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Government of India
Ministry of Jal Shakti
Department of Water Resources,
River Development & Ganga Rejuvenation

Compendium on Spillways and Energy Dissipators Design - A legacy of CWPRS

by
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CENTRAL WATER & POWER RESEARCH STATION
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Foreword

With immense pride and a deep sense of responsibility, I present this compendium, **"Spillways and Energy Dissipators Design: A Legacy of CWPRS".** This document encapsulates the unparalleled contributions of the Spillways and Energy Dissipators Division (SED) of the Central Water and Power Research Station (CWPRS), Pune, in advancing hydraulic engineering solutions critical to water and energy infrastructure.

Since its inception in 1916, CWPRS has been at the forefront of hydraulic research, serving as a cornerstone of India's water and energy security. While the SED Division was formally established in 1958, CWPRS's pioneering work in optimizing spillway designs began decades earlier with the first hydraulic model study conducted for the Malaprabha Weir Spillway in Karnataka during 1938-40. This early initiative laid the foundation for CWPRS's legacy of excellence, which now includes the optimization of over 180 spillways, serving national and international needs.

This compendium offers a detailed chronicle of SED's contributions to landmark national projects such as the Hirakud, Sardar Sarovar, Indirasagar, and Koyna double lake tapping projects that collectively secure over 258 billion cubic meters of water storage and generate millions of megawatt-hours of renewable energy annually. It also showcases the Division's expertise in managing high sediment loads and extreme floods in Himalayan River projects like Subansiri, Lower Siang, Teesta, and Kishanganga, where multitier spillways and sediment flushing techniques have been applied to meet unprecedented engineering challenges.

Internationally, CWPRS has left an indelible mark with its expertise extending to strategic projects such as the Salma Dam in Afghanistan, the Mangdechhu and Tala dams in Bhutan, and key hydraulic structures in Iraq and Iran. These endeavors have strengthened CWPRS's position as a global leader in hydraulic research, fostering technical collaborations and contributing to sustainable water resource management across borders.

The innovations highlighted in this compendium-ranging from hybrid modeling techniques that integrate physical and CFD tools, to state-of-the-art spillway aeration systems, and the optimization of plunge pools for ski-jump energy dissipators-reflect CWPRS's unwavering commitment to setting new benchmarks in hydraulic engineering. The Division's work has not only ensured the safety and sustainability of critical infrastructure but also significantly reduced project costs and timelines.

As we navigate the emerging challenges of climate change, water scarcity, and increasing demands on infrastructure, the expertise of institutions like CWPRS becomes even more indispensable. This compendium stands as a testament to the dedication, technical acumen, and collaborative spirit of CWPRS's scientists, engineers, and support staff, who have transformed the field of hydraulic engineering through their relentless pursuit of excellence.

I am confident that this compendium will serve as an invaluable resource for engineers, researchers, policymakers, and future innovators. It provides a wealth of knowledge and insights, inspiring a new generation to tackle the challenges of sustainable water resource management with innovation and resilience.

I extend my heartfelt congratulations to the authors and the entire team behind this compendium for their exemplary efforts in documenting CWPRS's legacy and ensuring its vast repository of knowledge remains accessible to all.

Dr. R. S. Kankara
Director, CWPRS

Executive Summary

The Central Water and Power Research Station (CWPRS), established in 1916 and renamed in 1951, is a premier institution dedicated to hydraulic and allied research, serving India's water and power sectors. Over a century of pioneering work, CWPRS has emerged as a central agency for innovation and consultation, delivering safe and economical designs for hydraulic structures critical to water resource management, river engineering, power generation, and coastal management.

The Spillways and Energy Dissipators Division (SED), established in 1958, specializes in the design and optimization of spillways and energy dissipators for irrigation, hydropower, and flood control projects. Spillways play a crucial role in dam safety by enabling the controlled release of excess water. Using physical and computational modeling, SED has developed efficient, safe, and cost-effective designs for spillways, energy dissipators, tunnels, sediment bypass systems, and desilting basins.

India's major river systems such as the Ganga, Brahmaputra, Indus, Narmada, Mahanadi, Godavari, Krishna, and Kaveri have greatly benefited from CWPRS's expertise in addressing challenges related to floods, droughts, food security, and energy security. CWPRS has played a pivotal role in landmark projects, including Indirasagar, Hirakud, Koyna, Bhakra, Omkareshwar, Nagarjunasagar, Polavaram, Subansiri, Kishanganga, and Sardar Sarovar, optimizing spillway designs and ensuring dam safety.

CWPRS's contributions extend internationally, with notable work on projects such as the Salma Dam in Afghanistan, Bakurman and Khaleelkan in Iraq and Iran, and hydropower development in Bhutan. Currently, CWPRS is involved in designs for innovative projects like the Kalpsar in Gujarat, addressing challenges posed by tidal influences and saline conditions in coastal reservoirs. It is also actively involved in hydropower projects in the Chenab Valley, including Rathle, Kiru, Kwar, and Pakal Dul, furthering its legacy of excellence.

Chapter 1, *"Overview of Spillways and Energy Dissipators"*, introduces the critical role of these structures in dam safety. It explores various types of spillways and energy dissipators, emphasizing the importance of physical and numerical modeling to address site-specific challenges. Case studies highlight their evolution to meet safety and efficiency demands.

Chapter 2, *"Challenges in the Design of Spillways and Energy Dissipators"*, discusses the complexities of designing these structures in geologically and hydrologically challenging regions such as the Himalayas and coastal areas. It addresses issues like sedimentation, glacial lake outburst floods (GLOFs), climate change, and narrow valleys. Innovative solutions, including multitier spillways for high heads and sediment-heavy flows, are explored.

Chapter 3, *"Contributions to National and International Projects"*, details CWPRS's pivotal role in optimizing designs for major projects like Kishanganga, Subansiri, and Lower Siang. International contributions, including Bhutan's Mangdechhu and Tala projects and Afghanistan's Salma Dam, underscore the institution's global expertise in safe, efficient, and cost-effective hydraulic designs.

Chapter 4, *"Innovations and Foundational Research"*, highlights CWPRS's advancements in hydraulic engineering. Foundational research on orifice spillways, hybrid modeling techniques, and sediment flushing has shaped design guidelines and informed solutions for emerging challenges.

Chapter 5, *"Lessons Learned and Future Directions"*, consolidates insights from recent projects, emphasizing the importance of site-specific, tailored solutions in hydraulic designs. It outlines the growing role of hybrid modeling and identifies future research directions to address challenges related to water security, climate resilience, and sustainable development.

CWPRS has pioneered cutting-edge hydraulic solutions, including orifice spillways for sediment-heavy rivers, multitier spillways for extreme flood conditions, and hybrid modeling techniques combining physical and CFD models for precision and cost-effectiveness.

Through its innovative designs and research, CWPRS has established itself as a cornerstone of India's water security, renewable energy development, and environmental sustainability. Its contributions continue to enhance the safety, efficiency, and cost-effectiveness of hydraulic projects across the globe.

Acknowledgements

The Spillways and Energy Dissipators Division (SED) was established in 1958 to study spillways for dams constructed post-independence for irrigation, power generation, and flood control. The division focuses on developing efficient, economical, and safe hydraulic designs for spillways, energy dissipators, headrace and tailrace tunnels, power intakes, water conductor systems, sediment bypass tunnels, and desilting basins for irrigation, hydropower, and multipurpose projects in India and abroad. These studies are conducted using physical models, numerical models, and desk studies.

The division's major research activities include assessing approach flow conditions upstream of spillways, evaluating discharging capacity under full and partial gate openings, analyzing cavitation potential on spillway surfaces, testing energy dissipator performance, designing plunge pools, and devising downstream protection works.

In addition to applied and basic research, SED scientists actively pursue state-of-the-art knowledge in the field and share their expertise through research and training. Many scientists have obtained master's degrees and doctorates from prestigious institutions while working in the division. The division's contributions to the development of BIS codes under WRD are notable, and the book "Hydraulics of Spillways and Energy Dissipators" by former Additional Director Sh. R. M. Khatsuria has become a globally recognized reference in hydraulic engineering.

The SED division has published over 350 papers in journals and international conferences, in addition various memoranda, and design guidelines are widely referenced by researchers worldwide. Its cumulative research has received recognition on multiple platforms, with scientists receiving awards from CBIP, ISH, and the Ministry. The division has also contributed to international relations by establishing hydraulic laboratories in Iraq and Iran and conducting studies for the Bakurman and Khaleelkan projects. Training programs for scientists from Iraq and Vietnam have been successfully conducted, further enhancing international cooperation. Many international dignitaries and researchers in the field have visited CWPRS to witness the model studies.

To disseminate its expertise, the division organizes training programs attended by industry stakeholders, academicians, and students. Its physical models are regularly displayed to dignitaries and the general public, showcasing its contributions. The division remains a hub of talented researchers and skilled staff.

The authors express their heartfelt gratitude for the invaluable contributions of the retired officers, whose unwavering dedication and efforts were pivotal to the success of these studies. Special acknowledgment is extended to S/Shri M. K. Verma (Sc D and Head of the Division), M. Z. Qamar (Scientist C), V. S. Ramarao (Scientist C), Ms. Sangeeta Patnaik (Scientist C), Ravindra Bhate (Scientist C), Kiran More (Scientist C), Amit Kulhare (Scientist C), B. S. Sundarlal (Scientist C), Ms. Sushma Vyas (Scientist C), Ms. Vaishali Gadhe (Scientist C), and Ms. Sumedha Kulkarni (Scientist C) for their significant contributions to the preparation of this compendium, titled "Spillways and Energy Dissipators Design- A Legacy of CWPRS".

Additionally, sincere acknowledgments are extended to the project authorities whose valuable inputs, insights, and cooperation have been instrumental in facilitating the successful completion of various studies and projects. Their support and collaboration have greatly enriched the outcomes and ensured the practical relevance and implementation of the research findings.

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CHAPTER 1

Overview of Spillways and Energy Dissipators

1.0 Introduction

Presently, India ranks third globally having 5254 large dams in operation and 457 under construction. Spillways are protection structures or safety devices in a dam-reservoir system. The spillways are used for maintaining normal river water functions, controlling floods, flushing of reservoirs, releasing surplus water and lowering water levels in an emergency. A typical spillway for a dam project has several components downstream including an approach channel, control structure, discharge channel, energy dissipator and tail channel from the reservoir to the river channel. Improper functioning of the spillway affects the overall safety of the dam/ reservoir and its allied structures. Some of the complexities that may arise include inadequate spillway capacity, dam overtopping, temporary gate failures, insufficient conveyance capacity, cavitation damage to the glacis, overtopping of chute or energy dissipator walls, damage from abrasion or cavitation, malfunctioning of the energy dissipator, undermining of the dam, and erosion downstream of the bucket.

There is a tremendous challenge ahead to meet the worldwide increasing demand for water and power, especially for fast developing countries like India by construction of environmentally sustainable and socially acceptable dams, as well as taking an international approach in sharing the water during the 21st century, requiring rigorous methodologies and strategies for sustainability.

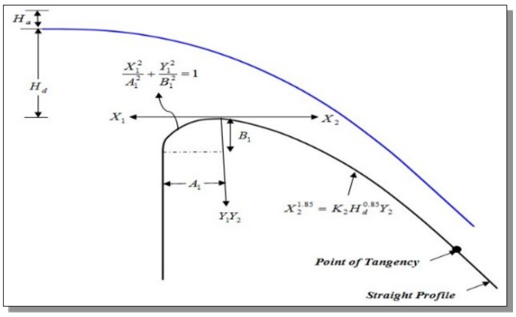
The construction of dams involves huge capital costs and recurring maintenance expenditures. Therefore, the dam hydraulics should be optimized functionally and economically before the execution of construction work. The design of a spillway requires the utmost attention. Many dam failures occurred in the past due to improperly designed spillways or inadequate capacity. For several decades, the art of hydraulic modelling has been an important tool in solving complex hydraulic problems. Nowadays, the Computational Fluid Dynamics (CFD) technique can be used as a complementary tool to the physical model in modelling spillway flows.

1.1 Types of Spillways

The spillway is an integral part of a dam and constitutes a significant percentage of the total cost of the dam. Proper spillway design is thus, very important from the standpoint of economy as well as safety. The spillway controls the overflow, particularly during floods and conveys the water away from the dam. There are various types of spillways based on functional requirements, topography, geology, dam safety and project economics. Spillways can be broadly classified into two types, viz. overflow spillway and orifice spillway based on the position of the inlet with reference to the Full Reservoir Level (FRL). The type of spillway to be adopted for a particular situation is governed by the purpose of the dam, the location of the dam, operating conditions and safety conditions consistent with the economy.

1.1.1 Overflow spillway

The ogee-crested spillway is one of the most studied hydraulic structures of overflow spillways. The two important characteristics of spillways are the profiles (shapes) of the spillway and the coefficient of discharge. The shape of the ogee-shaped spillway depends upon several factors such as head over the crest, height of the spillway above the stream bed or the bed of the entrance channel and the inclination of the upstream face of the spillway. USBR conducted extensive experiments to obtain the profile of the overflow spillways for various hydraulic parameters. The U.S. Army Corps of Engineers developed several standard shapes of the crests of overflow spillways based on U.S.B.R. data. The shapes are known as the W.E.S. standard spillway shapes, because they were developed at the Waterways Experiment Station at Vicksberg (W.E.S.), USA. The shape of the ogee spillway ordinarily conforms closely to the profile of the lower nappe of a ventilated sheet falling from a sharp-crested weir. For discharges at the design head, the flow glides over the crest and attains maximum discharge efficiency (USBR, 1987). Overflow spillways have been in use for many years in high-head storage dams of Peninsular India. Indirasagr in MP, Jigaon in Maharashtra, Omkareshwar in MP, Srisailam Dam in AP etc are examples of overflow-type spillways.



Definition sketch of overflow spillway

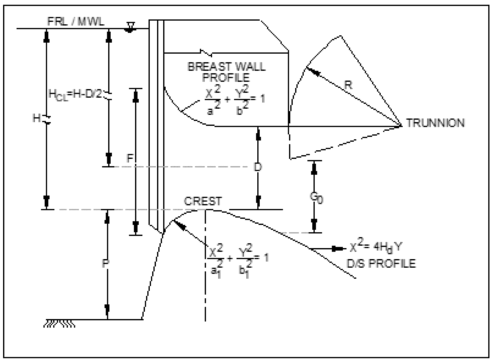
Typical view of overflow spillway

1.1.2 Orifice/Breastwall spillway

In the past, overflow spillways were being used on most of the dams. However, due to the sedimentation of dams especially in the Himalayan region, the design of overflow spillways was modified to orifice spillways which can carry out the dual function of passing the flood and flushing the sediment out of the reservoir. The current trend in the design of orifice spillways is keeping the crest as low and near the river bed as possible from consideration of the flushing of sediment from the reservoir. The main advantages of orifice spillway are:

- Can be accommodated in a narrow valley
- Reduction in height of spillway gates
- Reduction in the number of spillway spans
- Ease of regulating flood and storage
- Reduction in cost of gates and operating mechanism
- Can be used for diversion of flows during construction of the project
- Can also be used for flushing of sediments

Parbati stage II and Parbati stage III in HP, Pare dam in Arunachal Pradesh, Subansiri dam in Arunachal Pradesh/Assam, Tala dam in Bhutan etc, are examples of orifice spillways.



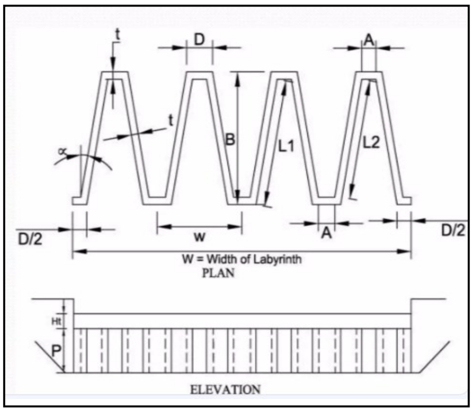
Definition sketch of orifice spillway

Typical view of orifice spillway

1.1.3 Uncommon types of spillways

Labyrinth/duckbill spillway/Piano key weir, stepped spillway, tunnel spillway/Shaft spillway, fuse plug, etc., are some of the uncommon types of spillways that are rarely used because of topography, geology and other hydraulic aspects.

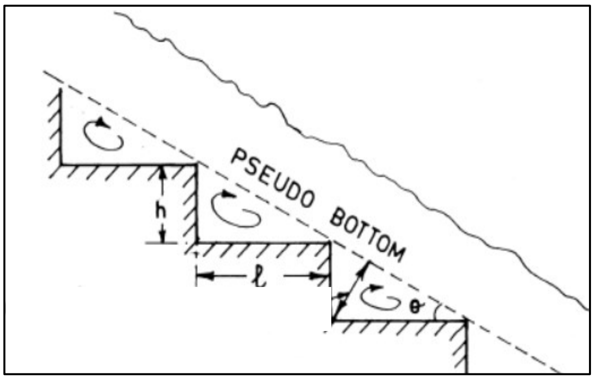
Labyrinth spillways are particularly suited to sites where the spillway width and upstream water surface are limited and larger discharging capacities are required. This may also provide additional storage capacity instead of a more costly gated structure. Labyrinth weirs can be particularly attractive for upgrading existing developments to satisfy more demanding design flood criteria in the limited waterway of an existing Spillway. Salauli Project is the first major irrigation project in Goa, where the ogee spillway was replaced by the duckbill spillway, a type of labyrinth spillway to pass the maximum discharge by increasing the waterway in the available width. The Piano Key Weir (PKW) is a modified labyrinth-type weir that makes use of inclined apexes to maximize the allowable weir length that can fit in a given channel width. The PKWs have emerged as innovative and viable solutions for both dam rehabilitation and new projects with space constraints.



Definition sketch of labyrinth spillway

Typical view of labyrinth spillway

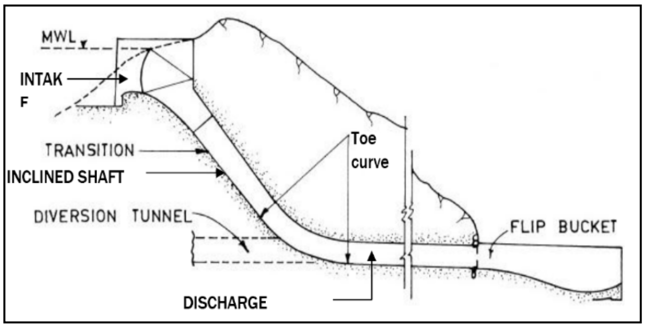
Stepped spillway chutes can be economically integrated into the downstream face of gravity dams, especially if roller-compacted concrete (RCC) is used for the construction. Another common application is using stepped overlays on embankment dams as emergency spillways. In both cases, a careful hydraulic and structural design of the complete spillway, including the energy dissipator, is necessary to ensure safe operation over the whole lifetime of the dam structure. The main advantage of using such spillways is a considerable amount of energy dissipation along the chute leading to a reduction in the size of the stilling basin. At present, the use of stepped spillways is limited to unit discharge up to 30 m^3/s/m, because of apprehension of cavitation damage for higher discharges.



Definition sketch of stepped spillway

Typical view of stepped spillway

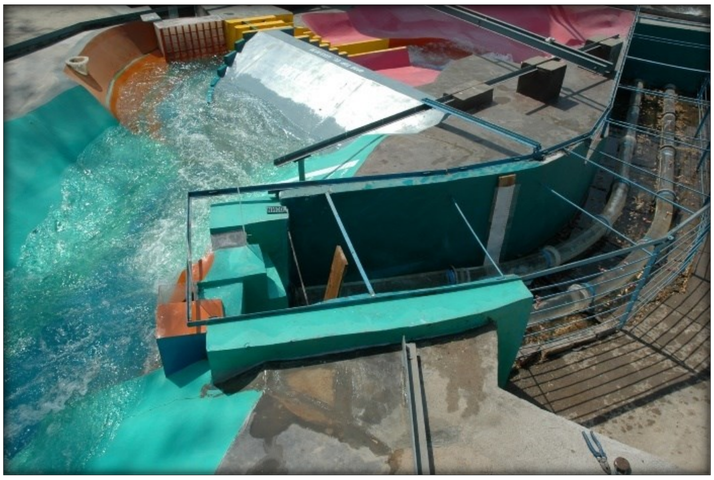
Tunnel spillways are provided in the rock fill, earth, and concrete-faced rockfill dams where it is difficult to accommodate the spillway in the river gorge. They are used advantageously at dam sites in narrow canyons with steep abutments or at sites where there is a danger to open channels from rock slides or snow. Most forms of control structures, including overflow crests, vertical or inclined orifice entrances, drop inlet entrances, and side channel crests, can be used with tunnel spillways. In the Dhauliganga Project, Uttarakhand, the original design having three spans of chute spillway was modified into two spans of chute spillway and one span of tunnel spillway. This modification was due to landslides along the right bank due to weak geological conditions and the non-availability of a foundation.



Definition sketch of tunnel Spillway

Typical view of tunnel spillway

In most cases, diversion tunnels constructed to divert the water during the construction of the projects were utilized for various purposes such as power tunnels, silt-flushing tunnels, irrigation outlets, and spillway tunnels. In India, at Pong Dam on the Beas River, out of 5 diversion tunnels, three were converted to power tunnels and two are being utilized as irrigation outlets. In the Baira Siul Project, HP the diversion tunnel is being utilized for flushing the sediment from the reservoir successfully. For Parbati stage-III, HP, the diversion tunnels would be used as a tunnel spillway to pass excess discharge from the river. The diversion tunnels have been utilized as spillway tunnels in many Latin American dams with high heads and large discharges, e.g. Funil Dam, Euclidesda Da Cunha Dam, Paraibina – Paraitinga Project.



Model view of diversion tunnels for Parbati Stage III Dam

A fuse plug is an earth and rockfill embankment designed to wash out completely in a predictable and controlled manner, when the spillway capacity of the service spillway and additional outlets, such as the bottom outlet, is exceeded. Along rivers, fuse plugs can provide a side spillway to prevent uncontrolled overtopping of the embankments. The following points should be taken into consideration while designing the fuse plug structure:

- It is necessary to have a saddle at a reasonable distance from the main dam along the rim of the reservoir for discharging the excess flood through a natural or artificial tail channel into the same river or a neighborhood valley.
- A good quality rock should be available for the foundation of the fuse plug to withstand the erosive action of the flow when the fuse plug is washed out.
- If deep overburden exists in the saddle, it would be necessary to provide concrete cut-off walls beneath the fuse plug embankment to restrict the undermining of the foundation.
- A suitable tail channel to lead the flow from the fuse plug into the main river should be available so that other adjacent structures are not threatened.
- The cost of rehabilitation measures for the fuse plug and repairs of damages to downstream facilities, if any, should be taken into account in economic analysis, even though it is infrequent and covers a short duration.

Fuse plugs have been adopted at very few projects such as Bartlett and Oxbow in the US, Victoria in Australia, Mnjoli in Swaziland, Gangapur and Muramsilli in India etc. The existing fuse plugs are constructed for unit discharge upto 83 m^3/s/m, height up to 10 m, maximum head of 13.5 m, and breaching length up to 1200 m.

Typical view of fuge plug spillway

1.2 Components of a Spillway

1.2.1 Entrance or approach channel

- Spillways placed through abutments or saddles or ridges may require approach channels leading flow to the spillway.
- The main function of the approach channel is to convey efficiently water with least afflux, and uniformly towards the spillway crest, to economize spillway width by increasing the coefficient of discharge.
- Non-uniform approach flow conditions result in the reduction of the coefficient of discharge of the spillway and also unequal flow depths in adjacent spillway spans. It also results in the cross-waves over the chute of the spillway which affects the performance of the energy dissipator while they all connect to the same tail water depths.
- The velocities at the entrance of the spillway should be limited. Alignment of the training walls in the approach channel should be such that the channel curvature and transitions should be gradual to minimize head loss.
- There is a necessity of model studies to optimize the layout of the approach channel which involves dressing the river bank upstream of the spillway so that flow is guided smoothly towards the spillway.

Non-Uniform approach flow conditions

Uniform approach flow conditions

1.2.2 Control structure

- The control structure usually consists of either an orifice or a weir. It controls the outflow from the reservoir. Since the flood water passes over the crest of the spillways, this part has to be designed carefully to pass the maximum flood.
- A control device limits or prevents outflows below fixed reservoir levels and regulates releases when the reservoir rises above that level. A control structure may consist of a sill, weir, orifice, or pipe.
- To have an economic and efficient design of spillway crest, it must be shaped such that it has a high discharge coefficient and results in acceptable pressure distribution. These aspects can be fulfilled, if the shape of the overflow spillway crest closely approximates that of a fully ventilated nappe of water flowing over a sharp-crested weir. The shape of such a profile is affected by the head on the spillway.
- Generally, the control structure is located at the upstream end of the spillway structure. However, in some cases, the control structure may be at the downstream end of the spillway structure. For example, in a shaft (or Morning Glory) spillway, the downstream tunnel controls the outflow at higher heads.

Ogee crest control

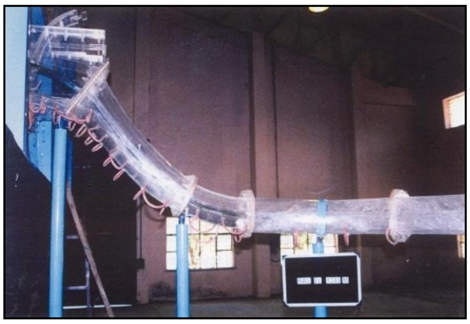
Morning Glory crest

1.2.3 Discharge channel/tunnel (or Waterway)

- Flow released through the control structure is usually conveyed to the streambed below the dam in a discharge channel or waterway.
- Exceptions are where the discharge falls freely from an arch dam crest or where the flow is released directly along the abutment hillside to cascade down the abutment face.
- The conveyance structure may be the downstream face of a concrete dam, an open channel excavated along the ground surface, a closed cut-and-cover conduit placed through or under a dam, or a tunnel excavated through an abutment.
- The profile may be variably flat or steep; the cross-section may be variably rectangular, trapezoidal, circular, or another shape; and the discharge channel may be wide or narrow, long or short.
- Discharge channel dimensions are governed primarily by hydraulic requirements, but the selection of profile, cross-sectional shape, width, length, etc., is influenced by the geologic and topographic characteristics of the site.

- Discharge channels must be cut through or lined with material that is resistant to the scouring action of the accelerating velocities and that is strong enough to withstand the forces from backfill, uplift, static and dynamic forces of water, etc.
- The width of the spillway plays a major role in the economic analysis. Normally, a narrow spillway with higher discharge intensities would be less expensive than a wider spillway with moderate discharge intensities.

Discharge channel

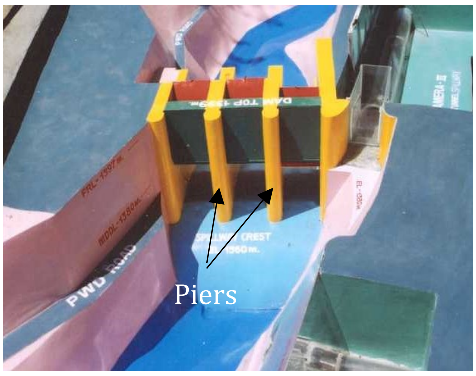


Discharge tunnel

1.2.4 Pier

- Crest piers are required when gates are to be installed to control the flow passing down the spillway. Piers may still be required for an ungated spillway for a road bridge on top.
- Piers should be inserted generally to start in the subcritical flow area to guide the flow properly.
- The most common shape of the pier includes a semi-circular upstream end kept flush with the upstream face of the crest.
- The design of the downstream end cut of the pier often tapers or includes specific shapes to reduce water turbulence and manage flow efficiently. The end cut is crucial because improper design or wear can lead to issues like increased turbulence, cavitation, and damage to both the piers and the spillway structure. Proper design adjustments are needed to prevent these problems, ensuring efficient water discharge and long-term stability of the spillway system. The downstream end cut may be terminated in a rectangular (90^0) shape to induce rooster tail-like flow conditions that generally assist in aeration.
- Piers projecting upstream of the spillway face may be required from structural considerations and have smaller contraction coefficients.
- Generally, the crest piers have a consistent thickness but those that taper in the flow direction are preferred, if permissible by structural considerations.

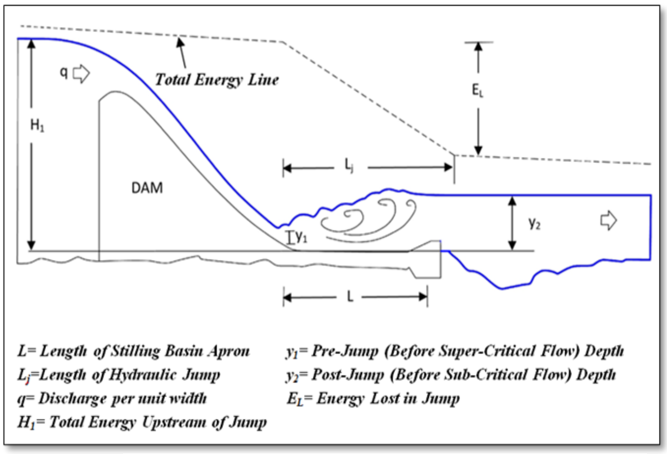
Downstream view of pier



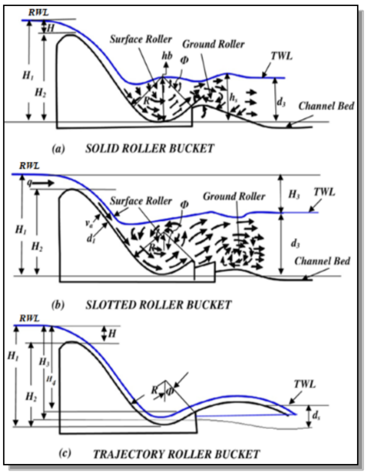
Upstream view of pier

1.2.5 Energy dissipator

- Energy dissipator is provided at the base of the spillway to dissipate the excess energy passed over the spillway and protect the riverbed and banks from erosion.
- In some cases, the discharge may be delivered at high velocities directly to the stream, where the energy is dissipated or transferred to other medium in the air, along the streambed by impact, turbulence, and friction. Such an arrangement is satisfactory where there is erosion-resistant bedrock at shallow depths in the channel and along the abutments or where the spillway outlet is far enough from the dam and other appurtenances to preclude damage by scour, undermining, or abutment sloughing.
- Stilling basins and roller/ski jump buckets are broadly used for dissipation of excess energy and provide safe flow conditions in the river downstream of the spillway.
- Sometimes, upturned deflectors, cantilevered extensions, or flip buckets can be provided to project the jet downstream from the end of the structure.



Stilling basin type energy dissipator



Bucket type energy dissipator

1.2.6 Tail Channel

The exit channels are provided to convey the spillway discharge from the energy dissipator to the river downstream. The flow leaving the energy dissipator is led to the river downstream of the main dam, either through a natural stream or an artificial channel. It is customary to provide a partial section, namely a pilot cut in the beginning, and allow it to attain its stable configuration in due course of time, provided erosion in the vicinity is not a problem. An exit channel is not required for the spillways which discharge water directly into the river downstream. However, in the case of spillways placed through abutments, saddles or ridges, the exit channel is usually required.

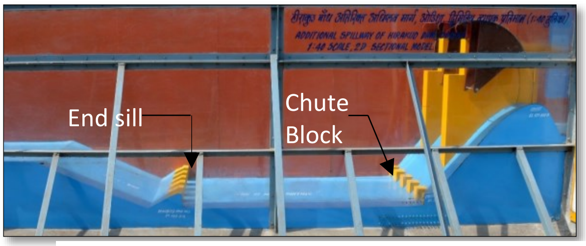
Tail channel for Telengiri dam Spillway

1.3 Types of Energy Dissipators

The factors that govern the choice of the particular type of energy dissipator are hydraulic considerations, topography, geology, type of dam, layout and other associated structures, economic considerations, frequency of usage etc.

1.3.1 Hydraulic jump stilling basins

Stilling basins are the most common types of energy dissipators provided for the dissipation of energy at the toe of spillways. The dissipation of energy takes place due to the formation of a hydraulic jump in the stilling basin. A hydraulic jump is a transition from supercritical to subcritical flow. This includes horizontal and sloping aprons and basins equipped with energy-dissipating appurtenances such as chute blocks, baffle piers, and dentated end sills. This is the most common type of energy dissipator for the spillways and outlets and dissipates up to 60% of the energy entering the basin, depending on the Froude number of the flow. For heads exceeding about 100 m, hydraulic jump stilling basins are not recommended because of the problems associated with turbulence like intermittent cavitation, vibration, uplift, and hydrodynamic loading.

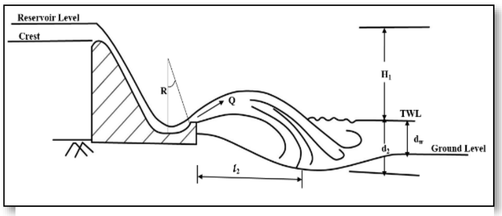


Typical model view of the stilling Basin

Typical prototype view of the stilling basin

1.3.2 Free jets and trajectory buckets

These are not dissipators of energy in the real sense. The bucket deflects the high-velocity jet into the air and is made to strike the downstream pool of water or riverbed at a considerable distance from the structure. Any scour that may occur in the impingement zone remains away from the structure and hence, does not endanger the stability of the structure. Nappe splitters and dispersers contribute to the dissipation of energy by spreading and aerating the jet. Nevertheless, in some projects, the formation of spray and retrogression of the scour hole towards the structure threatens the stability. Coupled with the plunge pools, part of the energy of the deflected jet can be dissipated by pool diffusion.



Typical section of trajectory bucket

Prototype view of trajectory bucket

1.3.3 Roller buckets

Roller buckets can be conceptualized as hydraulic jumps on a curved floor, as their performance is closely related to the Froude number of the incoming flow and tailwater depth. A solid roller bucket is a simple device that gives satisfactory performance, provided it is operated symmetrically. Asymmetrical operation results in a horizontal eddy downstream of the bucket that can carry loose material into the bucket causing abrasion damage. The slotted bucket, claimed to be an improvement over the solid bucket, has a self-cleansing potential by way of slots and teeth in the bucket. Despite this, many slotted buckets as solid roller buckets have been damaged due to abrasion and cavitation. The performance of the slotted bucket is more sensitive to tail water variation than that of the solid roller bucket.

Model view of the roller bucket of Omkareshwar spillway

1.3.4 Uncommon types of energy dissipators

Sometimes due to geological and hydrological issues, the common type of energy dissipators may not be suitable to dissipate the energy of spillway flows. In these cases, either the common types of energy dissipators are used in combination of one another or used with slight modification, or entirely different or newer/ uncommon types of energy dissipators are provided.

Many such designs have been developed for site-specific installations. Information about these types does not appear in the literature. These designs may be verified by either model or prototype tests. Some examples are:

- Lower Siang Dam Spillway, Arunachal Pradesh: Combination of stilling basin and ski-jump in Multi-Tier spillway system
- Supa Dam Spillway, Karnataka: Combination of stilling basin and ski-jump type of energy dissipator
- Koteshwar Dam Spillway, Uttarakhand: Combination of ski jump bucket and stilling basin
- Dantiwada Dam Spillway, Gujarat: Combination of ski-jump bucket and roller bucket

Exhaustive studies are required to arrive at a suitable type of energy dissipation arrangement.

Some other types of energy dissipators are being provided for spillways according to the requirements felt at the dam site. Some of these are:

- Cascades : Khadakwasla Dam, Pune
- Tandem-type stilling basins: Mangla Dam Spillway, Pakistan
- Duckbill spillways: Salauli Dam spillway, Goa
- Swirling Flows: Tehri H.E. Project, Stage – I, Uttarakhand

1.4 Physical Modelling

1.4.1 Need for physical modelling

The construction of dams involves huge capital costs and recurring maintenance expenditures. The hydraulic design of various components of a river valley project involves two types of problems viz. site-specific problems and problems connected with complex hydraulic flow phenomena. The site-specific problems are due to topography at the site, availability of foundation, nature of soil and rock strata etc. The problems associated with complex flow phenomena are many viz. non-uniform flow in the approach portion creating vortices, rapidly varied flow because of complex geometry, high velocities due to high heads leading to cavitations damages, high turbulence causing hydrodynamic forces on the structure and erosion of the river bed and banks downstream, flow-induced vibration for a wide range of operating conditions. These problems at present cannot be dealt with analytically and can be tackled by conducting studies on hydraulic models of these structures. For several decades, the art of hydraulic modelling has been an important tool in solving complex hydraulic problems.

The hydraulic similitude is indispensable in physical modelling. Mainly there are four types of forces acting on the fluid i.e. gravitation, viscosity, surface tension and elasticity. Perfect similarity of fluid motions and hydrodynamic forces between a model and its prototype is practically an impossible task. Full model–prototype similitude requires satisfaction of geometric similarity, kinematic and dynamic similarity. Spillway models are built geometrically similar to their prototypes. As the gravity force is predominant in spillway flows, the models are constructed according to the Froudian similarity law.

Model-proto conformity for Salma dam

1.4.2 Classification of spillway models

- **2D sectional models**

2D Sectional model

- ➢ Constructed in a glass-sided flume incorporating one or two spans.
- ➢ Detailed measurements of discharge, pressure, velocity and force as well as the facility of visual observation of flow conditions through glass are the main advantages of a sectional model.
- ➢ Desired modifications in the design can be easily carried out in a sectional model.

- **3D Comprehensive models**

3D Comprehensive model

- ➢ Constructed in a model tray incorporating the entire spillway, non-overflow dam, part of the reservoir and river downstream including other structures.
- ➢ Detailed study in terms of general flow conditions upstream and downstream of the spillway, pattern/ schedule of operation of spillway gates, flow conditions in the vicinity of ancillary structures such as training walls, powerhouse tail race, earth dam toe, studies with erodible bed downstream of the spillway to give qualitative indication of scour and requirement of protection.

1.4.3 Selection of scale

The first and most important step in the design is a careful selection of a model scale. Usually, the scale is selected as 1:40 to 1:60 and 1: 60 to 1:100 for the construction of 2D sectional model and 3D Comprehensive model respectively. The scale is selected in such a way that Reynolds number of the flow should be greater than $5x10^5$ to minimize the scale effects. The hydraulic models constructed according to Froudian criterion would not be able to simulate the air entrainment. To simulate air entrainment in the model, the models are required to be constructed to a scale ranging from 1:10 to 1:15 to achieve a Weber number of about > 500 to take into consideration the surface tension effects.

1.4.4 Data requirements for model studies

For conducting model experiments, it is necessary to obtain correct information from the prototype. The entire operation of the model depends on the quality of the prototype data. The data would help in establishing the model prototype conformity pattern and to enhance the predictability of the model. Generally, the following prototype data would be required for planning, construction of spillway models and conducting model studies.

- A copy of the latest project report highlighting salient features of the project such as purpose, scope, inter-relation with other projects, upstream and downstream of the proposed dam site, benefits derived, cost etc.
- Drawings of the existing or proposed structure, surrounding topography and/or river cross-sections,
- Geologic information for the nature of riverbed material downstream of the dam site upto 500 m.
- Hydrology including the probability of floods and frequency of various floods, Flood routing studies of the reservoir indicating maximum inflow, and the corresponding outflow and Gauge-discharge curve (tailwater rating curve) at 300 m downstream of the spillway up to the maximum outflow discharge.

1.4.5 Construction methodology of model

The construction of the model requires the following considerations:

- **Materials of construction:** A model need not be made of the same materials as the prototype. If surfaces over which water flows are reproduced in shape and roughness of the surfaces approximately to scale (in fact smoother in the model than corresponding to prototype roughness), the model will usually be satisfactory. Generally, the riverbed is made up of smooth cement plaster, spillways and piers are fabricated in transparent Perspex sheet and radial gates are fabricated in metal sheets.
- **Construction accuracy and other requirements:** Close tolerances, particularly in critical areas such as spillway crests, tangent points, energy dissipating appurtenances, model dimensions etc are essential. The greatest accuracy should be maintained where there will be rapid changes in the flow direction and very high velocities occur.
- **The extent of river topography to be reproduced in the model including nearby structures:** It is not possible to reproduce the entire reservoir upstream of the spillway nor it is necessary to do so. For the spillways located in the main river gorge with a practically straight river course, reproduction of about 600 to 800 m reach is usually adequate. Where the river has appreciable curvature immediately upstream of the dam, or where the spillway is located on a flank, so that obliquity of flow approaching the spillway is likely to occur, special care must be taken to incorporate these features. On the downstream, the river reach to be incorporated would be slightly beyond the section of stage-discharge measurement in the prototype.

1.4.6 Operation of model

Once the model is ready for experimentation, the operating program of the model should be carefully planned to evaluate the performance of the proposed design for critical flow conditions. The operating programme can be divided into two phases:

- Adjustment phase
- Experimental phase

The adjustment phase includes preliminary trials to identify model defects and inadequacies. The need for partial redesign, revision, or shifting of measuring instruments is often indicated by these trial runs. The experimental phase includes regular model studies after removing all the defects observed during the adjustment phase.

Hydraulic modelling techniques gain a great importance in refining the design of hydraulic structures. CWPRS has been at the forefront in finalizing the designs of complicated hydraulic structures for many mega projects constantly innovating new designs and modifications ultimately aiming at the increase in safety and the reduction of project cost.

1.4.7 Hydraulic aspects to be studied

To evolve the hydraulically efficient design of the spillway, the following aspects are to be considered:

- Approach flow conditions
- Discharging capacity
- Pressures and water surface profiles
- Energy dissipation arrangement under steady and transient flow conditions of tail water development
- Downstream flow conditions to mitigate cavitation

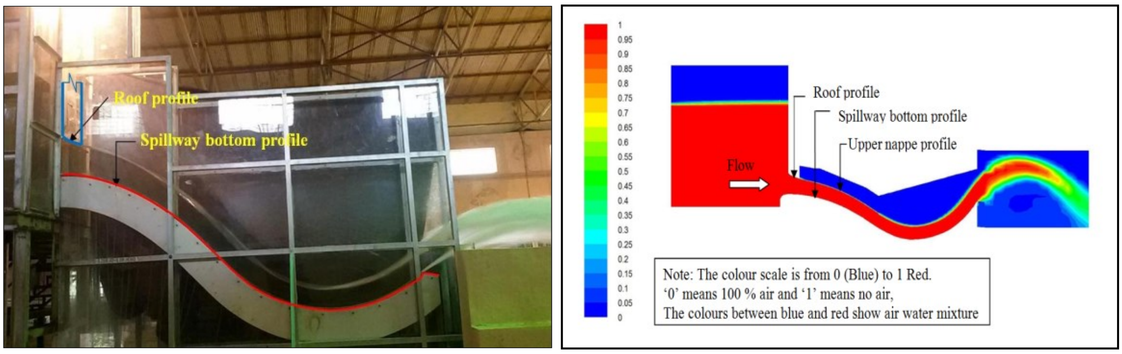
1.5 Numerical Modelling

The rapid growth of mathematical modelling techniques and software applications along with high-end computers in terms of computer memory and processing speed has enabled the numerical modeling of hydraulic structures as a viable complementary tool to physical modeling. Computational fluid dynamic (CFD) modeling is a cost-effective tool for solving many complex hydraulic problems. It gives an insight into flow patterns that are difficult, expensive, or impossible to study using traditional physical modelling techniques.

Computational Fluid Dynamics uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. The foundation on which CFD is built is the Navier-Stokes equations, the set of partial differential equations that describe fluid flow. With CFD, the area of interest is subdivided into a large number of cells or control volumes. In each of these cells, the Navier-Stokes partial differential equations can be rewritten as algebraic equations that relate the velocity, temperature and pressure. The resulting set of equations can then be solved iteratively, yielding a complete description of the flow throughout the domain. By solving the fundamental equations governing fluid flow processes, CFD provides information on important flow characteristics such as pressure loss, flow distribution and mixing rates. Various turbulence models available in different CFD Codes can compute highly turbulent complex flow phenomena over the spillway structure. A key advantage of CFD is that it is very compelling, non-intrusive and virtual modelling technique with powerful visualization capabilities.

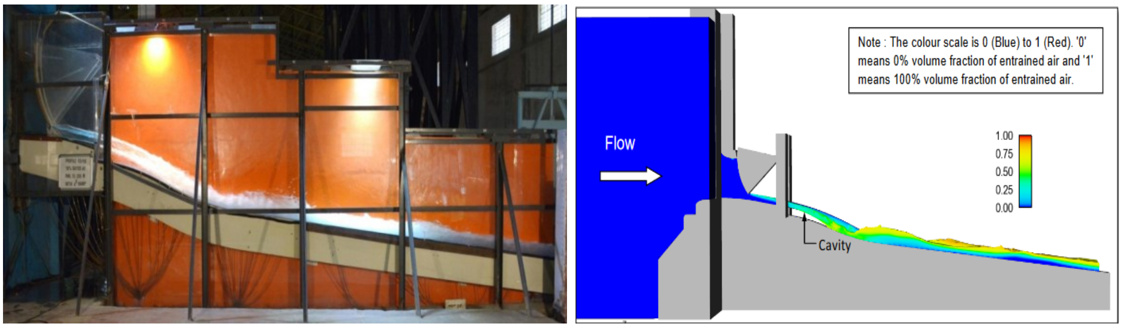
The advantages of both physical and numerical models should be exploited judiciously to optimize the spillway design. The accuracy of a physical model can be improved by selecting a proper scale and using state-of-the-art instrumentation. The accuracy of the CFD data can further be improved by using more stringent convergence criteria, the selection of turbulence model relevant to the hydraulic features to be investigated and supplemented with intense data mining of the simulation results. The decision, whether CFD or physical models are preferable, should be made neutrally considering the nature and complexity of the problem and available trained manpower and computer resources. Both experimental and computational fluid dynamic techniques have their pros and cons and may be used judiciously for arriving at a practical engineering solution for water resources projects.

Various case studies were carried out at CWPRS for simulating flow over the spillway and energy dissipators for various projects.



Note: The colour scale is from 0 (Blue) to 1 Red.
'0' means 100 % air and '1' means no air,
The colours between blue and red show air water mixture

Flow simulation over orifice spillway



Note : The colour scale is 0 (Blue) to 1 (Red). '0' means 0% volume fraction of entrained air and '1' means 100% volume fraction of entrained air.

Flow simulation over spillway aerator

1.6 Conclusion

This chapter underscores the critical role of spillways and energy dissipators in dam safety and functionality, emphasizing their importance in flood control, sediment management, and structural stability. With advancements in hydraulic and numerical modelling, modern spillway designs aim to balance economic feasibility and environmental sustainability while ensuring efficient energy dissipation. The need for meticulous planning, modelling, and maintenance remains paramount to address the growing challenges in dam construction and water resource management.

CHAPTER 2

Challenges in the Design of Spillways and Energy Dissipators

2.0 Introduction

Spillways are critical components of dam infrastructure, ensuring the controlled and safe passage of floodwaters from reservoirs to downstream areas. With approximately 57,000 large dams worldwide and around 5,254 large dams in India, most of these structures feature spillways tailored to their unique hydrological and topographical conditions. As dam construction progresses, particularly in challenging regions like the Himalayas and Northeast India, spillway design faces new complexities.

Future spillway designs will increasingly confront challenges related to narrow valleys, where the spillway must handle exceptionally high flood volumes. This may lead to the development of multi-tier spillways to manage these large discharges. Other critical challenges include addressing high sedimentation rates, which affect spillway functionality, and adjusting designs to accommodate upward flood revisions driven by rapid environmental changes and Glacial Lake Outburst Floods (GLOF) due to global warming and glacier melting.

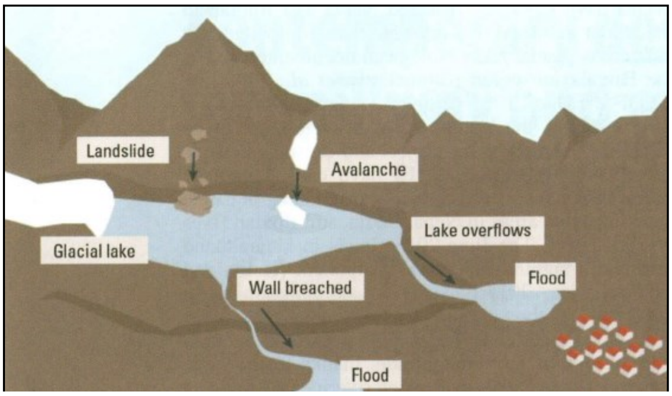
An emerging consideration is the potential for multipurpose dams built near coastal areas, particularly in gulf regions, to capture fresh water from rivers before it enters the sea. These projects would require specialized spillway designs that take into account tidal fluctuations and storm surges, which could affect the hydraulic performance of both the spillway and energy dissipation mechanisms. Additionally, to prevent saline intrusion into freshwater reservoirs, strict reservoir regulations would need to be enforced.

In such complex scenarios, hydraulic model studies play a pivotal role in understanding and optimizing spillway designs. These physical and numerical models provide insights into flow behavior, energy dissipation, sediment handling, and overall hydraulic performance. The knowledge gained from these studies ensures that spillways can perform effectively even under the most challenging conditions. Thus, future spillway designs must integrate advanced hydraulic modeling techniques to address the diverse and evolving challenges posed by climate change, topographical limitations, and extreme flood events.

2.1 Challenges in the Design of Hydropower Projects in the Himalayan Region

2.1.1 Glacial Lake Outburst Flood

The Himalayan region, home to the largest concentration of glaciers outside the polar zones, serves as a crucial freshwater reserve, supporting nine major river systems in Asia and sustaining nearly one-third of the global population. However, recent decades of climate change and climatic variability have significantly affected the lifecycle of these glaciers. The accelerated melting of glaciers has led to the formation of numerous glacial lakes, including Parechu Lake (Tibet), Dig Tsho Lake (Nepal), and Charobari Lake (Uttarakhand). The sudden release of water from these lakes, coupled with debris, can cause Glacial Lake Outburst Floods (GLOFs), which pose a significant threat to downstream communities and infrastructure.



Schematic representation of a glacial lake outburst flood

One notable GLOF event occurred in 1985, when Dig Tsho in the Khumbu Himal region of Nepal burst, destroying the Namche Small Hydel Project and wreaking havoc downstream. These floods not only impacted local areas but can also crossed international borders, with GLOFs from China causing damage in Nepal, India, and Bhutan. For instance, the sudden discharge from these lakes often carries silt, boulders, gravel, and debris, threatening infrastructure such as hydropower projects. In response, facilities like the Nathpa Jhakri Hydroelectric Project in Himachal Pradesh have implemented large sluice spillway openings and advanced warning systems to mitigate the effects of frequent flash floods.

In the June 2013 Uttarakhand floods, the Tehri reservoir played a vital role in controlling floodwaters, protecting millions of lives and averting disaster-related damages. This underscores the importance of robust flood management systems in high-risk regions.

Floods in Uttarakhand

As hydropower projects continue to be planned across India, Nepal, and Bhutan, particularly in the Himalayan regions, it becomes essential to consider GLOF risks in spillway designs. Hydraulic modeling is a critical tool in these cases, allowing engineers to predict the discharge capacity of spillways under Probable Maximum Flood (PMF) and GLOF conditions. These models help to determine key design levels such as the spillway crest, Full Reservoir Level (FRL), Minimum Draw Down Level (MDDL), and the invert of the power intake. Through accurate modeling and planning, engineers can ensure that dams and spillways are equipped to handle both regular and extreme flood events, minimizing the risk of damage and safeguarding communities downstream.

Given the increasing frequency of such events due to global warming and glacier melting, it is critical to adopt precautionary measures and improve scientific understanding of GLOF phenomena to enhance flood control systems in the Himalayas.

Magnitude of GLOF and PMF for various projects in the Himalayan region

Sr. No.	Project and Country	PMF (m^3/s)	GLOF (m^3/s)	PMF and GLOF (m^3/s)	GLOF in terms of PMF (%)
1.	Punatsanghchu –I, Bhutan	11,500	4300	15,800	37.4
2.	Punatsanghchu–II, Bhutan	11,726	4300	16,023	36.7
3.	Etalin, Dri Limb, Ar. Pradesh	11,811	1170	12,981	9.9
4.	Etalin Tangon Limb, Ar. Pradesh	10,218	2143	12,361	20.97
5.	Arun-III, Nepal	8880	6830	15,710	76.91
6.	Chamakharchhu, Bhutan	9406	5112	14,518	54.35
7.	Kwar, J&K	10,534	620	11,154	5.88
8.	Mangdechhu, Bhutan	6900	3715	10,615	53.84

2.1.2 Sedimentation

The Himalayan terrain presents numerous challenges for dam construction and hydropower projects due to its unique and harsh environmental features. These include high mountains, narrow gorges, fragile geology, and high seismicity, which make it difficult to establish stable structures. Furthermore, Himalayan rivers have extremely steep bed gradients, ranging from 1 in 30 to 1 in 100, leading to frequent flash floods and carrying large amounts of sediment. This sediment, when it accumulates in reservoirs, significantly reduces their live storage capacity.

Dams in the narrow valley-Mangdechhu HE Project, Bhutan

Sediment poses a particular challenge for hydropower plants. The highly abrasive silt particles can erode underwater parts of the water conductor system, leading to cavitation and damage. The issues faced by hydropower plants due to sediment include the choking of strainers, damage to turbine blades and seals, and problems with sealing in hydromechanical gates. Notable projects like

Baira-Siul, Maneri Bhali, Chilla, Nathpa Jhakri and Salal have reported damage caused by sediment, demonstrating how pervasive this issue is in Himalayan hydropower development.

Sediment-laden flow over Nathpa Jhakri dam spillway, H.P.

Sediment-laden flow over Salal dam spillway, J&K

a) Runner with cracked vanes in 2004

b) Eroded Runner

c) Coated guide apparatus after erosion

d) Coated guide apparatus (new) assembled at site

Damages in Nathpa Jhakri Project, H.P.

To mitigate these problems, sediment removal near the power intake is essential. Traditional designs, such as high ogee spillways, are not well-suited for floods carrying heavy sediment loads. The experience of dam silting and damage to power plants in the Himalayan region has shifted the focus toward run-of-the-river schemes, which avoid large storage and directly use stream flow as it comes. These schemes are now typically equipped with elaborate desilting arrangements before silt-laden water enters the power plant.

In response to the challenges posed by sediment-laden floods, orifice spillways (also known as breastwall or sluice spillways) have evolved. These spillways serve the dual purpose of flood disposal and sediment flushing, making them suitable for Himalayan rivers. However, the design of an orifice spillway is complex and challenging, requiring careful consideration of numerous parameters, such as the flow rate, sediment concentration, and hydraulic behavior of the river.

To ensure an effective and reliable spillway design, physical model studies are often employed. A physical model provides an accurate representation of the complex flow dynamics involved, allowing engineers to finalize the design of the spillway and ensure it meets both flood control and sediment management objectives. These models help in optimizing the structure for both safety and efficiency, making them indispensable in designing spillways for Himalayan hydropower projects.

By incorporating innovative designs like orifice spillways, and employing detailed studies, the hydropower sector in the Himalayas can effectively tackle the twin challenges of flood management and sediment control, ensuring the long-term sustainability and performance of dams and power plants in this sensitive and demanding environment.

2.1.3 Geological surprises

The features of hydroelectric projects are inherently site-specific and depend largely on the geology, topography, and hydrology of the project location. These factors influence not only the design but also the overall feasibility and safety of the project. Given the complexity of these natural elements, especially in mountainous regions like the Himalayas, careful and thorough planning is required.

The construction time of a hydropower project is significantly affected by the geological conditions at the site. Geological characteristics, such as rock type, fault lines, and sub-surface stability, directly impact the ease or difficulty of excavation, tunneling, and foundation laying. Accessibility to remote or rugged terrain also adds to the challenges, potentially delaying construction timelines.

To reduce risks and optimize the development process, it is critical to adopt state-of-the-art investigation and construction techniques. These include:

- ➢ Advanced geological surveys using remote sensing, seismic reflection, and borehole drilling to better understand the sub-surface conditions.
- ➢ Geotechnical investigations to assess soil and rock strength, water table levels, and potential seismic activity.
- ➢ Modern construction methods such as tunnel boring machines (TBMs) for efficient excavation in difficult rock strata, and advanced reinforcement and stabilization techniques for tunnels and dam foundations.

Despite extensive investigation efforts, geological uncertainties often remain. The complexity of sub-surface geology means that even with cutting-edge techniques, it is not always possible to fully predict the conditions encountered during construction. Geological surprises such as unexpected fault lines, water ingress, or unstable rock formations can arise, potentially leading to delays, cost overruns, and redesigns. Therefore, risk management strategies are essential for hydroelectric projects. These include:

- Flexible design approaches that allow for adjustments based on actual site conditions
- Contingency plans to handle unforeseen geological challenges
- Ongoing geotechnical monitoring throughout construction to identify issues early and take corrective action as needed

While modern investigation and construction technologies can significantly mitigate geological risks, the inherent uncertainty in sub-surface conditions requires careful management throughout the project lifecycle. The goal is to minimize the gestation period of hydroelectric projects while ensuring safety, cost-effectiveness, and long-term operational reliability.

Fragile geology in the Himalayan region

2.1.4 Climate change

Climate change is having a profound impact on the environment, particularly in terms of rising global temperatures, precipitation changes, and extreme weather events. These changes, such as rapidly retreating glaciers, shifting monsoon patterns, and increasing incidents of extreme events like heat waves, droughts, floods, and glacial lake outburst floods (GLOFs), pose serious challenges for the feasibility and sustainability of hydropower projects, especially in ecologically fragile and geologically young regions like India. The Himalayan region, in particular, is highly vulnerable to climate change impacts. The melting of glaciers and the formation of unstable glacial lakes create risks of catastrophic flooding downstream, while the changing monsoon patterns can cause unpredictable variations in river flows, affecting the consistency and reliability of hydropower generation. Additionally, the increased frequency of extreme weather events threatens the structural integrity of hydropower projects. Storms, storm surges, and coastal flooding could lead to unprecedented challenges in managing water resources, especially in projects situated in vulnerable and remote locations.

Given these challenges, it is clear that more research and thorough studies are necessary to understand the full impact of climate change on hydropower feasibility. These studies should focus on:

- Assessing long-term hydrological patterns and river flow variability to predict how climate change might affect water availability for hydropower generation.
- Developing climate-resilient designs for hydropower infrastructure, capable of withstanding more frequent and intense weather events.
- Conducting environmental impact assessments with a focus on changing climatic conditions to better predict risks like landslides, erosion, and flood-induced damage.
- Monitoring glacial and hydrological changes to mitigate risks associated with glacial lake outburst floods and unexpected river flow reductions.

As climate change continues to accelerate, hydropower projects must be carefully evaluated to ensure their viability, safety, and environmental sustainability.

2.2 Hydraulic Design Considerations for Spillways and Energy Dissipators in Himalayan Region

2.2.1 Design of Spillways

i) Orifice Spillway

The orifice spillway, commonly in the form of a breastwall/sluice, is widely used in dam projects, particularly in the Himalayan region, for its ability to serve dual purposes: flood control and sediment flushing from reservoirs. The unique design of the orifice spillway allows the spillway crest to be positioned at a lower elevation while maintaining a high dam that creates the necessary head for power generation. This lower crest near the riverbed enables effective sediment flushing, which is crucial for maintaining the reservoir's storage capacity and operational efficiency, especially in sediment-laden rivers.

Some of the key features and advantages of the orifice spillway design include:

- **Dual functionality**: The design allows both flood discharge and sediment flushing to be managed efficiently.
- **High efficiency**: The crest of the spillway, located close to the riverbed, aids in the removal of sediment while allowing the dam to store significant volumes of water for power generation.
- **Economy in construction**: The relatively smaller size of the radial gate reduces the overall cost of construction while still ensuring effective operation.
- **Optimized hydraulic performance**: The greater depth of flow over the crest allows the spillway to handle large discharges, offering greater flexibility in the placement of the power intake and reducing the risk of sediment deposition around the intake structure.

However, designing orifice spillways presents several challenges due to the high velocities and discharge intensities involved. These include:

- **High discharge intensities**: The design discharges are often very large, with orifice sizes ranging from 8-20 meters wide and 12-22 meters deep. Velocities can reach 30-40 m/s, with discharge intensities of 200-300 m^3/s per meter.
- **Erosion potential**: The high velocities, combined with the sediment-laden water in these river systems, can lead to significant cavitation and erosion damage. To mitigate these risks, advanced materials such as epoxy-bonded concrete, polymer concrete, or steel linings are used to protect critical areas of the spillway, such as the sluice barrel and discharge channel.
- **Structural considerations**: The breastwall must withstand the upstream water head and is typically integrated with piers into a single structural unit to ensure stability. The design of the radial gate also requires attention to ensure water tightness at the top seal.

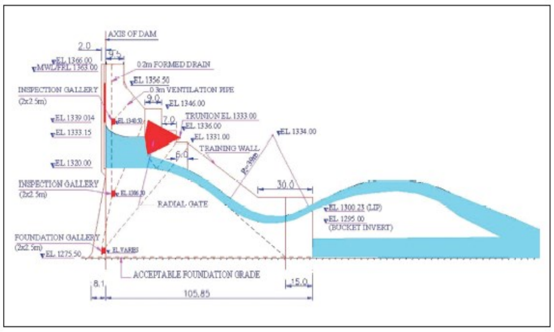
Key Design Considerations and Solutions

- **Orifice Roof and Bottom Profiles**: In the case of orifice spillways, the roof and bottom profiles must be carefully designed to avoid negative pressures. Aeration systems are essential to introduce air into the flow, reducing the risk of cavitation especially for high-head dams.
- **Energy Dissipation**: Proper stilling basin design is necessary to dissipate the energy of the high-velocity flows exiting the spillways. Modifications to the length and elevation of the basin help to control erosion and prevent damage to downstream structures.

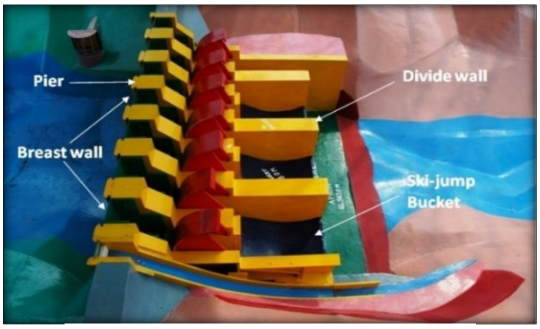
CWPRS (Central Water and Power Research Station) has played a significant role in developing and optimizing orifice spillway designs through hydraulic model studies. Over the past decade, CWPRS has contributed to more than 35 projects involving the safe and efficient hydraulic design of orifice spillways. Some notable projects include:

- Arun 3 Dam Spillway, Nepal
- Kishanganga Dam Spillway, Jammu & Kashmir
- Mangdechhu Dam Spillway, Bhutan
- Tala Dam Spillway, Bhutan
- Pare Dam Spillway, Arunachal Pradesh
- Sunansiri Dam Spillway, Arunachal Pradesh/Assam

In addition to these projects, CWPRS has conducted basic research to develop design guidelines for orifice spillways. This research focused on key hydraulic parameters such as water and pressure profiles, the coefficient of discharge, and orifice roof profiles using both physical and numerical model studies. These advancements in orifice spillway design are crucial for the future of dam construction, especially in regions with high sediment loads and challenging topography, such as the Himalayan region.



Typical section of orifice spillway



Model view of orifice spillway

ii) Multitier Spillways

In regions like the tributaries of the Brahmaputra River, engineers encounter numerous challenges when designing spillways for large hydropower projects due to narrow valleys, high discharges, and extremely high heads. These areas present unique topographical, geological, and hydrological conditions that require innovative approaches, such as the development of multitier spillways to address the dual challenge of flood management and sediment flushing.

Key Challenges in Spillway Design in Narrow Valleys:

- **Narrow Valleys**:
  The limited width of river gorges restricts the space available for constructing large, conventional spillways. Designing a spillway that can handle significant flood volumes without compromising structural stability is difficult in such settings.
- **High Discharges and Heads**:
  The available heads in these regions are often very high, providing a significant energy potential for hydropower generation but also introducing structural challenges. The pressure on the orifice spillways and gates due to these high heads can cause cavitation, erosion, and instability if not properly managed.
- **Fragile Geology**:
  The Himalayan region's geology is often fragile, with a high likelihood of landslides, unstable slopes, and seismic activity. These conditions complicate the design and construction of spillways and require additional engineering solutions to ensure long-term stability.

Multitier Spillways: An Innovative Solution

In response to these challenges, two-tier spillways offer an effective approach by distributing the flood discharge over several tiers and addressing sediment flushing. This design involves positioning spillways at multiple elevations to handle various aspects of flood management:

- **Lower-Level Sluices**

Positioned near the riverbed, the lower-level sluices primarily serve to flush sediment from the reservoir and manage a significant portion of the flood discharge. These sluices allow sediment to be removed from the system, preventing it from reducing reservoir storage capacity and damaging turbines and gates. However, designing these sluices in narrow valleys with high heads introduces structural constraints. The control gates must be robust to withstand the high forces exerted by the flow. Thick piers and strong gate systems are required, along with proper aeration to avoid negative pressures that could lead to cavitation damage.

- **Higher-Level Spillways**

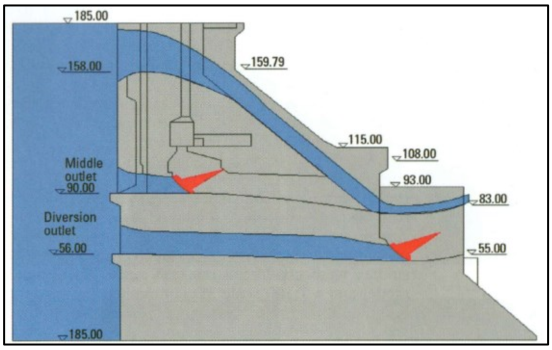
These are positioned above the lower sluices to handle the remaining floodwaters that cannot be managed by the lower-level orifice spillways. By distributing the discharge load across two tiers, the multitier system ensures that the total flood can be safely conveyed downstream, minimizing the risk of overtopping.

Case Study: Lower Siang Dam Spillway (Arunachal Pradesh)

A notable example of multitier spillway is the Lower Siang Dam spillway in Arunachal Pradesh, which was designed to manage a Probable Maximum Flood (PMF) of 60,315 m^3/s. The design was studied using physical hydraulic models at CWPRS, with several key adjustments made to improve performance:

- **Orifice roof and bottom profiles**: The orifice spillway profiles were optimized to enhance hydraulic efficiency and minimize cavitation risks.
- **Overflow spillway profile**: Adjustments were made to handle additional flood discharge safely, ensuring the system could handle the total design flow.
- **Stilling basin**: The length and elevation of the stilling basin were refined to dissipate the high energy of the flow and prevent downstream erosion.

The use of multitier spillways in narrow valleys with high discharges and heads presents a flexible and efficient solution for managing floodwaters and sediment in the Brahmaputra River's tributaries. By combining low-level sluices for sediment management with higher-level spillways for flood discharge, this innovative design addresses the unique challenges posed by the region's topography, hydrology, and geology. Projects like the Lower Siang Dam demonstrate how advanced hydraulic modeling and careful design adjustments can lead to safe and reliable spillway systems capable of handling extreme flood events in challenging environments.



Definition sketch of the multitier spillway

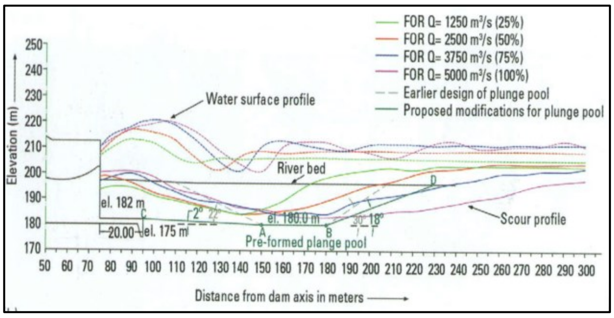
Model view showing the two-tier spillway of Siang Project

2.2.2 Design of energy dissipators

The factors influencing the choice of energy dissipator types include hydraulic considerations, topography, geology, dam type, layout, associated structures, economic comparisons, frequency of usage, and other relevant aspects. In the Himalayan regions, the topography is typically steep, with fragile geology, high-intensity rainfall, and a significant level of seismic activity, resulting in a high sediment load. Since the spillway must handle both floodwaters and sediment, special attention must be given to the design of suitable energy dissipators. The various types of conventional energy dissipators and the specific considerations for their design are discussed in the following sections.

i) Ski-jump bucket

- The ski-jump bucket is often considered the most suitable energy dissipator due to its significant advantage of minimizing sediment churning within the bucket. This design allows sediment to flow down the spillway in a supercritical state without accumulating in the bucket. Additionally, steep riverbed slopes result in low tailwater depths, making this energy dissipator an ideal choice.
- However, in the Himalayan region, where the rock is fragile, there is a risk of uncontrolled scour and landslides near the impact area of the ski-jump jet. To mitigate these hazards, preformed plunge pools are essential. The design of the plunge pool is a critical aspect of the energy dissipator, requiring careful consideration of its location and dimensions. It is important to assess the maximum potential scour depth to determine the appropriate plunge pool depth.
- The water and scour profiles for the entire range of discharges and reservoir water levels observed on the model provide a comprehensive picture of the ski-jump jet and scour profiles. These studies play an important role in deciding the location and size of the plunge pool. A scour pit is usually formed downstream of the point of impingement of the ski-jump jet. Depending on the site conditions, the plunge pool can be preformed, unlined or lined. The provision of a lined plunge pool seems impracticable; however, it needs to be adopted in cases of extremely fragile geology. Transverse slopes on both flanks of the plunge pool may be adopted, based on geological conditions at the site. The ski-jump jet is also likely to extend laterally in the downstream direction, and abrasion would occur along the side slopes. Therefore. suitable bank protection measures are necessary to protect the excavated banks.



A typical configuration of plunge pool based on scour envelope obtained from model studies

Typical plunge pool of Caruachi HE project

- Furthermore, incorporating a dividing wall up to the bucket lip plays a crucial role in limiting scour by preventing the formation of thick rooster tails, which are a primary cause of spray generation. These dividing walls also facilitate controlled spillway operations. During lean flood conditions, the jet can be directed away from the riverbanks by operating only the central bays, which allows for the maintenance of other spans while some remain operational. This operational arrangement has been proposed for the Subansiri Lower project in Arunachal Pradesh/Assam and the Tala Dam spillway in Bhutan.

Model view showing spillway operation for Subansiri Project with provision of divide walls

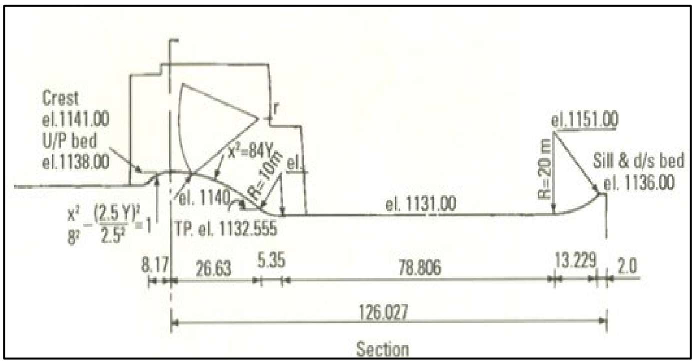
- To protect the toe of the dam from being undermined by the flow cascading over the bucket lip, it is essential to provide a concrete apron downstream of the ski-jump bucket. During the construction of the spillway, the flow over the partially completed blocks will cascade over the lip of the bucket. After the spillway is completed, cascading flow will occur both at the start and end of its operation. Properly anchored and keyed concrete aprons at the end of the ski-jump bucket are generally recommended to prevent undermining the toe.

ii) Stilling basin

- If tailwater levels and geological conditions are not favorable for a ski-jump bucket-type energy dissipator, a hydraulic jump-type stilling basin may need to be adopted. Since spillways serve the dual purposes of flood discharge and sediment disposal, it is crucial to design the stilling basin to meet both requirements. The high unit discharge, ranging from approximately 200 $m^3/s/m$ to 300 $m^3/s/m$, in a low-head spillway results in low Froude number conditions. Designing a stilling basin for a Froude number between 2.5 and 4.5 poses significant challenges in ensuring satisfactory performance across the entire range of discharges.
- Due to the need to accommodate silt-laden flows, the use of energy-dissipating structures, such as chutes and baffle blocks, is generally not advisable. Consequently, the stilling basin tends to be longer and often deeper, particularly because of the higher sequent depth or sound rock foundation below the general riverbed. This configuration makes it vulnerable to silt deposition during flushing operations. Achieving the optimal stilling basin floor level requires multiple trials to balance these conflicting requirements.
- Numerous studies on Himalayan projects illustrate these challenges. The contradictory demands create a risk of abrasion on the basin floor, leading to silting during low flows. Such silting can be particularly dangerous, as it may prevent the hydraulic jump from forming in the stilling basin due to insufficient sequent depth. If the jump fails to form, it may sweep out of the basin, causing significant scour downstream. The studies for Chamera-II project illustrate this feature. Experience with stilling basin of Chamera – II project shows that a trade-off is desirable between the hydraulic efficiency of energy dissipation and the self-cleansing potential of the stilling basin during flushing operation. Cylindrical end sills are generally preferred to facilitate sediment removal. Another significant drawback of the stilling basin is the substantial excavation required for its construction. High training walls are necessary to contain the basin. Therefore, estimating

the hydrodynamic forces on a deep-seated stilling basin floor and the training walls is essential for structural design.

Silt deposition in the stilling basin of Chamera II Project, HP



Cross section of spillway with stilling with cylindrical endsill

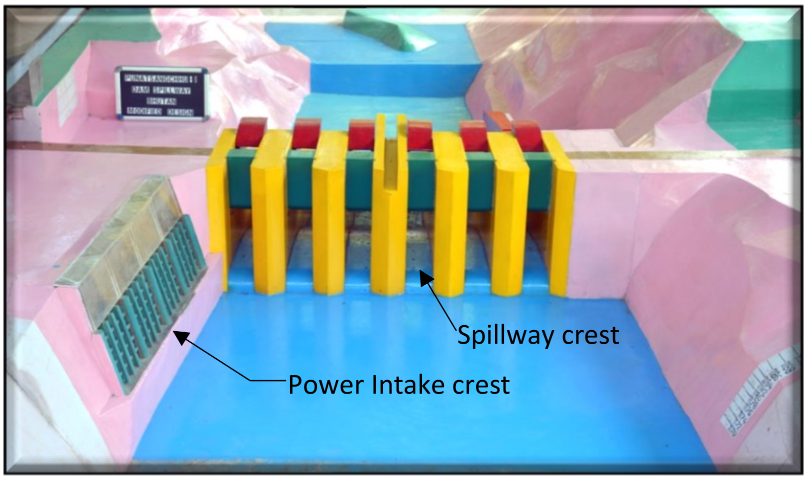
iii) Roller bucket

- A roller bucket is typically designed when the tailwater level exceeds 1.1 times the sequent depth necessary for the formation of a hydraulic jump in the stilling basin, as specified in IS 7365-1985, and when the riverbed rock is sound. In this design, energy dissipation primarily occurs within the bucket, where a surface roller forms above the bucket, moving counterclockwise, and a ground roller develops downstream, moving clockwise. However, the design of the roller bucket is complex and presents several limitations regarding its operation and effectiveness as an energy dissipator.
- Damage to roller buckets has been reported in various projects. A significant issue with solid roller buckets is the potential for damage due to churning material from downstream, particularly when uneven operation of spillway spans generates horizontal eddies downstream of the bucket. This material can cause abrasive damage to the bucket.
- To mitigate such damage, it is essential to line the riverbed to a depth of 1 to 1.5 meters below the bucket lip and to remove any loose material after construction and following each monsoon season. Unfortunately, this aspect is often overlooked. Additionally, the buildup of tailwater levels is a crucial factor in roller formation; if not managed, the roller bucket may behave like a ski-jump bucket, leading to excessive scour downstream. Several spillways featuring solid roller buckets have sustained damage due to these issues.
- The risk of abrasion damage is expected to be more significant when this type of dissipator is situated downstream of an orifice spillway, which tends to flush sediment out of the reservoir. Experience from model studies for the Teesta Low Dam Project Stage IV has demonstrated the challenges of successfully turning an 8-10 meter thick jet to form a surface roller. This thick jet results from the high discharge intensity characteristic of orifice spillways in the Himalayan region. Consequently, the use of a roller bucket may be better avoided in such scenarios.

Damage to roller bucket of Maneri Bhali spillway, Uttarakhand

2.2.3 Layout of the spillway and power intake

- The layout of the spillway and power intake is crucial for the efficient functioning of the intake, particularly in run-of-river projects where significant sediment inflow into the reservoir is expected. A recent trend in hydropower development in India is the construction of run-of-river schemes in cascades to optimize water resource utilization. However, these projects can lead to substantial sediment inflows, which, if not properly managed, may cause serious damage to the generating units and associated equipment in the power plants.
- Typically, the spillway crest is positioned well below the centerline of the power intakes. This design facilitates the flushing of the reservoir, ensuring that the sediment profile remains significantly lower than the power intake level. The most effective layout for the spillway features the intake axis oriented at right angles to the spillway axis, with the intakes located as close as possible to the spillway spans. This arrangement promotes the flushing of sediment in front of the intake.
- In designing the layout for the intakes, several factors must be considered: approach flow conditions, sediment deposition, and sediment flushing in the vicinity of the power intakes. These factors play a significant role in ensuring the optimal operation of the hydropower system.



Typical arrangement of spillway and power intake

2.3 Design of Spillway due to Upward Revision of Flood for Existing Dams

It is estimated that at least 50% of existing spillways in India are inadequate in terms of ensuring dam safety. Furthermore, many older dams were built in remote areas, whereas today, these projects are often located near urban developments. As a result, the potential damage from dam failure is far more severe than anticipated during their original design and construction. When a revised design flood is found to be significantly higher than the original estimate, the adequacy of the spillway capacity must be thoroughly reassessed.

To address increased design floods, the following mitigation measures can be considered:

- Provision of an additional spillway
- Augmenting the existing spillway capacity by incorporating Piano Key (PK) weirs or labyrinth spillways
- Provision of breaching sections or fuse plugs
- Increasing the freeboard above the Full Reservoir Level (FRL) by constructing a parapet wall
- Implementing an early warning system
- Lowering the water levels in the reservoir before the monsoon to enhance flood moderation

However, these measures are often constrained by the topography and geology at the dam site. A modest increase in discharge capacity can typically be achieved by refining the spillway crest shape or improving the channel, but these modifications come at a higher cost. A more common approach is to enlarge the existing spillway or construct a new one to accommodate larger floods. However, conventional methods have limitations and may require innovative designs.

A key priority of the national dam safety program is the verification and revision of dam design flood estimates, incorporating additional data and using modern flood estimation techniques. This is also a primary requirement under the ongoing Dam Rehabilitation and Improvement Program (DRIP). For example, under DRIP, the design flood for the Hirakud Dam spillway in Odisha has been revised upward to 69,632 m^3/s from the original 42,450 m^3/s. To manage this increased flood, two additional spillways, one on the right and another on the left side, are proposed to be constructed in phases.

The Central Water and Power Research Station (CWPRS) has been tasked with conducting hydraulic model studies to optimize the design of the additional spillway and energy dissipator on the left dyke during phase I. Two models, a 1:40 scale 2-D sectional model and a 1:100 scale 3-D comprehensive model have been developed to evaluate the discharging capacity of the spillway, the performance of the energy dissipator, and the flow conditions in the river during various operational scenarios, including the combined operation of the existing spillway on the main dam.

3D Comprehensive spillway model of Hirakud dam spillway

2D Sectional spillway model of Hirakud dam spillway

2.4 Design of Spillways in Coastal Regions

India has a coastline of approximately 7,515 km, with around 78% of the country's surface runoff flowing directly into the sea. Coastal reservoirs could provide a sustainable solution for the people living along the coastline. Currently, only one-sixth of the world's total surface runoff is utilized, while the remaining five-sixths discharges directly into the sea. This demonstrates that there is sufficient water available, but the problem lies in the lack of storage. The key to addressing this issue is conserving and utilizing the abundant monsoon water that otherwise runs off into the sea.

Over the next 100 years, population and water demands will rise significantly. Many existing inland reservoirs will likely become insufficient to meet the growing demand due to their structural lifespan and the effects of sedimentation. Consequently, the demand for coastal reservoirs will increase. These reservoirs are already successfully being used in countries like China, South Korea, Hong Kong, and Singapore, particularly in regions without further opportunities to build inland reservoirs.

Existing Coastal Reservoirs

Name of the reservoir	**Catchment (km^2)**	**Dam length (m)**	**Capacity (10^6 m^3)**	**Year completed**	**Country/river**
Qing Chaosha/Shanghai	1.8million	43,000	553	2011	China/Yangtze
Saemanguem	332	33000	530	2011	South Korea
Sihwa	---	12400	323	1994	South Korea
Marina Barrage	113	350	---	2008	Singapore
Chen Hang/Shanghai	1.8million	4700	8.3	1992	China/Yangtze
Yu Huan	166	1080	64.1	1998	China/ Zhejiang
Baogang/Shanghai	1.8million		12	1985	China/Yangtze
Plover Cove	45.9	2000	230	1968	Hong Kong
Thaneermukkom bund	1521	1402		1974	India

Coastal reservoirs represent a paradigm shift in water resources management, moving from storing water in inland dams to storing freshwater near the coast. This approach transforms floodwaters into valuable water resources. A coastal reservoir is a structure built in the sea to store a portion of river floodwaters that would otherwise flow into the ocean during the monsoon season, making it available for use during droughts. These reservoirs are typically constructed at estuaries, gulfs, or bays, where a river meets the sea, and the seawall or dike structure can extend for several kilometers, connecting points along the coastline in a chord-like configuration.

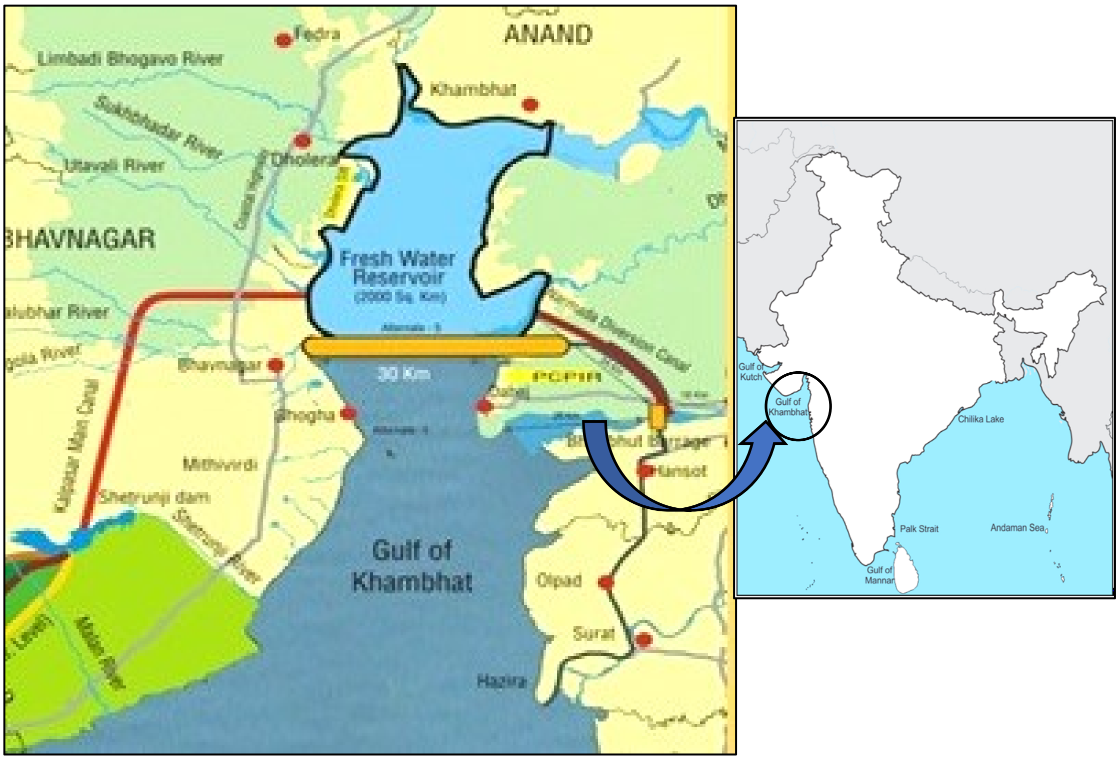
Thaneermukkom bund, India

Constructing a dam in the sea is a very challenging task as it involves understanding various aspects of natural phenomena like tides and waves, challenging foundation issues, complex hydraulics and ecology. Special design considerations are to be employed for spillway and energy dissipation arrangement as their operational performance is influenced by the cyclic tidal variations and storm surges. Stringent reservoir regulations are necessary to avoid the mixing of fresh water and saline water. For the design of the spillway, it is necessary to evolve the following parameters:

- Estimation of design flood
- Sizing of spillway capacity such that to avoid the flooding of the reclaimed areas without the water level in the reservoir exceeding a certain maximum level
- Tidal variation, storm surge and wave data
- Dam safety aspect with tidal effects on the dam and proposed spillway
- Reservoir operation simulations according to inflow, reservoir water levels and tidal variations
- Prevention of saline water into the freshwater lake
- Energy dissipation arrangement to avoid entry of high-velocity jets in the sea through spillway spans

One of the most ambitious coastal reservoir projects is the proposed Kalpasar Project, also known as the Gulf of Khambhat Development Project. This water resource project aims to create a freshwater reservoir in the Gulf of Khambhat to meet irrigation, domestic, and industrial water needs. Upon completion, it will be one of the largest freshwater reservoirs in the sea, prioritizing irrigation and drinking water supply for Saurashtra and Central Gujarat regions of India.

Hydraulic model studies play an important role in optimizing the spillway design and location and determining various aspects of the operation of coastal spillways as no readily available guidelines exist. The studies for this unique project are being carried out at CWPRS to study the performance of the spillway and energy dissipator for operating the spillway at different reservoir water levels and tidal variations downstream of the spillway.



Proposed Kalpasar project, Gujarat

Physical model of Kalpasar Dam spillway, Gujarat

2.5 Conclusion

The multifaceted challenges in designing spillways and energy dissipators, particularly in complex environments like the Himalayan and coastal regions are covered in this chapter. It highlights the critical role of adaptive designs, such as multitier spillways and orifice spillways, in managing floods, sedimentation, and climate-induced risks. With advancements in hydraulic modelling and innovative engineering solutions, spillway designs are evolving to ensure sustainability and resilience against extreme environmental conditions. The chapter underscores the importance of integrating scientific research and practical engineering to meet future demands in hydropower and water resource management.

CHAPTER 3

Contributions to National and International Projects

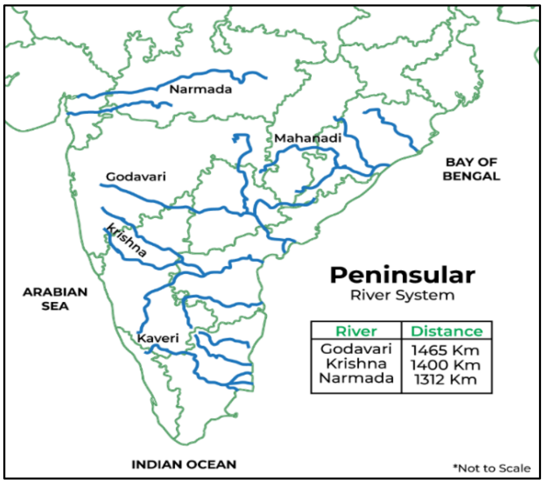
3.0 Introduction

After independence, the Government of India laid on the construction of large dam-based reservoirs called "Temples of Modern India" intended to store rainwater and use it for agriculture, municipal water supply, industry, hydropower, fisheries and recreation etc. There are about 57000 large dams constructed all across the world. There are currently about 5254 completed large dams in India. India is endowed with many rivers, some of them amongst the mightiest in the world. Indian rivers have great significance in our socio-cultural and religious ethos and have played a vital role in shaping the history and spirituality of this vast land. Almost all major cities of India are located along the rivers. They are the veritable lifeline of India and the livelihood of a large population is dependent on our rivers.

- **Peninsular River system**

India is a geographical paradise with many rivers flowing across the country. Peninsular rivers flow through the Indian peninsula, which is located in South Asia. The major peninsular rivers include the Godavari, the Krishna, the Cauvery, the Tapi and the Narmada. Godavari basin in the peninsula is the largest in the country, spanning an area of almost one-tenth of the country. The rivers Narmada (India's holiest river) and Tapti flow almost parallel to each other but empty themselves in opposite directions. The two rivers make the valley rich in alluvial soil and teak forests cover much of the land. The peninsular rivers are important for irrigation, drinking water, and hydroelectric power generation.

The Peninsular River System, despite its significant contributions, faces considerable challenges. Due to the high population density in the region, the water resources of these rivers are often heavily utilized and overused, leading to water scarcity and environmental degradation. Climate change, leading to altered rainfall patterns and prolonged droughts, threatens the water flow of these rivers. Pollution from industrial and agricultural activities further compromises water quality. Sustainable management practices are crucial for the future of these vital waterways. Conservation efforts aimed at protecting watersheds, enhancing water conservation techniques, and promoting responsible water.



Peninsular river system

- **Himalayan River System**

India has been blessed with perennial Himalayan rivers such as the Ganga, Brahmaputra, and Indus, which have large catchment areas compared to the Peninsular rivers that offer huge potential for developing hydropower projects. Historically, dam construction has focused on more accessible and ideal sites, leaving geologically and topographically challenging locations for future development. These remaining sites are primarily in the Himalayan and North-eastern regions. The North-eastern region, in particular, holds immense unexplored hydropower resources that could fulfill the future energy needs of this area.

The Himalayan rivers have a tremendous potential for hydroelectric generation. That potential was first harnessed intensively by India beginning in the 1950s. A giant multipurpose project is located at Bhakra-Nangal on the Sutlej River in the outer Himalayas; its reservoir was completed in 1963 and has a storage capacity of some 348 billion cubic feet (10 billion cubic meters) of water and a total installed generating capacity of 1,050 megawatts. Other Himalayan rivers including the Kosi, the Gandak (Narayani), and the Jaldhaka were then harnessed by India, which then supplied electric power to Nepal and Bhutan. Subsequent major projects in India included the Nathpa Jhakri dam on the Sutlej in Himachal Pradesh and, just downstream from that site, the Rampur station, which became operational in 2014. Nepal has also constructed hydropower projects in the Himalayas, which completed the Zangmu station on the Yarlung Zangbo (Brahmaputra) River in Tibet in 2015.

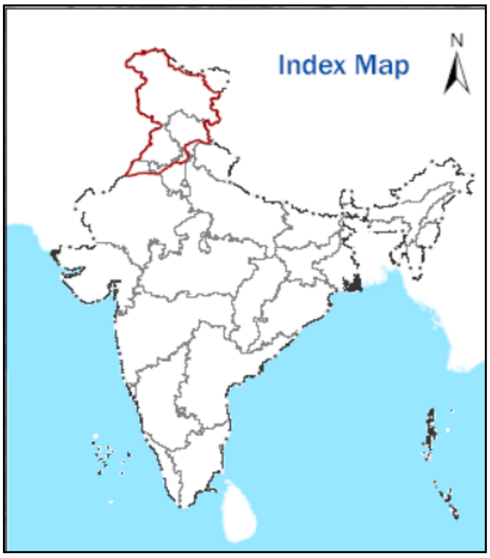
The Indus and Bramhaputra basin has a large hydropower potential. Some of the important upcoming hydropower projects in the Chenab basin are Pakal Dul (1000 MW), Kiru (620 MW), Kwar (540 MW) and Ratle (850 MW). Dibang Multipurpose Project is a hydropower cum flood moderation scheme proposed on the Dibang River in the Lower Dibang Valley District of Arunachal Pradesh. If constructed, it will be India's largest dam and the world's tallest concrete gravity dam, standing 288 m high. The Dibang Dam is expected to provide up to 2880 MW of hydroelectric power and will also assist with flood control in the Dibang Valley.

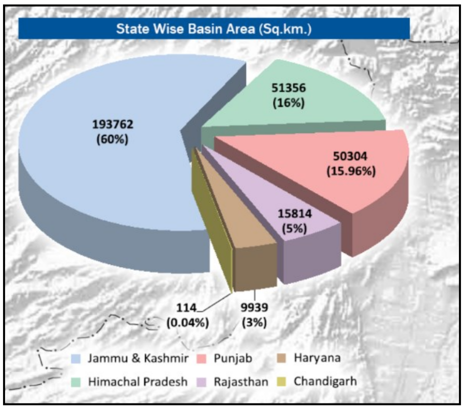
Himalayan river system

3.1 INDUS RIVER BASIN

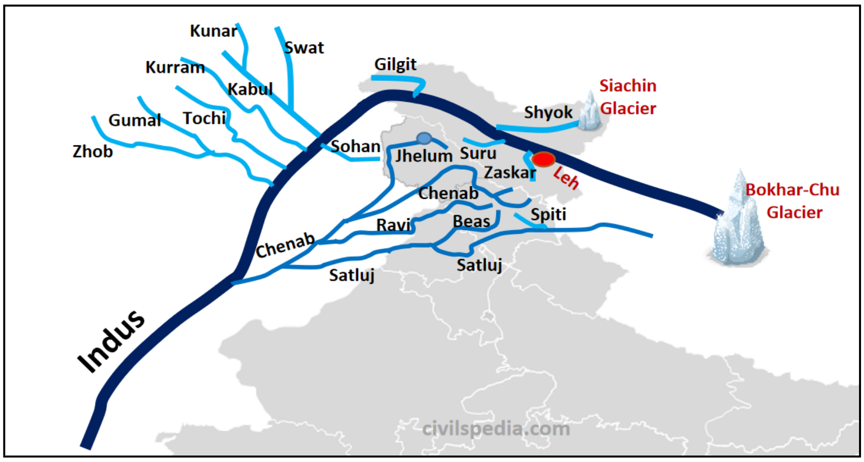
The Indus basin spans across China (Tibet), India, Afghanistan, and Pakistan, covering an area of 1,165,500 sq. km. Within India, it extends over the states of Jammu & Kashmir, Himachal Pradesh, Punjab, and parts of Rajasthan and Haryana, as well as the Union Territory of Chandigarh, encompassing a total area of 321,289 sq. km, which accounts for nearly 9.8% of India's geographical area. Originating from the high mountains of the Himalayas near Lake Manas Sarovar in Tibet, the Indus River travels a total length of 2,880 km before discharging into the Arabian Sea, with 801 km of its course passing through India.

The major tributaries of the Indus in India include the Jhelum, Chenab, Ravi, Beas, and Satluj rivers. According to the India-WRIS database, the Indus basin is home to 55 hydroelectric projects and 59 powerhouses. Key projects within this basin have been studied at CWPRS, and a discussion of some notable projects is provided below.





State wise drainage area of the basin



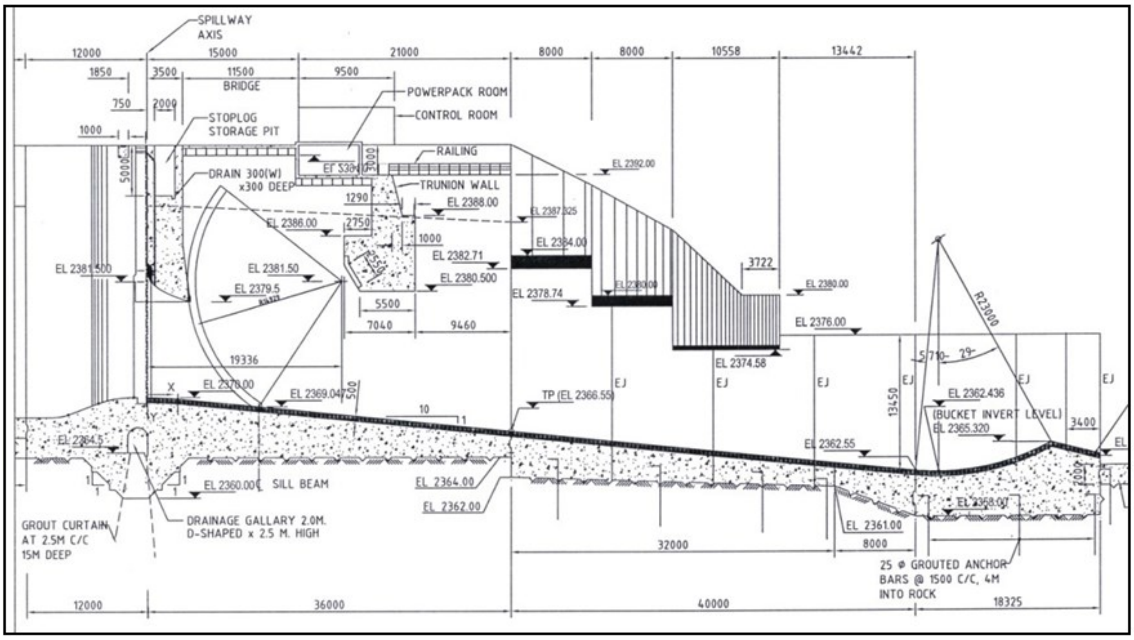
Major rivers of the basin

3.1.1 Kishanganga H.E. Project, J&K

Kishanganga H.E. Project is located in Baramulla District of Jammu and Kashmir state of India. It is a run of river scheme that involves the transfer of water from the Kishanganga River, tributary of the Zhelum River in Gurez valley to the Bonar nallah near Bandipora in Kashmir Valley.

❖ Project Overview

- Dam dimensions: 37 m high and 160 m long concrete-faced rockfill dam
- Power installed capacity: 330 MW
- Spillway details: Orifice spillway with 3 gates of size 7 m wide and 9.5 m high, Crest El. 2370 m, FRL El. 2390 m, high-level ice channel spillway with crest El. 2389 m, Auxiliary spillway with Crest El. 2389 m.
- Energy dissipator : Ski jump
- Design Discharge: 2000m^3/s



Cross section of the spillway

❖ Contributions of CWPRS

The studies were carried out on 2D sectional and 3D comprehensive models to evaluate the performance of spillway and energy dissipator. The major contributions from the studies are:

- **Roof profile of orifice**

  The original roof profile was in the form of $\frac{x^2}{(4.22)^2} + \frac{y^2}{(2.0)^2} = 1$. This profile was observed to be too flat, causing the jet's top profile to detach inconsistently rather than adhere properly. This detachment could lead to vibrations and reduced discharge capacity. To address this, the roof profile was adjusted to a steeper angle, ensuring that the jet separates at the orifice's end under most flow conditions, which in turn enhances the spillway's discharge capacity. The profile was then modified in the form of $y = \left(\frac{B^{2.4}}{A}\right)^{1/2.4} (x)^{1/2.4}$, where A=4.221 and B = 3.1.

- **Energy dissipator**

- A ski jump-type energy dissipator was proposed for the spillway. However, its performance was initially hindered by raised tailwater levels, resulting from the limited elevation difference between the bucket lip and the downstream concrete apron. Additionally, a low available head and an insufficient exit angle reduced the flow velocity at the bucket entry, further compromising the ski jump action.
- To address these issues, adjustments were made to the bucket parameters. The bucket lip was raised by 2 meters (from El. 2363 m to El. 2365.32 m), the downstream apron was lowered by 1 meter (from El. 2363 m to El. 2362 m), and the exit angle was increased from 20° to 33.78°. These modifications successfully enabled a clear ski jump formation, significantly improving energy dissipation during gated spillway operations.
- For ungated operations, the ski-jump bucket's performance could be sustained with appropriate measures to protect the spillway glacis from abrasive damage caused by the roller action of the hydraulic jump formed in the bucket.

- **Rotation of spillway axis**

- During a spillway operation, the flow was observed to be attacking the left bank of the channel downstream, particularly between chainages 100-300 meters, where velocities reached 13-15 m/s for a discharge of 2,000 m^3/s. The flow was riding along the left bank due to the operation of the spillway's two right spans, while the flow was deflected towards the right at the bucket. With the central span closed, water from the left and right end spans converged at the center, creating a rooster tail effect that rode over the ski-jump jet.
- To mitigate this issue, the spillway axis was rotated by 5^0 to guide the flow more centrally toward the river valley downstream. This adjustment effectively redistributed the energy, reducing its impact on the steep slopes of the valley. This design modification contributed to a more controlled flow, improving spillway efficiency and reducing the risk of erosion along the channel's left bank.

- **Approach channel**

The approach channel upstream of the spillway was originally designed with two berms, or benches, one at elevation 2375 m and the second at elevation 2368 m. However, sediment accumulation on these benches posed a risk of sediment entry into the intakes. Model studies suggested that replacing these with a single bench at elevation 2368 m would help prevent silt deposition near the spillway and power intake, improving intake performance and reducing maintenance requirements.

- **Protection to the left bank**

  For the modified design of the ski jump bucket and rotation of the spillway axis, high-velocity flow along the left bank with a velocity of the order of 20 m/s was observed up to 80 m downstream of the ski-jump bucket for the discharge of 2,000 m^3/s. Therefore, necessary protection measures were suggested for the dressed left bank to withstand the flow velocities of 20 m/s.

- **Auxiliary spillway**

➢ The original design of the auxiliary spillway did not perform satisfactorily, as the flow was cascading over large steps and falling as a jet onto the main spillway chute, causing potential erosion and flow disturbance. To address this, the auxiliary spillway was redesigned to improve its functionality. The revised design involved relocating the steps as upstream as possible, minimizing the elevation difference between the last step and the main spillway chute. Additionally, the number of steps was increased from three to seven, with each step having a uniform width and height. This reduction in step height improved the spillway's efficiency by allowing a more gradual flow, helping to stabilize the discharge.

➢ In its new form, the auxiliary spillway acted as a stepped spillway with a flat crest, which significantly improved its performance. The modification enabled it to flush ice cubes more effectively, with minimal disturbance to the main spillway flow. This revision was found to be satisfactory and enhanced the overall operational efficiency of the spillway system.

- **Installation of a log boom**: Given the extreme cold weather conditions at the project site, ice formation on the reservoir surface could pose a risk to spillway operations. To address this, it was recommended to install ice/log booms in front of the spillway spans, with provisions to guide ice blocks toward the auxiliary spillway for downstream flushing. Model results, including surface velocities observed in the reservoir area, were instrumental in designing the layout and specifications of the ice/log booms for optimal performance.

View of the physical model

View at the dam site

3.1.2 Chamera Stage I, II and III H.E. Projects

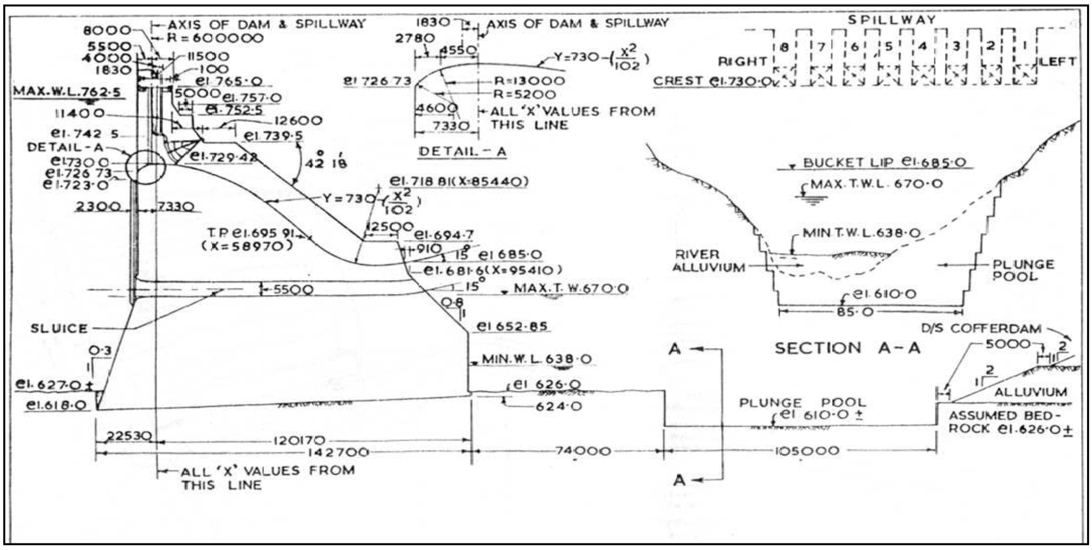
The hydropower potential of the Ravi River system had been assessed as 3229 MW out of which 2177 MW have already been tapped by constructing a fair number of hydropower projects by the concerned State Governments, State and Central PSUs, and private developers. There are 7 dams, 3 barrages, 1 weir, 2 lift irrigation schemes, and 9 powerhouses in Ravi Basin. Himachal Pradesh has four hydro power projects namely 180 MW Baira Siul, 540 MW Chamera I,300 MW Chamera II, 231 MW Chamera III. Sewa II having 120 MW on Sewa River, 600 MW Ranjit Sagar (Thein) dam on Ravi River fall in Kathua district of J&K. Shahpur Kandi Dam having 206 MW on Ravi River is in Gurdaspur district of Punjab. Sewa-III and Ujh Level Crossing Barrages are in the Kathua District of J&K. Madhopur Barrage is situated in Gurdaspur district of Punjab.

Chamera Hydro-Electric Project, Stage-I, II and III with a gross installed capacity of 1071 MW across River Ravi in India were designed as a cascade hydroelectric project.

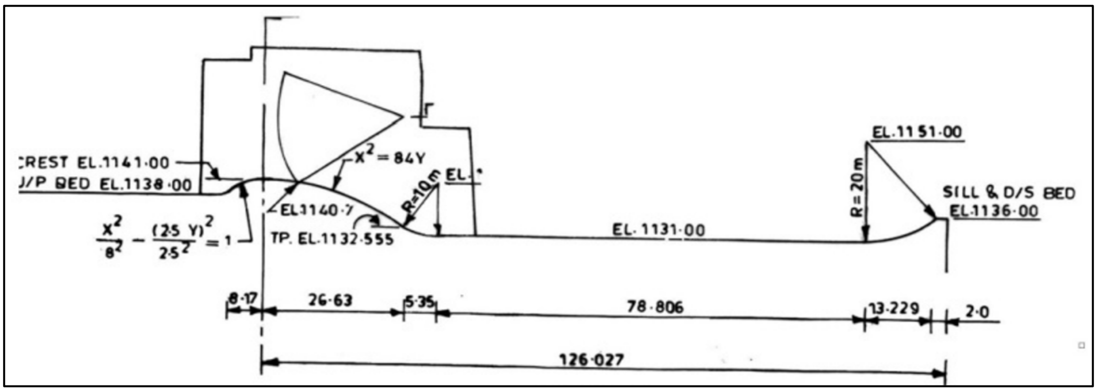
- **Project Overview**

Name of H.E. Project	Type of Dam	Dam height	Design Flood	Spillway/ EDA type	Installed capacity
Chamera -I	Concrete Gravity Dam	125 m	22,000 m^3/s	Breast wall with 8 gates of size 10 m x 12.8 m, Crest El. 730 m, FRL El. 760 m, Ski-Jump bucket as an energy dissipator	540 MW
Chamera-II	Concrete Gravity Dam	43 m	9,000 m^3/s	Low level with 4 gates of size 12.5 m x 21 m, Crest El. 1141 m, FRL El. 1162 m, stilling Basin as an energy dissipator	300 MW
Chamera-III	Concrete Gravity Dam	68 m	11,400 m^3/s	Breast wall with 3 gates of size 12.5 m x 16.5 m, Crest El.1360 m, FRL El. 1397 m, stilling Basin as energy dissipator	231 MW

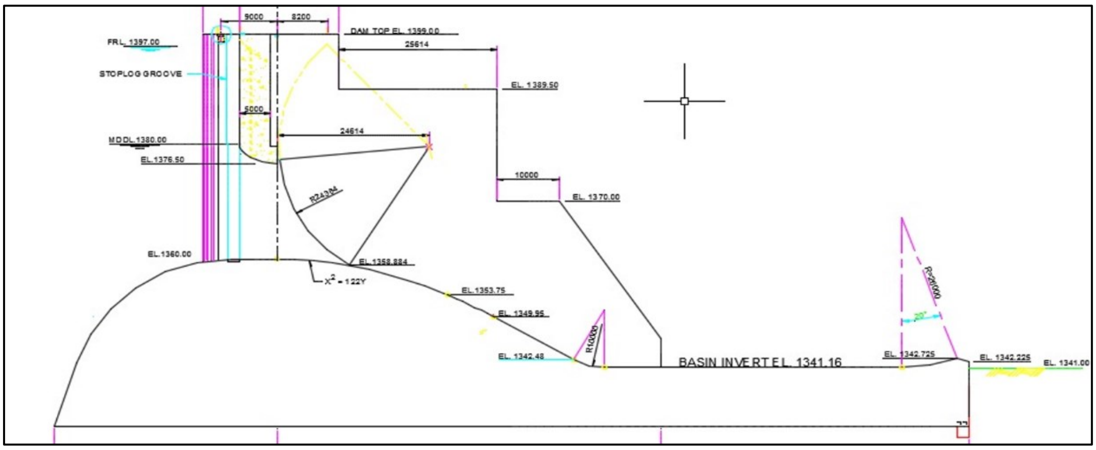
All three projects were designed differently based on the location and geological conditions at the site. Chamera-I is designed as a storage dam with a breast wall spillway and ski jump bucket as EDA. Chamera-II is a diversion dam with a 21.5 m radial gate over a low-level spillway crest and stilling basin as EDA. Chamera-III is a 68 m high dam with a Chute spillway having a breast wall. Energy dissipation is provided in the form of a stilling basin.



Cross section of Chamera stage I spillway



Cross section of Chamera stage II spillway



Cross section of Chamera stage III spillway

CWPRS Contribution for Chamera Stage I Project

- **Roof profile of orifice**

  Spillway spans were reduced to eight numbers to accommodate spillway flow within the main river course and to avoid hitting of jet on the left bank. The original roof profile was in the form of $\frac{x^2}{(4)^2}+\frac{y^2}{(2)^2}=1$. This profile was observed to be too flat, causing the jet's top profile to detach inconsistently rather than adhere properly. This detachment could lead to vibrations and reduced discharge capacity. To address this, the roof profile was adjusted to a steeper angle with equation $\frac{x^2}{(10)^2}+\frac{y^2}{(5)^2}=1$ as a part of a quarter of the ellipse having a 4 m width of breast wall, ensuring jet separates at the orifice's end under most flow conditions, which in turn enhances the spillway's discharge capacity.

- **Spillway chute**

  The spillway axis was originally set at a 65^0 angle relative to the river's general flow direction. To effectively redirect the spillway discharge toward the pre-excavated plunge pool located in the main river section, a curved spillway chute with superelevation was suggested. This design adjustment would help realign the spillway discharge towards the plunge pool, ensuring water is directed efficiently without causing erosion along the riverbanks. By guiding the water into the plunge pool, the design promotes effective energy dissipation, minimizing potential downstream impact. This configuration, with its carefully considered angle and curvature, is intended to balance the flow management requirements with the site's topographical constraints, optimizing spillway performance.

- **Divide walls**

  The divide walls were modified to align with the curved spillway chute, which incorporated both curvature and super-elevation to redirect the flow. However, the curvature of the chute, combined with the supercritical flow conditions, led to a difference in water levels across the chute. To address this, the divide walls' height was increased to match the chute's superelevation, helping to contain the flow within the chute, preventing spillovers, and managing the water level. Based on pressure measurements along the sides of the divide wall, it was found that additional thickness would provide the necessary structural stability under supercritical flow conditions, reducing the risk of wall deformation or failure due to high lateral pressures. These modifications were essential to ensure both the structural integrity of the divide walls and effective flow management through the curved spillway chute, thus enhancing the overall performance and durability of the spillway system in supercritical conditions.

- **Ski-jump Bucket**

  To achieve a more uniform distribution of discharge in the plunge pool, alternate spans of the spillway were designed with flip buckets having differing lip angles. One with steeper lip angle of 35°, directs the flow with a more pronounced trajectory, resulting in a higher, more concentrated jet that reaches deeper into the plunge pool. Another bucket with 15° lip angle disperses the water over a broader area with a lower trajectory, producing a gentler impact on the pool. By alternating these angles, the flow entering the plunge pool is spread more evenly across the area, reducing localized erosion, distributing energy dissipation more effectively, and helping to mitigate the risk of deeper local scour. This configuration enhances the longevity of the plunge pool and improves the overall hydraulic performance of the spillway system.

View of physical Model

View of the dam site

❖ CWPRS Contribution for Chamera Stage II Project

The studies were carried out on 2-D sectional model and 3-D comprehensive model. The major contributions from the studies are:

- **Spillway downstream profile**

  The initial design of a low-level spillway featured a crest 3 meters above the average riverbed, but its discharge coefficient of 0.57 limited its capacity to handle high flows. The low efficiency was attributed to two factors: an overly flat crest profile ($x^2 = 100y$) and partial submergence of the crest by tailwater levels. These conditions restricted flow velocity over the crest, reducing its ability to pass floodwaters effectively. To improve performance, the crest profile was revised to $x^2 = 84\,y$, creating a steeper geometry better suited to the flow dynamics. This adjustment increased the discharge coefficient to 0.62, significantly enhancing the spillway's efficiency. The improved design accommodated a maximum head of 21 meters, ensuring more effective flood routing and optimizing the spillway's performance under high-head conditions.

- **Stilling basin**

  During initial observations, an oscillating hydraulic jump was forming in the stilling basin, especially for discharges of 50% and above, where energy dissipation proved inadequate. Turbulence extended beyond the end sill, and high-velocity flow continued downstream along the bed. This sweep-out effect was also noted during partial gate operations, with discharges of 25% and higher contributing to the instability. To address these challenges, the stilling basin apron level was lowered by 5 meters, which improved the stability of the hydraulic jump, providing better energy dissipation. For added protection, a 15 m long apron extension downstream of the end sill was recommended to further mitigate high-velocity flow and prevent downstream erosion. After these modifications, the stilling basin performance improved significantly, effectively managing energy dissipation and minimizing turbulence in the flow path.

- **Power Intake**

The original alignment of the power intake, positioned at a 100° angle to the dam axis on the right bank, contributed to return flows and strong vortices near the right spillway span due to the sharp river curvature in front of the intake. These return flows and vortices created inefficient flow conditions near the spillway structure. To address these issues, the alignment of the power intake was tilted leftward to form a 90° angle with the dam axis. This modification led to a noticeable improvement in flow conditions. Return flows were eliminated in front of the intake, allowing for smoother water entry. The intensity of vortices near the right spillway span was significantly reduced. These improvements resulted in more stable and efficient flow conditions at the power intake and spillway.

View of physical Model

View of the dam site

❖ CWPRS Contribution for Chamera Stage III Project

The studies were carried out on a 3-D comprehensive model. The major contributions from the studies are:

- **Orifice spillway**

For high discharges, the trunnion beam was observed to be submerged. To address this and ensure optimal operation, it was suggested to raise the trunnion elevation by 1 m. This adjustment was recommended with due consideration for the water surface profile to prevent submergence under peak flows, flow bulking due to high velocities, which increases water height over the spillway, and sufficient freeboard to account for dynamic fluctuations. By raising the trunnion elevation, submergence risks were minimized, maintaining effective spillway functionality and structural safety during high discharge events.

- **Stilling basin**

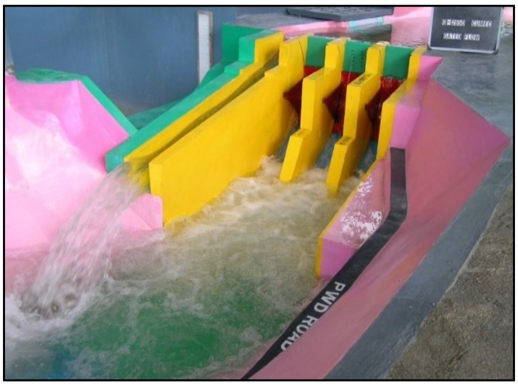
In this typical low Froude number (2 to 5), high discharge intensity stilling basin, the jump was experiencing sweep out at lower discharges and becoming highly turbulent at higher discharges. Additionally, the jump was very sensitive to tailwater level (TWL) fluctuations, creating operational challenges. To improve performance the basin invert was lowered by 5 m. This adjustment helped stabilize the jump by providing better control over flow patterns within the basin. Extending the Stilling Basin length by 30 m offered more space for energy dissipation and helped to manage high discharge intensities. A concrete apron of 30 m in length was provided to protect against erosion and bed scouring downstream of the basin, especially under high-velocity flows. The contours in front of the stilling basin were dressed down to mitigate return eddies that were disrupting the flow and compromising energy dissipation. These adjustments create a more stable hydraulic jump, reduce turbulence, and enhance the basin's performance across varying discharges.

- **Training wall**

In the original design of the stilling basin, the left training wall was splayed in by 6°, causing a constriction in the basin width and resulting in return eddies on the left side. To address these issues and enhance flow stability, the training walls on both sides were kept straight. Providing straight walls minimizes constrictions, reducing return eddies and allowing for smoother flow through the stilling basin. The training wall elevation was raised to 1370 m, positioned above the tailwater level for a discharge of 5700 m^3/s (50% of PMF), which prevents overtopping and helps contain the flow within the basin during high discharges. These modifications improved the energy dissipation within the stilling basin and ensured more stable, controlled flow conditions, reducing turbulence and eddy formation.

- **Auxiliary Spillway**

The auxiliary spillway was in the form of a tunnel spillway. Specifically, for discharges around 50% and above, through both the surface and tunnel spillways, high tailwater levels at the tunnel's outlet led to the backing of flow, which disrupted the intended ski action, causing the formation of a hydraulic jump that choked the tunnel and restricted discharge efficiency. Additionally, the design faced structural limitations, including insufficient rock cover over the tunnel, a steep slope on the right bank, which increased stability concerns. To address these issues, it was recommended to convert the tunnel spillway into a chute spillway with a ski-jump bucket positioned adjacent to the right span of the spillway. This modification alleviated the backing and hydraulic jump formation issues, effectively managing high discharges without the limitations posed by the tunnel configuration.



View of the physical model

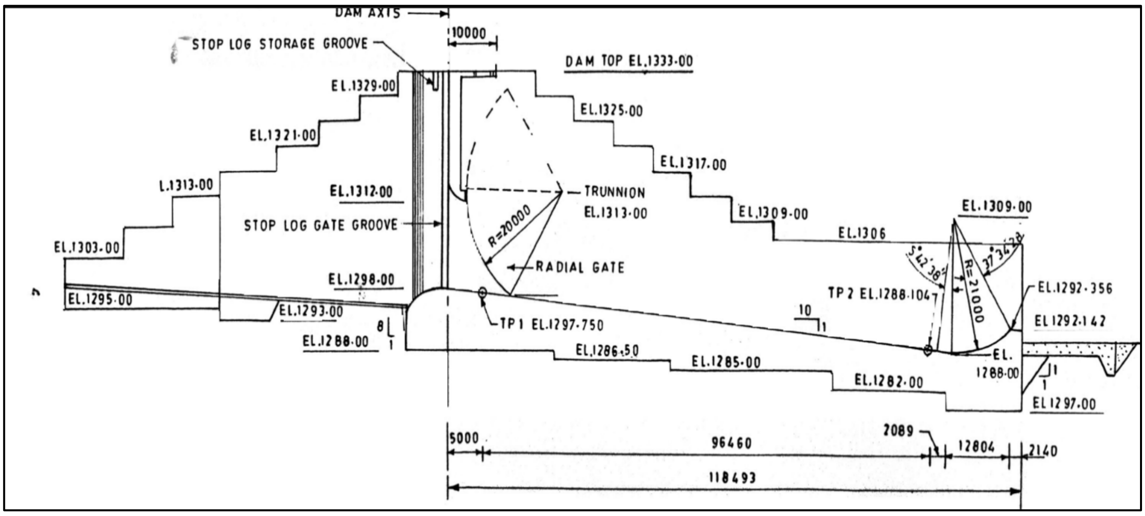
View of the dam site

3.1.3 Parbati Stage-III, Himachal Pradesh

The Parbati Stage–III H.E. Project is a run-of-the-river scheme on the River Sainj, a tributary of the Beas River in Kullu district of Himachal Pradesh. The project utilizes tail race releases of the Parbati Stage II powerhouse and inflows from Sainj River.

❖ **Project Overview**

- Dam dimensions: 43 m high rockfill dam
- Power installed capacity: 520 MW
- Spillway details: Orifice spillway with 2 gates of size 7.2 m wide and 14 m high, Crest El. 1298 m, FRL El. 1330 m, two horseshoe shaped diversion tunnels to be used as spillway tunnels later
- Energy dissipator : Stilling basin
- Design Discharge: 3300 m^3/s through orifice spillway & 1300 m^3/s through tunnel spillway



Cross section of spillway

❖ **Contributions of CWPRS**

The studies were carried out on 3D comprehensive models to evaluate the performance of spillway and energy dissipator. The major contributions from the studies are:

- **Ski jump bucket of orifice spillway**

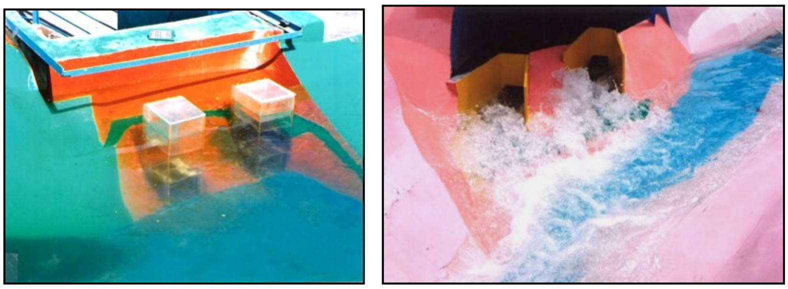
Initially, a ski jump energy dissipator with superelevation to all three spans was designed for the orifice spillway. However, the superelevation provided along left training wall with lip angle 40^0 and lip El. 1292.5 m and along right training wall with lip angle 35^0 and lip El. 1291.77 m in the bucket was not effective in deflecting the jet towards the river. The ski jump bucket was modified by keeping the bucket lip of all three spans at the same level with lip angle 37^0 and lip El. 1292.356 m. With this modification, the ski-jump jet hits the left bank at about 50 m downstream of the lip. Hence, dressing to the left bank was suggested for clear ski jump formation. A pre-formed plunge pool was suggested to dissipate the excess energy of the ski-jump jet.

- **Modification of tunnel intakes**

A strong air-entraining vortex was observed at RWL 1325 m and above due to the stagged position of the intake. This air-entraining vortex may produce various problems such as discharge reduction, vibration, excessive air entrainment etc., during the intake operation. Thus, the layout was modified by aligning the intakes in a straight line and dressing the right bank upstream of the right tunnel intake. This resulted in reducing the intensity and frequency of vortex formation in front of the intake.

- **Modification of energy dissipators at the outlet of the tunnel**

- For the maximum discharge of 1300 m^3/s, velocity at both tunnel outlets was 20 m/s. Because of the large thickness and comparatively less velocity, the ski-jump buckets provided at the outlet of the tunnel were not effective in lifting the jets and throwing them in the river. Jet was hitting the left bank causing erosion and damage to the bank. Thus, the bucket was replaced by providing a stilling basin with baffle blocks and an end sill as an energy dissipator.
- Various alternative designs of the stilling basin and its appurtenant structures were tested on the model. After extensive studies the final design of the stilling basin was recommended in the form of 22 m long stilling basin with a flared training wall, three rows of baffle blocks and an oblique end sill, considering the space limitation of the site. Modification in the design of the energy dissipator from the ski jump to the stilling basin helped to reduce the velocity from 20 m/s to 13 m/s till the end sill. The high velocity of flow leaving the end sill would be further dissipated due to the tailwater depth. Suitable protection was suggested to the left bank to sustain the high velocity of flow of 4 to 5 m/s observed just downstream of the end sill.
- Due to encroachment of the end sill of the stilling basin in the river portion, the provision of an apron downstream of the end sill to prevent erosion at the toe was ruled out. Therefore, it was recommended that a key may be provided of at least 6 to 7 m into the fresh rock downstream of the end sill to protect the stilling basin from undermining.



View of the physical model

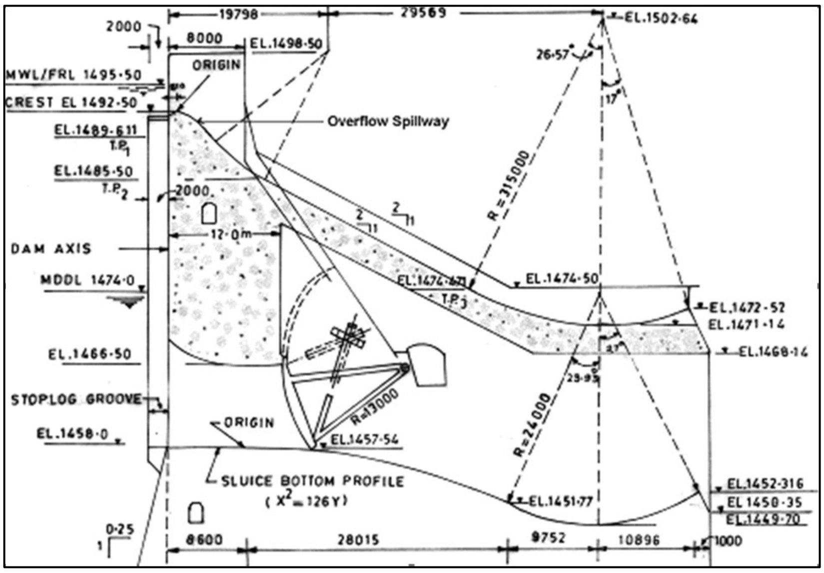
View of the dam site

3.1.4 Nathpa Jhakri Project, Himachal Pradesh

The Nathpa Jhakri H.E. Project in Kinnaur district, Himachal Pradesh is one of the largest run-of-the-river schemes. River Satluj has a catchment of 49,820 Sq. km at Nathpa (12,920 sq. Km is in India and 36,900 sq. Km in Tibet/China). Because of fragile geology and steep slopes, the soil erosion rate is high during snowmelt. River blockades on account of avalanches and landslides are common because of steep banks. When these blockades breach, flash floods are caused and silt concentration increases because of increased erosion.

❖ Project Overview

- Dam dimensions: 65 m high concrete dam
- Power installed capacity: 1500 MW
- Spillway details: Sluices with 6 gates of size 7m wide and 7.35 m high, Crest El. 1458 m, FRL/MWL El. 1495.5 m, an overflow spillway of length 15 m with its crest at El. 1488 m on the right flank.
- Energy dissipator : Ski Jump
- Design Discharge: 5660 m^3/s



Cross section of spillway

❖ Contributions of CWPRS

Extensive model studies were carried out at CWPRS for evolving economic and efficient hydraulic design of sluice spillways, overflow spillways and energy dissipators. The findings from the studies are described below:

- **The layout of the under sluices and overflow spillway**

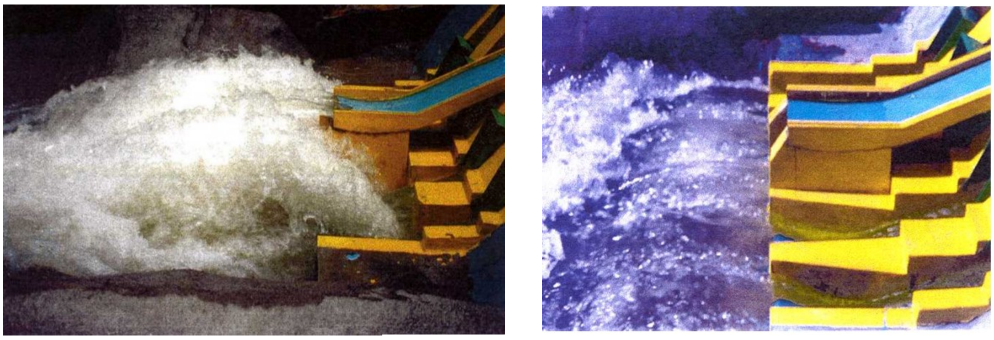
The initial design of the ski-jump bucket encountered performance issues due to tailwater level buildup downstream, which impacted the apron located downstream of the bucket. The flow from the ski-jump bucket, particularly from the right-side sluices, forcefully impacted the excavated right bank and the pit downstream of the bucket. This impingement was intense and violent, resulting in strong return flows towards the spillway. To enhance approach flow conditions and improve the operation of the right-end sluices, modifications to the right bank upstream of the dam were needed to smoothen and direct flows effectively. The number of sluices was reduced from 6 to 5 to accommodate the narrow waterway at the dam site. The size of each sluice was increased from 7.0 m x 7.35 m to 7.5 m (width) x 8.5 m (height) for better capacity and control. The central overflow spillway was moved from the right-end sluice to the central sluice. This adjustment helped to concentrate scouring action within the river channel, reducing the impact on the right bank and improving overall erosion management downstream. These modifications collectively aimed to manage violent return flows, reduce the erosive impact on the right bank, and optimize sluice performance within the constraints of the dam site’s narrow waterway.

- **Ski jump energy dissipator**

The lip angle of the ski-jump bucket was reduced from 30 degrees to 27 degrees to decrease return flows at low discharge levels. Additionally, it was recommended to construct a 20-meter-wide concrete apron at multiple elevations along the rock line, based on the observed scour levels at the toe of the spillway. This apron will help prevent undermining of the bucket's toe caused by cascading flows. To ensure stability, the apron should be securely keyed into fresh rock at its downstream end.

- **Extension of intermediate piers up to the lip of the bucket**

The piers were extended up to the bucket lip to protect the slopes on both flanks from landslides caused by the high rooster tail formed by the interaction of jets from adjacent spans. The pier width was also tapered from 8.5 meters to 4 meters at the bucket lip, effectively reducing the flow intensity from 150 to 94 $m^3/s/m$ and directing the flow towards the center of the river.

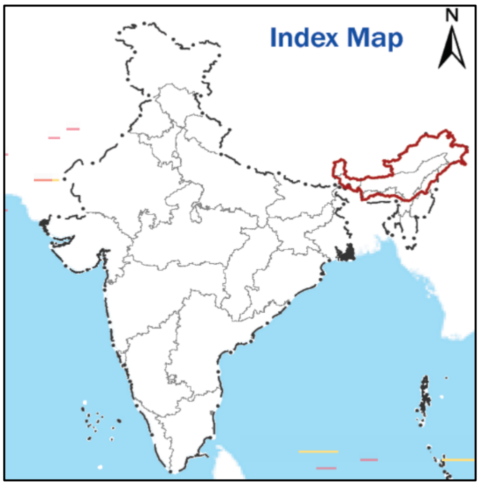


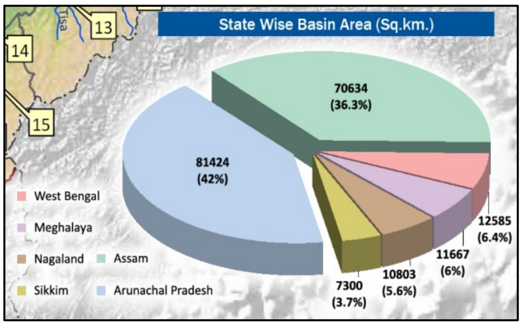
View of physical model

View of the dam site

3.2 BRAHMAPUTRA RIVER BASIN

The Brahmaputra River, one of Asia's largest and most significant rivers, spans 2,900 kilometers across four countries—Tibet (China), Bhutan, India, and Bangladesh—before flowing into the Bay of Bengal. The Brahmaputra basin covers an area of 580,000 square kilometers, distributed across Tibet (50.5%), India (33.6%), Bangladesh (8.1%), and Bhutan (7.8%). Although the main river does not flow directly through Bhutan, 96% of Bhutan’s territory lies within this basin. The basin has an irregular shape, with a maximum east-west length of 1,540 kilometers and a maximum north-south width of 682 kilometers. In India, the basin spans the states of Arunachal Pradesh, Assam, West Bengal, Meghalaya, Nagaland, and Sikkim.





State-wise drainage area of the basin

Major rivers in the basin

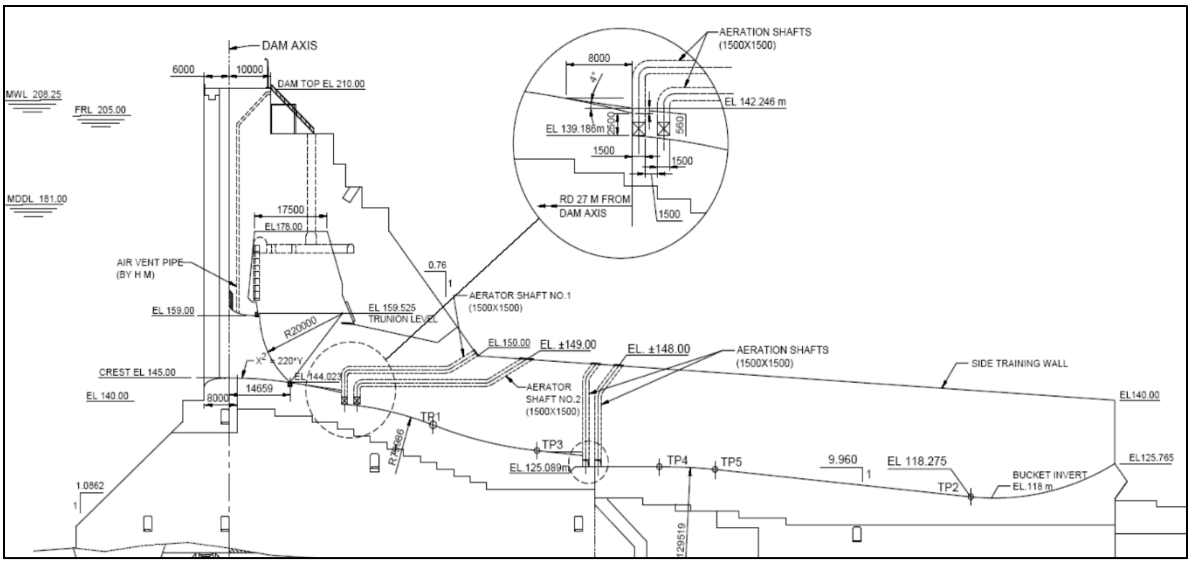
The Brahmaputra basin is rich in hydropower potential. Several hydropower projects in this region, such as the Kopili (200 MW), Khandong (75 MW), and Karbi Langpi (100 MW) projects in Assam; the Lower Subansiri (2,000 MW), Dibang (3,000 MW), Kameng (600 MW), and Ranganadi (405 MW) projects in Arunachal Pradesh; the Teesta-V (510 MW) project in West Bengal; and the Umiam-Umtru Power Complex (174 MW) in Meghalaya, are currently in various stages of planning and development. The contribution of CWPRS in some of the important hydropower projects is discussed below.

3.2.1 Subansiri H.E. Project , Arunachal Pradesh/Assam

Subansiri Lower H. E. Project is one of the largest hydroelectric projects undertaken in India on the lower reach of Subansiri River, a tributary of Brahmaputra River, on the border of Arunachal Pradesh and Assam.

❖ Project Overview

- Dam dimensions: 116 m high and 271 m long concrete gravity dam
- Power installed capacity: 2000 MW (8 units of 250 MW each)
- Spillway details: Orifice spillway with 9 gates of size 11.5 m wide and 14 m high with three different geometries of spillway profile, crest El. 145 m, FRL El. 205 m, MWL El. 208.25 m, 3 chute profiles with varying slopes of 10^0, 6^0 and 2.3^0
- Energy dissipator: Ski jump energy dissipator for all three chute profiles with varying bucket geometry.
- Maximum outflow flood: 35,000 m^3/s



Cross section of spillway

❖ Contributions of CWPRS

The narrow valley, high discharge intensity, incoming sediment, and high flow velocity posed significant challenges in the structure's design. Extensive studies were conducted at CWPRS up until 2021 to evaluate both original and alternative designs for the spillway, energy dissipator, and power intake. The main findings from the hydraulic model studies, taking into account the site constraints, are discussed below.

- **Crest of the spillway/alignment of power intake**

It was observed that silt accumulated near the power intake when there was a 10-meter difference between the intake sill and the spillway crest, and the intake was positioned in a staggered alignment. To enable more effective sediment flushing from the reservoir, the spillway crest was lowered by 5 meters, and the intakes were aligned in a single line.

- **Spillway Profiles (3 different chute profiles)**

  A high negative pressure, reaching 2.5 meters with a cavitation index below the critical threshold of 0.2, was observed on the long chute profiles with slopes of 10^0 and 6^0. Severe cavitation damage was noted on the spillway surface, especially during operations with lower gate openings under high flow velocities of 35 to 40 m/s. Extensive studies on various gate operations highlighted the need for an aerator to protect the spillway surface.

  The spillway profiles were subsequently modified to incorporate an aeration system along the smooth, long chute profile. The aerator design, featuring an offset, ramp, and air supply system with two aeration shafts on either side of the spillway span, was finalized after a thorough analysis of key hydraulic parameters, including:

  - Pressures and velocities on the spillway surface
  - Jet/cavity length
  - Cavity pressures
  - Velocity within the aeration shaft
  - Air concentration near the spillway bed

  Additionally, the optimal location and number of aerators required to protect the full length of the spillway bed were determined. The size and number of air vents were also finalized to ensure adequate air supply in the cavity beneath the jet for effective aerator operation.

- **Energy dissipator**

  The river valley in the immediate downstream of the Subansiri spillway is very narrow and has a steep sloped hill. The spillway was originally provided with a ski jump type of energy dissipator. It was modified by the provision of a superelevated Ski-jump bucket and energy dissipator with a curved deflector wall to deflect the flow toward the plunge pool and protect the bank slopes from the direct impact of the ski-jump jet.

- **Pre-formed plunge pool**

  Based on water and scour profiles obtained from the model studies; and also considering the constraints at the site such as the location of the downstream coffer dam and powerhouse tail pool; the pre-formed plunge pool was proposed downstream of ski jump bucket to reduce high energy flow and consequently dampen the uncontrolled erosion ensuring the safety of the structure.

- **Deflection along the left training wall**

  While passing 50% design discharge through all spans equally and partially, the 10 m long and 5^0 deflector wall along right training wall was able to divert the flow towards the plunge pool.

The ski-jump jet issuing from the extreme left bay could be seen impinging just on the left edge of the plunge pool. It is suggested to increase the curvature of the left deflector wall from 12^0 to 16^0 to deflect the flow toward the plunge pool. It was suggested to connect the deflector wall and training wall by slope to avoid splashing of jet on the raised vertical face of the deflector wall.

- **Height of Training/Divide walls**

Inputs in terms of water surface profiles were submitted to decide the heights of the divide/ training walls for different bays keeping in view the bulking of flow in the prototype due to air entrainment and freeboard.

View of the physical model

31.5.2023 10.20

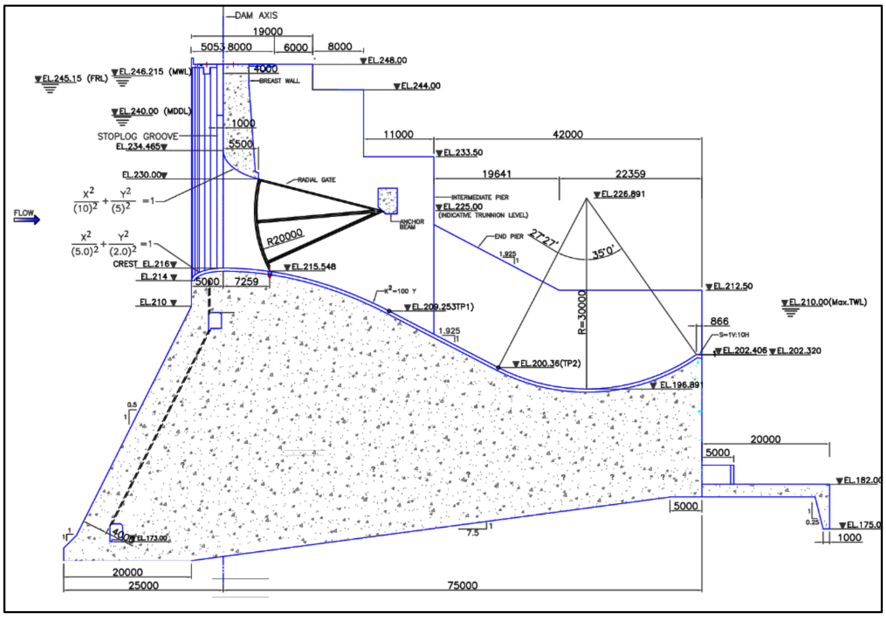
View of the dam site

3.2.2 Pare H.E. Project, Arunachal Pradesh

The Pare H.E. Project is planned as a run-of-river scheme on the Dikrong / Pare river downstream of the powerhouse of the first stage of Ranganadi H.E. Project in the Papumpare district of Arunachal Pradesh.

❖ Project Overview

- Dam dimensions: 78 m high concrete gravity dam
- Power installed capacity: 110 MW (4 units of 130 MW each)
- Spillway details: Orifice spillway with 3 gates of size 10.4 m wide and 14 m high, Crest El. 216 m, FRL El. 245.15 m, MWL El. 246.215 m
- Energy dissipator: Ski jump bucket
- Maximum outflow flood: 5,000 m^3/s
- Plunge pool: Preformed plunge pool



Cross section of spillway

❖ Contribution of CWPRS

- **Bottom and roof profile of spillway**

The original roof profile was in the form of $\frac{x^2}{(4.22)^2}+\frac{y^2}{(2.0)^2}=1$ and the downstream profile was $x^2 = 116.6\ y$. These profiles were observed to be too flat, reducing discharging capacity by about 16 % for one gate inoperative condition as recommended in BIS No. IS: 11223-1985. Therefore, the profiles were made steeper viz roof profile in the form of $\frac{x^2}{(10)^2}+\frac{y^2}{(5)^2}=1$ as a part of a quarter of an ellipse having a 5.5 m width of breast wall and bottom profile in the form of $x^2 = 100\ y$. These modifications increased the discharge capacity of the spillway.

- **Ski Jump bucket**

The performance of the ski jump bucket with a lip angle of 40^0 and elevation of 199.08 m was not satisfactory as no clear ski jump action was observed. Due to the high tailwater level, the ski-jump jet was unable to lift into the air, preventing the formation of a clear ski action under any operating condition. Consequently, the lip of the bucket was raised by 3 meters 199.08 m to 202.406 m and the bucket angle was changed from 40^0 to 35^0 to enhance the performance of the ski jump bucket. Divide walls were also suggested by extending intermediate piers up to the lip to confine the jet in the middle of the river. As the jet issuing from the bucket was hitting the left bank, the dressing to the bank was suggested to prevent the bank erosion. Also, the height of the left and right training walls was increased by 3.5 to avoid overtopping of flow.

- **Pre-formed plunge pool**

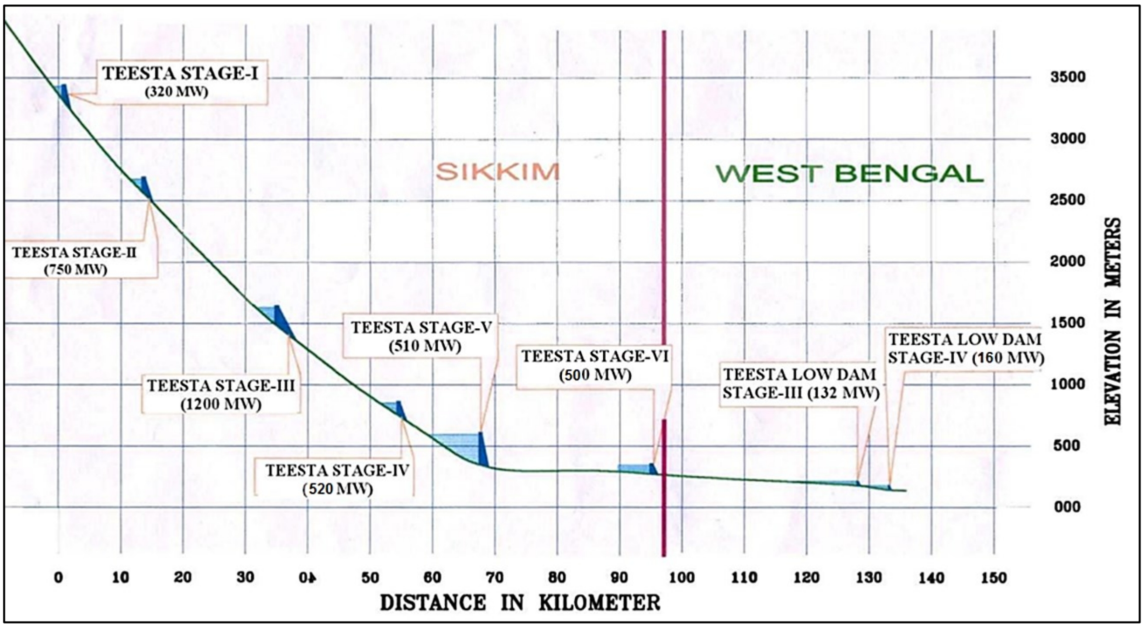
The flow conditions in the river downstream after the impact of the jet were violent with a velocity of 20 to 25 m/s. The impact of high velocity jet cause erosion to the riverbed and the bank, especially in the initial years of spillway operation. To prevent uncontrolled erosion, a pre-formed plunge pool was recommended to dissipate the excess energy of the ski-jump jet. The model studies indicated that with the provision of the plunge pool, the excess energy dissipated and the flow in the river beyond the point of impingement remained subcritical with a velocity of about 5 to 10 m/s, thus minimized the chances of erosion.

Plunge pool in the model **Plunge pool in the dam site**

Ski-jump performance in physical model

3.2.3 Teesta H.E. Projects, Sikkim

The Teesta River originates from the Pahunri Glacier and flows southward through deep and narrow gorges and rapids in Sikkim. Throughout its course, the river is turbulent, maintaining a high velocity as it navigates a deep valley with a steep gradient of approximately 1:125. The hydroelectric potential of the Teesta basin is estimated to be 4,180.5 MW, with a head of 3,500 meters available over a distance of 150 km. The rapid descent of the river from high elevations makes it particularly well-suited for hydropower development.



Cascade development in the Teesta basin

The most significant development activity on the River Teesta is the construction of a series of cascade dams for hydropower generation in the state of Sikkim. Some of the major hydropower projects in Sikkim include TLDP-III (132 MW), TLDP-IV (160 MW), Teesta Stage-II (330 MW), Teesta Stage-III (1200 MW), Teesta Stage-IV (520 MW), Teesta Stage-V (510 MW), Teesta Stage -VI (500 MW).

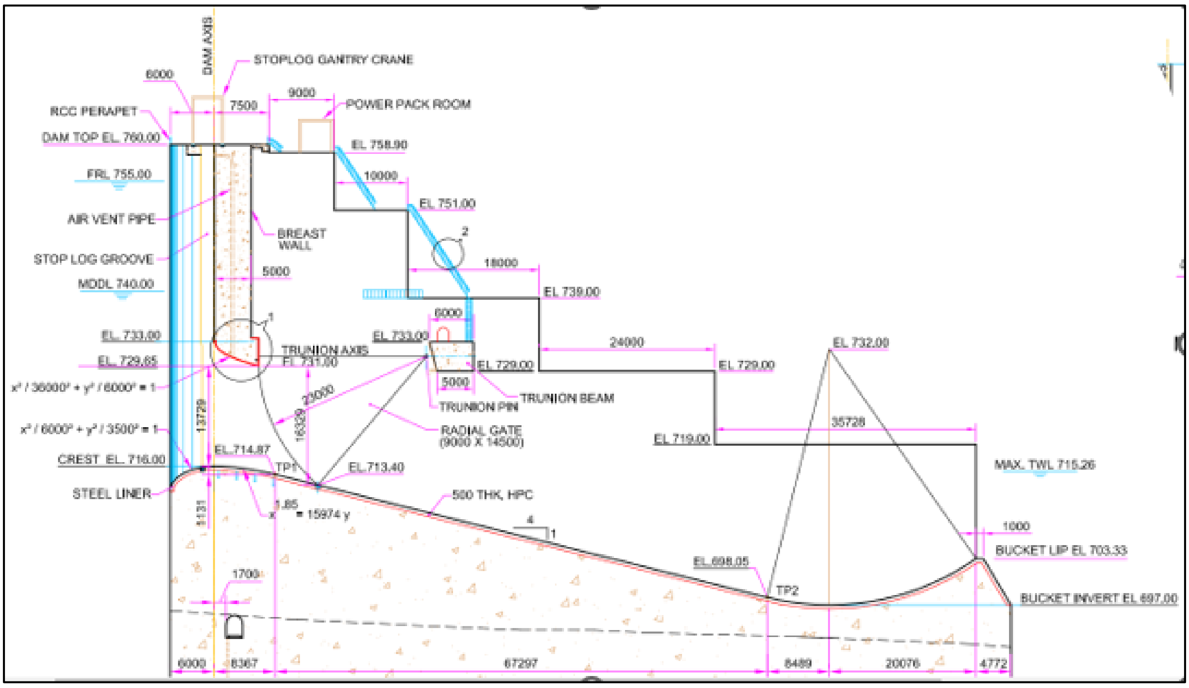
The contribution of CWPRS in some of the important hydropower projects is discussed below.

❖ Teesta Stage-IV Project

The Teesta H. E. Project, Stage-IV is a run-of-the-river scheme located on River Teesta after its confluence with tributary Runchu in Sikkim. The project is a part of the hydropower-rich Teesta cascade between the Teesta-III project on the upstream and the Teesta-V project on the downstream.

❖ Project Overview

- Dam dimensions: 65 m high and 197.2 m long concrete gravity dam
- Power installed capacity: 520 MW (4 units of 130 MW each)
- Spillway details: Orifice spillway with 6 gates of size 9 m wide and 14.5 m high, Crest El. 716 m, FRL El. 755 m, MDDL El. 740 m
- Energy dissipator: Ski jump energy dissipator
- Maximum outflow flood: 13,000 m³/s
- Plunge pool: Preformed plunge pool



Cross section of spillway

❖ Contributions of CWPRS

Extensive studies were conducted at CWPRS until 2022 to evaluate both original and alternative designs for the spillway, energy dissipator, and power intake. The major findings from the hydraulic model studies were as follows:

- **Roof Profile of Orifice**

  The original roof profile was in the form of $\frac{x^2}{(6)^2}+\frac{y^2}{(2.5)^2}=1$. The profile was observed to be too flat, reducing discharging capacity of the spillway. Therefore, the profiles was made steeper viz., roof profile in the form of $\frac{x^2}{(36)^2}+\frac{y^2}{(6)^2}=1$ as a part of a quarter of the ellipse having 6 m width of breast wall. This modification increased the coefficient of discharge from 0.78 to 0.84, thus resulted in increasing the discharge capacity of the spillway by about 8%.

- **Tilting and curving of dam axis and provision of pre-formed plunge pool**

- Model studies indicated that the flow was concentrated towards the right bank in the plunge pool and hit the bank when the dam axis was straight.
- To address the issue of uncontrolled erosion along the right bank and to achieve a uniform flow distribution across the river valley downstream of the spillway, several modifications were implemented. The dam axis was curved and tilted counter-clockwise by approximately 5°. Additionally, the spillway layout was shifted one span towards the left side, ensuring better alignment with the river valley and flow direction.
- To further stabilize the right bank, dressing was recommended to smoothen and reinforce the terrain, minimizing erosion risk. A plunge pool was incorporated downstream of the ski-jump bucket to dissipate energy effectively and mitigate the erosive impact of high-velocity flows. These measures collectively enhanced the structural stability and hydraulic performance of the dam and its spillway system.
- This modification improved the flow conditions in the plunge pool. However, protection to the right bank was suggested by the way of providing concrete cladding to withstand the impact of the ski-jump jet and to avoid undermining steep hill slopes leading to landslides.

- **Power Intake**

Mild vortices were observed in front of all four units of power intake for the entire range of discharges with the gated and ungated spillway operation. Therefore, the centreline elevation of the intake was lowered by 1m from El. 729.25 m to El. 728.25 m, ensuring adequate submergence for preventing the formation of vortices.

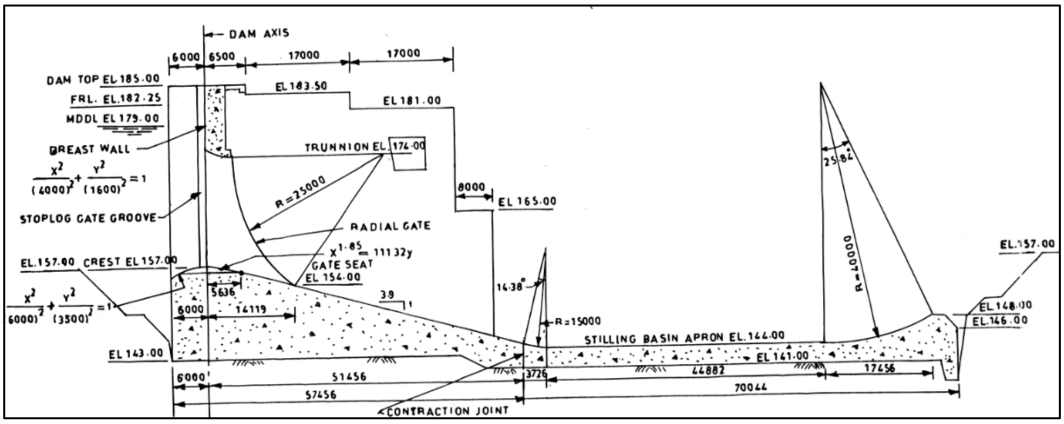
View of the physical model

❖ Teesta Low Dam Project, Stage – IV, West Bengal

Teesta low dam project, Stage – IV is located on river Teesta in the state of West Bengal. It is part of the cascade development of projects on the lower stretch of river Teesta, which happens to be the last one and is a run-off-the-river scheme.

❖ Project Overview

- Dam dimensions: 30 m high and 511 m long Concrete gravity dam
- Power installed capacity: 160 MW
- Spillway details: Orifice spillway with breast walls 7 gates of size 11m wide and 17 m high, Crest El. 157.0 m, FRL El. 182.25 m
- Energy dissipator: Stilling basin
- Maximum outflow flood: 15,400 m^3 /sec



Cross section of the spillway

❖ Contributions of CWPRS

The studies were carried out on 3D comprehensive models to evaluate the performance of spillway and energy dissipator. The major contributions from the studies are:

- **Energy dissipator**

  The energy dissipator provided was in the form of a solid roller bucket with its invert at El. 145.0 m and lip angle of 40° in the initial design. The lip elevation was at 148.5 m. The original design consisted of a spillway rear slope of 1:4 and a bucket with a radius of 15 m. The performance of the solid roller bucket was not satisfactory for the entire range of discharges as the surface and ground rollers were not forming properly. A drowned ski-action was seen with the backup of flow like a hydraulic jump in the bucket. roller formation did not occur in the bucket due to high discharge intensity of up to 200 $m^3/s/m$ and incoming velocities of the order of 20-25 m/s. For the dissipation of this excess energy, a stilling basin-type energy dissipator with a floor level of 144 m was recommended.

- **Training walls**

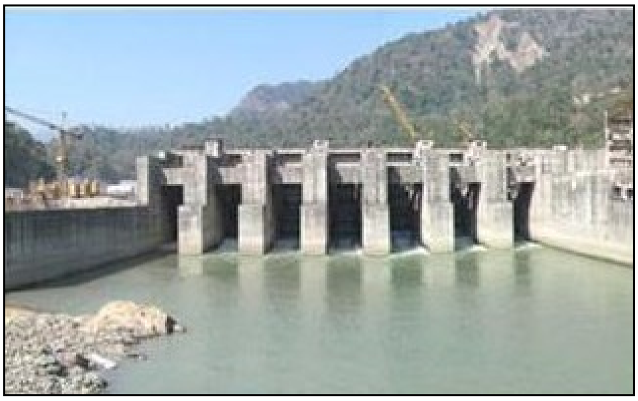
  To optimize the design while ensuring economic feasibility, it was recommended to set the top elevation of the training walls based on the water profile corresponding to 50% of the maximum discharge**.** This approach balances structural safety with cost efficiency, avoiding unnecessary over-design while maintaining effective flow management during standard operational conditions.

- **Raising of Power intake crest level**

  Model studies and theoretical analyses revealed that the power intake crest could be raised by approximately 1m. This adjustment optimizes the design by ensuring sufficient submergence to prevent vortex formation and air entrainment while effectively managing sediment entry. This modification enhances operational efficiency and reduces maintenance challenges due to sediment deposition.

Flow conditions in the bucket

Flow conditions in the stilling basin



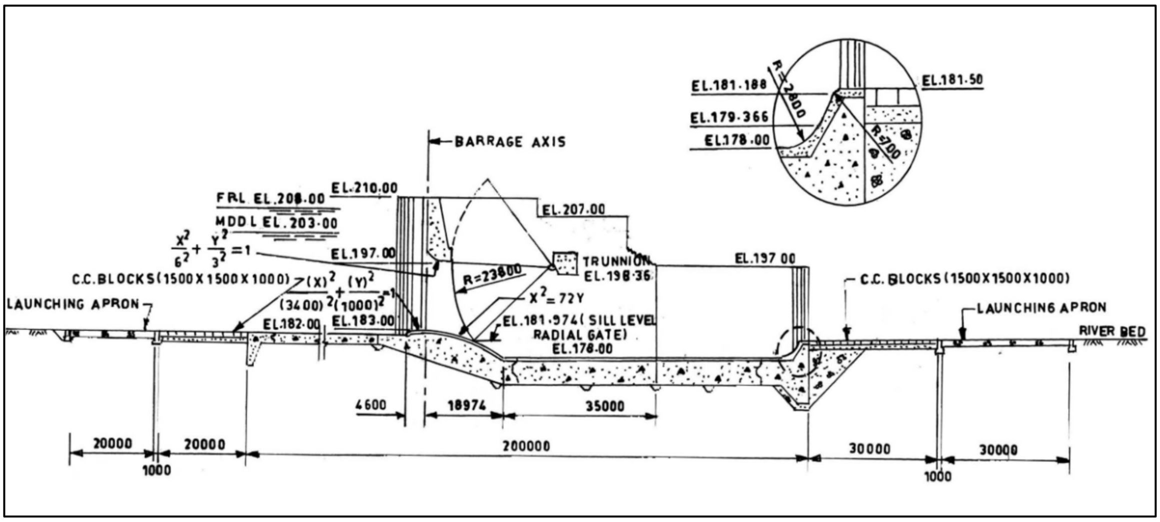
View of stilling basin at the dam site

❖ Teesta Low Dam Project-III West Bengal

Run-of-the-river schemes in cascades with suitable sediment disposal arrangements, instead of large storage dams on the rivers, are in vogue to minimize silt deposition in the reservoirs. Teesta Low Dam Spillway Stage – III is one such scheme in Teesta valley. Teesta Low Dam Projects Stage – III is the last but one at the far end of the Teesta River. It is typically a low-level diversion structure with a dam-foot powerhouse.

❖ Project Overview

- Dam dimensions: 32 m high and 140 m long barrage with RCC raft and piers
- Power installed capacity: 132 MW
- Spillway details: Gated weir with breast walls 7 gates of size 14m wide and 14 m high, Crest El. 183 m, FRL El. 208 m, Maximum design discharge: 10,430 m^3/s
- Energy dissipator: Stilling basin as dissipator



Cross section of the spillway

❖ Contributions of CWPRS

The studies were carried out on 3D comprehensive models to evaluate the performance of spillway and energy dissipator. The major contributions from the studies are:

- **Spillway profile**

  Original spillway design consisted of a flat crest for a distance of 3.4 m on the u/s and d/s profile in the form of a slope of 1:3. The spillway profile has to cater for a head of 25 m which will result in high velocity flow which would lead to separation on the glacis. In view of this, the design of the spillway was revised. Revised spillway design consists of crest profile conforming to $x^2=72y$ downstream of barrage axis and u/s equation as $\frac{x^2}{(3.4)^2}+\frac{y^2}{(1.0)^2}=1$.

- **Trunnion axis of the Spillway**

  Trunnion axis of the spillway was raised by 2m to avoid the water surface profile touching the trunnion of the radial gate for the gated and ungated operation of the spillway for the design maximum discharge of 10,430 m^3/sec. Accordingly, the centreline of the trunnion elevation was raised from El. 196.53 m to El. 198.36 m. It was found that the water surface profile for the design maximum discharge of 10430 m^3/sec was just below the raised trunnion.

- **Head race channel**

  Excavation and modifications to the river right bank at the Head Race Channel in the vicinity of power intake were recommended which lead to improvement in the flow conditions with respect to the silt flushing aspect.

- **Training walls and divide walls and left guide bund on d/s**

  Raising the height of the left and right training walls (Cellular wall), intermediate divide walls, and the left guide bund to contain the water profile to avoid overtopping was recommended.

- **Protection works upstream of the spillway**

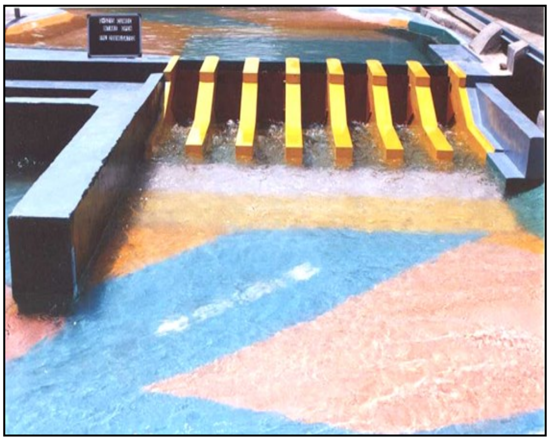
  Heavy protection works on the left bank upstream of the spillway beyond the left training wall were recommended as the structure is being constructed on alluvial reaches. These protection works should be designed for velocities of the order of 3.8 m/s to 1 m/s along the u/s of spillway.

- **Rising of the centre line of power intake**

  Model studies and theoretical analysis carried out indicated that that the center line of the power intake could be raised by about 0.5 m from 192.2 m to 192.7 m to optimize the design of the intake.

- **Tail race channel**

  It was recommended that the sharp curve on the right bank portion of the tail race channel be modified with a mild curvature with a radius of 330 m to eliminate return velocities.

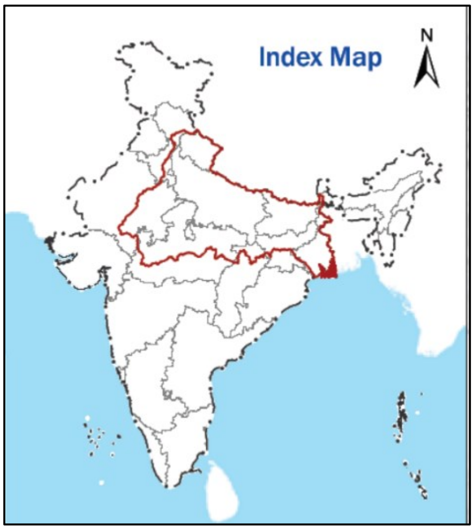


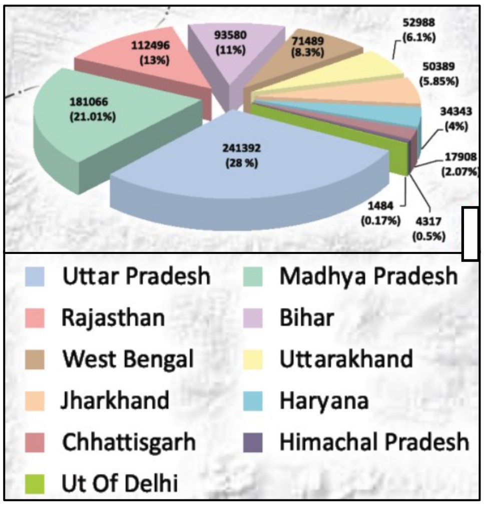
View of the physical model

View of the dam site

3.3 GANGA RIVER BASIN

The Ganga basin outspreads in India, Tibet (China), Nepal and Bangladesh over 10,86.000 Sq.km. the major part of the geographical area of the Ganga basin lies in India and it is the biggest river basin in the country draining an area of 8,61,452 Sq.km which is slightly more than one-fourth (26.3%) of the total geographical area of the country. In India, it covers the states of Uttarakhand, Uttar Pradesh, Haryana, Himachal Pradesh, Delhi, Bihar, Jharkhand, Rajasthan, Madhya Pradesh, Chhattisgarh and West Bengal. The Ganga is the 20th longest river in Asia and the 41th longest in the World. The total length of the river Ganga up to its outfall into Bay of Bengal is 2525 km. With extensive monotonous regions and multiple of tributaries, The Ganga basin is rich in various projects. According to India-WRIS, the basin consists of 39 hydroelectric projects and 56 powerhouses are testament to the importance of the region to India's overall hydroelectricity portfolio.





State-wise drainage area of the basin

Major rivers in the basin

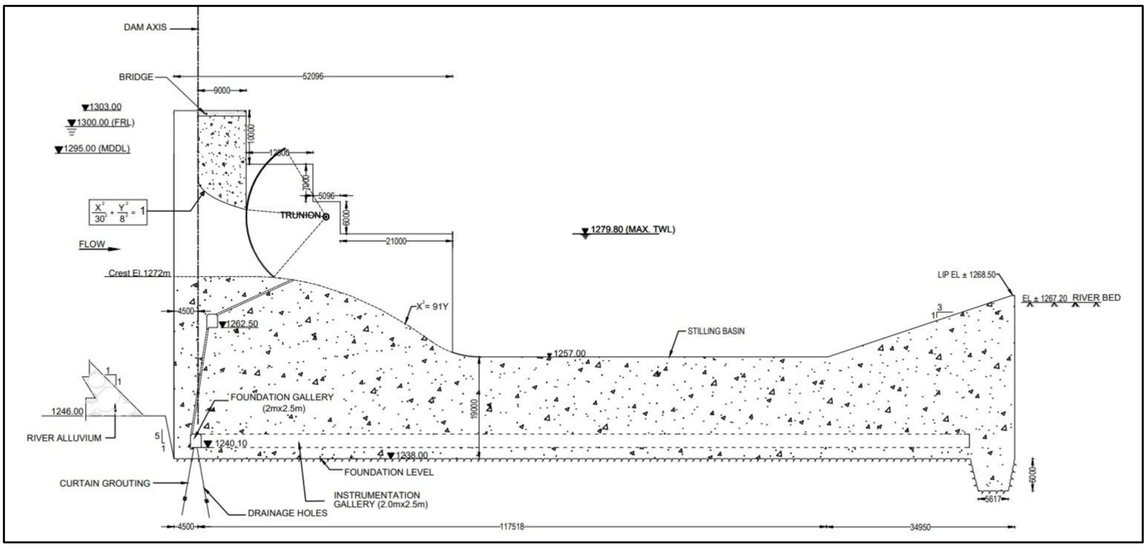
Several hydropower projects in this region, such a Tehri Project (100MW), Koteshwar (400MW), Ramganga Project (198 MW), Kotli Bhel (1000MW), Maneri Bhali Stage 1 (90 MW), Maneri Bhali Stage 1 304 MW), Devsari (252 MW), Tanakpur Project (120MW) are the important river valley project, are currently in various stages of planning and development. The contribution of CWPRS in some of the important hydropower projects is discussed.

3.3.1 Devsari Hydropower Project, Uttarakhand

The Devsari Hydro-Electric Project (DHEP) is a diurnal pondage run-of-the-river scheme proposed on the Pinder River, near Devsari village in Chamoli district, Uttarakhand.

❖ Project Overview

- Dam dimensions: 35 m high concrete gravity dam
- Power installed capacity: 252 MW
- Spillway details: Orifice spillway with 5 gates of size 12.5 m wide and 8.5 m high, Crest El. 1272 m, FRL El. 1300 m, MWL El. 1301 m
- Energy dissipator: Stilling Basin
- PMF: 6,969 m^3/s



Cross section of spillway

❖ Contribution of CWPRS

- **Energy dissipator**

➢ The ski jump bucket in the original design was ineffective in dissipating the energy for different spillway operating conditions due to high tailwater levels. The difference between the bucket lip elevation and the crest elevation was minimal, approximately 3.8 meters, with the crest elevation at 1272 m. The tailwater level (TWL) for higher discharges was significantly high at around 1280 m. Raising the bucket lip elevation poses challenges, as it would encroach upon the crest. Therefore, the design was changed into a stilling basin-type energy dissipator with a basin elevation of 1252.5 m. For entire ranges of discharges, it was found that the hydraulic jump forms over the glacis of the spillway upstream of the toe and the front of the jump fluctuates (oscillates) between chainage 20 to 40 over the spillway glacis.

- Taking due cognizance of the observations from the model studies and the possibility of deposition of sediment in the stilling basin, the stilling basin elevation was raised by about 5 m from El. 1252.5 m El. 1257 m and with the flatter slope of the end sill (1:3).
- This modification improved the flow conditions over the spillway by shifting the location of the front of the hydraulic jump slightly to the downstream on the spillway glacis. This minimizes the risk of submergence of the spillway crest for higher discharges. The jump was found to be stable even for minor variation (retrograded) tail water level conditions. Due to the flattening of the slope of the end sill (1:3), the stilling basin has the self-cleansing potential as it can flush out the sediments from the basin. Raising of stilling basin floor level at El. 1257 m ensured relatively stable hydraulic jump formation for all discharges.

- **Training wall**

The water surface profile was seen intermittently overtopping the training walls (El. 1281 m) for 3,485 m^3/s and higher discharges. Therefore, the top elevation of training walls was suggested to be raise by about 5 m considering the free board requirement and bulking of flow due to air entrainment in the prototype.

Flow condition in ski-jump bucket

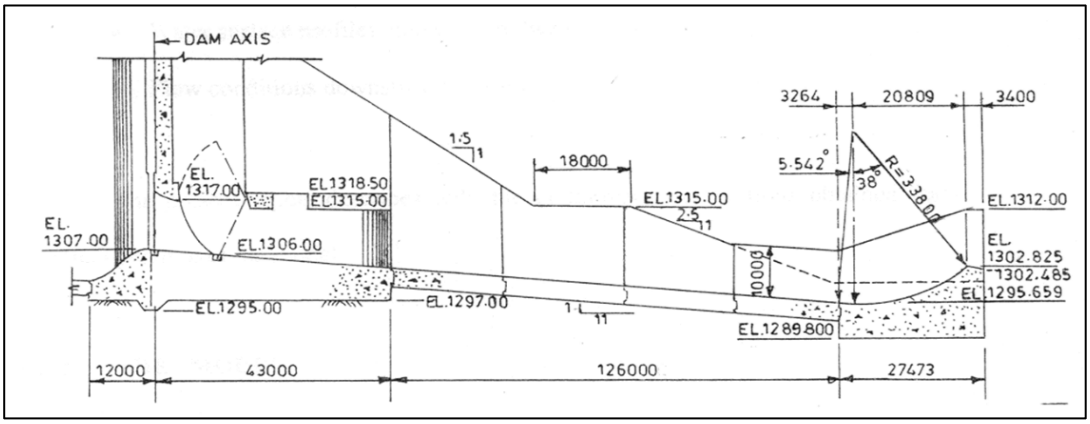
Flow condition in Stilling basin

3.3.2 Dhauliganga H E Project, Uttarakhand

Dhauliganga H.E. Project in Uttar Pradesh has envisaged construction of 56 m high Rockfill Dam in Pithorgarh district, for harnessing river Dhauliganga.

- **Project Overview**

- Dam dimensions: 56 m high and 342 m long Rock fill dam
- Power installed capacity: 280 MW
- Spillway details: Orifice spillway with breast walls, 2 spans of 6 m x 12 m and a 9 m diameter tunnel spillway (Original design 3 No of spans of size 6.0 m x 10.0 m each), Crest El. 1307 m, FRL El. 1345 m, Maximum design discharge: 3,200 m^3/sec
- Energy dissipator: Ski-jump bucket



Cross section of the spillway

- **Contributions of CWPRS**

- **Original Design**

The studies were carried out on 3D comprehensive models to evaluate the performance of spillway and energy dissipator. The original design of spillway consisted of three spans of 6.0 m (W) x 10.0 m (H) with 3 m thick breast wall separated by 6.0 m thick piers. The spillway crest at El. 1307 m was designed to pass the maximum outflow flood of 3200 m^3/s at MWL El. 1348.5 m. The chute spillway was followed by a ski-jump bucket type of energy dissipater having radius of 33.8 m and a lip angle of 35°. However, the design of the chute spillway was modified due to a landslide along the right bank due to weak geological conditions and the non-availability of foundation. The chute spillway is now provided with two spans keeping the design of chute and energy dissipator same as per the original design. One span of 9 m width was provided in the form of a tunnel spillway along the right bank of the approach channel of the chute spillway. This tunnel spillway would join the 10 m diameter horse shoe shaped diversion tunnel.

- **Modified Design:** The major contributions from the modified design of the spillway are:

- **Chute and Ski-jump bucket**

- The constriction of the chute from 30.0 m to 20.0 m in a distance of 83 m increased the discharge intensity from 106 m^3/s /m at the beginning of the chute to 160 $m^3/s/m$ towards the end of constriction for the design outflow flood of 3200 m^3/s.
- The increased discharge intensity in the bucket region, together with the inadequate chute slope hindered the performance of the ski-jump bucket leading to the formation of cross waves and non-uniform flow distribution across the width of the bucket.
- The ski-jump jet issuing from the lip of the bucket was abrading along the dressed right bank downstream of the bucket. It was apprehended that the impingement of the ski-jump jet would cause a deep scour hole along the dressed right bank and thereby endangering the stability of the right bank and the road on the right bank.
- Therefore, the design of the chute slope and bucket was revised. The revised design incorporated the chute slope of 1:7.734 in place of 1:11 from downstream of the crest piers, and lip angle of the bucket was modified by 38^0 to 35^0. The spillway axis was tilted by 1.591^0 to the right to divert the flow into the river channel and safeguard the right bank.

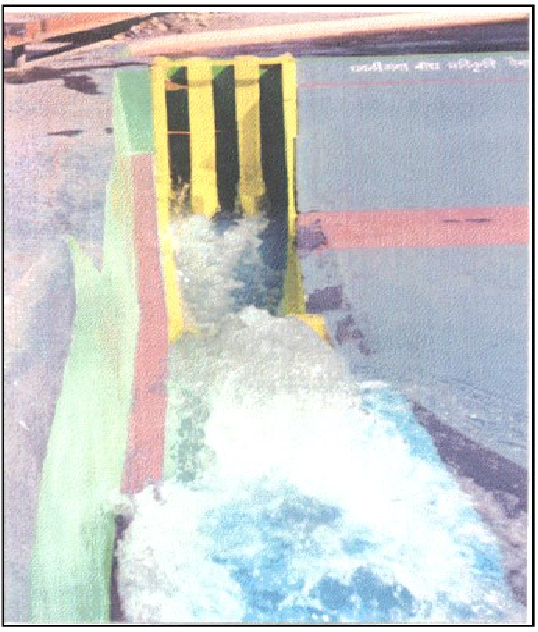
- **Training walls**

As far as the deflection of the flow towards the left was concerned, the various alternative designs viz., the addition of a wedge to the right and left training walls in the bucket portion, the addition of a deflector wall to the right training wall downstream of the bucket lip, curtailment in the length of the left training wall were tested on the model. Accordingly, the design was modified in the form of an extension of the right training wall downstream of the lip in the form of 10° deflector wall over 20 m extended length and the left training wall retained up to Ch. 140 m for deflecting the flow issuing from the bucket towards left to safeguard the right excavated face of the hill slope in the downstream vicinity of the bucket.

- **Tunnel spillway**

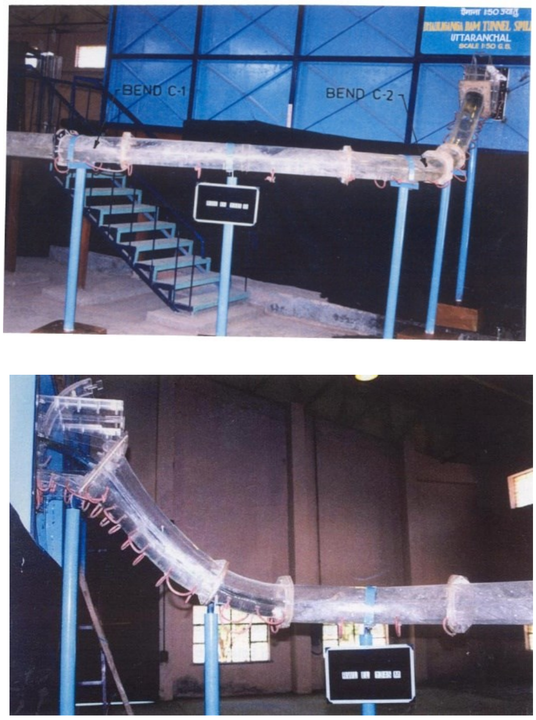
The flow conditions were not satisfactory in the tunnel from the starting of the horizontal bend C2 up to the tunnel outlet. The horizontal bend C2 was not able to guide the high-velocity flow toward the straight portion of the diversion tunnel downstream. The flow was seen riding along the outer side of the bend C2 up to the roof and got deflected towards the inner side. The riding and deflection of the flow continued for a considerable length downstream of bend C1. The following alternatives were carried out on the model to improve the flow conditions in the tunnel.

- A single curve of large radius replacing the curves C2 and C1
- Vertical shaft and a control structure at the outlet of the diversion tunnel
- Incorporating orifices in the tunnel
- Provision of a vertical shaft at the intersection of the centre lines of the tunnel by keeping the bottom level of the shaft the same as the bottom level of the diversion tunnel and providing a low-level sluice was suggested.

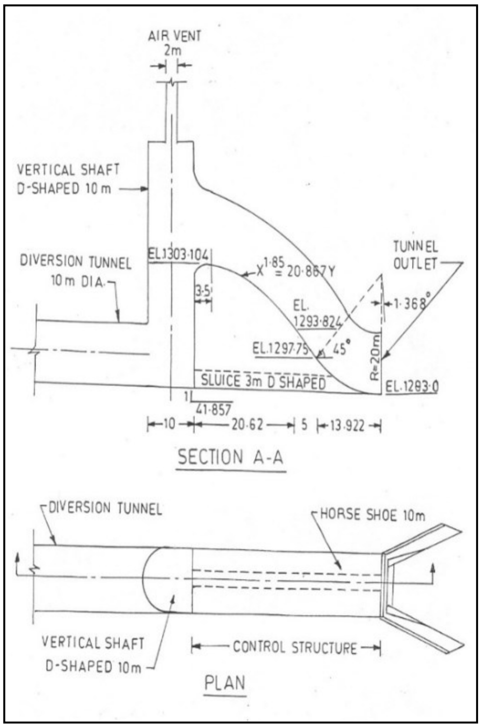


Original design of chute spillway

Revised design of chute spillway



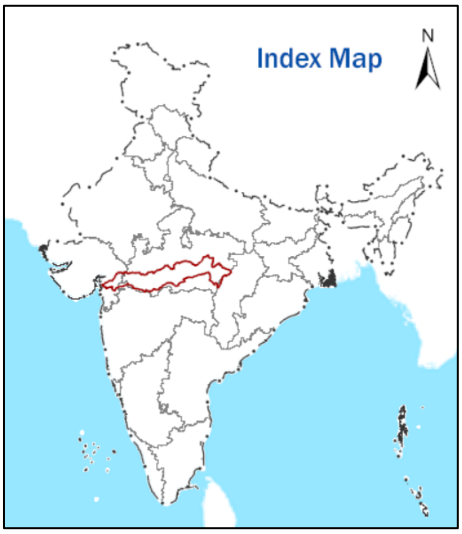
Original design of tunnel

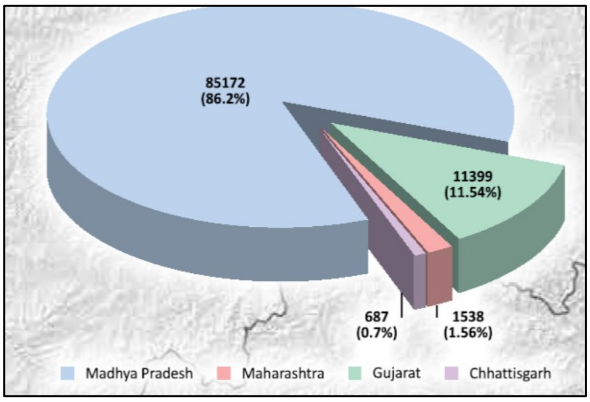


Modified design of tunnel

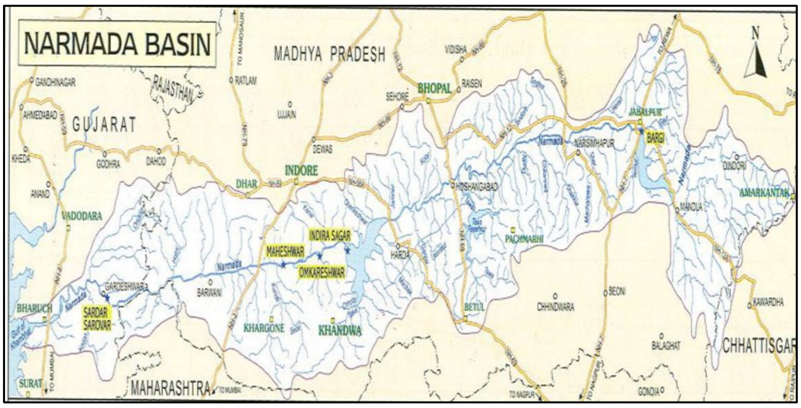
3.4 NARMADA RIVER BASIN

The Narmada River, indeed one of India's major rivers, holds significant geographical and economic importance. The river extends over states of Madhya Pradesh, Gujarat, Maharashtra, Chhattisgarh having an area of 98,796 sq.km. which is nearly 3% of the total geographical area of the country. Originating from Amarkantak in Madhya Pradesh, it flows westward over 1,312 km and eventually drains into the Gulf of Khambat near Gujarat. As the largest west-flowing river of the Indian Peninsula, it is notable for shaping the landscapes and livelihoods of the regions it traverses. The river's elongated basin, almost ribbon-like in shape, measures 953 km in length and 234 km in width, marking it as a prominent geographical feature in central and western India. Its waters support the ecosystem, economy, and cultural heritage of the regions in which it flows.





State-wise drainage area of the basin



Major rivers in the basin

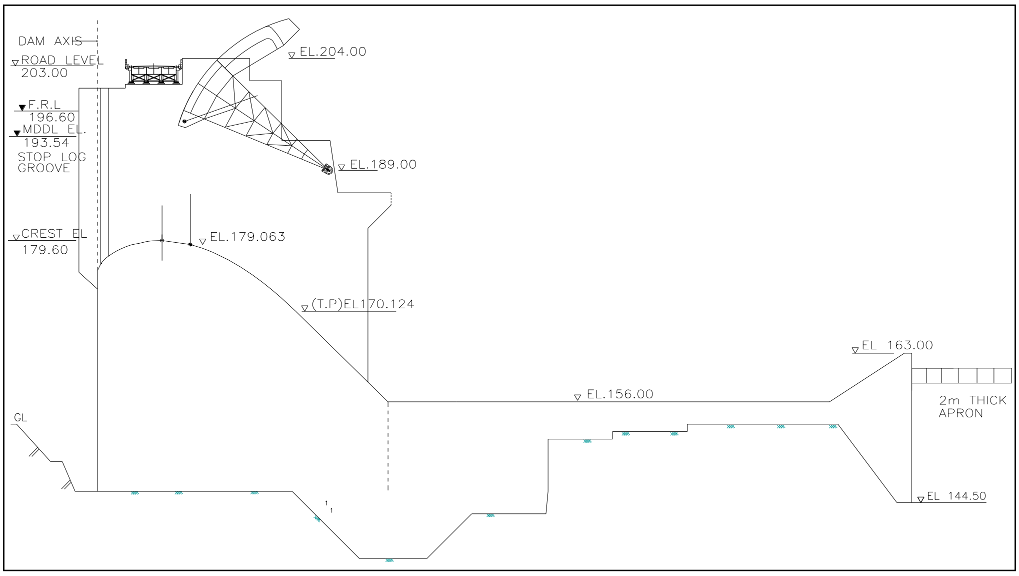
There are three major projects on the main river. Indira Sagar (1000MW) is the largest project in Madhya Pradesh with the largest water storage capacity in India (12.22 Bm^3), which ensures regulated releases of water throughout the year to downstream projects viz. Omkareshwar (520 MW) and Sardar Sarovar (1450 MW) in Gujarat. Major contribution of CWPRS for Sardar Sarovar and Indirasagar projects are highlighted in Chapter 4.

3.4.1 Omkareshwar Multipurpose Project, Madhya Pradesh

The Omkareshwar Project is a key run-of-river hydropower project that utilizes regulated releases from the Indira Sagar Project for both power generation and irrigation. Here are the major details and contributions to its design and operation:

❖ Project Overview

- Dam dimensions: 64 m high concrete gravity dam
- Power installed capacity: 520 MW (8 units of 65 MW each)
- Spillway details: Ogee spillway with 23 gates of size 20 m wide and 18.03 m high, Crest El. 179.6 m, FRL El. 199.62 m
- Energy dissipator: Stilling basin
- Maximum outflow flood: 88,315 m^3/s



Cross section of spillway

❖ Contributions of CWPRS

The Central Water and Power Research Station (CWPRS) conducted extensive studies on 2D sectional and 3D comprehensive models to address the issues. Several key recommendations were implemented:

- **Modification of Energy Dissipator**

- ➢ The slotted roller bucket was replaced with a stilling basin-type energy dissipator due to the high discharge intensity (up to 155 $m^3/s/m$) and incoming velocities (25-28 m/s).
- ➢ The stilling basin was restricted to a length of 70 meters due to site constraints, such as downstream cofferdam location and river morphology.

- After studying different designs, the final stilling basin featured a high solid end sill with a 2:1 upstream slope, with a 20-meter concrete apron anchored to the rock downstream to ensure structural stability and mitigate the effects of scour.

- **Provision of Divide Walls**

- The original design of two divide walls was increased to four to prevent material deposition in the stilling basin and reduce return eddies.
- This also enabled easier maintenance and repair by allowing the dewatering of specific zones within the stilling basin.

- **Training Wall Extension**

The left and right training walls were extended up to the 20-meter apron and keyed into the rock to prevent scour at the wall toes due to return flows.

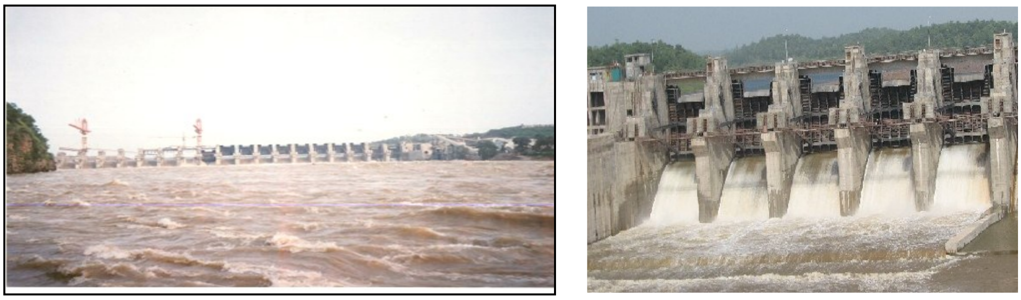
- **Headrace and Tailrace Channel Adjustments**

- A divide was introduced between the spillway and the power intake in the headrace channel to prevent cross-flow.
- The layout of the tailrace channel was modified to divert more water into the **Narmada branch**, optimizing the head for power generation. This change mitigated the observed high water levels in the **Kaveri branch**, which had been reducing the effective head and power generation.

- **Flood and Powerhouse Coordination**

During flood events when the powerhouse is closed, return flow velocities of 2-3 m/s were observed in the tailrace channel. Water level fluctuations in the tailrace channel ranged from 0.7 to 1 meter. These observations prompted changes in the channel layout for better water management and head optimization.

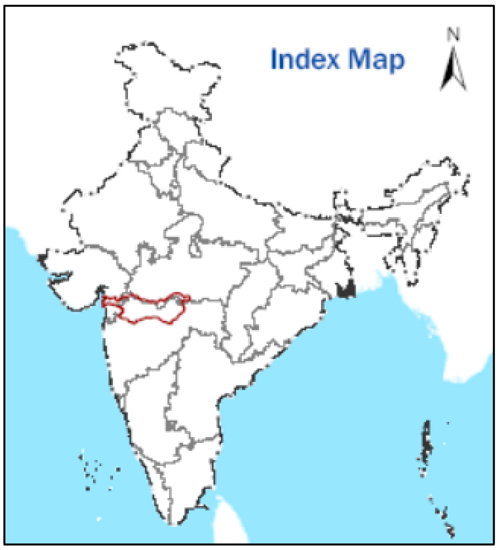
View of the physical model

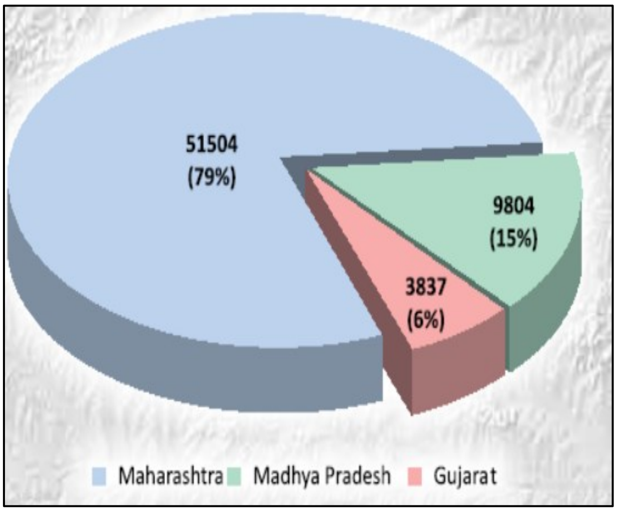


View of the dam site

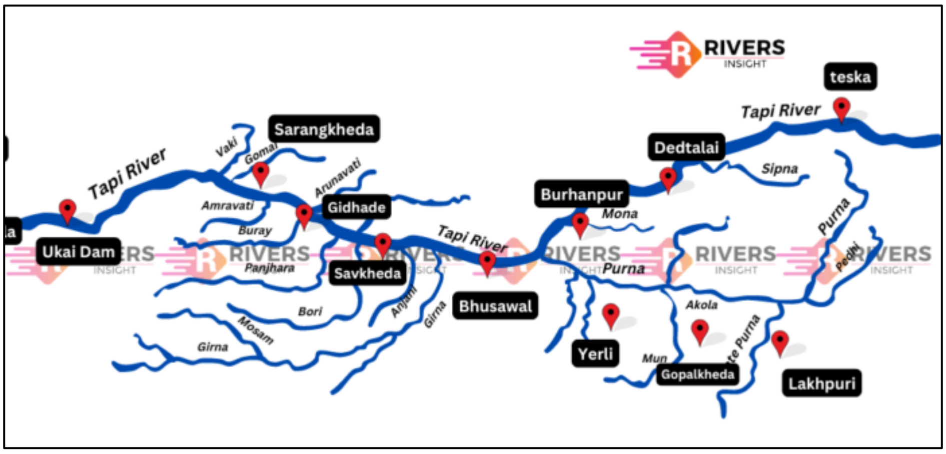
3.5 TAPI RIVER BASIN

The Tapi basin is the second largest westward draining river of the Peninsula. It originates near Multai reserve forest in Betul district of Madhya Pradesh at an elevation of 752 km. The total length of the river from origin to outfall intoArabian Sea is 724 km. It extends over the states of Maharashtra, Madhya Pradesh and Gujarat having an area of 65,145 se.km. with a maximum length and width of 534 and 196 km. The major part of the basin is covered with agriculture accounting for 66.19% of the total area and 2.99% of the basin is covered by water bodies.





State-wise drainage area of the basin



Major rivers in the basin

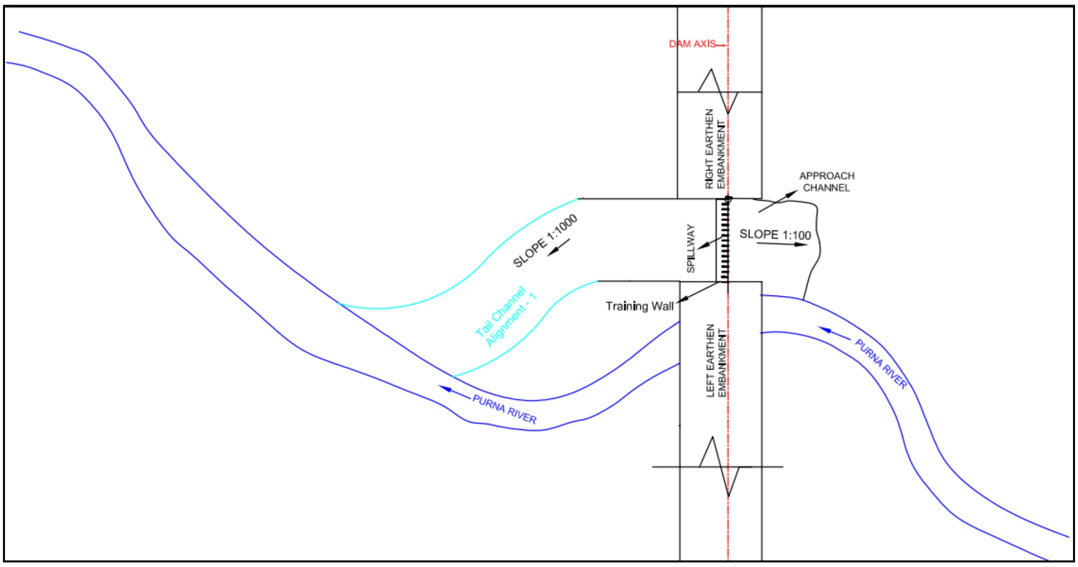
There are 13 Major and 68 Medium Irrigation projects completed in the form of reservoirs or weirs in the Tapi catchment. The basin consists of 356 dams. Out of which 96 % of Dams are used for irrigation purpose. .Hathnur Dam (Maharashtra), Girna Dam (Maharashtra), Purna (Maharashtra), Waghur (Maharashtra), Jigaon (Maharashtra) are some of the major/medium irrigation projects on Tapi river. Ukai dam is the hydropower project in the basin.

3.5.1 Jigaon Project, Maharashtra

The Jigaon Project is a significant irrigation initiative in the Vidarbha region of Maharashtra, aimed at enhancing water availability and agricultural productivity. Currently under construction, the project is located on the Purna River, a left-bank tributary of the Tapi River, downstream of Jigaon village in Buldhana district. Once completed, it is expected to support irrigation, water supply, and regional development in this agriculturally important but water-scarce region.

❖ Project Overview

- Dam dimensions: 35.245 m high and 8240 m long earthen dam
- Spillway details: Overflow spillway with 16 gates of size 15 m wide and 12 m high, Crest El. 227.21 m, MWL El. 240.561m, FRL El. 239.21 m, MDDL El. 233 m
- Energy dissipator: Stilling Basin
- Maximum outflow flood: 24131 m³/s



Layout of the dam

❖ Contributions of CWPRS

Extensive hydraulic model studies were conducted at CWPRS until 2020 to optimize the design of the spillway, energy dissipator, and power intake for the Jigaon Project. Key recommendations and modifications derived from these studies include:

- **Increased Stilling Basin Length**

  To ensure proper hydraulic jump formation across the entire range of discharges, the stilling basin length was extended from 10 m to 91.1 m.

- **Upstream Curved Guide Walls**

  - The flow entering the approach channel was observed to directly impact the upstream left training wall in front of the first span, leading to intermixing and turbulence caused by an abrupt change in flow direction. To mitigate this issue, five alternative designs were evaluated.
  - The optimal solution involved aligning the guide wall with the training wall and incorporating a curved guide wall with a slope of 1(V):4(H). This modification streamlined the flow, minimized turbulence, and improved the hydraulic performance of the approach channel, ensuring efficient water delivery to the spillway.

- **Submersible divide walls**

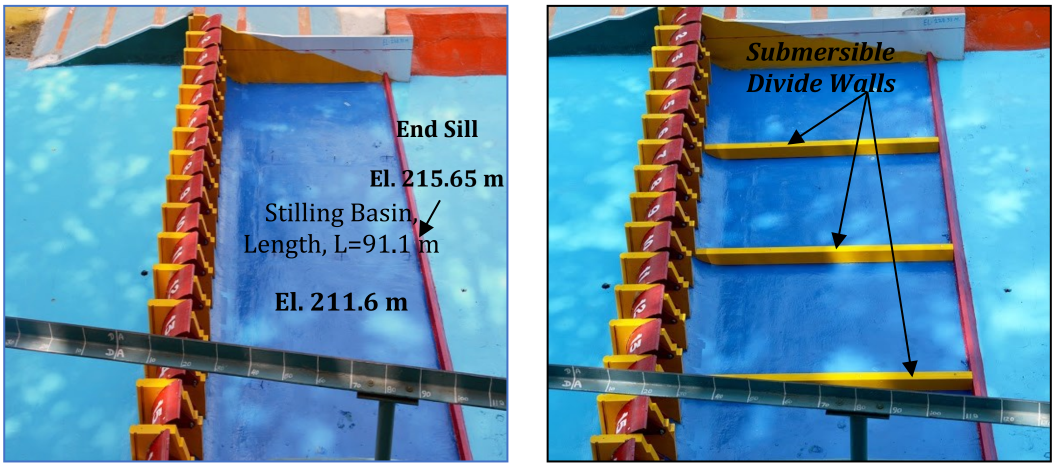
  - The Jigaon spillway, consisting of 16 spans, requires simultaneous and equal operation of all gates to ensure the proper functioning of the stilling basin. Uneven gate operation can lead to the formation of lateral eddies, disrupting the hydraulic performance of the basin. These eddies have the potential to carry loose river material from downstream, causing abrasion damage to the stilling basin floor.
  - To address this, the implementation of three submersible divide walls was recommended. These walls divide the stilling basin into four bays, ensuring smoother flow distribution and reducing the formation of eddies. This design modification enhances the stability and performance of the stilling basin, safeguarding it from potential damage.

- **Reduced end sill height**

  As the flow condition downstream of the end sill was not satisfactory, the height of the end sill was reduced by 1 m with the sloping portion facing towards the upstream to improve hydraulic jump formation.

- **Raised training walls and tail channel embankments**

  The flow was spilling over the top of the training walls and the embankment of the tail channel resulting in spreading over the flood plains. Therefore, the height of the downstream training wall was raised to avoid spilling of water over the rear slope of the earthen embankment and the embankment height was raised to increase the carrying capacity of the tail channel. These modifications ensure the safe and efficient operation of the spillway and associated structures while mitigating risks of erosion and damage.



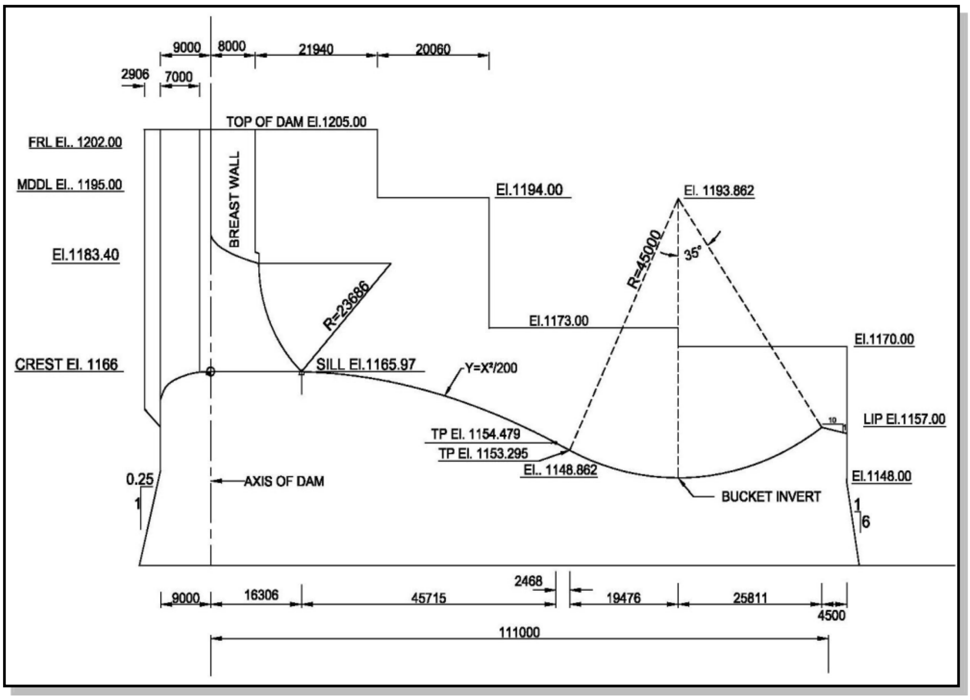
View of the physical model

3.6 PUNATSANGCHHU RIVER BASIN, BHUTAN

Punatsangchhu, Stage – I Hydropower Project : Punatsangchhu-I H.E. Project is located on Punatsangchhu River in Wangdue Phodrang Dzongkhag in Western Bhutan. The project envisages the construction of a 136 m high concrete gravity dam.

❖ Project Overview

- Dam dimensions: 136 m high concrete gravity dam
- Power installed capacity:1200 MW
- Spillway details: Orifice spillway with 5 gates of size 9.6 m wide and 17.4 m high, Crest El. 1166 m, FRL El. 1202 m, MDDL El. 1195 m
- Energy dissipator: Stilling basin type energy dissipator
- Maximum outflow flood: PMF-11,500 m^3/s and GLOF- 4,300 m^3/s
- Plunge pool: Pre-excavated plunge pool downstream



Cross section of spillway

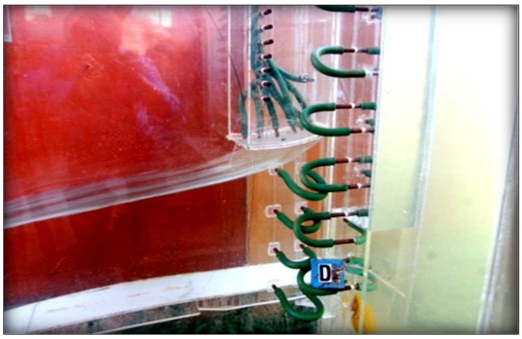
❖ Contribution of CWPRS

- **Roof profile of orifice**

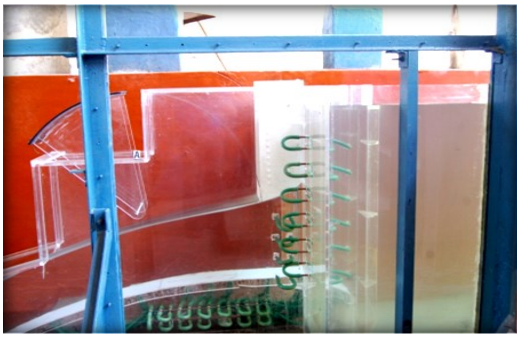
The original roof profile of the spillway, described by the equation $\frac{x^2}{(8.66)^2}+\frac{y^2}{(2.0)^2}=1$, was too flat, leading to inconsistent detachment of the water jet's top profile. This resulted in vibrations and a 15% reduction in discharge capacity. To rectify this, the roof profile was steepened to conform to the equation $\frac{x^2}{(40)^2}+\frac{y^2}{(8)^2}=1$, forming a quarter of an ellipse with an 8.66 m width of the breast wall. These changes improved jet adherence, eliminated vibration issues, and increased the spillway's discharge capacity, ensuring smoother operation under varying flow conditions.

- **Energy Dissipator**

- The alternative designs of energy dissipators were tested on the model due to various site constraints. Originally, the ski jump type of energy dissipater was provided, however, it was modified to hydraulic jump type ED.
- The original ski jump bucket faced high submergence, preventing proper ski action due to a pool formed by valley constriction about 500 meters downstream. The pool caused submergence extending up to the spillway.
- To address this bucket lip elevation was increased by 9 m (from 1148 m to 1157 m), reducing submergence and enhancing performance. Bank dressing was suggested to lower the tailwater level, minimizing the submerging effect on the bucket. A 10^0 deflector wall was proposed at the rightmost spillway span to redirect flow toward the center of the river. This design effectively diverted flow by 8-9 m, ensuring better energy dissipation and reducing erosion risks near the banks.
- These interventions collectively improved the hydraulic efficiency of the bucket and enhanced its operational performance under high-flow conditions.
- Due to a massive landslide that occurred on the right bank of the dam axis, some protection measures were undertaken to protect the bank. The design of the spillway was modified by reducing the spans from seven to five by changing gate size from 8 x15 m to 9.6 x17.4 m and providing the stilling basin as energy dissipator.

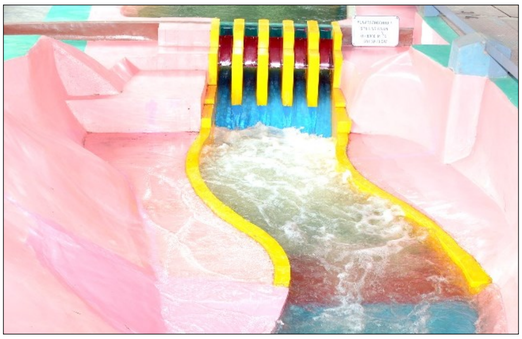


Flow condition near original roof profile



Flow condition near modified roof profile

Flow conditions in the ski-jump bucket



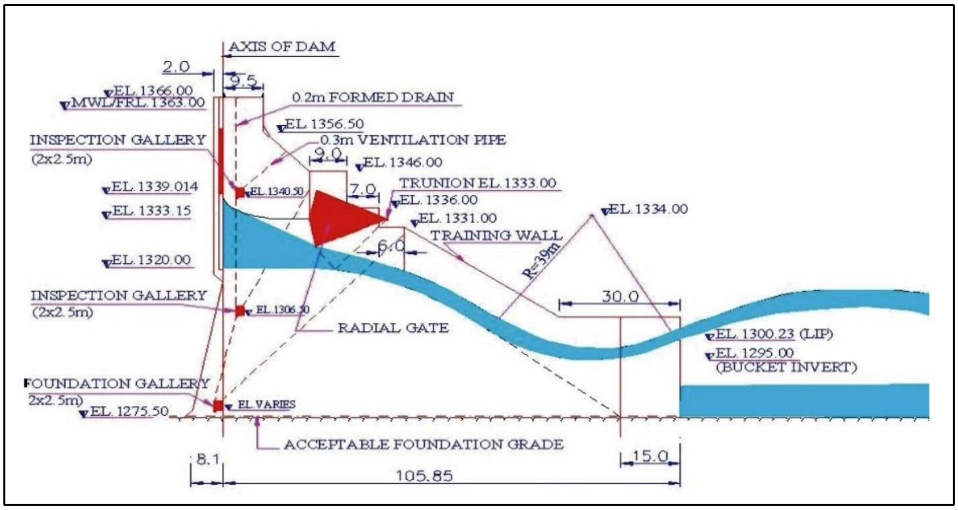
Flow conditions in the stilling basin

3.7 TALA RIVER BASIN, BHUTAN

Tala H.E. Project: The Tala Hydroelectric Project, with a capacity of 1,020 MW, stands as one of the largest collaborative endeavors between India and Bhutan. Located on the Wangchu River in western Bhutan, this project highlights the close bilateral ties between the two nations in the field of sustainable energy development. The Tala project significantly contributes to Bhutan's economy by generating hydroelectric power, a major source of revenue for the country, while supplying clean energy to India, fostering regional cooperation and mutual growth.

❖ Project Overview

- Dam dimension: 91 m high concrete gravity dam
- Power installed capacity: 1020 MW
- Spillway details: Orifice/Sluice spillway with 4 gates 8 m wide and 13.15 m high, Crest El. 1320 m, FRL El. 1363 m, and an Overflow spillway of size 8 m wide and 11 m high with crest El. 1352 m near the left bank to pass floating debris such as trees and logs downstream
- Energy dissipator: Ski jump bucket



Cross section of the spillway

❖ Contribution of CWPRS

- **Roof profile of orifice**

  During hydraulic model testing for the Probable Maximum Flood (PMF) discharge of 10,600 m^3/s under free-flow conditions, a negative pressure of 13.5 m was observed on the roof profile. Such negative pressures pose a risk of cavitation damage to the surface. To address this, various alternative roof profiles were analyzed by adjusting the tangents of the profile. The optimal design was finalized as a circular profile making a 45° angle with the vertical at the upstream face. This modification effectively increased pressures on the surface, mitigating the likelihood of cavitation damage and ensuring safer and more reliable operation of the structure.

- **Raising of trunnion axis and height of training wall**

  During hydraulic model studies, water surface profiles were found to override the training walls due to strong rooster tail formations, particularly in the bucket region. Additionally, the trunnion axis of the radial gates for the sluices was submerged at discharges of 8,000 m^3/s and above when the gates were fully open. These conditions posed risks to structural safety and operational efficiency. To address these issues, it was recommended to raise the trunnion axis level of the radial gates and increase the height of the training walls, ensuring effective containment of flow and preventing the submergence of critical components.

- **Intermediate divide walls**

  During the operation of two or three sluices for passing low floods, the jets spread across the entire spillway width, impinging on the training walls and downstream banks, leading to potential erosion. To address this, the introduction of divide walls along the rear slope of the spillway was recommended. These walls would confine the jet flow, enabling the passage of normal floods through the central sluices while keeping the side gates closed. This arrangement ensured the ski-jump trajectory stayed away from the banks, effectively reducing erosion risks and safeguarding the downstream structures.

- **Reduction of the number of spans**

  To enhance the structural efficiency and operational performance of the spillway, five sluice bays measuring 6.5 m x 13.15 m were proposed instead of the initially planned four bays of 8 m x 13.15 m. Additionally, an overflow bay with dimensions of 4 m x 3 m was recommended, replacing the earlier design of 8 m x 11 m. This adjustment aimed to reduce the overall spillway width and confine scour to the river's natural width. The modified overflow spillway design would also facilitate the passage of floating logs and debris downstream, preventing obstructions near the power intake structures.

- **Plunge pool**

  The flow conditions at the ski-jump impingement were highly turbulent, posing a risk of significant erosion to the riverbed and banks, thereby endangering their structural stability. To mitigate this, a pre-excavated plunge pool was recommended. The plunge pool design was developed using a combination of empirical formulae, model study observations, and insights from similar projects, while also accommodating the site's topographic constraints. Additionally, measures to strengthen the rock mass along the plunge pool's bed and sides were proposed to prevent uncontrolled scour and ensure the long-term safety of the banks and surrounding structures.

View of the physical model

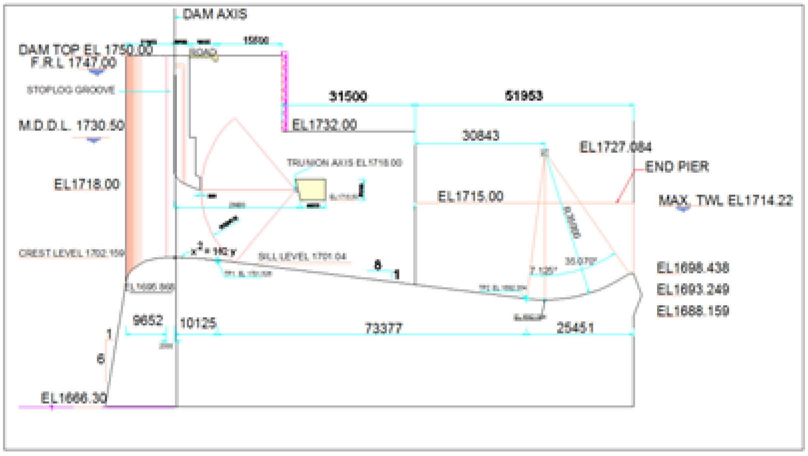
View of the dam site

3.8 MANGDECHHU RIVER BASIN, BHUTAN

Mangdechhu H.E. Project: Mangdechhu Hydroelectric Project with an installed capacity of 720 MW is one of the ten Hydro Electric Projects planned under the 10,1000 MW hydropower development program by the Royal Government of Bhutan supported by the Government of India. It is known as the Bhutan-India friendship project. It is located on river Mangdechhu in Trongsa Dzongkhag (District) in Central Bhutan.

❖ Project Overview

- Dam dimensions: 56 m high and 141.28 m long concrete gravity dam / RCC
- Power installed capacity: 720 MW
- Spillway details: Orifice spillway with breast walls 4 spans of size 10m wide and 16 m high, Crest El. 1702.159 m, FRL El. 1747 m
- Energy dissipator: Ski-jump bucket,
- Maximum outflow flood: 8500 m^3/s



Cross section of spillway

❖ Contribution of CWPRS

- Modified design of the Ski-jump bucket consisted of the crest at El 1702.59 m, invert at El. 1692.084 m, Lip level at 1698.438 m. The Lip angle was 35.07^0 and the radius of the bucket was 35 m. These modifications in the design of the ski-jump bucket have improved the ski-action for better energy dissipation under gated operation.

- Breast wall bottom profile was changed from $X^2/6000^2 + Y/2000^2 = 1$ to $X^2/32000^2 + Y^2/7000^2 = 1$. Marginal increase in discharging capacity was observed with modifications of breast wall bottom profile. The discharging capacity of the spillway was found to be adequate.

- Recommended to take protection measures for the Upstream right bank and power intake area.

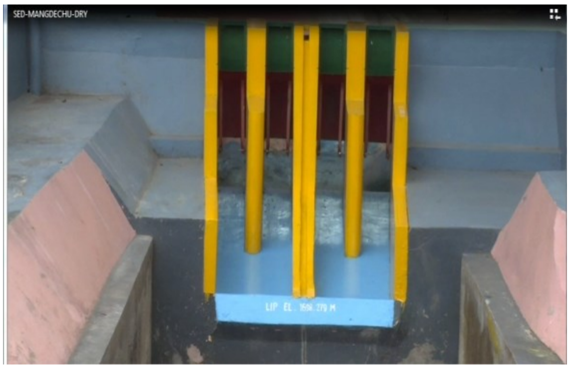
- The change in position of the log chute to the center has resulted in uniform distribution of flow in the ski-jump bucket resulting in improved performance of ski-jump bucket. It is further suggested that the log chute pier may be extended up to the end of the bucket lip to avoid return flows in the bucket and consequent abrasion damage to the bucket lip caused by debris/logs passing over the log chute under high velocities. In response to this log chute plan and section, have been revised.

- Special structural measures in the form of steel liners are recommended to protect the surface of the ski-jump bucket against abrasion damage due to the roller action of the hydraulic jump in the bucket region.

- Water surface profiles on the upstream and downstream of the ski-jump bucket were helpful to the design/site engineers in deciding the height of concrete cladding provided on the right bank of the upstream and downstream of the spillway as protection measures.

- The design of the plunge pool based on the scour profiles obtained on the model has facilitated the project engineers to carry out the timely excavation at site.

- Additional Hydraulic model studies conducted on the existing 1:60 scale 3-D comprehensive model for assessing the discharging capacity of spillway with partial gate operation while operating spans S1, S2 and S3, S4 separately, especially for low flows up to a discharge of 400 m^3/s are very useful to the project Engineers for spillway operation.



View of the physical model

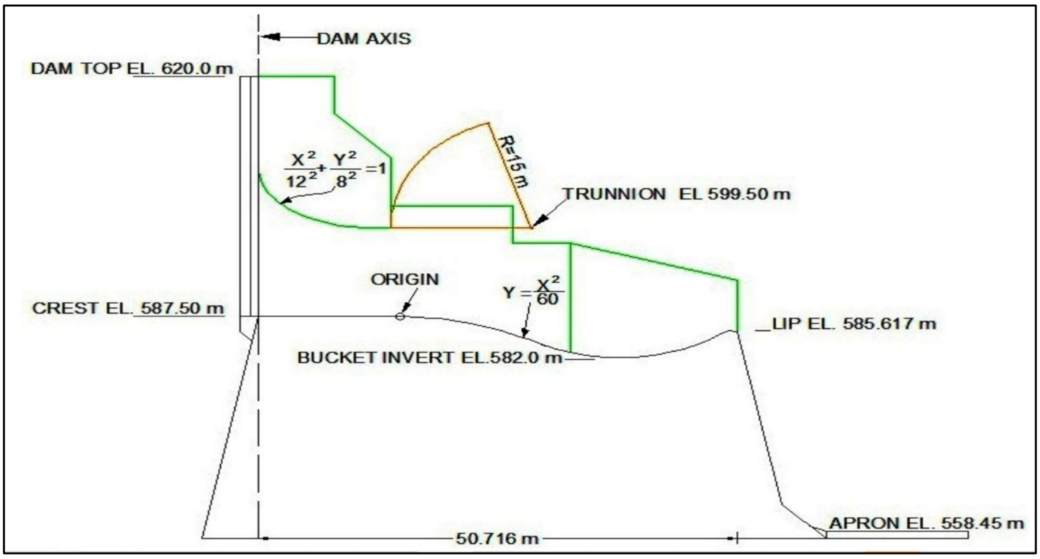
View of the dam site

3.9 MYNTDU RIVER BASIN, MEGHALAYA

Myntdu (leshka)H.E Project : The Myntdu (Leshka) Dam is a diversion dam located on the Myntdu River, situated 350 m downstream of the confluence of the Myntdu, Umshakian, and Lamu rivers. The tributaries contribute significantly to the flow, with the Umshakian River providing 11% and the Lamu River contributing 5% of the total discharge. Named after this tri-junction, the dam serves as a key infrastructure project, enabling water diversion via a 4 km-long conductor system comprising a tunnel, surge shaft, a high-pressure tunnel, and Penstocks. This system channels water to a powerhouse located on the Lynriang River bank, where it generates 84 MW of electricity, contributing significantly to the region's power supply.

❖ Project Overview

- Dam dimensions: 59 m high concrete gravity dam
- Power installed capacity: 84 MW (2 units of 42 MW each)
- Spillway details: Sluice spillway with 7 gates of size 8 m wide and 12 m high, Crest El. 587.5 m, FRL El. 618 m, MDDL El. 606.15 m
- Energy dissipator: Ski jump bucket
- Maximum outflow flood: 10,440 m^3/s
- Plunge pool: Preformed plunge pool



Cross section of the spillway

❖ Contribution of CWPRS

- **Spillway Profile**

The original spillway design featured a spillway profile defined by the equation $x^2 = 60\,y$. During testing, negative pressures were observed at specific locations under gated operation, raising concerns about potential cavitation damage to the spillway surface. To address this, the profile was modified to a flatter form defined by the equation $x^2 = 80\,y$. This adjustment improved the hydrostatic pressure distribution, effectively reducing negative pressures and enhancing the surface's resistance to cavitation, ensuring the spillway's structural safety and long-term performance.

- **Ski Jump bucket**

For higher discharges, the ski-jump jet with lip angle 35^0 was not getting lifted sufficiently because of the thick water jet. The flow conditions in the bucket were violent because of the rooster tails. Therefore, the intermediate piers were extended up to the lip of the bucket and the lip was lowered by 4 m from 585 m to 581.617 m to improve the performance.

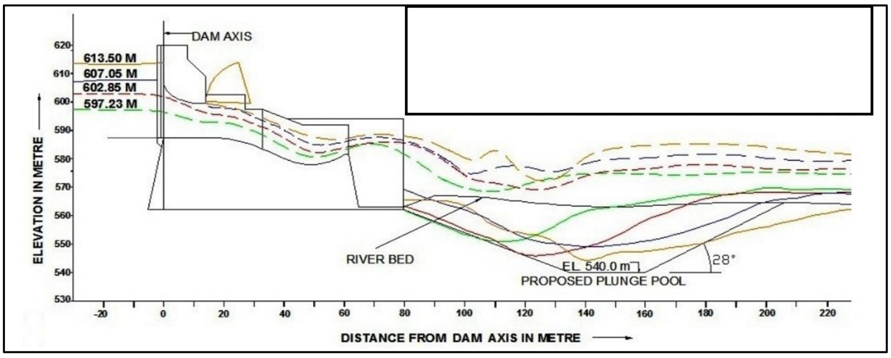
- **Pre-formed plunge pool**

During the initial years of spillway operation, the ski-jump jet's impact on the river bed and high-velocity supercritical flow downstream of the order of 25m/s would result in progressive erosion of the river bed and banks. To avoid uncontrolled erosion of the river bed and banks, it was recommended to provide a pre-formed plunge pool to dissipate the excess energy of the ski-jump jet.

- **Dressing the left bank**

The left bank was recommended to be dressed as the jet issuing from the bucket was hitting it and causing erosion. The left training wall was extended up to the end of the concrete apron to protect the left bank from erosion. The top of the left and right training walls was raised by 3 m to avoid overtopping of flow.

View of the physical model



Proposed plunge pool

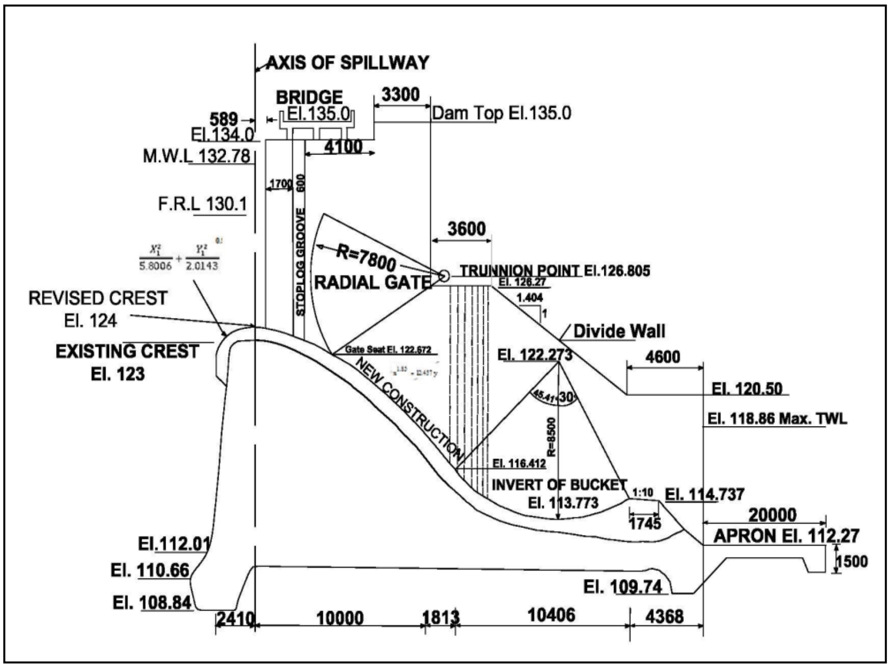
3.10 UMTRU RIVER BASIN, MEGHALAYA

Umtru H.E. Project : The Umtru River, a tributary of the Brahmaputra River, is the major source of Hydro Power in the State of Meghalaya. The New Umtru H. E. Project on river Umtru in Meghalaya was planned to upgrade the existing 4 x 2.8 MW Umtru Project. The existing project had an un-gated spillway of length 106.71 m. The proposed modifications were planned to optimally utilize the continuous spillage of river flows over the existing spillway to produce 2 X 20 MW of power.

❖ Project Overview

Dam dimensions: 25.98m high and length 106.71 m Masonry cum Concrete Dam.

- Spillway details: Ogee spillway with 06 gates of size 14.3 m wide and 7.728 m high, Crest El. 124 m, MWL El. 132.8 m, FRL El. 130.1 m.
- Energy dissipator: Ski Jump Bucket
- Probable Maximum Flood: 3500 m³/s



$\frac{X_1^2}{5.8006} + \frac{Y_1^2}{2.0143}$

Section of the Spillway

❖ Contributions of CWPRS

Extensive hydraulic model studies were conducted at CWPRS from 2010-2012 on 2-D sectional model for of new Umtru H.E. Project to optimize the design of the spillway, energy dissipator. Key recommendations and modifications derived from these studies include:

- **Modification in the location and upstream face of the pier**

➢ The flow did not adhere to the piers, leading to separation and the formation of cavities along their surfaces. These irregularities posed a risk of significant performance issues in the prototype. To address this, the studies recommended extending the piers to originate from the upstream face of the spillway. Additionally, the upstream nose of the piers was modified from a triangular to a semicircular shape to ensure smoother flow conditions.

- In the revised design, the piers were shifted from 0.589 m downstream of the dam axis to 2.410 m upstream of the spillway axis, starting at the upstream face of the spillway The flow follows the modified piers with a semicircular upstream nose. A significant improvement in flow conditions has been observed compared to the original placement arrangement of the piers.

- **Modification in the apron length**

- Furthermore, the model studies highlighted that the ski jump bucket was unable to perform effectively at higher discharges. The flow conditions at discharges above 1750 m^3/s resulted in inadequate ski action, mainly due to unsatisfactory approach flow, inadequate bucket radius, and excessive tailwater levels. It was recommended to reduce the length of the apron from 20 m to 10 m, ensuring more efficient energy dissipation.
- The apron length was shortened from 20 m to 10 m. The performance of the ski jump bucket improved and was found to be satisfactory for the design discharges through the spillway. Proper ski action was observed for all discharges, with a clear, aerated bottom nappe of the ski jump jet.

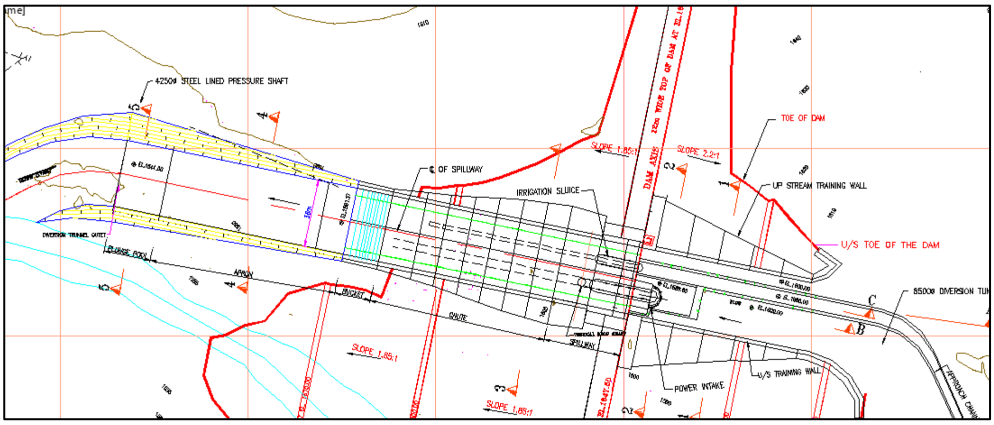
View of the physical model

3.11 HARI RIVER BASIN , AFGHANISTHAN

Salma Multipurpose Project: The Salma Dam is a multi-purpose project on river Hari Rud in Herat Province in Afghanistan, commissioned in June 2016. The dam was constructed to divert flow towards the powerhouse located on the right bank downstream of the dam. The construction of the Salma dam was completed and the various recommendations given by CWPRS The Salma (Indo-Afghan Friendship dam) was inaugurated by the Hon. President of Afghanistan Shri Ashraf Ghani and Hon. Prime Minister of India Shri Narendra Modi on 4th June, 2016, in Herat, Afghanistan.

❖ Project Overview

- Dam dimensions : 56 m high concrete gravity dam
- Power installed capacity: 42 MW
- Irrigation potential : 75,000 hectares
- Spillway details : Orifice spillway with 3 gates of size 8 m wide and 11.17 m high, Crest El. 1633.5 m and FRL El. 1643.5 m
- Energy dissipator : Ski jump-type energy dissipator
- PMF : 2,100 m^3/s



Layout plan of the spillway

❖ Contribution of CWPRS

- **Divide walls**

  The approach flow conditions upstream of the spillway were oblique due to the provision of asymmetrical piers. These oblique flows were creating unequal flow distribution over the glacis of the spillway and creating cross flows. Hence, two divide walls, 4 m high (on the left side) and 7 m high (on the right side) were recommended along the glacis of the spillway at suitable spacing, to reduce asymmetric cross waves formed on the spillway chute. Moreover, these divide walls would reduce the flaring of the ski-jump jet and its impingement on the right bank.

- **Ski jump bucket**

  The ski jump bucket should be able to throw away the flood to a faraway distance from the lip of the bucket, without causing cascades, to avoid the undermining of the structure. Since it was observed that the flow cascades over the bucket between 350 to 500 m^3/s, it was recommended that the lip angle of the bucket be reduced from 40^o to 30^o to avoid cascading flow over the bucket for lower discharges.

- **Deflector wall**

  Deflector walls would be recommended when there is a possibility of ski jump jet hit the river banks and cause subsidence of the river banks. For Salma Dam, provision of a deflector wall was suggested to avoid ski-jump impingement on the right bank of the proposed plunge pool, to guide the flow towards the plunge pool.

- **Plunge pool**

  A pre formed plunge pool is provided downstream of the spillway, to dissipate the energy of the impinging jet by containing it fully in the plunge pool. Based on the scour studies, a plunge pool was suggested with concrete linings to protect it against the high energy impact of the jet, as scoured areas can endanger the stability of the excavated right bank hill slopes due to undermining.

View of the physical model

View of the dam site

3.12 Conclusion

In this chapter, the significant contributions of CWPRS in optimizing hydropower projects across diverse and challenging river basins in India and neighbouring countries are highlighted. Through rigorous hydraulic modelling and design interventions, CWPRS has enhanced the efficiency, safety, and sustainability of spillways, energy dissipators, and related infrastructure. The chapter showcases the integration of innovative solutions tailored to site-specific challenges, ensuring long-term performance and resilience of these critical water resource projects.

CHAPTER 4

Innovations and Foundational Research

4.0 Introduction

Innovative Case Studies

CWPRS has played a pivotal role in providing hydraulically sound and cost-effective solutions to complex challenges in the design of spillways and energy dissipators for several hydropower, irrigation, and multipurpose projects. By employing both physical and numerical model studies, CWPRS has addressed unique, site-specific layouts and structures. The hydraulic design of river valley projects often involves two types of challenges: site-specific problems and issues related to complex hydraulic flow phenomena. Site-specific challenges stem from the topography, foundation conditions, soil and rock strata, and other local characteristics. Complex flow issues, on the other hand, include nonuniform flow in the approach channel creating vortices, rapidly varied flow due to intricate geometries, high velocities from steep gradients causing cavitation damage, intense turbulence leading to hydrodynamic forces on structures, and erosion of the downstream riverbed and banks, as well as flow-induced vibrations across operating conditions.

These problems are not easily addressed through analytical methods and thus require physical model studies to effectively simulate and solve. For several decades, hydraulic modelling has proven to be a valuable tool for resolving complex hydraulic challenges. This chapter discusses key case studies involving such challenges, including the Sardar Sarovar Project in Gujarat, the Subansiri Project in Arunachal Pradesh/Assam, the Indirasagar Project in Madhya Pradesh, Koyna double lake tapping Project in Maharashtra, and the Salauli Irrigation Project in Goa.

Basic Research Studies

Overflow spillways have long been used in high-head storage dams in Peninsular India. With a shift toward the North and Northeast Himalayan regions to harness perennial discharges for hydropower, innovative designs like orifice spillways have become popular. Orifice spillways offer the dual benefits of flood management and sediment flushing from reservoirs. Although many large dams have been built with orifice spillways, systematic design guidelines for orifice spillways are limited, unlike for overflow spillways. The extensive data collected from physical model studies of around 35 orifice spillways at CWPRS has proven invaluable for developing preliminary orifice spillway designs. However, due to the site-specific nature of each case, comprehensive guidelines could not be universally established.

As a result, CWPRS has initiated basic research to develop hydraulic design guidelines specifically for orifice spillways. This chapter discusses these guidelines in detail, focusing on roof profile design and aerator configuration, derived from extensive physical and numerical model studies.

4.1 SARDAR SAROVAR PROJECT, GUJARAT

4.1.1 Introduction

The Sardar Sarovar Dam Project is one of India's largest and most significant infrastructural undertakings. This project features a 165 m high concrete gravity dam across the Narmada River, with an irrigation potential spanning 3.2 million hectares and a power generation capacity of 1,450 MW. The dam site topography allows for two spillways: the main service spillway in the river's main section with 23 spans (gate size 18.29 m x 16.76 m), handling frequent flood events, and an auxiliary spillway on the left bank with 7 spans (gate size 18.29 m x 18.29 m), activated during extreme flood events. The spillway is designed to manage a 1-in-1000-year flood event of 86944 m^3/s through both service and auxiliary spans. The dam’s Full Reservoir Level (FRL) is at 138.68 m, the Maximum Water Level (MWL) at 140.21 m, and the minimum draw-down level at 110.64 m. The dam hosts two powerhouses with a total capacity of 1,450 MW, with power shared among Madhya Pradesh (57%), Maharashtra (27%), and Gujarat (16%).

4.1.2 Studies Conducted on the Physical Model

To optimize the design of the spillway, CWPRS conducted extensive studies on five major models, focusing on:

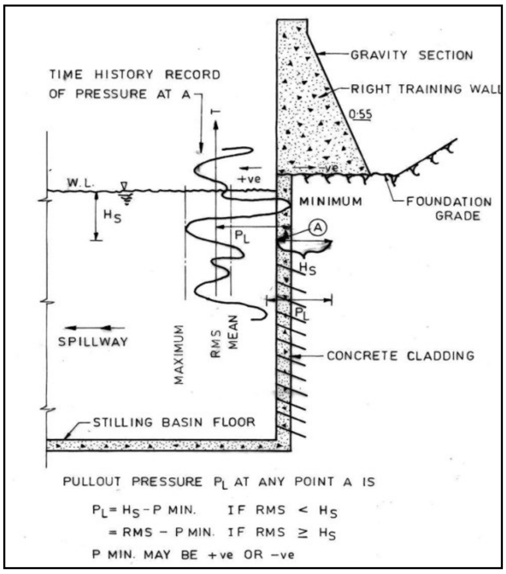
- Spillway layout and design
- Discharging capacity
- Energy dissipator performance
- Hydrodynamic forces on the low divide walls in the stilling basin
- Uplift forces on the stilling basin floor slab
- Pull-out forces on the right training wall
- Alternative crest profiles
- Right training wall extension
- Spillway construction stages
- Aeration groove design

4.1.3 Study Outcomes

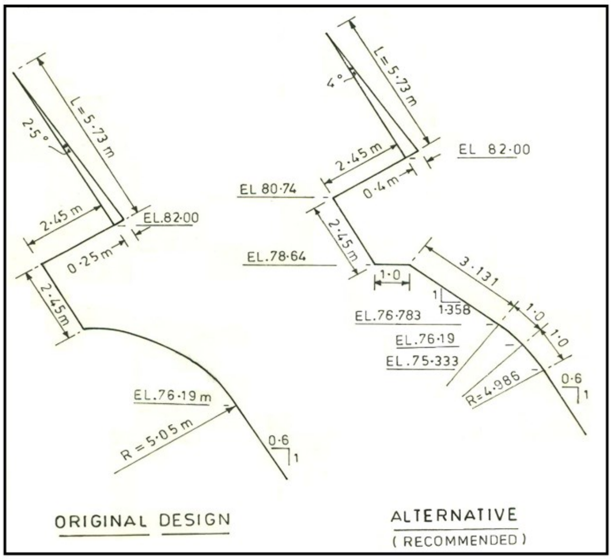
Between 1979 and 1981, six alternative spillway layouts and energy dissipators were tested based on approach flow, discharge capacity, and energy dissipator performance. Key findings from these studies are outlined below:

- **Discharging Capacity**: The spillway was designed for a 1-in-1000-year flood of 86944 m^3/s. The service spillway can pass 67,000 m^3/s at FRL El. 138.68 m and 74,720 m^3/s at MWL El. 140.2 m. Both spillways combined can safely handle a discharge of 96,600 m^3/s, confirming satisfactory discharging capacity.
- **Divide Walls**: Simulations of one- or two-span closures showed potential damage due to return eddies on the apron. Intermediate divide walls were added to segregate flows in spillway bays, confining eddy currents and minimizing the risk of damage.

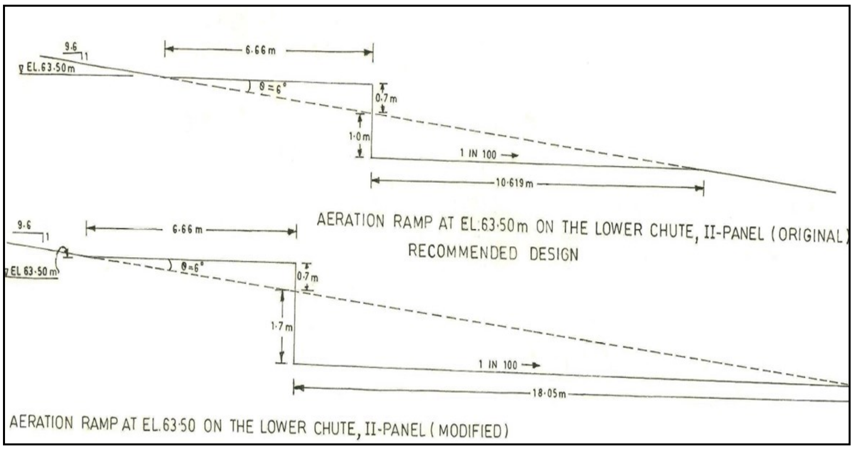
- **Bending Moments**: The divide walls' structural design required data on differential pressures and bending moments under varied conditions. Tests using transducers showed bending moments from 12,000 to 18,000 KNm/m, 1.8 to 2.7 times the 6,700 KNm/m from traditional hydrostatic analysis.
- **Pull-Out Forces on Training Wall**: The right training wall, a massive structure reaching 45.2 m at its highest point, is needed to withstand pull-out forces due to hydraulic jump turbulence. The forces varied from 12,000 to 24,000 KN as discharge increased from 65,000 to 141,500 m^3/s.
- **Uplift Forces on Stilling Basin Slab**: Pressure fluctuations during hydraulic jumps caused hydrodynamic uplift forces. Uplift forces were measured with a maximum of 11,000 KN observed in the model. A design value of 5,000 KN was adopted for sustained average load conditions.
- **Service Spillway Aeration Groove**: For high-head spillways, high flow velocities (30-40 m/s) can lead to cavitation. To mitigate this, aerators were installed in the service and auxiliary spillways. After testing, a 2.45 m x 2.45 m groove with a 4° ramp angle and 0.4 m ramp height was finalized, along with air intake towers in the divide walls.
- **Auxiliary Spillway Aeration Groove**: Cavitation tests on the auxiliary spillway's upper chute showed no need for an aerator, as the cavitation index remained above 0.2. However, for the lower chute, a ramp aerator was initially tested but later removed from the design due to the risk of cavitation in partial gate operations. The upper aerator performed well across discharge ranges.
- **Spillway Construction Stages**: Due to delays, hydraulic model studies at scales of 1:150 and 1:85 assessed upstream water levels, discharge capacity, and flow conditions on the partly completed spillway. For higher discharges, flow tended to separate from the surface and impact the toe of the dam. To direct flow and prevent structural vibration, a crest hump was added, guiding flow onto the spillway's rear slope and away from the joint with the energy dissipator.



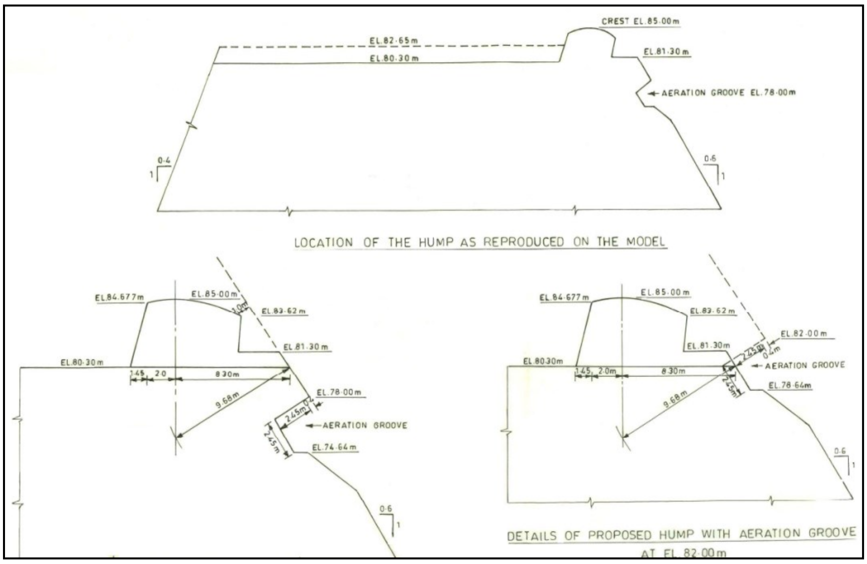
Definition sketch of the pull out forces



Details of the aerator of the service spillway



Details of the aerators for the lower chute auxiliary spillway



Location and details of hump

4.1.4 Significant Achievements

Hydraulic model studies were instrumental in developing the robust design of the Sardar Sarovar Project’s massive spillway and related structures.

- Beyond traditional analyses such as spillway discharge capacity, crest pressure, and energy dissipator performance, specialized studies focused on hydrodynamic bending moments on divide walls, pull-out forces on the training wall, uplift forces on the basin floor, aerator design, and a unique low-level hump design for the partially completed spillway. These pioneering studies, some of which were conducted for the first time in India, provided valuable insights into structural design.
- The turbulence from hydraulic jumps imposed fluctuating forces on stilling basin slabs and divide walls. Extensive experiments helped estimate the pressures, forces, and bending moments across the spillway components, supplying essential data for refining structural designs to include the hydrodynamic loads. Unique construction stage studies further aided in planning for Rehabilitation and Resettlement (R&R) efforts.
- The Sardar Sarovar Project stands out globally for its impressive engineering and technological feats and the substantial long-term benefits it brings. These include water, energy, and food security that

support Gujarat’s sustainable development. SSP’s successful navigation of complex engineering challenges reflects its significant impact on the quality of life for millions.

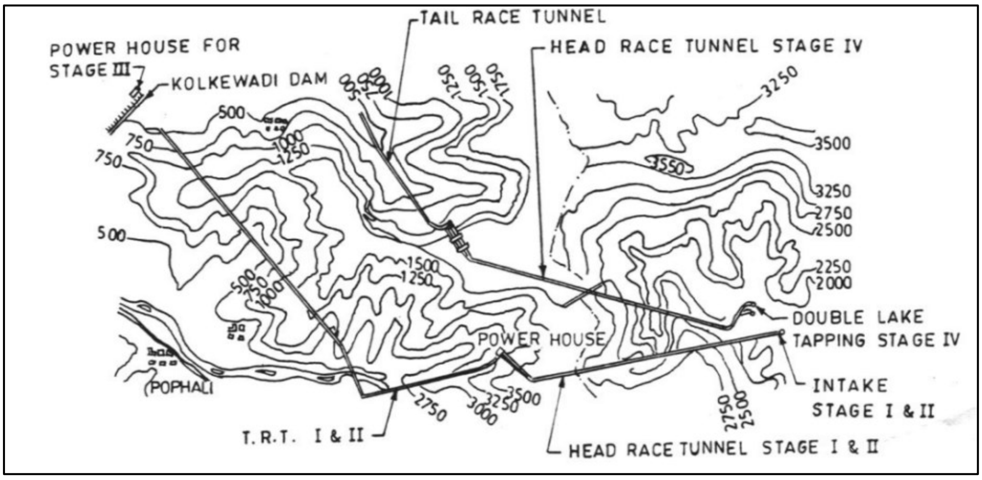
View of the physical model

View of the dam site

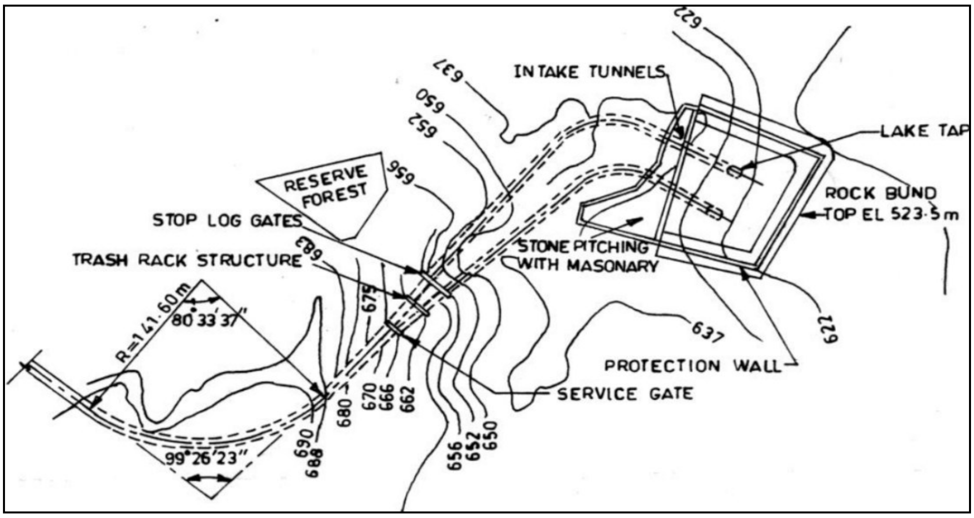
4.2 KOYNA DOUBLE LAKE TAPPING STUDIES, MAHARASHTRA

4.2.1 Introduction

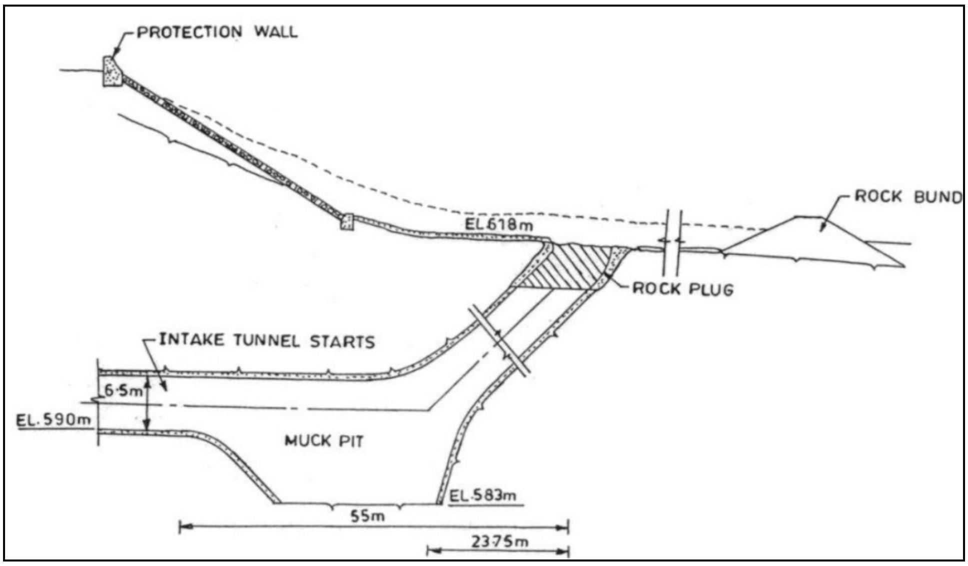
The Koyna Hydroelectric Project, located in Maharashtra, involved an innovative lake-tapping method for power generation by piercing the lake bottom. The project comprises four stages, leveraging the Western Ghats' elevation and reliable monsoon rainfall. Stages I and II utilized the 103 m high Koyna Dam and 500 m head to produce 560 MW. Stage III generated an additional 320 MW using the tailwater from the first two stages and a 140 m head. Stage IV, with a capacity of 1000 MW, was designed as a peaking power facility without constructing an additional dam. Water is conveyed through inclined tunnels connected to intake structures, then to a headrace tunnel leading to turbines in an underground powerhouse.



General layout plan



Layout plan of double lake tapping



Section of lake tap

4.2.2 Studies on the physical model

A 1:30 scale model replicated key components of the system, including the double lake tappings, muck pits, and intake gate structures. An elevated steel tank accommodated the lake's contours, and transparent Perspex allowed visualization of water flow conditions.

4.2.3 Study outcomes

Simulation of Rock Plug Blasting

The model simulated the rock plug blasting process to simulate the water, air, and rock fragments set in motion. Although the model couldn't replicate the explosion's full force, it qualitatively demonstrated the rock fragments being displaced by water pressure. The simulation used scaled rock fragments and an artificial "pre-blasted" rock plug, with observations indicating a reduced water rise in the gate shaft compared to real-world conditions.

Flow Conditions during Plug Blast

Further studies focused on water flow dynamics, muck pit behavior, and water level fluctuations during simulated blasting. To prevent rock debris from reaching the gates, the tunnels were filled with water before simulated blasts, leaving an air gap below the rock plug. A rubber bladder, covered with gravel to represent rock fragments, was rapidly removed to simulate blasting conditions. Observations under different reservoir levels showed that higher tunnel filling levels resulted in less turbulence, while lower levels intensified flow conditions. Adjusting the muck pit's downstream side to a vertical orientation helped trap debris effectively. Final designs ensured that nearly all debris settled in the muck pit, protecting the intake tunnel system.

Water levels in the gate shaft decreased as filling levels increased, reducing upsurges and allowing safe operation. Actual lake blast observations confirmed the model's findings, with an upsurge level reaching close to predicted values.

4.2.4 Significant Achievement

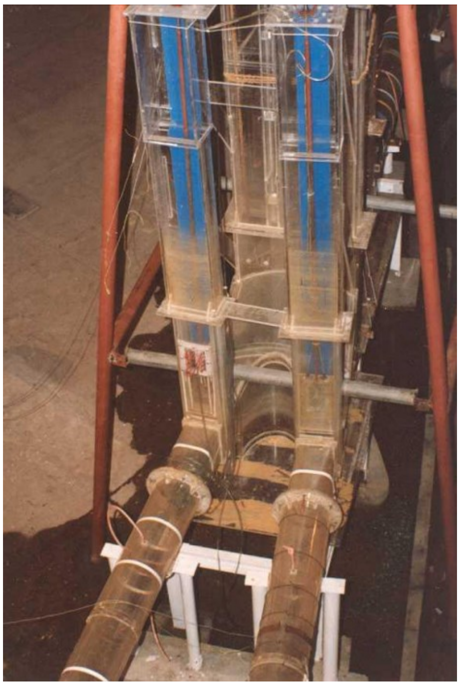
The Koyna Double Lake Tapping Project was a pioneering effort in India, involving specialized model studies and close collaboration between design, research, and project engineers.

- **Simulation Insights**: Model studies effectively simulated lake blasting conditions, allowing qualitative prediction of flow behavior and pressure fluctuations on the stop log gate. These studies showed an accurate correlation between the model's hydrodynamic pressure measurements and actual on-site observations.
- **Design Modifications**: Observations led to modifications in the muck pit design, with vertical adjustments on the downstream side that helped trap debris efficiently. After implementing these changes, the muck pit successfully captured all debris from the lake blast, preventing it from entering the water conductor system.
- **Flow Management**: For normal turbine operations, the model detected vortex formation for discharges of 195 m^3/s and 260 m^3/s. Engineers suggested an alternative pier arrangement to minimize the vortex intensity, enhancing operational stability.
- **Confidence Building**: The model studies allowed project engineers to observe and prepare for this unique phenomenon, boosting their confidence in the system’s capability to handle blast pressures and informing the stop log gate design to endure such forces.

These achievements underscore the unique technical advances of the Koyna Project, ensuring the effective and safe operation of the innovative double lake tapping system.

View of the physical model

View of the muck pit



View of stop log gates

4.3 SALAULI IRRIGATION PROJECT, GOA

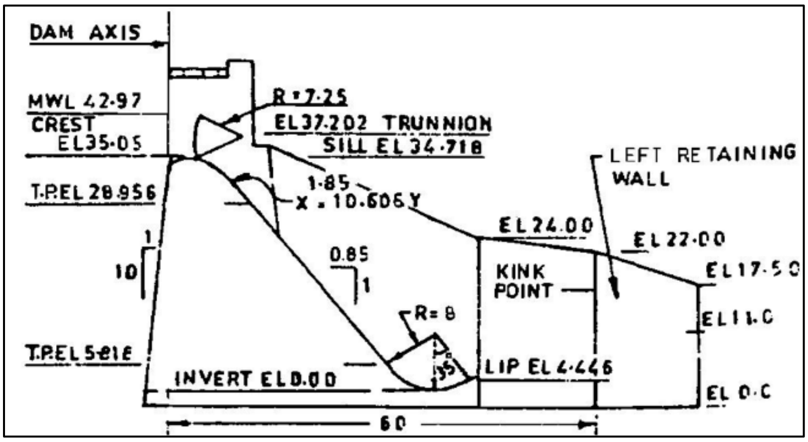
4.3.1 Introduction

The Salauli Project is the first major irrigation initiative in Goa, aimed at enhancing agricultural productivity in the region. The project involves the construction of a 1003-meter-long, 42-meter-high composite dam featuring a central masonry spillway and earth dams on both flanks across the Sanguem River. This dam has a storage capacity of approximately 227 million cubic m, which was proposed to irrigate 14,500 hectares through a 25-kilometer-long canal with a capacity of 14 m^3/s.

Construction began in 1976, and by 1980, several portions of the earth dam were completed. However, construction of the central masonry spillway encountered delays due to foundation issues. The initial layout included a masonry dam with five 10.7-meter-wide blocks, two spillway gates of size 10.7 x 6.09 m, and a ski-jump bucket for energy dissipation. The design is intended to manage a flood discharge of 430 m^3/s.

4.3.2 Original Design with Ogee Crested Spillway

Studies on a 1:40 scale model indicated that the maximum design outflow flood of 430 m^3/s could be managed by a single span, with a reservoir water level at El. 42.3 m, just below the design maximum water level of El. 42.98 m. For optimal spillway operation, it was recommended to operate both spans simultaneously to ensure an even discharge intensity at the bucket lip. Later, due to foundation challenges, the spillway design was modified to include a single gate measuring 10.7 x 8.1 m, with the crest level lowered from elevation 35.05 to 33.0 m, allowing for a modified outflow flood of 618 m^3/s. The model tests confirmed that this design could accommodate the revised discharge with a reservoir level of 42.15 m.

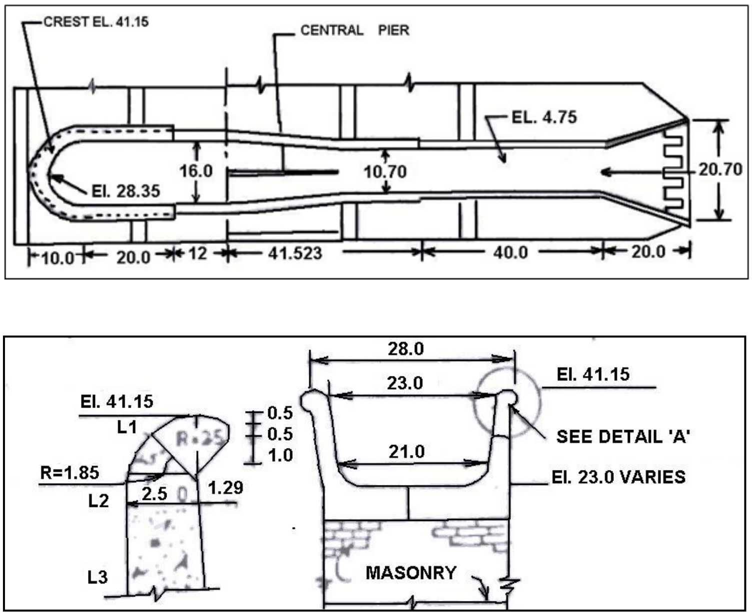


Original Design of the spillway and ski-jump bucket

4.3.3 Modified design with duckbill spillway

An increase in the design flood to 1470 m³/s revealed that the single-span spillway would not suffice without encroaching on the freeboard. Since the earth dam was already constructed, raising the maximum reservoir water level was not an option. A duckbill spillway was proposed to handle the increased discharge within the available width while minimizing the rise in upstream water levels.

The initial design of the duckbill spillway featured a crest length of 63.56 m, a semi-circular nose, and a central pier in the spillway trough. However, this design was inadequate as it resulted in submergence across the crest length, reducing discharge efficiency and increasing upstream levels. The central pier also experienced violent flow conditions. The revised design extended the crest length to 73.87 m with circular arcs and removed the central pier. For storage considerations, the crest level was set at an elevation 41.15 m, while the maximum water level (MWL) was raised to an elevation 44.5 m.



Revised design of Duck bill Spillway

The discharge coefficient achieved was approximately 0.75, allowing a discharge of 975 m^3/s at the revised MWL El. of 44.5 m. However, reaching the maximum outflow of 1470 m^3/s required an upstream water level of 45.5 m, slightly encroaching on the dam's freeboard. Parapet walls on the earth dam were added to address this encroachment.

Downstream flow conditions in the trough portion of the duckbill spillway were initially violent and pulsating, causing uneven flow distribution. Various solutions, including deepening the trough, lowering its downstream end, and adding a secondary weir, were tested. A weir with a crest at an elevation 30 m provided satisfactory flow conditions even at maximum discharge.

Flow condition in duckbill spillway

4.3.4 Alternative designs for energy dissipators

The original energy dissipation design included a ski jump bucket with an 8-meter radius and a lip angle of 35 degrees. However, turbulent conditions downstream led to return velocities of around 4.5 m/s along the left and right training walls. To protect the earth dam's toe, extensions of 20 m and 15 m were recommended for the left and right training walls, respectively. Due to insufficient rock quality, the ski jump bucket was replaced with a stilling basin.

During excavation for the masonry dam, geological challenges, including deeply weathered channels and cavernous rock on the left side, were encountered, necessitating a shift of the spillway downstream and to the right. This adjustment led to a curved stilling basin that integrated with the river course. The revised routed flood was increased to 1470 m^3/s, and by then, substantial portions of the stilling basin apron had been laid at elevation -4.75 m, which could not effectively manage the new discharge levels.

Various solutions were explored through hydraulic model studies at a 1:40 scale at CWPRS, Pune. Given the high discharge intensity, the flow from the apron impacted the right flared section of the stilling basin, creating return flows along the left side. To counteract this, two baffle blocks measuring 5 m high were added to the apron. The basin has a 10.7m wide rectangular section, followed by a trapezoidal section lined with concrete on a curved alignment to merge with the natural river channel.

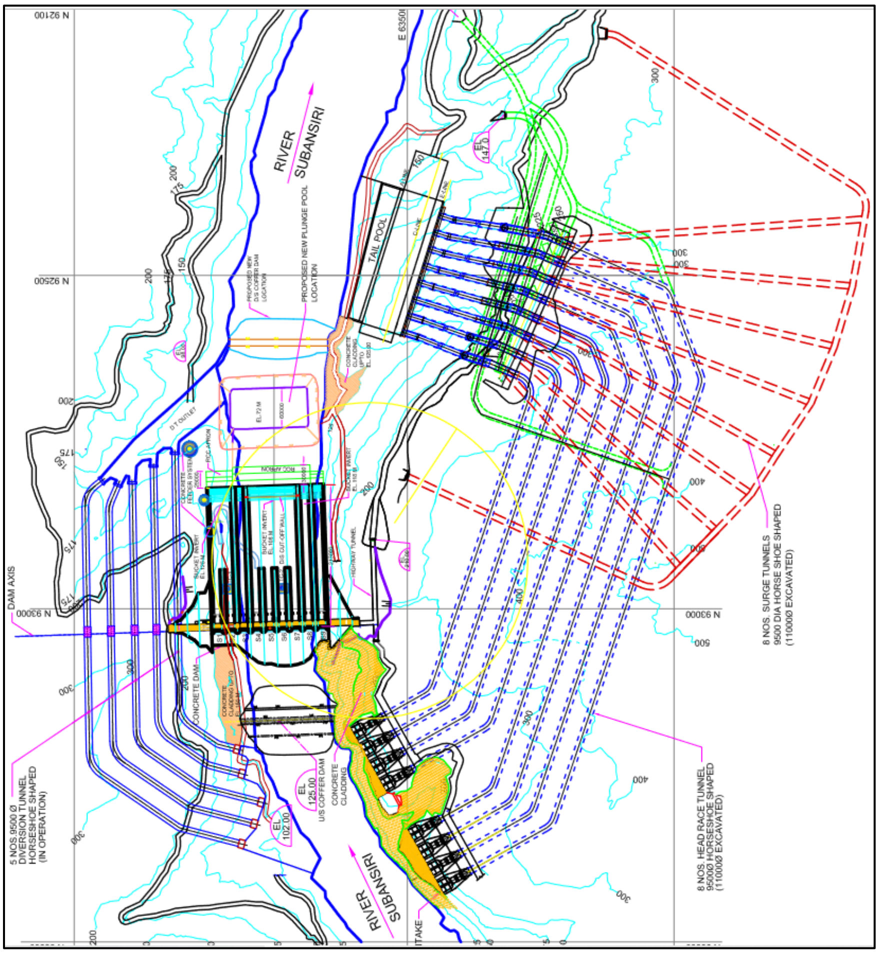
4.3.5 Significant Achievement

The hydraulic model studies were instrumental in developing the unique duckbill spillway design and unconventional stilling basin for the Salauli Project in Goa. The combination of uncertain hydrology, challenging geological and topographical features, and ongoing construction activities resulted in a distinctive spillway design, making it a notable achievement in Indian hydraulic engineering.

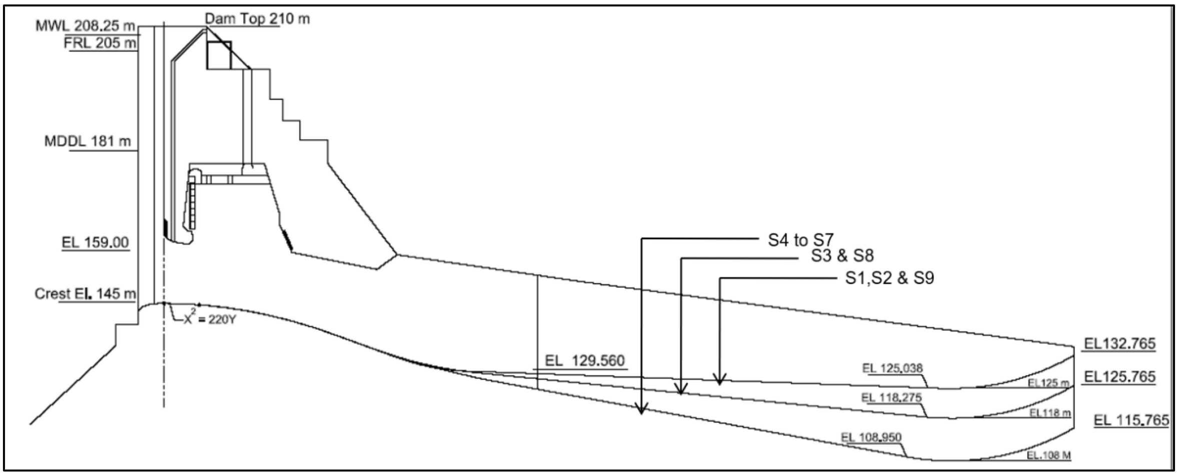
4.4 SUBANSIRI HE PROJECT, ARUNACHAL PRADESH/ASSAM

4.4.1 Introduction

The Subansiri Lower Project is situated on the Subansiri River, straddling the border of Arunachal Pradesh and Assam. The project involves constructing a 116 m high, 271 m long concrete gravity dam. It aims to utilize a maximum gross head of 91 m for power generation, with a proposed surface powerhouse on the right side of the spillway, accommodating an installed capacity of 2000 MW (8 units of 250 MW each). The spillway comprises nine spans, each 11.5 m wide and 14 m high, with a breast wall and a crest elevation of 145 m. The Full Reservoir Level (FRL) is set at 205 m, and the downstream profile follows the equation $x^2 = 220y$. The spillway is designed to manage a maximum outflow flood of 35,000 m^3/s at a maximum water level (MWL) of El. 208.25 m.



General layout plan of the dam complex



Cross section of spillways

4.4.2 Background of earlier studies

Extensive physical model studies were conducted to finalize the crest, downstream profile, and energy dissipation system for the spillway. To facilitate sediment flushing and flood discharge, the crest elevation was set at 145 m, and the downstream profile of the spillway was defined by$x^2 = 220y$. Several alternatives for energy dissipation were analyzed on a 1:90 scale 3D hydraulic model between 2003 and 2013 to assess how effectively different designs could protect the spillway's downstream area when handling floods up to the probable maximum flood of 35,000 m^3/s. A stilling basin with an invert level of 85 m was initially proposed, but it did not adequately dissipate energy during the design flood, especially as sediment accumulated up to an elevation 94 m. Consequently, an innovative multilevel ski-jump bucket was designed to enhance stability and energy dissipation along the extended spillway. The design features three different chutes (S4 to S7, S3 & S8, and S1-S2 & S9) with varied slopes, each ending in ski-jump buckets at elevations of 108 m, 118 m, and 125 m. This layout represents a novel approach to spillway energy dissipation, differing from conventional methods.

4.4.3 Studies for spillway surface protection

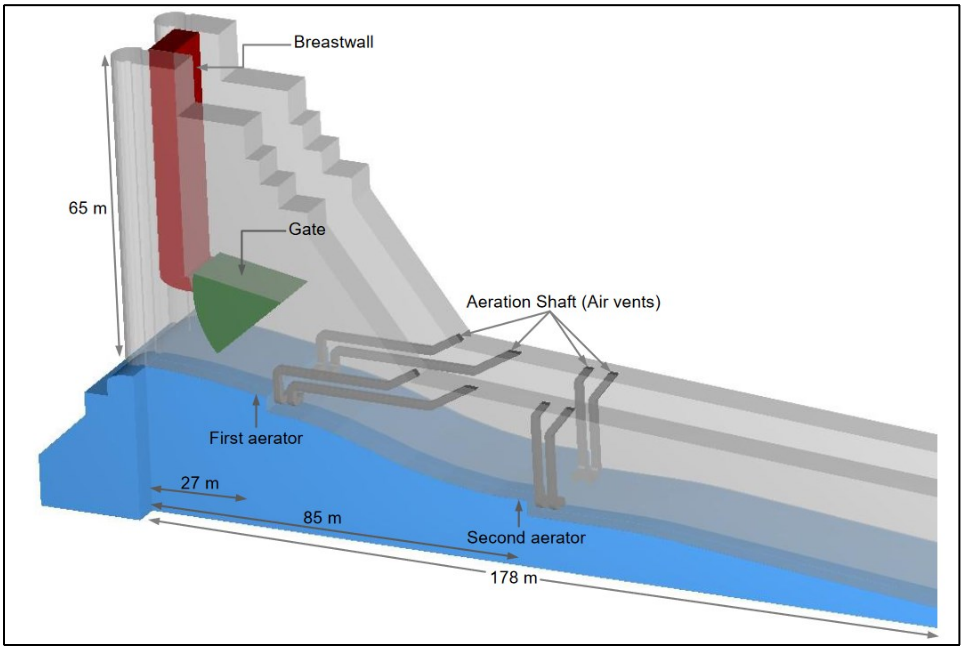
A 1:70 scale 2D sectional model was used to test the modified spillway and energy dissipator designs under different flow conditions. The studies showed that negative pressures between -1.5 to -2.5 m (CI 0.13 to 0.16) and -1.16 to -2.33 m (CI 0.13 to 0.1) observed across the entire chute surfaces of profiles S4 to S7 and S3 & S8, respectively. Due to flow velocities reaching 35-40 m/s along the chutes, the spillway profiles showed susceptibility to cavitation damage, with cavitation indices falling below the critical threshold of 0.2, necessitating protective measures. The studies recommended adding aerators on chutes S4 to S7 and S3 & S8 to improve performance and reduce cavitation risk. For spillway spans S1-S2 and S9, no aerators were required, as pressures remained positive across all discharges, with cavitation indices above the 0.2 threshold.

4.4.4 Aerator design on the spillway chute

Due to the absence of established guidelines for aerator design on orifice spillways, various designs were tested on both physical and numerical models to analyze air-water flow dynamics over the spillway surface and optimize the aerator design. Multiple configurations involving offsets and varied ramp heights were evaluated, focusing on parameters like surface pressures, water velocities, air velocity and concentration near the chute bed, and jet length.

The finalized aerator design includes:

- **For S4 to S7**: The first aerator has a 2.5 m offset, a 4° ramp angle, and a 0.56 m ramp height, positioned 27 m downstream of the dam axis. A second aerator has the same offset, a 5.36° ramp angle, and a 0.75 m ramp height at 88 m downstream.
- **For S3 & S8**: The first aerator has a 2.5 m offset, a 4° ramp angle, and a 0.56mramp height, located 27 m downstream of the dam axis. A second aerator has the same offset, a 5.36° ramp angle, and a 0.75 m ramp height at 85 m downstream.



Cross section of spillway with aerators

4.4.5 Findings from the studies

The following key findings of the studies helped in deciding the performance of the aerator and finalizing the design of the spillway for profiles S4 to S7 and S3 & S8:

- **Flow detachment and air entrapment**: The first aerator's offset at 27 m caused flow detachment from the spillway floor, creating a cavity under the jet, which allowed air to enter through vents on either side of the span. The second aerator at 88 m also created a cavity where air was entrained, ensuring adequate aeration of the lower jet layer. Flow remained within the side walls until the pier's end, after which jets interacted, enhancing air entrainment along the pier's centerline.
- **Acceptable pressures and cavitation index**: For different spillway operating conditions, spillway surface pressures and cavitation indices remained above the critical threshold of 0.2, with air concentrations near the bed above 10%, helping protect the spillway from cavitation damage.

- **Efficient aeration**: The aerators performed well under various conditions, maintaining adequate cavity pressures, air velocity, jet trajectory lengths, and air concentrations, ensuring effective spillway surface protection. No cavity blockages were observed.

4.4.6 Significant achievement

The aerator design for the Subansiri Project spillway is intricate, given the diverse hydraulic parameters affecting air-water interactions over the spillway surface. Existing literature provides limited guidance on designing and evaluating aerator performance, especially for high-head, long chute spillways. Findings from this project provide valuable insights into aerator device design and performance evaluation, which will aid in designing similar structures in the future.

4.5 INDIRA SAGAR MULTIPURPOSE PROJECT, MADHYA PRADESH

4.5.1 Introduction

The Indira Sagar Project (ISP) is located on the Narmada River in the Khandwa district of Madhya Pradesh. This multipurpose project has an installed power generation capacity of 1000 MW and provides irrigation to approximately 123,000 hectares. The dam has a catchment area of 61,642 km^2 and serves as the primary project for downstream developments in the Narmada Basin. ISP contains India’s largest reservoir, with a storage capacity of 12.22 billion cubic m (BCM). The gravity dam measures 653 m in length and 92 m in height. Its main and auxiliary spillways consist of 12 and 8 spans, respectively, each with dimensions of 20 m by 17 m. The revised probable maximum flood (PMF) at the dam site is 89,252 m^3/s. For energy dissipation, a slotted roller bucket was initially used, with varying invert levels for each spillway. A surface powerhouse on the river's right bank houses 8 Francis turbines, each with a 125 MW capacity. The water conductor system includes a headrace channel capable of carrying 2200 m^3/s, discharging water back into the Narmada River through an 850-meter-long tailrace channel after power generation.

Layout of the Indira Sagar Project, MP

4.5.2 Challenges at the site

Operational since 2004-05, the ISP spillway, which utilized a slotted roller bucket for energy dissipation, suffered significant damage during continuous use in the 2013 flood, where discharges ranged from 20,000 to 35,000 m^3/s. Damage to the spillway glacis and the roller bucket of the main spillway was attributed to low tailwater levels, ski action during early operation, high hydrodynamic pressures from roller formation, and negative pressures on the bucket teeth due to incoming velocities of around 35 m/s.

To address these issues, a ski-jump bucket was proposed as a replacement for the roller bucket, after considering hydraulic, structural, and economic factors. Extensive hydraulic model studies were conducted at CWPRS from 2016 to 2023 to assess spillway performance, energy dissipation, and power intake. It was found that 56,309 m^3/s could be discharged through both spillways with a 10% gate inoperative (through 18 spans) at a maximum water level (MWL) elevation of 263.35 m. Given the upward revisions in SPF to 78,576 m^3/s and PMF to 89,252 m^3/s, alternative arrangements were recommended to manage additional flood discharge.

4.5.3 Findings from the Studies

The studies, conducted using both 2D sectional and 3D models, yielded the following findings:

- **Ski-Jump bucket performance**: For the main spillway, the ski-jump bucket demonstrated satisfactory performance with effective ski action, achieving a throw distance of approximately 86 m from the bucket lip at a reservoir level of FRL El. 262.13 m. Extending the left training wall was recommended to prevent return flow along the left bank.
- **Flow circulation and return currents**: By extending the left training wall to an elevation of around El. 220 m, circulating and return currents near this wall were minimized, thereby controlling flow along the left bank.
- **Auxiliary spillway performance**: No roller action was observed in the auxiliary spillway's bucket. A hydraulic jump formed within the bucket, and water cascaded over the apron, passing a discharge of 4718 m^3/s when water levels reached the top of the downstream protection wall. With further discharge, a tendency for overflow toward the powerhouse tail pool was noted, indicating unsatisfactory performance. A revised design for the auxiliary spillway's energy dissipator was recommended.
- **Tailrace channel and flood discharge**: To protect the powerhouse area during flood release through the tailrace channel, it was suggested that part of the auxiliary spillway discharge be diverted to the main river via a 60-meter cut near the divide wall. This would increase the auxiliary spillway's discharge capacity in high-flood conditions.
- **Guide wall design**: The guide wall design, including height specifications, was finalized after analyzing the bifurcation of auxiliary spillway floodwater between the main river course and the powerhouse tailrace channel.
- **Erosion protection**: Heavy fluctuations were observed along both the left and right banks downstream, raising erosion concerns. To protect the left bank, erosion control measures were recommended up to 700 m downstream from the dam axis.

- **Plunge pool design**: A pre-formed plunge pool downstream of the ski-jump bucket was proposed based on scour studies. This feature would mitigate high-energy flow, control erosion, and enhance structural stability.
- **Spillway discharge capacity**: The 2D and 3D model studies assessed discharge capacities for various gate openings, identifying the range of discharges and reservoir levels from MWL to the spillway crest. These results informed spillway gate operation planning.
- **Prototype observation**: CWPRS officers observed the performance of the newly constructed energy dissipator apparatus (EDA) on the main spillway. All main spillway gates were gradually opened up to 3.0 m at a reservoir level of El. 260.75 m. A clear ski action was achieved in the prototype, consistent with model observations, underscoring the reliability of model studies.

4.5.4 Significant achievement

The studies conducted for the Indira Sagar dam spillway represent a successful example of model-prototype conformity. After the roller bucket-type energy dissipation system was damaged, CWPRS, in collaboration with CWC and NHDC, recommended a ski-jump bucket as a revised energy dissipator. In 2019, CWPRS scientists observed the improved performance of the ski-jump bucket during floods, reinforcing the credibility of physical modelling in hydraulic engineering. The successful implementation of the new spillway design enhanced flood management and established valuable insights for future dam projects.

View of the physical model

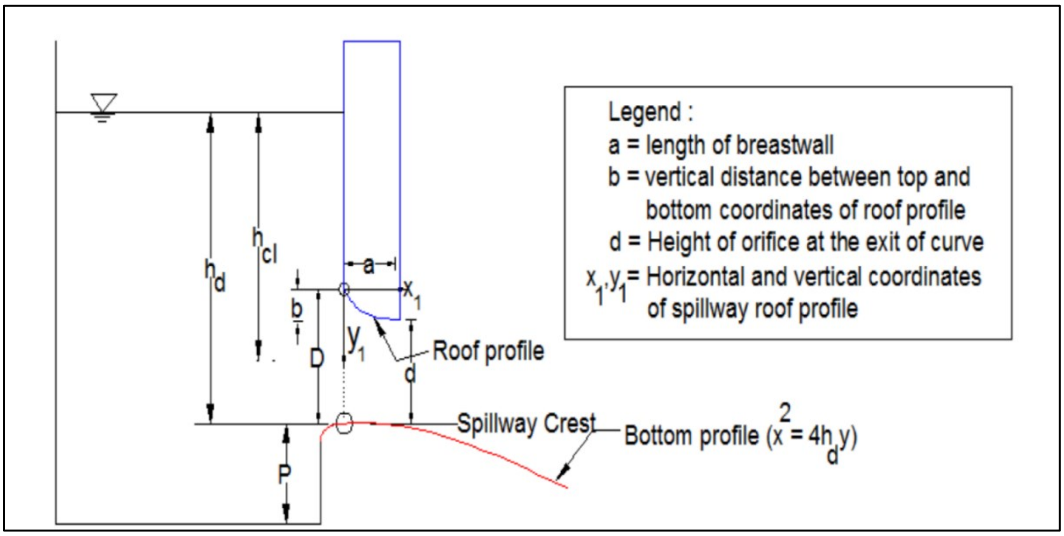
View of the dam site

4.6 GUIDELINES FOR DESIGN OF ROOF PROFILE OF ORIFICE SPILLWAY

The development of design guidelines for the roof profile of orifice spillways was pursued through extensive research, using both physical and numerical modelling. This work aimed to improve the spillway's discharging capacity, which is essential for ensuring dam safety by effectively managing floodwaters. The primary findings, methods, and significant achievements are summarized below:

4.6.1 Need for the basic research

The spillway's discharging capacity is crucial for dam safety and can be calculated using the formula $Q = C_d * A * \sqrt{2gh_d}$, where Q is the discharge over the spillway, A is the orifice opening area, h_d is the design head,C_d is the discharge coefficient.



Definition sketch of orifice spillway

Many dam failures in the past have been attributed to improperly designed spillways or spillways with inadequate capacity. Estimating the coefficient of discharge (C_d) for the spillway is a critical step in the design process, as the discharge capacity of the spillway directly depends on it. Accurate assessment of C_d is essential for the preliminary design of the spillway to ensure sufficient waterway capacity and the ability to pass the probable maximum flood (PMF) at maximum reservoir water levels.

In an orifice spillway, the coefficient of discharge is influenced by various parameters, including the shape of the spillway (upstream, downstream, and roof profile), the head over the spillway crest, the upstream depth of the spillway crest relative to the riverbed, river slope, width of piers, shape of the pier nose, aspect ratio of the orifice opening, and approach flow conditions. For instance, the C_d for the Nathpa Jhakri Project reached a maximum of 0.9 due to large transitions in plan and section, leading to a smooth entry of flow. A similar outcome was observed in the Tala project. In both cases, the length of the roof profile (8 m and 13 m) exceeded the usual thickness of 6-7 m, indicating that a larger and steeper roof profile is favorable for achieving a higher C_d.

Conversely, the coefficient of discharge was found to be at its minimum for the Chamera-III project, where the orifice opening is excessively large (16.5 m). The upstream profile of Chamera-III is flat, resembling a broad-crested weir from structural considerations, which negatively impacted the Cd, placing it in the range of 0.67 to 0.78 lower than that of other projects. In the Punatsangchhu I project, the C_d with the original elliptical roof profile was 0.68, which increased to 0.77 after modifying the profile to be steeper and increasing the height of the roof. This modification led to an approximately 15% increase in discharging capacity.

Assessing the coefficient of discharge is therefore a complex task due to its dependence on various governing parameters. CWPRS has contributed to more than 35 orifice spillway projects. In most of the cases, inadequate discharging capacity was one of the main problems faced during the study. It was experienced from the model study that in addition to the height of the orifice and design head, the shape of the roof profile also affects the discharge capacity. As no guidelines were provided for its design, it was felt necessary to conduct basic research to develop the guidelines for the design of the roof profile of the orifice spillway.

4.6.2 Studies conducted on physical and numerical models

A physical model of the orifice spillway was developed in a facility with a 22 m (W) x 60 m (L) hangar. This model included a water recirculation system, pumps, and an approach channel. The model scale was set as 1:50, and the Reynolds number calculated ranging from 5.6×10^5 and 1.8×10^6 ensured turbulent flow conditions.

The numerical studies were conducted using CFD software FLUENT, and the results were validated against the physical model. Tests covered:

- Design heads (h_d) from 30 to 70 m,
- Orifice heights (d) from 10 to 20 m,
- Spillway crest heights (P) from upstream river bed from 10 to 20 m.

Over 230 studies were conducted to formulate the guidelines for the orifice spillway roof profile.

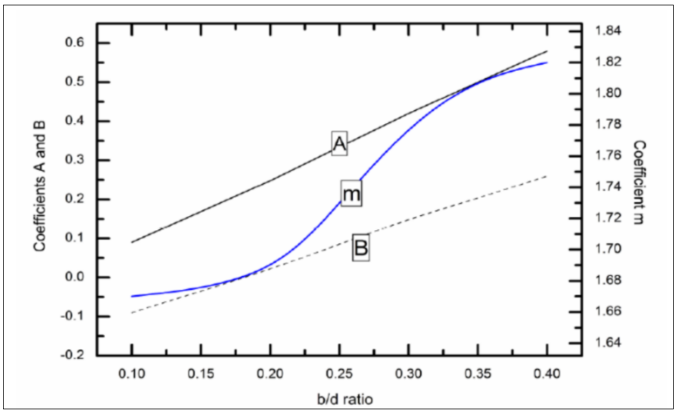
View of the physical model

4.6.3 Significant Achievements

a) **Equation for roof profile design:** A new equation was developed for the design of the roof profile,

$$x_1 = a\left(\frac{y_1}{b}\right)^m \text{ … (Eq. 1)}$$

$$a = Ad\left(\frac{h_d}{d}\right)^B \text{ …. (Eq. 2)}$$



Plot for coefficients A, B and m

The equations 1 and 2 are valid within the following ranges:

- 30 m ≤h_d ≤ 70 m
- 10 m ≤ d ≤ 20 m
- 0.8 ≤ h_e/h_d ≤ 1.33; where, h_e is effective head and h_d is design head,
- 0.2 ≤ b/d ≤ 0.4; where, b is orifice width and d is orifice height
- Downstream profile $x^2 = 4h_dy$

The orifice height d should accommodate maximum design discharge within the gorge width. For optimal discharge capacity, the roof profile should correspond to a b/d ratio of 0.4, as this creates a wider, steeper profile for better flow guidance.

b) Equation for estimating coefficient of discharge: Another equation was developed for the discharge coefficient for orifice spillways,

$$C_d = 0.933\left(\frac{h_{cl}}{d}\right)^{-0.0131}\left(\frac{h_{cl}}{h_d}\right)^{0.0834} \quad \text{(Eq. 3)}$$

The equation 3 is valid within the following ranges

- 30 m ≤h_d ≤ 70 m
- 10 m ≤ d ≤ 20 m
- 0.8 ≤ h_e/h_d ≤ 1.33; where, h_e is effective head and h_d is design head,
- b/d = 0.4; where, b is orifice width and d is Orifice
- Downstream profile $x^2 = 4h_dy$
- Roof profile as proposed in equation 1 and 2

These equations offer standardized methods for optimizing the discharging capacity of orifice spillways by fine-tuning the roof profile, ensuring dam safety and efficiency.

4.7 GUIDELINES FOR DESIGN OF SPILLWAY AERATOR

This section outlines the research conducted to develop guidelines specifically for aerators in orifice spillways.

4.7.1 Need for provision of the aerator on spillway surface

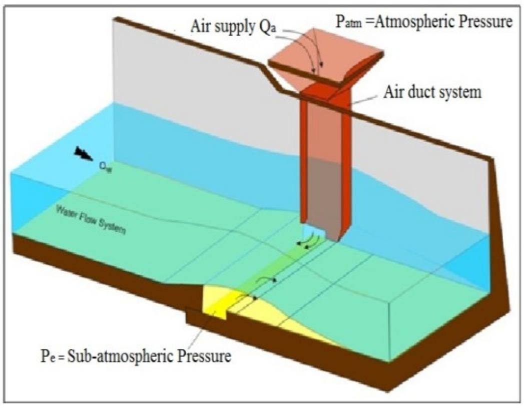
Aeration is essential for high-head orifice spillways to prevent cavitation damage caused by high-velocity flows. Cavitation is a complex hydrodynamic phenomenon that can cause serious damage to spillway surfaces. It is influenced by factors such as pressure, velocity, and the duration of spillway operation. Cavitation occurs when the local pressure in a flowing water mass drops to the vapor pressure of the water, causing the cavitation index to fall below 0.2. Cavitation damage is a growing concern in the design and operation of high-head orifice spillways, given the need to maintain the structural integrity of the spillway and protect the large capital investment involved. Preventing or minimizing the chances of cavitation damage is crucial.

Cavitation damages on spillway surfaces

Aeration is one of the most effective methods for mitigating cavitation damage. During high-velocity flows over the spillways, the flow turbulence gives rise to surface disturbances, which lead to air entrainment.

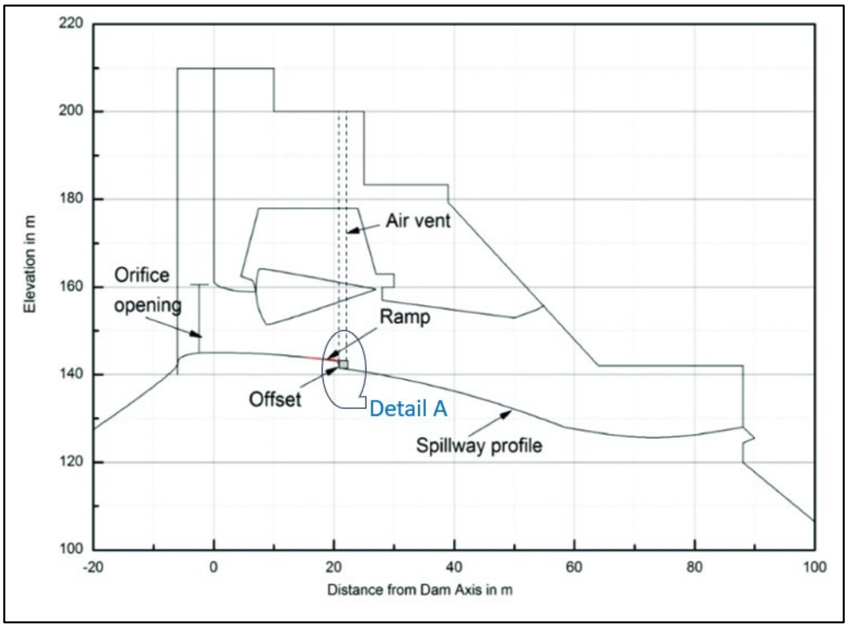
Sometimes, self-aeration in spillways does not always cause sufficient air concentration at the spillway surface due to high discharge intensity and flow depths. Therefore, the air is induced at the bottom layers of the spillway using the aerator. In this process, air is introduced to the water flow by installing aeration devices on the spillway surface. These devices can include deflectors or ramps, offsets, steps, grooves, or a combination of these features. The air introduced creates a cushioning effect in the form of a compressible air-water mixture that protects the concrete surface from cavitation erosion. Peterka (1953) demonstrated that small volumes of air near a concrete surface can significantly reduce cavitation damage. Air bubble concentrations of about 1 to 2% drastically reduce cavitation erosion, while concentrations of 6 to 8% virtually eliminate it.

Self-aeration on spillway surface

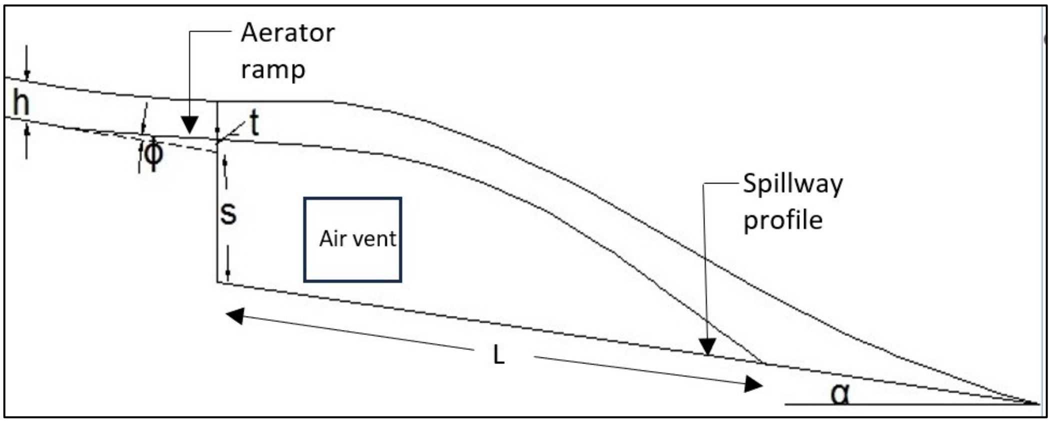


Typical aeration system

Designing aeration systems is a complex task that depends on several factors, including spillway slope, the incoming Froude number of the flow, and the geometry of the aerator. Proper aerator design requires determining flow velocities and pressures on the spillway surface to assess cavitation risk, estimating the amount of air needed to prevent cavitation damage, and developing the aerator's geometry and location.



Definition sketch of spillway with aerator



Definition sketch of the spillway with aerator (Detail A)

4.7.2 Need for basic research

Orifice spillways with heads of 50 m or more can experience velocities of 30 to 40 m/s, increasing the risk of cavitation damage. Aeration of the spillway surface helps mitigate this risk and is a practical, cost-effective method widely used for spillway protection. Although guidelines for overflow spillways exist, they are not suitable for the unique hydraulic characteristics of orifice spillways, which often have flatter slopes. As orifice spillways are frequently used in the hydropower projects of Northern and Northeastern India, there was a need to establish specific guidelines for aerators on orifice spillways.

The research considered the following parameters for designing aerators:

- Need for an aerator to prevent cavitation,
- Placement of the first aerator,
- Entrainment rate,
- Spacing between aerators,
- Desired air concentration in the flow,
- Aerator geometry and size,
- Air supply system size, geometry, and location.

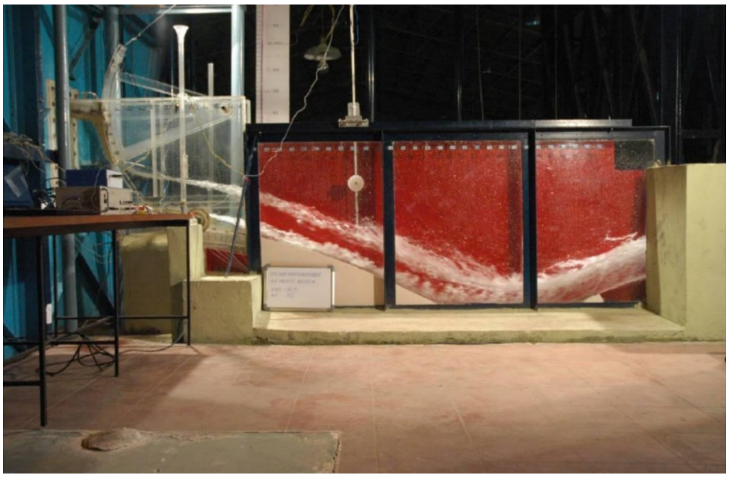
4.7.3 Studies conducted on physical and numerical models

A physical model for the orifice spillway aerator was built in a 22 m (W) x 60 m (L) hangar with a water recirculation system. The model is connected to a 5 m (L) x 3 m (W) x 4.8 m (H) steel tank, with two pumps providing 0.28 m^3/s (10 m^3/s) of water flow through a constant overhead tank. Froude similitude was applied to simulate free surface flows accurately, ensuring gravitational and inertia forces were represented properly. The scale was set at 1:25 to achieve a Reynolds number over 10^5 and a Weber number over 110, which are essential for modelling air entrainment.

Numerical simulations were also conducted using CFD software FLUENT, validated by comparing key hydraulic parameters with the physical model. Studies focused on several design configurations, including:

- Crest profile matching $x^2=220y$
- A design head of 60 m over the crest
- Aerators with 0.25 m ramp and without ramp
- Spillway slopes from 10^0 to 20^0
- Air vent diameters of 0.25, 0.35, 0.625, and 1.25 m

Parameters like water surface profiles, pressure profiles, water and air velocities and discharges, hydrodynamic pressure on the lip of the aerator and air entrainment were measured to compute important non-dimensional parameters like jet length, cavity pressure, air entrainment coefficient and air concentration near the solid surface. More than 230 studies were carried out to develop the design guidelines for the orifice spillway.



View of the physical model

4.7.4 Significant Achievements

Two critical non-dimensional parameters were identified for evaluating aerator performance:

- **Jet length (λ)** – Used to gauge how far the water jet travels before reattaching, important for effective aeration.
- **Air entrainment coefficient (β)** – Used to measure the volume of air introduced into the water flow, essential for reducing cavitation risk.

These parameters help optimize aerator design on orifice spillways to maximize cavitation protection and operational efficiency.

c) Equations of non-dimensional jet length (λ) and air entrainment coefficient (β) for Aerator on Orifice Spillway with Parabolic Profile:

- $\lambda = \frac{L}{h} = 0.83 * Fr^{1.21} * (1 + sin\alpha)^{4.296} * \left(\frac{A_a}{A_w}\right)^{0.129} * \left(\frac{s+t}{h}\right)^{0.201} * (1 + tan\varphi)^{5.393}$

For $0.72<\lambda<35$ .....(Eq. 4)

- $\beta = 0.01011 * Fr^{1.52} * \left(\frac{A_a}{A_w}\right)^{0.4244} * (1 + tan\varphi)^{7.22} * (1 + sin\alpha)^{1.8789} * \left(\frac{s+t}{h}\right)^{-0.4796}$

For $0<\beta<0.34$ ….. (Eq. 5)

Equations 4 and 5 may be applied to aerators consisting of ramp, offsets or combinations and valid for:

2.23 <Fr< 9.81
0.13 < (s + t) / h < 1.77
$10^0<\alpha<20^0$
$0^0<\varphi<3^0$
$0.001<\frac{A_a}{A_w}< 0.32$

d) **Estimation of non-dimensional jet length (λ) for aerator on orifice spillway for constant slope profile**

- $\lambda = 0.4781 * Fr^{1.3464} * (1 + sin\alpha)^{4.7762} * \left(\frac{A_a}{A_w}\right)^{-0.04553} * \left(\frac{s+t}{h}\right)^{0.3265} * (1 + tan\varphi)^{5.3569}$

For $0.72 <\lambda< 48$….. (Eq. 6)

- $\beta = 0.00604 * Fr^{1.5151} * \left(\frac{A_a}{A_w}\right)^{0.4686} * (1 + tan\varphi)^{6.4491} * (1 + sin\alpha)^{4.8592} * \left(\frac{s+t}{h}\right)^{-0.3029}$

For $0 <\beta< 0.56$ …….(Eq. 7)

Equations 6 and 7 may be applied to aerators consisting of ramps, offsets, or combinations and are valid for:

2.23 <Fr< 9.81
0.13 < (s + t) / h < 1.77
$10^0<\alpha<20^0$
$0^0<\varphi<3^0$
$0.03 <\frac{A_a}{A_w}< 0.32$

Where,

λ = non dimensional jet length = L/h
β= air entrainment coefficient = Q_a/Q_w
Fr = Froude number
α = spillway angle in degrees
φ = ramp angle in degrees
s = offset height in m
tr = ramp height in m
h = incoming depth of flow in m
A_a = area of air vent in m^2
A_w = area of water flow in m^2

4.8 Conclusion

This chapter showcases the innovative approaches and basic research studies conducted by CWPRS, addressing complex hydraulic challenges in spillway and energy dissipator designs. By leveraging physical and numerical models, the studies led to practical, cost-effective solutions for high-head dams, orifice spillways, and sediment management systems. The development of novel design guidelines and case-specific engineering interventions exemplifies the role of CWPRS in advancing sustainable and efficient hydraulic infrastructure.

CHAPTER 5

Lessons Learned and Future Directions

5.1 Hydropower Development Challenges and Innovations

Hydropower development is inherently site-specific, with each project presenting unique engineering challenges due to vast variations in hydrology, geology, geomorphology, seismology, and topography. Standardized designs are impractical, necessitating site-specific studies to evolve economical, efficient, and environmentally friendly designs for water resource projects.

5.2 CWPRS Contributions

CWPRS has consistently been at the forefront of refining hydraulic designs for numerous mega-projects. Through physical and numerical modelling, the institution has provided innovative solutions and modifications that ensure hydraulically sound and economically viable designs. The integration of both modeling techniques has significantly enhanced spillway and energy dissipator performance across various national and international projects. The list of the projects studied at CWPRS is enclosed as Annexure 1.

5.3 Site-Specific Solutions

For challenging environments, such as the Himalayan region, CWPRS has provided solutions to address issues like glacial lake outburst floods (GLOFs), sedimentation, and complex topographical conditions. Innovative designs such as orifice and multitier spillways have been instrumental in mitigating these challenges while optimizing sediment flushing and flood management.

5.4 Innovative Approaches

CWPRS has pioneered hybrid modelling approaches, blending physical models with computational fluid dynamics (CFD) simulations. This has enabled precise assessments of hydraulic behaviour, particularly for complex flow scenarios, enhancing both safety and cost-efficiency. The use of such techniques has set new benchmarks in dam hydraulics and spillway design.

5.5 Case Studies and Research Outcomes

CWPRS's studies for major projects like the Subansiri Lower Hydroelectric Project, Indira Sagar Dam, and Sardar Sarovar Dam have demonstrated the institution's expertise in optimizing designs. Key accomplishments include fine-tuning spillway dimensions, energy dissipation systems, and aeration configurations. Observations from prototypes have validated model findings, reinforcing the credibility of CWPRS's methodologies.

5.6 Future Directions

Lessons learned from recent projects emphasize the need for tailored hydraulic designs to address site-specific conditions. The growing importance of hybrid modelling and advanced hydraulic techniques highlights the path forward in addressing water security, climate resilience, and sustainable development. The institution's ongoing work, such as the Kalpasar Project, underscores its commitment to tackling emerging challenges in coastal and inland water resource management.

5.7 Conclusion

This chapter encapsulates CWPRS's remarkable contributions to hydraulic engineering, highlighting its pivotal role in optimizing spillway and energy dissipator designs for diverse, complex projects. Through innovative physical and numerical modelling, CWPRS has provided techno-economically viable solutions, fostering cost savings, operational efficiency, and project sustainability. The integration of applied and basic research, including the development of standardized guidelines, has positioned CWPRS as a leader in hydraulic infrastructure development, addressing both national and international challenges. Looking ahead, the adoption of hybrid modelling approaches signifies CWPRS's readiness to tackle future engineering complexities with greater precision and efficiency.

Annexure 1

List of studies conducted on spillways at CWPRS

Sr. No.	Name of Project	State	Years in which studied	Type of Spillway
1	Malaprabha	Karnataka	1939, 40	Weir
2	Aurthur Hill, Bhandardara	Maharashtra	1939, 40, 48	Weir
3	Jamshedpur Dam	Bihar	1939, 40, 43	Siphon
4	Markonhalli Dam	Karnataka	1945	Siphon
5	Tansa Dam	Maharashtra	1945, 47	High Ogee
6	Ranghola Dam	Gujarat	1946,	High Ogee
7	Vaitarna Dam	Maharashtra	1948, 49, 53, 54	High Ogee
8	Dimna Dam	Bihar	1948, 49	Weir
9	Kolisagar Dam	Andhra Pradesh	1948	Siphon
10	Radhanagar Dam	Maharashtra	1949, 62	High Ogee
11	Kosi Dam	Nepal	1949	High Ogee
12	Wanakbori Dam	Gujarat	1950, 55	High Ogee
13	Dharma Dam	Karnataka	1950	High Ogee
14	Hirebhasagar Dam	Karnataka	1950, 51, 52, 53	Siphon
15	Hirakud Dam	Orissa	1951, 52, 53, 54, 56	High Ogee
16	Ghataprabha Dam	Karnataka	1951, 52, 53, 56	High Ogee
17	Kakrapar Dam	Gujarat	1951, 52, 53, 54	Weir
18	Khodshi Weir	Maharashtra	1951	High Ogee
19	Kota Dam	Rajasthan	1951, 54, 55, 60, 63, 64, 65	Barrage
20	Gandhisagar Dam	M.P.	1952 to 54, 63, 64	High Ogee
21	Jawai Dam	Rajasthan	1954	High Ogee
22	Gambheri Dam	Rajasthan	1954, 55	High Ogee
23	Umtru Dam	Assam	1954, 73	Barrage
24	Hanumansagar Dam	Bihar	1954, 56, 59	High Ogee
25	Shetrunji Dam	Gujarat	1956, 57, 58, 59	High Ogee
26	Koyna Dam	Maharashtra	1955 to 58 and 63 to 65	High Ogee

Sr. No.	Name of Project	State	Years in which studied	Type of Spillway
27	Malaprabha	Karnataka	1956	High Ogee
28	Bhadar Dam	Gujarat	1956, 60, 61	High Ogee
29	Bhudial Tank	Maharashtra	1955, 65	High Ogee
30	Kadana Dam	Gujarat	19578, 59, 62, 68 to 75, 77	High Ogee
31	Yeldari Dam	Maharashtra	1957 to 60, 67	High Ogee
32	Mandira Dam	Orissa	1957 to 59, 64, 66	High Ogee
33	Brahmani Dam	Bihar	1957	Weir
34	Mundali Dam		1958, 59	Weir
35	Girna Dam	Maharashtra	1959	High Ogee
36	Banas Dam	Gujarat	1959, 60	High Ogee
37	Badua Dam	Bihar	1960 to 62	Chute Spillway
38	Meshwa Dam	Gujarat	1960, 63	High Ogee
39	Umium Barapani	Meghalaya	1961, 62	High Ogee
40	Salandi Dam	Orissa	1961 to 68	High Ogee
41	Kunu Dam	M.P.	1961	Siphon
42	Kohira Dam	Bihar	1962	High Ogee
43	Tawa Dam	M.P.	1962	High Ogee
44	Hasdeo	M.P.	1962 to 64	High Ogee
45	Ranapratapsagar	Rajasthan	1962 to 64, 67	High Ogee
46	Trisuli	Nepal	1962	High Ogee
47	Suthana Dam	M.P.	1962	Weir
48	Barna Dam	M.P.	1962, 69, 70, 71, 73	High Ogee
49	Hathmati Dam	Gujarat	1963	High Ogee
50	Pandoh Dam	H.P.	1963 to 67, 1970 to 73	Chute Spillway
51	Kalisindh	Rajasthan	1963	Weir
52	Jawaharsagar	Rajasthan	1963, 69	High Ogee
53	Ukai Dam	Gujarat	1963 to 67, 69, 71, 75	High Ogee
54	Machhu II	Gujarat	1964, 66, 72	High Ogee
55	Beas Dam at Pong	H.P.	1964 to 66, 68, 70	Chute spillway
56	Tenughat Dam	Bihar	1965 to 69	High Ogee

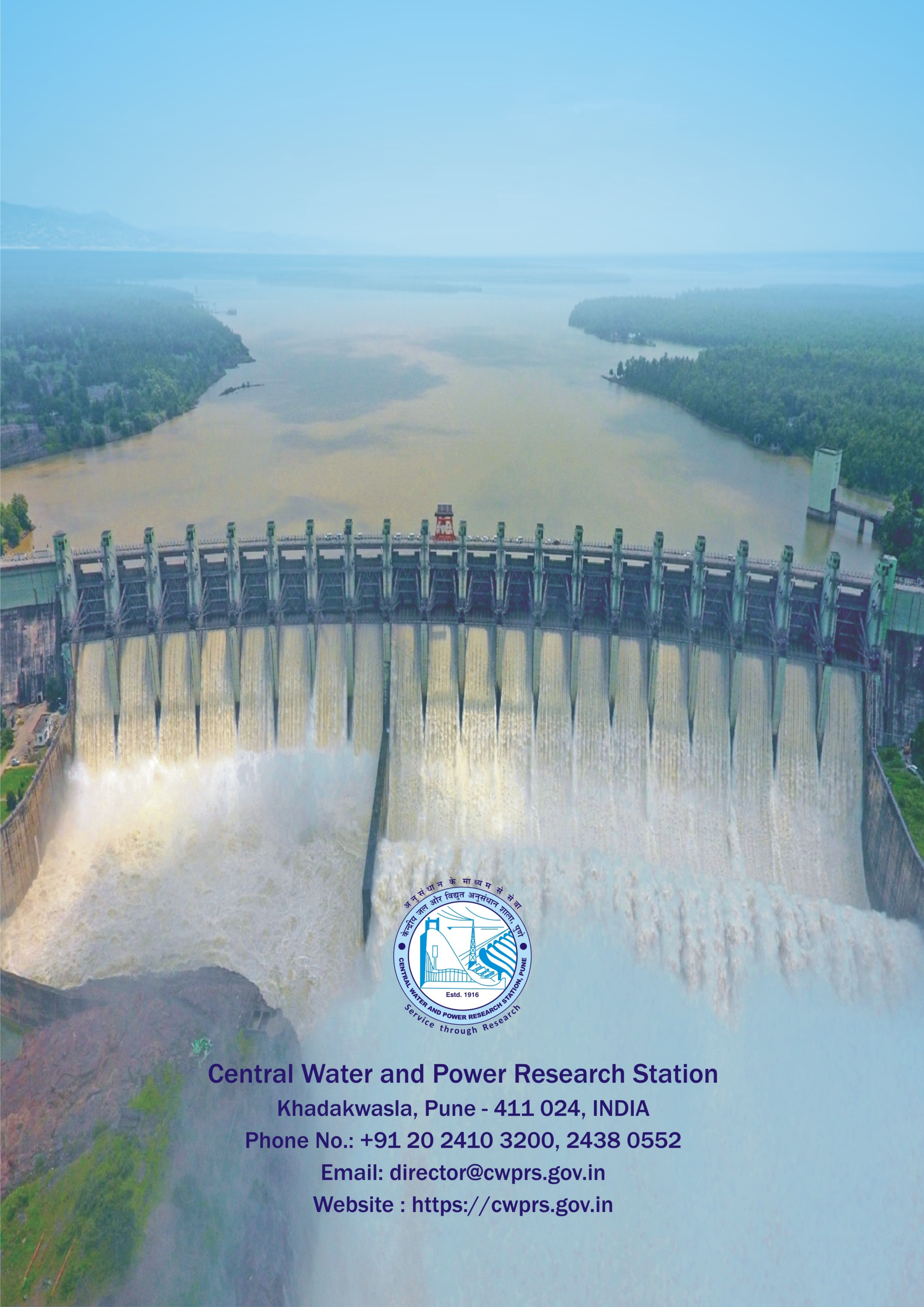
Sr. No.	Name of Project	State	Years in which studied	Type of Spillway
57	Dahisar Dam	Maharashtra	1965, 66	High Ogee
58	Srisailam Dam	A.P.	1966 to 77, 97, 98	High Ogee
59	Tapar Dam	Gujarat	1966, 67, 69	Chute Spillway
60	Jayakwadi Dam	Maharashtra	1967, 68, 73	High Ogee
61	Matrikunda Dam	Rajasthan	1971	High Ogee
62	Salal Dam	Jammu & Kashmir	1971, 72, 74 to 81, 88, 90, 91	High Ogee
63	Jakham Dam	Rajasthan	1971, 72, 75, 77	High Ogee
64	Baira Siul Dam	H.P.	1972 to 77	Chute Spillway
65	Mahi Bajaj Sagar	Rajasthan	1972, 74, 75, 76, 88	High Ogee
66	Bhakra Dam	Punjab	1972, 73	High Ogee
67	Balimela Dam	Orissa	1973	High Ogee
68	Supa Dam	Karnataka	1976, 77, 98, 99	High Ogee
69	Rengali Dam	Orissa	1976, 77	High Ogee
70	Singda Dam	Manipur	1977	Side channel Chute
71	Yeshwantsagar Dam	M.P.	1977	Siphon
72	Som Kagdar Dam	Rajasthan	1978	High Ogee
73	Som Kamala Amba	Rajasthan	1978	High Ogee
74	North Koel Dam	Bihar	1974	High Ogee
75.	Sedawgyi Dam	Myanmar	1978	High Ogee
76	Chukha Dam	Bhutan	1978, 2010	High Ogee
77	Upper Kolab Dam	Orissa	1978	Chute spillway
78	Sardar Sarovar Dam	Gujarat	1978 to 80 1986 to 2011	High Ogee
79	Khandong Dam	Assam	1978	
80	Salauli Dam	Goa	1976	High Ogee
81	Bango Dam	M.P.	1980	High Ogee
82	Bansagar Dam	M.P.	1980	High Ogee
Sr. No.	**Name of Project**	**State**	**Years in which studied**	**Type of Spillway**

83	Rajghat Dam	M.P.	1980, 89, 92	High Ogee
84	Langpi Dam (Advice without model)	Assam	1982	High Ogee
85	Ranjitsagar Dam	Punjab	1982, 86, 88 to 90	Chute Spillway
86	Narmadasagar Dam	M.P.	1982	High Ogee
87	Chamera Dam (Stage I)	H.P.	1984, 86	High Ogee
88	Thoubal Dam	Manipur	1986, 88, 91	Chute Spillway
89	Salauli	Goa	1986	Duck bill Spillway
90	Chandil Dam (Subernarekha)	Bihar	1986 to 90	High Ogee
91	Karbui Langpi	Assam	1988	High Ogee
92	Bekhme		1986-92	ogee
93	Doyang Dam	Nagaland	1990, 92	Chute Spillway with ogee crest
94	Chhapi Dam	Rajasthan	1990	Ogee
95	Bakruman*	Iraq	1990	Sluice Spillway
96	Kalilkan*	Iraq	1990	Low Ogee
97	Icha Dam	Bihar	1991, 93	Ogee
98	Ranganadi Dam	Arunachal Pradesh	1991-95	Orifice
99	Tipaimukh Dam	Manipur/ Mizoram	1991, 95, 96	Tunnel-cum-chute spillway
100	Nathpa Jhakri Dam	H.P.	1993, 97, 98, 99	Sluice spillway
101	Maheshwar	M.P.	1993	Low Ogee
102	Gotta Barrage (Desk studies)	A.P.	1995	Barrage
103	Gandorinala (Desk studies)	Karnataka	1997	Chute Spillway
104	Lower Mullamari (Desk studies)	Karnataka	1998-99	Chute Spillway
105	Kurichu Dam	Bhutan	1998-99	Spillway with breast wall
106	Tala Dam	Bhutan	1999-2006 2006-09	Sluice Spillway
107	Dhauliganga Dam	Uttarakhand	1999-2000 2002-07	Chute Spillway with breast wall Tunnel spillway
108	Tehri Dam (Desk Studies)	Uttarakhand	1999	Chute Spillway and two shaft spillway

Sr. No.	**Name of Project**	**State**	**Years in which studied**	**Type of Spillway**
109	Chamera Stage II	H.P.	2000-02	Flat low head spillway with trajectory profile
110	Parbati Stage – II Dam	H.P.	2001-03 2007	Orifice
111	Teesta Stage V	Sikkim	2001-02	Ogee with gated sluice
112	Teesta Stage III (TLDP)	West Bengal	2003-07	Breast wall
113	Subansiri Lower Dam	Ar.P.	2004-15	Orifice
114	Omkareshwar Dam	Madhya Pradesh	2004-07	Ogee
115	Parbati Stage – III Dam	H.P.	2004-08	Orifice Tunnel
116	Chamera – III	H.P.	2004-07	Orifice / Chute
117	Uri – II Dam`	Jammu & Kashmir	2004-06	Orifice with Breast Wall
118	Sewa – II Dam`	Jammu & Kashmir	2004-09	Orifice with Breast Wall
119	Myntdu (Leshka) Dam	Meghalaya	2004-07	Sluice
120	Teesta Stage IV (TLDP)	West Bengal	2004-07	Sluice with breastwall
121	Salma Dam	Afghanistan	2006-09	Chute spillway
122	Kotlibhel 1-A Dam	Uttarakhand	2006-10	Orifice
123	Kotlibhel 1-B Dam	Uttarakhand	2006-10	Orifice with breast wall
124	Kotlibhel II Dam	Uttarakhand	2007-10	Orifice
125	Rangpo	Sikkim	2006-2009	Ogee
126	Nimo Bazgo	Leh Ladak	2004-2008	Orifice with breast wall
127	Dhanikari Dam	Andaman & Nicobar	2008-10	Breastwall
128	Chhukha Dam	Bhutan	2009-10	Overflow
129	Umtru Dam	Meghalaya	2009-11	Ogee spillway

Sr. No.	Name of Project	State	Years in which studied	Type of Spillway
130	Pare Dam	Arunachal Pradesh	2009-11	Breastwall
131	Punatsangchhu-I Dam	Bhutan	2009-11	Orifice
132	Lower Siang Dam	Arunachal Pradesh	2009-11	Sluice + Ogee
133	Kishanganga Dam	Jammu & Kashmir	2010-11	Chute spillway with breastwall
134	Garudeshwar Weir	Gujarat	2010-12	Ungated ogee shaped
135	Mangdechhu Dam	Bhutan	2011	Orifice
136	Teesta – IV Dam	Sikkim	2012	Orifice
137	Punatsangchhu-II Dam	Bhutan	2012	Orifice
138	Telengiri Dam	Odisha	2012	Ogee
139	Devsari	Uttrakhand	2013	Sluice
140	Indira Sagar	Madhya Pradesh	2014	Overflow
141	Jigaon Dam	Maharashtra	2015	Overflow
142	Salma	Afghanisthan	2015	Overflow
142	Tangon	Arunachal Pradesh	2014-16	Orifice with Breast Wall
143	Additional Spillway of Hirakud Dam	Odisha	2017	Overflow
144	Punatsangchhu-I H.E. Project	Bhutan	2017	Sluice
145	Polavaram Irrigation Project	Andhra Pradesh	2017-24	Overflow
146	Punatsangchhu-II	Bhutan	2018	Orifice with Breast Wall
147	Kwar HE Project	J&K	2018	Orifice and Overflow
148	Lakhwar H.E. Project	Uttarakhand	2018	Sluice
149	Mangdechhu H. E Project,	Bhutan	2018	Orifice with Breast Wall
150	Arun-3 H.E. Project	Nepal	2018	Sluice

Sr. No.	**Name of Project**	**State**	**Years in which studied**	**Type of Spillway**
151	Kiru H.E. Project	J &K	2018-2024	Orifice and Overflow
152	Devsarti H.E. Project (Modified design)	Uttarakhand	2019	Sluice
153	Subansiri	Arunachal Pradesh/ Assam	2020	Orifice with Breast Wall
154	Pakal Dul H E Project	J&K	2020	Overflow Surface spillway+Tunnel spillway
155	Dugar HE Project	Himachal Pradesh	2022	Orifice and Overflow
156	Ratle	J&K	2023-24	Orifice with Breast Wall



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