RESTORATION AND REHABILITATION OF SPILLWAY WITH MODIFIED ENERGY DISSIPATOR-A CASE STUDY

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ABSTRACT

Damages to the slotted roller buckets as an energy dissipator are reported on several projects both due to abrasion in the bucket on account of entry of material into the bucket and subsequent roll-mill action and cavitation. The energy dissipators are designed with the help of existing design manual to give satisfactory results, for the given design conditions and if the operating conditions differ from the design conditions; it may give unsatisfactory results and consequent damages to the appurtenant structures under transient and unsymmetrical flow conditions. Although model studies invariably advocate equal and symmetrical opening of spillway gates, practical difficulties on spillways with a large number of gates often compel unsymmetrical operation. As such, slotted buckets would be advantageous only for the spillways with few spans or ungated spillways where the symmetry of operation could be ensured and tail water levels prevail for formation of roller action.

Indira Sagar Project (ISP) is situated on river Narmada in Khandwa district of Madhya Pradesh, India. The project is in operation since 2004-05. The energy dissipator was in the form of slotted roller bucket with different bucket invert levels for both main and auxiliary spillways. It was observed by the project authorities that during every monsoon, the bucket area of the main spillway gets damaged and there is recurring need to restore the damaged area. During the site inspection of design and project engineers, it was observed that the spillway glacis and a slotted roller bucket of main spillway have been damaged badly. The spillway was operated continuously for a considerable time during the 2013 flood with high discharges of the order of 20,000-35,000 m3/s. It was concluded based on theoretical calculations and site observations that the damages to the energy dissipators are due to hydraulic as well as structural reasons. Deficient tail water levels during initial period of operation leading to ski action, generation of high hydrodynamic pressures during roller formation due to very high incoming velocities of the order of 35 m/s and negative pressures on the teeth, were few of the hydraulic parameters leading to the damages to the bucket. It was proposed jointly by CWC and CWPRS to provide ski-jump bucket in place of slotted roller bucket considering the prevailing site conditions, hydraulic, structural and economic aspects. In the present paper efforts are made to analyse the possible cause of damages, modification of energy dissipator of the main spillway of Indira Sagar Dam. This paper describes the hydraulic model studies conducted at CWPRS, Pune, which played an important role in modifying the overall performance of the energy dissipation arrangement of main spillway and the prototype investigation fully interpreted the model results thereby showing model-prototype conformity.

1. INTRODUCTION

Spillway and energy dissipators are vital parts of dam provided to pass the flood and to limit the erosion downstream of spillway. Different kinds of energy dissipators such as stilling basin, ski jump and roller buckets are designed depending on the availability of tail water and type of rock at dam site. Roller bucket is used when the tail water depth is higher than the sequent depth and river bed rock is sound. Roller buckets have been embraced for low and medium head dams in many projects in India and abroad, first being applied in Grand Coulee dam in USA. The energy dissipation occurs mainly in the bucket by formation of surface roller over the bucket moving counter clockwise and ground roller downstream of the bucket moving clockwise. Slotted roller bucket is an enhancement over the solid roller bucket as the flow passes through the slots, dispersed over a greater area providing less violent flow conditions as compared to solid roller bucket.

The slotted roller bucket is more susceptible to damage than the solid roller bucket due to the teeth. A survey conducted by Maharashtra Engineering Research Institute (CBIP Publication 247, 1995) reports 14 dams and unfortunately all of these showed distress of some magnitude causing damages to bucket, teeth, downstream apron and river bed. The teeth and the slots between them are subjected to negative pressure leading to cavitation damage. Most of these spillways have not been subjected to design floods. The main causes of damage identified were.

- Non uniform release of discharges with respect to time and quantity. Non adherence of gate operation schedule
- Non removal of obstruction downstream of bucket lip
- Deficient tail water initially and excess tail water during receding flood
- Sudden reduction in spillway flow when the tail water is high, causing return flow and thus bringing debris in to bucket

Thus, it can be seen that the design of slotted roller buckets is complex and extremely sensitive to tail water level. Therefore, it has several limitations. The same have been discussed by Bhosekar et.al (2012). Therefore, the limitations in design of slotted roller bucket and sensitivity to the tail water level, modification and findings of the model studies at CWPRS for a project and prototype experience for slotted roller bucket as an energy dissipator are discussed in this paper.

1.1 The Project

Indira Sagar Project (ISP) is situated on river Narmada in Khandwa district of Madhya Pradesh. ISP is a multipurpose Project with an installed capacity of 1000 MW and provides irrigation benefits to about 1.23 lakh hectares. Indira Sagar dam is a 653 m long and 92 m high gravity dam, with curved dam axis having radius of 880 m. Main and auxiliary spillways comprise of 12 and 8 spans respectively of size 20 m x 17 m and are designed to dispose off a PMF of 83,400 m3/s. The energy dissipator was in the form of slotted roller bucket with different bucket invert levels for both the spillways. The project is in operation since 2005. It was observed by the project authorities that the slotted roller bucket of the main spillway was getting damaged during every monsoon. During 2013, discharges of the magnitude of 30,000 m^3/s were released for a considerable time and it was observed that the entire slotted roller bucket in front of spans 6 to 12 was washed off. CWPRS and CWC officers along with the project authorities visited dam site to inspect and a ski jump type of energy dissipator was proposed in place of slotted roller bucket for the main spillway considering the prevailing site conditions, hydraulic, structural and economic aspects. The ski-jump bucket with bucket radius 50 m, invert El.199.75 m and lip at El. 210 m was designed by CWC in consultation with CWPRS. Figures 1 to 4 show the damages on the bucket of main spillway, general layout, cross section of original and modified design of main spillway and auxiliary spillway, respectively.

Figure 1 : Damages to bucket of main spillway

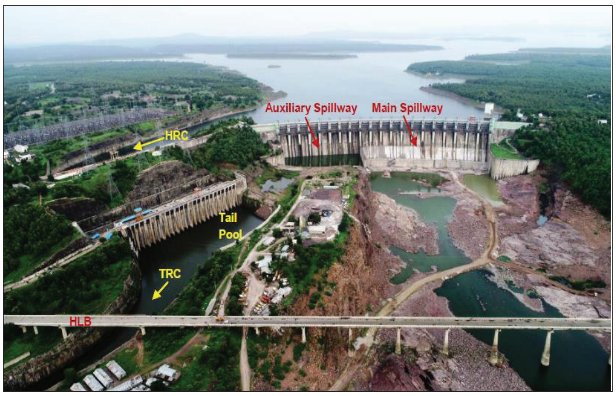


Figure 2 : General layout

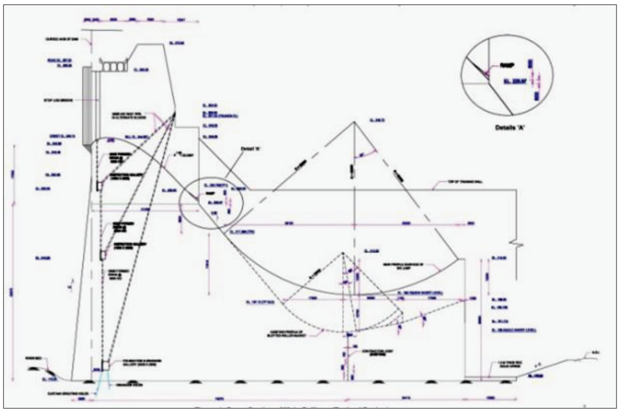


Figure 3 : Original and modified design of main spillway

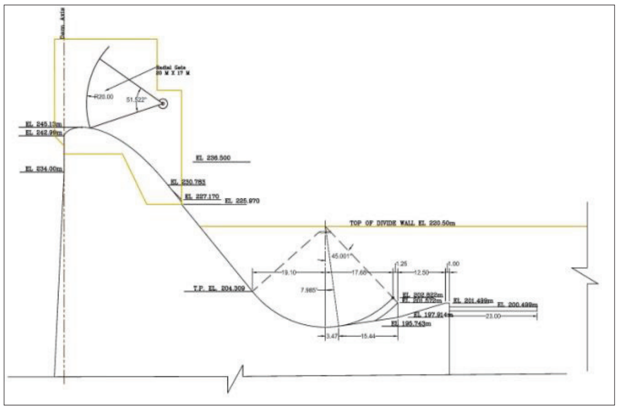


Figure 4 : Cross section of auxiliary spillway

2. HYDRAULIC MODEL STUDIES

Hydraulic model studies were conducted on a 1.60 scale 2-D sectional model for assessing the performance of proposed energy dissipator and finalizing the design of the main spillway. One full span and two half spans with two full piers along with ski-jump bucket were incorporated in the model. Studies were conducted in a 1 m wide flume at CWPRS, Pune. The main findings of the studies on 2-D sectional model were as follows.

- A discharge of 35,537 m^3/s could be passed at full reservoir level (FRL) El. 262.13 m and a discharge of 38,896 m^3/s could be passed at MWL El. 263.25 m with all 12 spans of main spillway fully open.
- Isolated negative pressures of the order of -0.03 to -1.75 m are observed at the inlet to the bucket and the corresponding cavitation index is in the vicinity of critical cavitation index of 0.2. Also, this region is aerated from the air entrained jet from the aerator. Negative pressures are observed at the bucket lip due to suction in the unventilated cavity below the ski jump jet in the sectional model. However, the lip will be ventilated from downstream in the prototype with lateral aeration from the sides. Hence, this isolated negative pressure can be accepted.
- Clear ski action was observed for discharges up to 17,769 m^3/s (50%) for gated and ungated operation of the spillway. Submerged ski action was observed for higher discharges. The throw distances were found to be varying between 52 m to 72 m for the ungated and gated operation of spillway for the various discharges. Thus, the performance of spillway and ski jump bucket was found to be satisfactory.
- The flow was cascading over the bucket lip while passing the lower discharges. Therefore, a 15 m wide concrete apron may be provided downstream of ski jump bucket with end key firmly anchored to the fresh rock to prevent undermining of the spillway toe due to cascading flows.

As per the recommendations of CWPRS, CWC and the Dam Safety Review Panel, it was decided to conduct hydraulic model studies on the 3-D comprehensive model for assessing the performance of ski- jump bucket, flow conditions emerging at the junction of outlet channel of main and auxiliary spillways and in the vicinity of tail race channel of power house.

(a) Q = 17,769 m^3/s at FRL El. 262.13 m (b) Q = 35,537 m^3/s at FRL El. 262.13 m

Figure 5 : Flow condition for (a) gated and (b) ungated operation of main spillway

2.1 The Model

A 1:130 scale geometrically similar 3-D comprehensive model of main and auxiliary spillways is constructed as per the recommendations based on the studies conducted for main spillway on the 2-D sectional model. The model incorporates main and auxiliary spillways, eight units of power house and tail race channel. River reach up to 1365 m upstream and

2015 m downstream of the dam axis was reproduced with smooth cement plaster. High Level Bridge (HLB) situated at about 600 m downstream of dam axis is also reproduced. Figures 6 & 7 show the view of the model constructed in a hangar at CWPRS, Pune.

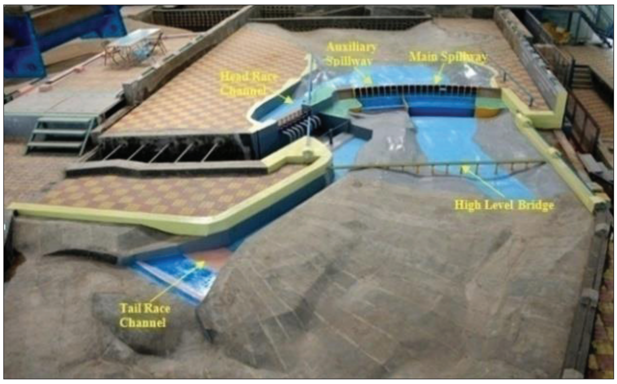


Figure 6 : Full view of model tray

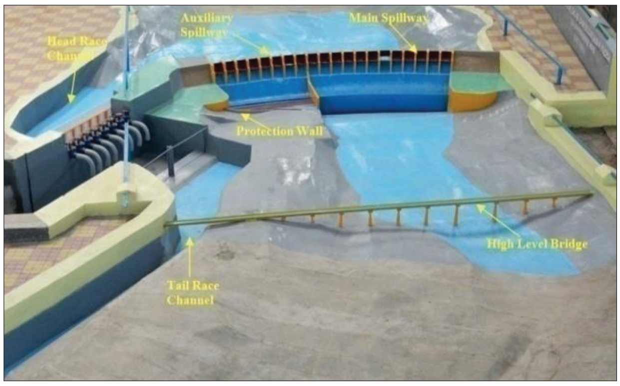


Figure 7 : Closer view of the model

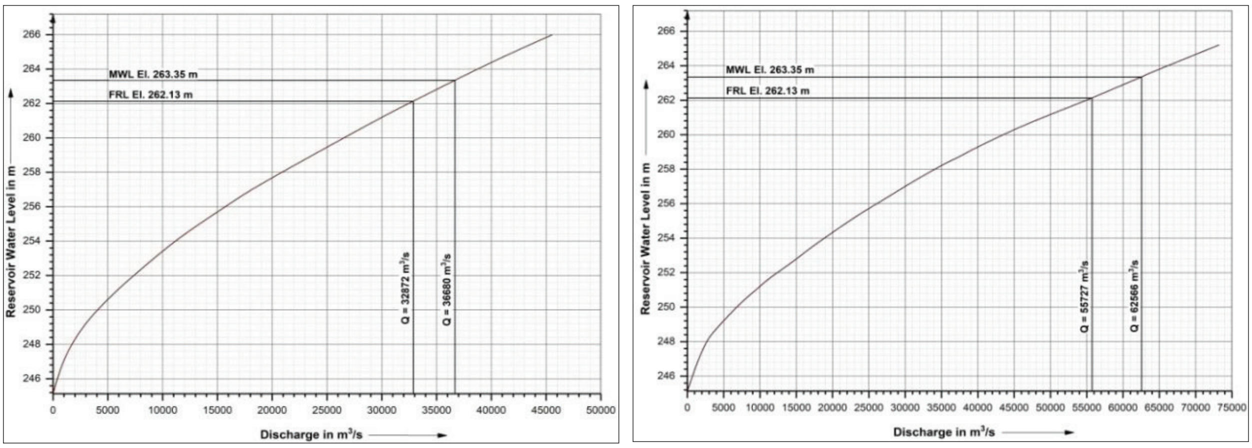
2.2 Model Studies

Hydraulic model studies were conducted on 3-D comprehensive model to assess the perfomance of main and auxiliary spillways in respect of discharging capacity, water surface profiles and efficacy of energy dissipater in the form of ski-jump bucket and slotted roller bucket for the entire range of discharges.

2.2.1 *Discharging capacity of spillways*

Hydraulic model studies were conducted for assessing the discharging capacity of main spillway. It was observed that a discharge of 32,872 m^3/s could be passed at FRL El. 262.13 m with all 12 spans fully open. It was seen that a discharge of 36,680 m^3/s could be passed at MWL El. 263.35 m with all 12 spans fully open. Figure 8(a) shows the discharging capacity curve for the main spillway.

Hydraulic model studies were conducted for assessing the discharging capacity of both main and auxiliary spillways. It was observed that a discharge of 55,727 m^3/s could be passed at FRL El. 262.13 m with all 20 spans fully open. It was seen that a discharge of 62,566 m^3/s could be passed at MWL El. 263.35 m with all 20 spans fully open. Figure 8(b) shows the discharging capacity curve for both main and auxiliary spillways. Hydraulic model studies were also conducted for assessing the discharging capacity of both main and auxiliary spillways for 10% of gate inoperative condition. It was observed that a discharge of 56,309 m^3/s could be passed at maximum water level (MWL) El. 263.35 m with 18 spans fully open.



(a) Only main spillway (b) Both main and auxiliary spillway

Figure 8 : Discharging capacity curve

2.2.2 *Performance of spillways and energy dissipators*

It was seen that the discharge of about 32,872 m^3/s could be passed through the main spillway at FRL without operation of power intake units. Clear ski action was seen downstream of the bucket. The throw distance was found to be about 86 m from the lip of the main spillway. Pier caps of the HLB for pier nos. 5, 6 & 7 from left were getting submerged intermittently due to afflux. Velocities ranging from 14 to 27 m/s were found in the upstream region of HLB and return velocity of 8.7 m/s was found along the left bank. Stagnation of water along the left bank was seen and there was a mild return flow along left bank near HLB. Thus, it can be inferred that the ski jump bucket is functioning satisfactorily for this particular operating condition. Tail water level (TWL) corresponding to the discharge of 32,872 m^3/s realized on the model was about 8 m below than tail water rating curve supplied by the project. Mild return flows along the left bank and heavy fluctuations of the water level 3-10 m near the downstream of the HLB were observed. Figure 9 shows the flow conditions in the downstream for the ungated operation of the main spillway at FRL.

Studies were conducted for ungated operation of main spillway and gated operation of auxiliary spillway at FRL El. 262.13 m until water overflows the downstream protection wall towards tail race channel (TRC). Downstream protection wall has been provided to prevent the flow of water to the tail pool of TRC downstream of the powerhouse. A discharge of 37,590 m^3/s could be passed with ungated operation of main spillway and gates of auxiliary spillway partially and equally open keeping the reservoir water level at FRL. It shows that auxiliary spillway can only pass a discharge of 4,718 m^3/s, when the water level touches the top of protection wall downstream of auxiliary spillway with all gates equally open by 1.58 m above crest of spillway. Performance of ski-jump bucket of main spillway was satisfactory as the clear ski action was seen forming. No roller action was seen in the bucket of auxiliary spillway. Hydraulic jump was seen forming in the bucket and the flow was cascading over the apron. Hence, performance of slotted roller bucket was not satisfactory as no roller action was seen. Finally, the flow was seen entering the main river channel of main spillway falling over the 60 m wide cut provided in front of divide wall between main and auxiliary spillways. Tail water level corresponding to the discharge of 37,590 m^3/s realized on the model was 8 m below from rating curve. Stagnation of water along the left bank was seen and there was a mild return flow along left bank near the HLB. Mild return flows along the left bank and heavy fluctuations of the water were seen. Figure 10 shows the flow conditions in the downstream for the same.

Figure 9 : Ungated operation of main spillway only

Figure 10 : Main spillway ungated and auxiliary spillway gated operation

Studies were conducted for gated operation of auxiliary spillway only at FRL El. 262.13 m until water overflows the downstream protection wall towards tail race channel. It was observed that auxiliary spillway can pass a discharge of 4,718 m^3/s with all gates equally open by 1.58 m above crest of spillway. No roller action was seen in the bucket of auxiliary spillway. Hydraulic jump was seen forming in the bucket and the flow was cascading over the apron. Then the flow was diverted to the main river channel. Hence, performance of slotted roller bucket was not satisfactory as no roller action was seen. Figure 11 shows the flow conditions in the downstream for only auxiliary spillway operating with gated operation.

Studies were conducted for ungated operation of both main as well as auxiliary spillways at FRL El. 262.13 m. Performance of ski-jump bucket of main spillway was satisfactory as the clear ski action was seen forming. The observed throw distance was about 86 m from the bucket lip of the main spillway. Tail water level corresponding to the discharge of 55,727 m^3/s realised on the model was 11 m below against the tail water rating curve. Velocities ranging from 3.4 to 11.4 m/s were found in the upstream region of HLB and return velocity of 1.5 m/s was found along the left bank. No roller action was seen in the slotted roller bucket of auxiliary spillway and flow was cascading over the bucket. The cascading flow was seen spilling over the divide wall. It was also seen that the flow overtops right training wall intermittently. The water overtops the protection wall and overflows in the powerhouse tail pool and channel. There is a need of providing a tail channel downstream of auxiliary spillway to increase the discharge carrying capacity and to guide the flow towards the main river course followed by a common plunge pool for both main and auxiliary spillways. By providing tail channel, sweepout condition would occur over the slotted roller bucket due to lowered tail water level and it may damage the teeth of the bucket. An alternative arrangement for energy dissipation in the form of two stage energy dissipator by providing weir downstream of slotted roller bucket to create pondage for maintaining tail water and a sloping tail channel downstream of the weir up to the main river channel may be considered. Many alternatives can be studied in the physical model to finalise the energy dissipator and spill channel. Figure 12 shows the flow conditions in the downstream for ungated operation of both the spillways at FRL.

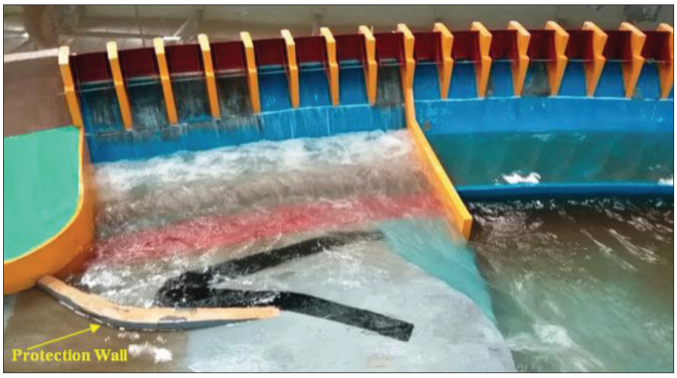


Figure 11 : Gated operation of auxiliary spillway only

Figure 12 : Ungated operation of main and auxiliary spillway

It can be inferred from the model studies that the performance of modified design of energy dissipator as a ski-jump bucket for main spillway was found to be satisfactory.

3. PROTOTYPE EXPERIENCE AND MODEL-PROTOTYPE CONFORMITY

Modified design of energy dissipator as Ski-jump bucket for the main spillway as suggested by CWPRS, is adopted and implemented by the project authority and construction was completed in 2018. After construction of the energy dissipator of the main spillway, spillway was first operated during the month of August 2019. CWPRS officers along with the design and project engineers witnessed the performance of the newly constructed EDA in the prototype.

During the model studies conducted in the 2D sectional model at CWPRS, it was observed that the flow over the ski-jump bucket was cascading till gate opening of 3 m for equal partial gate operation for all spans while raising the gates gradually with reservoir water level (RWL) El 261.4 m. The model based results and observations were compared with prototype measurements and operations to evaluate the accuracy of model behaviour. In this connection, the same gate operations with gradual raising the gate at an interval of 0.5 m till 3 m gate opening were tested in the prototype. Figures 13 & 14 show the partial gate operation of main spillway at RWL El.261.40 m with all gates partially open with gate opening of 2.5 m each.

Figure 13 : Gated operation of main spillway with GO 2.5 m (2D model view)

Figure 14 : Gated operation of main spillway with GO 2.5 m (Project site)

It can be seen from Figures 13 & 14, the flow was cascading over the ski-jump bucket in the model and also in the prototype for the above mentioned operating condition of the main spillway. Figures 15 & 16 show the partial gate operation of main spillway at RWL El. 261.40 m with all gates partially open with gate opening of 3 m each.

Figure 15 : Gated operation of main spillway with GO 3 m (2D model view)

Figure 16 : Gated operation of main spillway with GO 3 m (Project site)

It can also be seen from Figures 15 & 16, the ski action was formed by ski-jump bucket in the model and also in the prototype, when the main spillway was operated with gate opening of 3 m with all 12 spans partially open with RWL El 260.75 m.

CWPRS has been associated in evolving new and efficient designs by conducting model studies for several spillways during the last few decades and has witnessed number of new developments in the design. Hydraulic model studies conducted at CWPRS, Pune, which played an important role in modifying the overall performance of the energy dissipation arrangement of main spillway and the prototype investigation fully interpreted the model results thereby showing model-prototype conformity.

4 CONCLUSIONS

- Based on the model studies conducted on 3-D comprehensive model with various combinations for spillways, it was suggested to remove the debris lying in front of main spillway at site and to review the design of bridge piers and consider the strengthening of high level bridge piers, if required, to sustain with high velocity flows coming from the main spillway after the modification of energy dissipator from roller to ski-jump bucket.
- It was also suggested to provide plunge pool to reduce the downstream velocities near the bridge and to avoid the uncontrolled erosion of the river bed and banks. As the slotted roller bucket of auxiliary spillway is not performing satisfactorily for any of the operating conditions, there is a necessity of providing the tail channel in front of auxiliary spillway so as to guide the flow towards the main river channel for the discharges higher than 4700 m^3/s.
- Performance of slotted roller bucket is extremely sensitive to tail water levels and the primary cause of unsatisfactory performance of the same and consequent damage. Therefore, the slotted roller buckets should be designed carefully and comprehensive model studies should be conducted before adopting the design for execution on prototype to avoid recurring damages of energy dissipator and to ensure satisfactory performance for all possible scenarios.

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