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Recent challenges in design of spillway – An Indian scenario

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Abstract: *There are about 5264 completed large dams in India. These dams are invariably equipped with some or other kind of spillway. As this dam building activity has been going on for many years, all easy sites have already been tapped and are left with sites where designers have to face challenges from nature. Recently, while harnessing the hydropower potential of Himalayan rivers, designers are facing issues like high sedimentation concentration flows, narrow valleys with a high magnitude of the flood, leading to the provision of an additional spillway or multi-tier spillways. Melting of glaciers resulting in increased rates of Glacial Lake Outburst Flow (GLOF) is challenging tasks to design a spillway for debris flow. On the other hand, for existing dams in India, there is a large upward revision in the design flood due to improvements in flood assessment techniques and the availability of huge data for flood assessment. This demands an increase in discharging capacity of the spillways by increasing crest length or providing breaching sections. India has got a large seashore and to utilize the freshwater from the rivers joining the sea, multipurpose dams across the sea in the vicinity of the Gulf can be considered. Special design considerations are to be employed for spillway and energy dissipation arrangements as their operational performance is influenced by cyclic tidal variations and storm surges. This paper makes an attempt to discuss the relevant hydraulic aspects for the design of spillways and energy dissipators for efficient and safe operation.*

Keywords: *Orifice Spillway, Sediments, Flood, GLOF, Coastal reservoir, Hydraulic model*

1. Introduction

Since its independence, India has invested a huge amount in creating big infrastructures to store the surface runoff in the reservoirs for irrigation, drinking water supply and hydropower in the form of large, medium and small dams. The dam building activities over the years have been concentrated on the ideal and easy sites. This leaves the geologically and topographically complex and difficult sites for future activities. These sites have been identified mainly in the Himalayan and North Eastern regions. High mountains, deep narrow valleys, complex geological strata with occasional problems of stability of hill slopes, and generally high levels of seismicity characterize the Himalayan terrain. Majority of these rivers have a very steep bed gradient in the range of 1 in 30 to 1 in 100. These give rise to flash floods and sediment load. This sediment would ultimately settle in the reservoir resulting in the reduction of live storage capacity. To utilize the high heads and discharge available in this region for power generation this sediment should be flushed regularly. The overflow spillways using conventional methods i.e. high head storage dams for river valley projects in Himalayan regions are not suitable. The spillways considered in such topography required to perform dual roles i.e. passing the flood as well as flushing the sediments. Many spillways are also designed considering the flash floods caused by Glacial Lake Outburst Flood (GLOF). Due to the potential impacts of climate change on glacier dynamics, catastrophic GLOF may increase future flood risks for infrastructure and population. This is particularly relevant given the current development of hydropower projects in the Himalaya. These flash floods also contribute to the major part of the sediment in glacierized catchments. In such a complex hydrological scenario, assessing the hydraulic performance of spillways with a sediment flushing facility would be of vital importance.

In terms of large dams, India is now ranked third in the world after the United States of America and China (ICOLD, 2011). There are currently about 5260 completed large dams in India and 437 under construction (CWC, 2018). Many of these dams are decades old and for these dams, spillways were designed for original design floods based on empirical formulae with applied discretions by experienced designers. Checking and upgrading the dam design flood estimates incorporating the available extended data sets and latest flood estimation methods has been given technical priority in the national dam safety programme (Pandya et.al., 2014). Based on outcomes of the substantial sets of design reviews under Dam Rehabilitation and Improvement Programme (DRIP), it is found that in more than 50% of cases the original flood needs an upward revision of 50% to 100%. As per data collected by Indian Commission on Large Dams (ICOLD) on the failure of large dams, nearly 35% of dams have failed globally due to causes related to inadequate spillway capacity and hence this becomes a major concern in a Dam safety programme (CWC, 2018). This necessitates the need of redesigning the spillways and energy dissipators to cater to this revised flood as a structural measure.

India has got about 7515 km of coastline and the majority of surface runoff is directly delivered into the sea. This highlights the fact that there is enough water available but the deficiency is in storage. Hence, the solution lies in utilizing (or) conserving the abundant monsoon water which runs off into the sea (Yang, 2015). The coastal reservoir is a paradigm shift in water resources development from storing water in inland dams to storing freshwater by the coast. This converts flood water into valuable water resources. A coastal reservoir is a reservoir in the sea to store a portion of the river flood waters that joins the ocean during the monsoon period and use it during the drought periods. It is a unique hydraulic structure constructed at an estuary, gulf, or bay or in the sea (at the point where a river meets a sea) to store the portion of excess water at flood times. This seawall or dike structure may run for several kilometres joining the curved coastline in the form of chord length. The requirement for the design of spillways and energy dissipators for coastal reservoirs are unique. Tidal levels and storm surge downstream (seaside) plays important role in the design and operation of the spillway.

This paper makes an attempt to discuss the relevant hydraulic aspects under such challenging scenarios for design of spillway and energy dissipators for efficient and safe operation.

2. Challenges in design of spillways in Himalayan region

The major causes that are responsible for sediment-laden floods and flash-floods in Himalayan Rivers are:

1. Cloudburst in the catchment of the river
2. Heavy rainfall in the upper reaches of the river
3. Sudden breach or bursts of glacial lakes
4. Landslides and GLOF
5. Earthquake prone zone leading to slope failure and landslides

These rivers carry heavy sediment load during monsoon and snowmelt in summer, which has to be efficiently managed to ensure the long term sustainability of hydropower projects. Conventional designs viz. high ogee spillways in storage dams are not suitable to deal with floods carrying heavy sediment. Considering the experience of silting of dams and damages to power plants, the trend has been changed to designing run-of-the-river schemes which utilize the stream flow as it comes without any large storage. Innovative designs of spillways have evolved based on the concept of flushing. Recent trends in designing the spillways are by modifying the low level sluices with due consideration for flushing (Deolalikar et.al., 2008). Orifice spillways (Breastwall / sluice spillways) are thus evolved over the last few years to cater to both flood disposal and flushing of sediments. The important parameters required to be determined while designing orifice spillways are; Bottom profile of spillway crest conforming to the flow through orifice, the roof profile of the orifice, size and dimensions of the orifice, protection of spillway to resist abrasion and choice of energy dissipator. The performance of the orifice spillway is affected by the head over the opening, size of the sluice barrel, and entrance shape of the sluice bellmouth. The hydraulics of the orifice spillway change with the varying reservoir levels. The flow is free flow for reservoir water levels below the top of the roof of the sluice. For higher water levels the flow is orifice flow. The crest profile is required to be designed for orifice (pressurized) flow. Figure 1 shows the definition sketch of the orifice spillway. It has been experienced from the physical model studies that the flow through sluice barrel do not get fully developed and that flow separation takes place on the sluice roof profile resulting in negative pressure for high head spillways. Such high head sluice spillways should be checked against the presence of sub-atmospheric pressures on the bell-mouth roof to avoid cavitation damage. The roof profile has not been standardized with respect to the upstream head because of many hydraulic and structural parameters such as thickness of the breast wall and piers, the bottom profile of spillway, width of the opening and sediment flushing requirements etc. There is a need for evolving hydraulically efficient crest and roof profiles for high head orifice spillways. To address these short comings, systematic studies were carried out at Central Water and Power Research Station using physical and numerical modelling for evolving the design of orifice spillway (Bhosekar and Gadge, 2018).

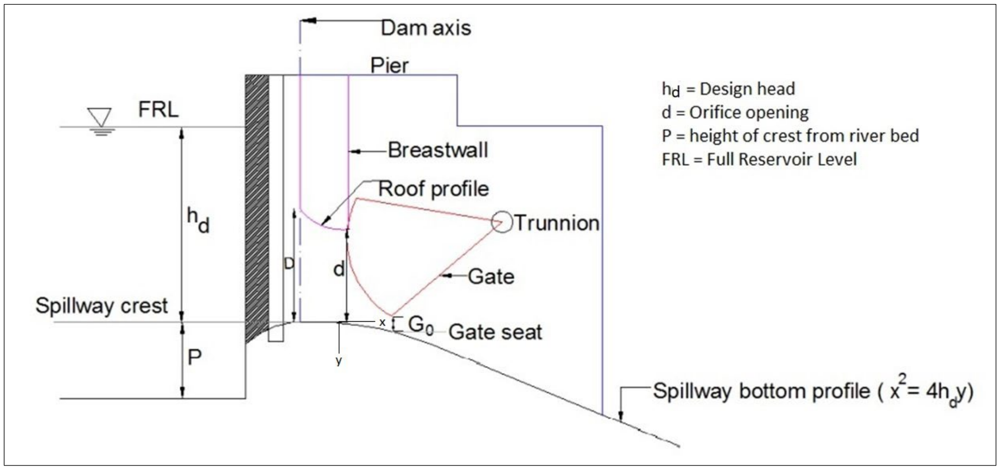

Figure 1. Definition Sketch of Orifice Spillway

Orifice spillways necessitate some special design considerations. The larger velocities associated with the high heads may increase the potential for cavitation and erosion damage to the structure. Adequate protection measures should be taken during the construction of the sluice barrel and breast wall spillway, to withstand the erosive power of the silt-laden water while flushing the reservoir and flood routing, by way of a special type of concreting (epoxy-bonded epoxy mortar, polymer concrete, or epoxy-bonded replacement concrete) or providing steel lining along the discharge channel of the spillway.

Orifice spillways have effectively been used on many run of the river hydro power projects in Himalaya since last two decades. Pandoh, Dulhasti, Nathpa Jhakari, Chamera-III, Sewa, Parbati-II, Uri-II, Teesta cascade projects etc are some of the projects where the orifice spillways have effectively been used for passing flood and flushing sediments. The experience from these projects has lead to improvement in refinement of design of orifice spillway and energy dissipator.

Based on site-specific constraints of geological and topographical considerations, innovative spillways are evolved. For example, rockfill or concrete faced rockfill dams are designed due to weak geology for the diversion dam. In such cases, the spillway is provided along the banks of the reservoir. Long chutes instead of the short spillway are provided for discharging the flow in the river downstream as in the case of the Kishanganga and Dhauliganga H. E. projects. Tunnel spillways are often provided when the river gorge is narrow and the discharge to be passed is not large enough for designing a two tier spillway. A tunnel spillway can also be provided for diverting silt-laden flows, e.g. Parbati-III project. Many a time diversion tunnels used during the construction stage of the dam are converted into spillway tunnels, e.g. Dhauliganga project, the Tehri project.

2.1. Two Tier Spillway

In the upper reaches of mighty rivers like the Brahmaputra, the river gorges are narrow and the discharges to be passed through spillway are high. Therefore, designing an orifice spillway with large opening becomes difficult due to construction and operational aspects. Multi-tier spillways have evolved to overcome this difficulty. Two/ three orifice spillways and an overflow spillway on the top can form a multi-tier spillway. The bottom orifice spillway is designed to take care of normal floods as well flushing of sediment and the upper spillways will cater to excess flood to be passed through reservoir. The energy dissipator for these spillways may be common or independent.

One such spillway has been designed for PMF of 60,315 m^3/s and studied at Central Water and Power Research Station, Pune for the Lower Siang Dam spillway in Arunachal Pradesh. A common energy dissipator in the form of stilling basin has been provided for both the orifice and overflow spillway. The design has evolved into a sectional model to solve the complex flow problems at the junction of the spillways. Figure 2 shows a view of the sectional model in operation.

Figure 2. View of the sectional model of two tier spillway

Sometimes, based on techno-economic feasibility considerations, power intake and powerhouse structure and tailrace channel have to be provided in the body of the dam, if the fragile geology of the Himalaya does not permit an independent layout for power intake, water conductor system, and huge underground powerhouse cavern. This type of two-tier spillway and dam foot powerhouse has been considered for the Siang Lower run-of-the-river H. E. Project in Arunachal Pradesh. The project envisages the construction of an 86 m high concrete gravity dam across river Siang to generate power of 2700 MW utilizing a net head of 55 m. The spillway arrangement and construction schedule envisaged are unique. A two-tier spillway comprising of overflow ogee spillway on the top tier and a sluice spillway below is proposed. Sluice spillway performs a dual function of disposing of the flood as well as flushing of sediment out of a reservoir of diversion dam of a run- of-the river scheme. The design of these structures cannot be standardized and depend on site-specific conditions. Extensive physical model studies were conducted on the 1:55 scale 2-D sectional model and 1:100 scale 3-D comprehensive model for finalizing/ optimizing the design. These studies played an important role in enhancing the overall performance of the spillway and energy dissipator by incorporating various modifications to the orifice roof & bottom profile, overflow spillway profile, length, and elevation of the stilling basin, finalizing the height of the cofferdam required during construction phases, etc.

2.2. Special design considerations for energy dissipator

The factors that govern the choice of the type of energy dissipator are hydraulic considerations, topography, geology, type of dam, layout and other associated structures, economic comparisons, frequency of usage etc. In Himalayan regions the topography is normally steep, fragile geology, high intensity of rain, high level of seismicity, etc. cause a high load of sediments. Since the spillway has to surplus both the flood and sediment, special considerations are required for the design of suitable energy dissipators. A ski-jump bucket is found to be the most suitable form of energy dissipator because of its obvious advantage during the flushing operation. The sediment passes down the spillway with the supercritical flow without deposition and churning in the bucket. Fortunately, steep bed slopes of the rivers result in low tail-water depth permitting two choices of energy dissipator. The water and scour profiles for the entire range of discharges and reservoir water levels observed on the model provide a comprehensive picture of ski jump jet and scour profiles. These studies play important role in deciding the location and size of a plunge pool. In many projects like Nathpa Jhakri, Tala, Chamera- I, Dhauliganga, and Ranganadi, a ski-jump bucket has been provided as an energy dissipator. If, however, geological conditions are not favorable, a hydraulic jump stilling basin may have to be adopted. The high unit discharge passing down low head results in a low Froude number conditions.

The stilling basins for the Froude number in the range of 2.5 – 4.5 are rather difficult to design to ensure satisfactory performance for the entire range of discharge. Because of the requirement of passing silt-laden flows, the use of energy dissipating appurtenances like chute and baffle blocks is not advisable. The resulting basin is excessively long and often deep-seated below the general river bed, making it vulnerable to deposition by silt during the flushing operation. Experience with stilling basin of the 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 the flushing operation. Cylindrical end-sills are generally preferred for easy movement of sediment out of the basin. The provision of a roller bucket is generally avoided as an energy dissipator due to the likelihood of abrasion damage to the bucket due to the churning of sediment.

3. Impact of Himalayan Glaciers and GLOF on spillway design flood

The Himalayas have the largest concentration of glaciers outside the polar region. These glaciers are a freshwater reserve for nine major river systems in Asia – a lifeline for almost one-third of humanity. The climatic change/variability in recent decades has made considerable impacts on the glacier life cycle in the Himalayan region. As a result, many big glaciers melted, forming a large number of glacial lakes e.g. Parechu Lake (Tibet), Dig Tsho Lake (Nepal) and Charobari Lake (Uttarakhand). Due to an increase in the rate at which ice and snow melted, the accumulation of water in these lakes started increasing. Sudden discharge of large volumes of water with debris from these lakes potentially causes glacial lake outburst floods (GLOFs) in valleys downstream. These in turn give rise to an increase in the potential threat of glacial lake outburst floods occurring. A number of hydroelectric projects in India, Bhutan and Nepal are being planned in the Himalayan regions. It has become necessary for the project planners and designers to account for the GLOF also along with the Probable Maximum Flood (PMF) due to rainfall for deciding the spillway capacity of projects. Table 1 shows the magnitude of GLOF considered for various hydropower projects in Himalaya in addition to Probable Maximum Flood (PMF) for which hydraulic model studies for spillways were carried out or being referred for studies at the CWPRS, Pune.

Table 1. Magnitude of GLOF and PMF for various projects in Himalayan region

Sl. No.	Name of the Project	PMF in m^3/s	GLOF in m^3/s	PMF + GLOF m^3/s	Percentage of GLOF wrt PMF
1	Punatsangchhu-I H.E. Project, Bhutan	11,500	4,300	15,800	37.4
2	Punatsangchhu-II H.E. Project, Bhutan	11,723	4,300	16,023	36.7
3	Etalin H.E. Project, Dri Limb, Ar. Pradesh	11,811	1,170	12,981	9.9
4	Etalin H.E. Project, Tangon Limb, Ar.Pradesh	10,218	2,143	12,361	20.97
5	Arun-III H.E. Project, Nepal	8,880	6,830	15,710	76.91
6	Chamakharchhu H.E. Project, Bhutan	9,406	5,112	14,518	54.35
7	Kwar H.E. Project, J & K	10534	620	11,154	5.88
8	Mangdechhu H.E. Project, Bhutan	6,900	3,715	10,615	53.84

Approximately 15,000 glaciers (covering an area of 33,340 sq.km.), and 9000 glacial lakes throughout Bhutan, Nepal and Pakistan, as well as selected river basins in China and India were documented in a baseline study conducted earlier by International Center for Integrated Mountain Development (ICIMOD), United Nations Development Programme (UNEP), and the Asia Pacific Network for Global Change Research (APN) (Bajaracharya et.al, 2006). There are about 2028 glacial lakes and water bodies which contributes the rivers flowing into India. GLOF events have adversely affected Nepal and Bhutan in the recent past and to date over 200 potentially dangerous glacial lakes have been documented across the Himalayan region (Bajracharya et.al., 2006). A GLOF event of 1985 originating from Dig Tsho, a glacial lake in the Khumbu Himal, Nepal, destroyed the Namche Small Hydel Project and caused extensive damage downstream. GLOFs have caused damage across national borders; outbursts originating in China have impacted areas in Nepal, India, and Bhutan (Ives et.al., 2010). June 2013 floods in Uttarakhand also have a big GLOF component. The Nathpa Jhakri Hydroelectric Project situated in Himachal Pradesh has dealt with success since its commissioning in 2000 the frequent flash floods of large magnitudes due to large sluice spillway openings create riverine flows and accurate warning system so that sufficient time is available for proper assessment of flood and depleting the Nathpa reservoir in anticipation of heavy inflows and timely operation of orifice spillway gates. The GLOF of the order of 4500 m^3/s was observed on 26th June 2005 due to a breach of an artificial lake formed on the Parechu river (in the Tibet region). Since necessary measures had already been taken, no major damages occurred to the project. During the floods, the river carried a lot of silt, boulders, gravel, & trash, etc. and the intake gates of the water conductor system of the powerhouse were closed to avert damages to the Power House in Jhakri. Urgent action by the international community to develop an even better scientific understanding of the consequences of global climate change on GLOF and to take corrective and precautionary measures is required. Monitoring and tracking of the lakes in West and North Sikkim have revealed that quite a few of them are expanding due to accelerated glacial retreat and melting due to climate change impacts. In addition, new lakes have also developed due to glacier retreat and melting. During the retreat, the glaciers leave behind moraines (accumulation of boulders, stones, or other debris) in the valley. Hydraulic modeling of the spillway is very important in the case of a Himalayan project to predict the discharging capacity of the spillway for PMF + GLOF condition and fix the important levels like the crest of the spillway, FRL, MDDL, invert of power intake, and top of the dam.

4. Upward revision of flood for existing dams

Previous design flood selection criteria considered factors such as dam height, storage volume, and downstream development and related design floods to downstream hazard classifications. The current practice is to classify dams based on the consequences of dam failure. This requires the identification of potential failure modes and a quantitative evaluation of the consequences of dam failure. The spillway design flood is based on these considerations. All existing dams whose failure would result in loss of life, significant economic or environmental damage or other unacceptable consequences for any condition will require corrective actions. Quantitative risk assessment includes the probability of adverse loading, the type of response, the probability of an adverse response and the consequences in terms of expected losses. It is seen that when such an analysis is applied to existing structures, in most of the cases, the spillway comes out to be of inadequate capacity. It is estimated that in India at least 50% of the existing spillways are inadequate in respect of the safety of the dams. Another consideration is that a dam constructed in the olden days was in remote areas whereas these days, the projects are very close to urban development and the potential damage due to the failure of such a dam is now many folds more severe than anticipated at the time of design or construction. The existing spillways are therefore required to be remodeled to handle larger floods. Increased spillway capacity to handle larger floods can be achieved by increasing spillway crest length, the addition of spillway bays, an increase in the operating head, or improving the discharge co-efficient. However, these measures are often governed by the topography and geology at the dam site. A modest increase in the discharge coefficient can generally be realized by refinement of the spillway crest shape and by channel improvement but at a greater cost. A more common modification to the existing dam to accommodate larger floods is an enlargement of the existing spillway or the construction of a new spillway. All these conventional methods have many limitations and call for design innovations.

Verifying and revising the dam design flood estimates- incorporating additional available data and modern methods of flood estimation-is the key technical priority in the national dam safety programme; and, this activity is also the prime requirement under the ongoing Dam Rehabilitation and Improvement Programme (DRIP). A review of design flood estimates has been completed for 217 dams. The review indicates that there is an upward revision of 50% for 58% of dams and an upward revision of 100% for 36% of dams. For a few dams, the revised flood values have exceeded their adopted design value by substantial orders. To name a few, the Kharadi dam of Madhya Pradesh exceeded by 929%, Sher tank (M.P.) exceeded by 503%, Manimukhanadhi dam in Tamilnadu exceeded 384% (Pillai et.al., 2013). Once the reviewed design flood is found to be significantly higher than the original flood, the adequacy of spillway capacity needs to be thoroughly reviewed. If this structural method is found to be inadequate, non-structural methods are required to be adopted. The solution adopted may vary from case to case. The following are the few alternatives that can be adopted to mitigate the increased design flood:

- Augmenting the existing spillway capacity by providing PK weirs, Labyrinth spillways
- Provision of breaching section or fuse plugs
- Increasing the freeboard above FRL by provision of Parapet wall etc.
- Implementation of early warning system
- Lowering the water levels in the reservoir before monsoon such that flood moderation can be enhanced

For an increase in the existing spillway capacity, structural options like the provision of an additional spillway, where the site is available, or an increase in spillway crest length by the provision of a P K Weir, labyrinth spillway or duckbill spillway, breaching section in the form of fuse-gates, etc can be thought of. Use of breach sections in the form of fuse gates etc can also be provided in the saddle on the reservoir rim from where flood discharge can be safely passed. The rate at which the fuse plug washes out is of primary importance and depends upon the fuse-plug geometry, the depth of flow, and the gradation and compaction of embankment material.

In the case of the dams having gated spillways, the provision of devices like P K Weir, labyrinth spillways etc may not be suitable. Although special arrangements for providing necessary waterway for such devices could be made through abutments or saddles in the reservoir, these may prove to be costly. For the gravity dams, especially concrete dams, allowing overtopping for floods of rare occurrences may prove to be more economical and effective provided necessary safety measures are taken care of. In the case of narrow valleys, options like tunnel spillways can augment the existing spillway capacity.

Under the DRIP programme, the design flood for Hirakud dam spillway, Odisha has been revised to 69,632 m^3/s from original design discharge 42,450 m^3/s i.e.upward revision by 27,182 m^3/s. To pass this increased flood, two additional spillways, one on right side and another on left is proposed to be constructed in the phased manner. CWPRS has been entrusted with hydraulic model studies for optimizing the design of the additional spillway and energy dissipator on the left dyke during phase-I. Two models, 1:40 scale 2-D sectional model and 1:100 scale 3-D comprehensive model have been constructed to assess the discharging capacity of spillway, overall performance of energy dissipator and spill channel and flow conditions in the river for various scenarios during combined operation of existing spillway on main Dam. Hydraulic model studies are a very important tool to understand the complex hydraulics of flow over spillways and appurtenant structures and the safety of mega projects like Hirakud Dam.

5. Spillway design considerations for coastal reservoirs

Coastal reservoirs have the potential to become a major source of fresh water in coastal areas. By definition, a coastal reservoir is freshwater storage located in coastal waters (river mouth, lagoon, gulf or protected bay) being fed by a sustainable freshwater flow. Coastal reservoirs have an impermeable barrier isolating the freshwater storage from intrusion by the surrounding brackish seawater. Depending on its location, water captured in a coastal reservoir will be of varying quality for domestic, agricultural or industrial water use. India has got about 7515 km of coastline and about 78% of surface runoff is directly delivered into the sea. For the benefit of the people living along the coastline, coastal reservoirs can be a better solution. Now, the world is using only 1/6th of total surface runoff and the other 5/6th part are directly discharging into the sea (Yang, 2015). This highlights the fact that there is enough water available but the deficiency is in storage. Hence, the solution lies in utilizing (or) conserving the abundant monsoon water which runs off into the sea. In the next 100 years, population and water demands may continue to increase significantly and the majority of the existing inland reservoirs will be deficient to fulfill the demand of increased population due to their structural life span and sedimentation. Hence, in the future, there will be more demand for coastal reservoirs. Coastal Reservoirs are already being used in China, South Korea, Hong Kong, and Singapore (Table 2) and have been largely successful, especially in places where there are no more opportunities to build inland reservoirs.

Table 2. Existing coastal reservoirs in the World (Yang, 2015)

Name	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

5.1 Coastal reservoirs in India

Thanneermukkom bund: Thanneermukkom bund was constructed as part of the Kuttanad lowland development scheme and the creation of a freshwater reservoir in the coastal area of Kerala, India (Figure 3). It divides Vembanad Lake into a freshwater lake fed by the rivers draining into the lake and a brackish water lake fed by ocean currents into the lowlands of Kuttanad. The four major rivers of Kerala, the Pamba, Meenachil, Achankovil, and Manimala, flow into the region before their confluence with the Arabian Sea. The regions receive a good amount of annual rainfall, which is above 3,000 mm, and these four rivers bring a large quantity of water into the lake before joining the sea. By constructing the saltwater barrier, a coastal reservoir having freshwater has been created for increasing agricultural activities in the area in addition to land development. The Thanneermukkom Bund has a total span of 1,410 metres and has a total of 90 shutters including 31 shutters each on the western and eastern sides and 28 shutters have replaced the old earthen bund.

Figure 3. View of Thanneermukkom Barrage

Kalpasar Project: The proposed gigantic Kalpasar project, also known as the Gulf of Khambhat development project is mainly a water resources project involving the creation of a freshwater reservoir in the Gulf of Khambhat for meeting the demands of irrigation, domestic and industrial water supply (Figure 4). Associated components related to the freshwater reservoir are the use of the top of the dam across the Gulf as a surface transport link, potential development of fisheries, and reclamation of saline land around the freshwater reservoir. The Kalpasar Project envisages building a 30 km long dam across the Gulf of Khambhat for establishing a huge freshwater reservoir for irrigation, drinking, and industrial purposes. Once constructed it will be one of the largest freshwater reservoirs in the sea with the highest priority for irrigation and drinking water in the region of Saurashtra and the Central Gujarat regions of India. (https://kalpasar.gujarat.gov.in/)

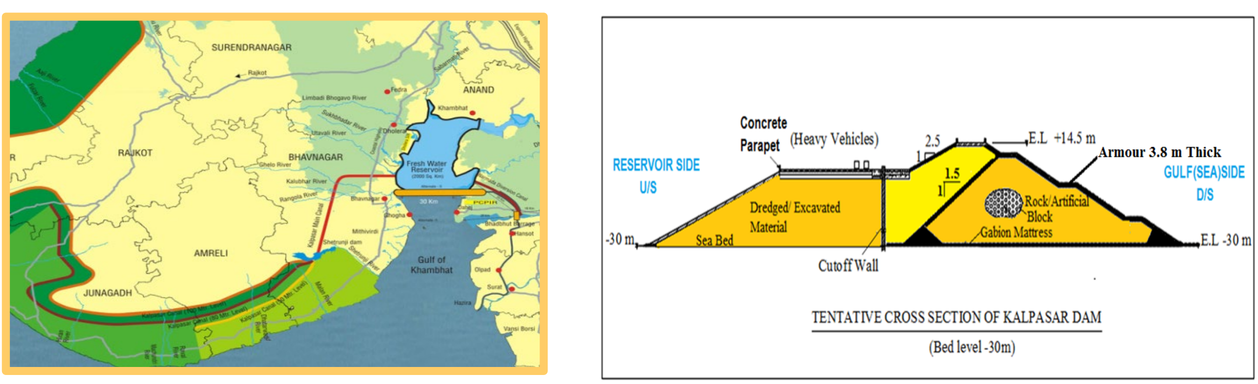

Figure 4. Tentative layout and cross section of Kalpasar dam ((https://kalpasar.gujarat.gov.in/)

5.2 Design considerations for coastal spillway and energy dissipation arrangement

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 arrangements 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 a 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 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 in to fresh water lake
- Energy dissipation arrangement to avoid entry of high velocity jets in the sea through spillway spans

From the schematic view shown in figure 5, it can be seen that it is possible to operate the spillway only during low tide when the sea water level is below or equal to the reservoir water level. This point is required to be kept in mind while designing the reservoir capacity considering design outflow limitation against the inflow flood. It is necessary to find out the discharging capacity of the spillway for free-flowing condition and partial downstream submergence conditions. Hydraulic model studies play an important role to optimize the spillway design and location and determine a various aspects of the operation of the coastal spillway as no readily available guidelines exist.

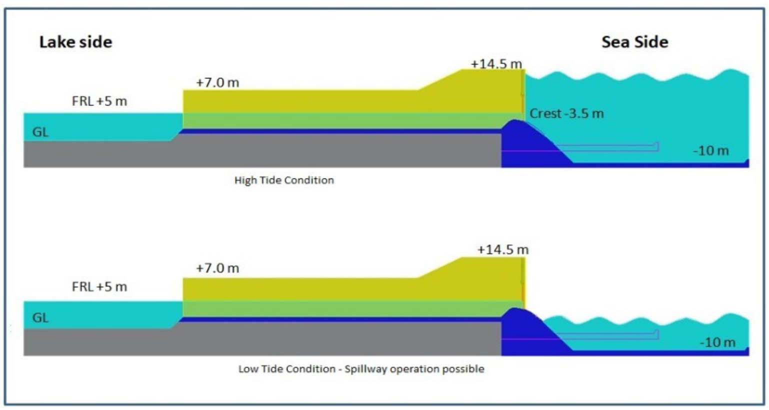

Figure 5. The schematic view of the coastal reservoir spillway

6. Conclusions

Spillways and energy dissipators are of paramount importance and the most integral part of dams. As the dam building activity is going on for years together, almost all easy sites have already been tapped. In this paper, an attempt has been made to identify the situations where there are challenges in front of the designer for future projects. Designing the spillways considering flash floods, GLOF and Himalayan fragile geology leading to high silt load are some of the challenges for the designers. The spillway will play a major role in designing sustainable projects in this region. Under DRIP, many old dams in India are assessed for design flood and there is an upward revision in the design flood for many of the dams. To minimize the risk of overtopping the dam, designers have to think of enhancing the existing spillway capacity and/or alternative methods to pass the revised flood. To conserve the excess runoff flowing into the sea, and to avoid submergence of landmass and rehabilitation issues in inland dam building, coastal reservoirs will be an attractive option in the future. As India got about 7500 km coastline, there is a future for building big coastal reservoirs for various purposes.Hydraulic model studies play a very important role in optimizing the design and layout of the spillways and associated appurtenant structures as scanty guidelines are available for designing spillways and energy dissipators under such situations.

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