbine) mode, the upstream flow velocities should be limited to 1.5 m/s to 2 m/s as the flow approaches the intake structure. However, velocities may increase to 2 to 3 m/s in the proximity of the intake, ensuring that adequate depth is maintained across the entire range of reservoir water level. Furthermore, to guide the flow downstream and minimize flow disturbances, submersible divide walls may be incorporated in the design in front of the intake. These walls will help prevent circulatory currents and ensure a uniform flow towards the intake.





7 Conclusion

The study highlights the critical influence of intake geometry on hydraulic performance in pumped storage systems. Diffuser-type intakes exhibit challenges such as non-uniform flow distribution and higher losses, whereas bellmouth configurations provide improved flow stability and reduced hydraulic losses. The incorporation of optimized design features including bellmouth entrances, divide walls, and flow-conditioning devices can significantly enhance intake performance under both pumping and generation modes. These improvements contribute to increased efficiency, reliability, and operational stability of pumped storage power plants. The paper also describes the improved flow conditions especially during pumping operation where frictional losses in the diffuser type intake are proportionately on higher side as compared to the bellmouth intake. Also, the energy dissipation and flow conditions in the reservoir are tending to uniform flow with minimum return eddies because of larger volume of water is available for sudden impact of flow from the intake on the reservoir.

Infraplan Hydraulic Laboratory, Pune, India is actively involved in the physical as well as mathematical model studies for intakes pertaining to pumped hydro storage projects and the detailed studies on efficient intake design.

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