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Effect of deficient tailwater on the performance of slotted roller bucket of Indira Sagar Dam, Madhya Pradesh

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Abstract: *Slotted roller bucket type energy dissipators are provided for spillways when the tailwater depth is 1.2 times the sequent depth required for the formation of a hydraulic jump. In slotted roller buckets, the dissipation of energy occurs by the lateral spreading of jet passing through bucket slots in addition to the formation of two complementary rollers as in the solid bucket. These are provided for spillways where the downstream river bed is of sound rock. However, when the tailwater levels are not realised during the release of floods over the spillway and surface and ground rollers are not formed, it results in a possible sweep of the flood out of the bucket. Deficient tailwater levels during the initial period of operation of the bucket leading to ski action, generation of high hydrodynamic pressures during roller formation due to very high incoming velocities and occurrence of negative pressures on the bucket teeth, are some of the hydraulic parameters that lead to damage to the slotted roller bucket. Indira Sagar Dam is 653 m long and 92 m in height and was built on the River Narmada in Madhya Pradesh. The main and auxiliary spillway comprises 12 and 8 spans respectively of size each 20 m x 17 m and is designed to dispose of a Probable Maximum Flood of 83,400 m^3/s. The energy dissipator provided was original in the form of a slotted roller bucket. The project is in operation from 2004-2005. Discharges of the magnitude 30,000 m^3/s were released during the monsoon of 2013 and then it was observed that the entire slotted roller bucket in front of spans 6 to 12 was washed away. The teeth of the roller bucket were overturned and thrown away by the flood waters. Theoretical analysis for actual discharges passed over the spillway from 2006 to 2012 indicated that the roller action was not forming for these conditions and instead ski action was taking place due to deficient tailwater levels. There was also a transition from ski action to roller action for increasing discharges till the tailwater build was realised. In fact, this is the inherent shortcoming of roller bucket type of energy dissipators and damages to the bucket have been reported elsewhere also. In this paper, the authors account for the causes that damaged the slotted roller bucket of Indira Sagar dam, M.P and recommendations suggested for improving the performance of energy dissipation arrangement.*

Keywords*: Slotted roller bucket, tailwater level, bucket teeth, apron, ground roller, surface roller, ski jump bucket*

1. Introduction

Slotted roller buckets are provided as energy dissipators for spillways. In the slotted roller buckets, a part of the flow passes through the slots, spreads laterally and is lifted away from the channel bottom by a short apron at the downstream end of the bucket and the flow is depressed and distributed over a great area providing less violent flow concentrations compared to those in a solid roller bucket. The velocity distribution just downstream of the bucket is more akin to that in a natural stream, that is high velocities at the surface and lower velocities at the bottom (IS 7365, 2010). However, it must be ensured sufficient raise of tailwater levels while designing the slotted roller buckets otherwise it would affect the functioning of the same, causing erosion of the bucket and its downstream. While designing of slotted roller bucket, for a high head spillway exceeding the total head of 50 m or so, specific care should be taken especially for the design of the teeth, to ensure that the teeth will perform cavitation free. After positive assurance of tailwater level within operating range between minimum and maximum tailwater depth limits and availability of rocky bed, the slotted roller buckets are required to be designed in such a way that, incoming, velocity is less than 15 m/s and the bucket lip is set above the river bed (IS 7365, 2010). The slotted bucket is self-cleaning, provides protection against excessive scour and undermining of the bucket structure and is shown to be of minimum size consistent with good performance.

Indira Sagar Project (ISP) is situated on River Narmada, 10 km from village Punasa in Khandwa district of Madhya Pradesh. ISP is a multipurpose project with an installed capacity of 1000 Mega Watt and provides irrigation benefits to about 1,23,000 hectares. ISP is the mother project for the downstream projects in Narmada Basin with the largest reservoir in India, having 12.22×10^9 m^3 storage. Indira Sagar dam is a 653 m long and 92 m high gravity dam, with a curved dam axis having a radius of 880 m. Main and auxiliary spillways comprise 12 and 8 spans respectively of size 20 m x 17 m and are designed to dispose of a PMF of 83,400 m^3/s. The original energy dissipator was in the form of a slotted roller bucket with different bucket invert levels for both the spillways. The surface Power House is situated on the right bank of the river to house 8 Francis turbines of 125 Mega Watt each. The water conductor system consists of Head Race Channel with carrying capacity of 2200 m^3/s and the water is discharged back into the river Narmada through 850 m long Tail Race Channel after power generation. Slotted roller bucket of Indira Sagar

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spillway was designed to handle the design head of 74.65 m (Head difference between Maximum Water Level (MWL) El. 263.35 m and bucket invert El. 189 m). Figure 1 shows the original cross section of the main spillway.

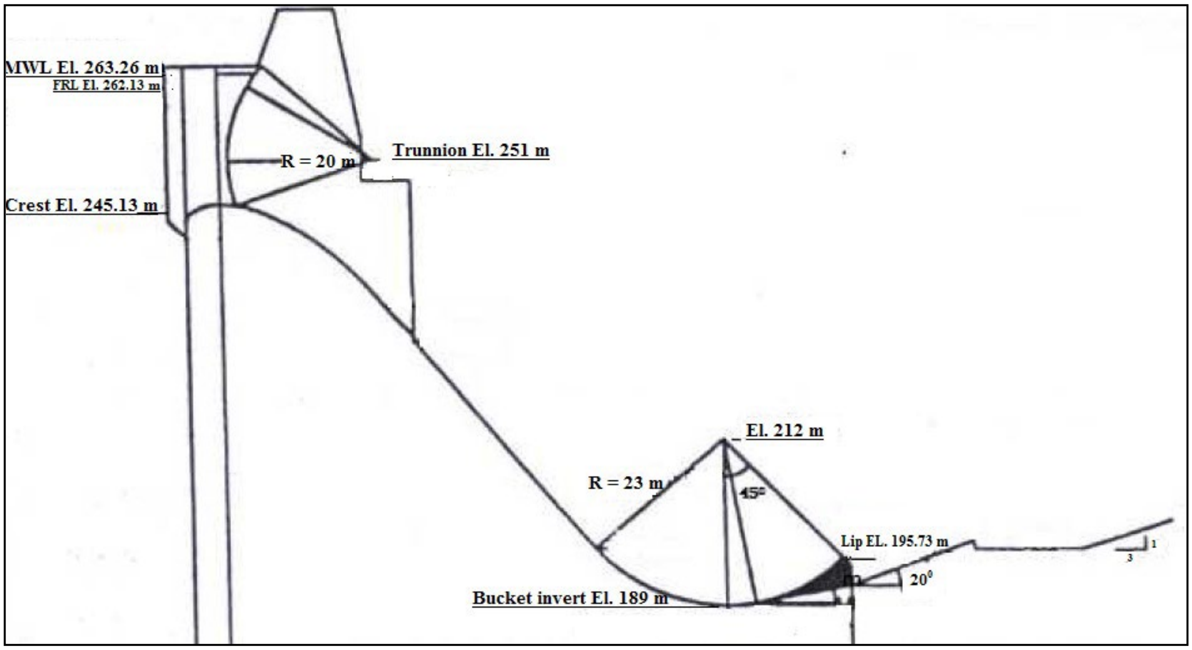

Figure 1. Cross section of main spillway of Indira Sagar dam, Madhya Pradesh

2. Performance of slotted roller bucket of main spillway

The Indira Sagar project is in operation from 2004-2005. According to Project authorities, it was observed that discharges of the magnitude 30,000 m^3/s were released for a considerable time during the monsoon of 2013 and it was observed that the entire slotted roller bucket in front of spans 6 to 12 was washed away. It was necessary to assess the possible reasons for the damage to the energy dissipator and recommendation of remedial measures. It was observed that the slotted roller bucket of the Indira Sagar dam spillway was damaged remarkably. Almost all the teeth of the bucket along with the apron downstream of the lip were overturned and thrown away by the flood waters. Out of the total 71 teeth of the main spillway only about 33 were seen intact, the remaining teeth were seen at a distance of about 100-150 m from bucket invert. Lip and teeth of the bucket in bays 6-12 have got dislodged from the main dam. The spillway was in operation with high discharges and it was opined that the damage to the energy dissipation arrangement is due to both hydraulic as well as structural reasons. Deficient tailwater levels during the 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 30 m/s and negative pressures on the teeth, were few of the hydraulic parameters leading to damage to the bucket. Damages to surface concrete were observed at various locations of the area of lip/ downstream apron. The surface of the teeth intact was found damaged due to abrasion/ erosion of concrete. These damages may have failed to boost up required tailwater levels resulting progressive erosion of bucket downstream. Photos 1 to 4 show the eroded bucket portion of spillway and severity of damage occurred to bucket. While designing slotted roller buckets, specific model tests should therefore be conducted to verify the pressures on the teeth and bucket invert should accordingly be fixed at such an elevation as to restrict the sub-atmospheric pressures to the permissible magnitude. As per calculations the velocities of flow for the period under consideration (2006-12) were about 30 m/s. It was opined that energy dissipator blocks got separated from the spillway due to untreated lift joints. These lift joints were formed possibly due to the placement of concrete at the lift joint after considerable time leading to separation due to shrinkage and no cold joint treatment. These construction joints facilitated ingress of water and high hydrodynamic pressures as a result major part of the energy dissipation arrangement got dislodged. The dislodged blocks were carried by the flow and dumped at about 100-150 m downstream forming an endsill type structure. This facilitated rise in tailwater besides the building of tailwater in due course of time and formation of the hydraulic jump at the toe of the spillway, which may prevent further damage to the spillway toe.

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Photo 1. Damage to bucket portion of spillway

Photo 2. The eroded apron of bucket

Photo 3. The detachment of bucket teeth

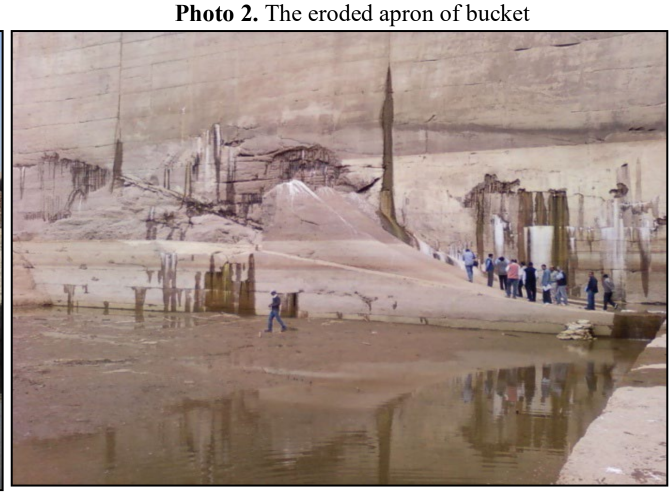

Photo 4. Exposed reinforcement of teeth

2.1 Analysis of data (CWPRS TR No. 5223, 2014)

The provision of slotted roller buckets is based on the availability of high tailwater levels and good rock downstream of bucket. The performance of a slotted roller bucket depends upon the following factors:

1) Magnitude and duration of floods passed over the spillway and corresponding reservoir water levels.
2) Schedule of operation of spillway gates while passing the above floods
3) Tailwater levels realized downstream of slotted roller bucket corresponding to various floods.
4) Tailwater rating curve adopted while designing energy dissipation arrangement.
5) Hydraulic parameters viz. intensity of discharge, velocity, Froude Number, Bucket radius factor, minimum, maximum and sweep-out tailwater levels for different design discharge conditions.

The discharges released through the main spillway and the corresponding tailwater levels observed are tabulated in Table 1. The analysis of data indicated that the observed tailwater levels were below or marginally above the design tailwater levels for most of the flood conditions. Building up of tailwater may take considerable time with heavy flood releases with considerable high velocities. The analysis indicated that the roller action was not forming for most of these conditions and instead ski action might be taking place due to deficient tailwater levels. There was also a transition from ski action to roller action for increasing discharges till the tailwater build was realised. The Froude number was found to be of the order of 9. In fact, this is the inherent shortcoming of roller bucket type of energy dissipators and damages to the bucket have been reported elsewhere also (CBIP Publication No. 247, 1998). From the data, it is known that the tailwater available was marginally above or sometimes lesser than the sweep out depth for the floods under review. Fig 2 shows the plot between the tailwater depth and sweep-out depth for various

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floods under review. Slotted roller bucket type energy dissipators are provided for spillways when the tailwater depth is 1.2 times the sequent depth required for the formation of a hydraulic jump. But, for most of the flood releases, the observed tailwater levels were marginally above the jump height levels and also lesser than the designed tailwater rating curve for which the slotted roller bucket was designed. Fig 3 shows the plot of designed tailwater depth, observed tailwater depths and jump height for the discharges under review.

Table 1. Tailwater depth realised corresponding to the outflow flood (IS 7395, 2010)

S. No	Disch. observed, *Q*	Width of spillway (*m*)	Intensity of disch., *q*	Res. Water Level	Tail water level	FRL-TWL (*m*)	FRL - crest (*m*)	Theo Velocity, V_1	Actual Velocity of flow entering the bucket, *Va*	Initial depth, d_1	Froude Number, *F*	Available tailwater Depth, = Max.TWL- 189 (*m*)	Sweep out depth (*m*)
1	9140	258.46	35.36	254.66	204.0	50.66	9.53	31.53	29.95	1.18	8.80	15.00	17.59
2	9254	258.46	35.80	259.13	206.5	52.63	14.0	32.13	30.53	1.17	9.00	17.50	17.59
3	9576	258.46	37.05	259.94	206.5	53.44	14.8	32.38	30.76	1.20	8.95	17.50	18.07
4	13272	258.46	51.35	259.95	207.5	52.45	14.8	32.08	30.48	1.68	7.50	18.50	19.38
5	14370	258.46	55.60	254.74	208.5	46.24	9.61	30.12	28.61	1.94	6.55	19.50	19.43
6	14843	258.46	57.43	254.76	209.7	45.06	9.63	29.73	28.25	2.03	6.32	20.70	19.31
7	15372	258.46	59.48	259.68	210.6	49.08	14.5	31.03	29.48	2.02	6.63	21.60	20.17
8	15588	258.46	60.31	259.94	210.5	49.44	14.8	31.15	29.59	2.04	6.62	21.50	20.18
9	16692	258.46	64.58	259.94	210.8	49.14	14.8	31.05	29.50	2.19	6.36	21.80	20.80
10	17772	258.46	68.76	259.94	210.8	49.14	14.8	31.05	29.50	2.33	6.17	21.80	21.45
11	23100	258.46	89.38	259.70	211.5	48.20	14.5	30.75	29.21	3.06	5.33	22.50	23.25

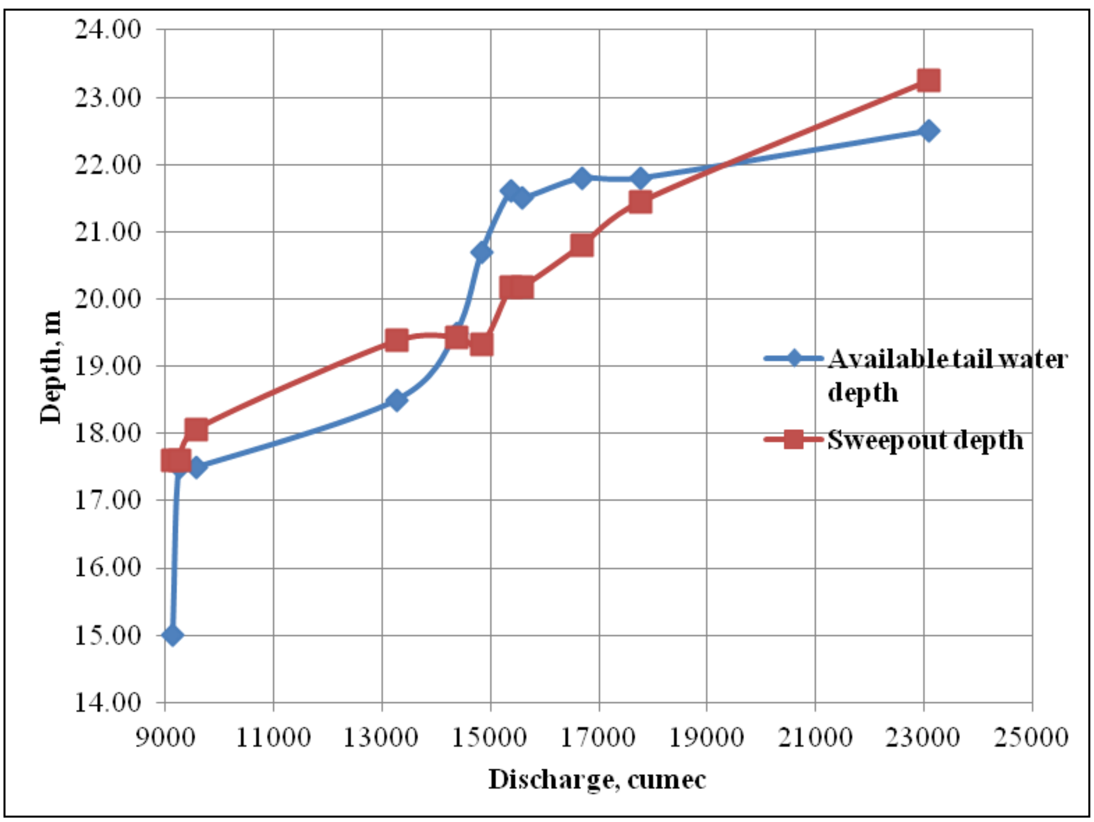

Figure 2. Tailwater depth realised versus sweep out depth

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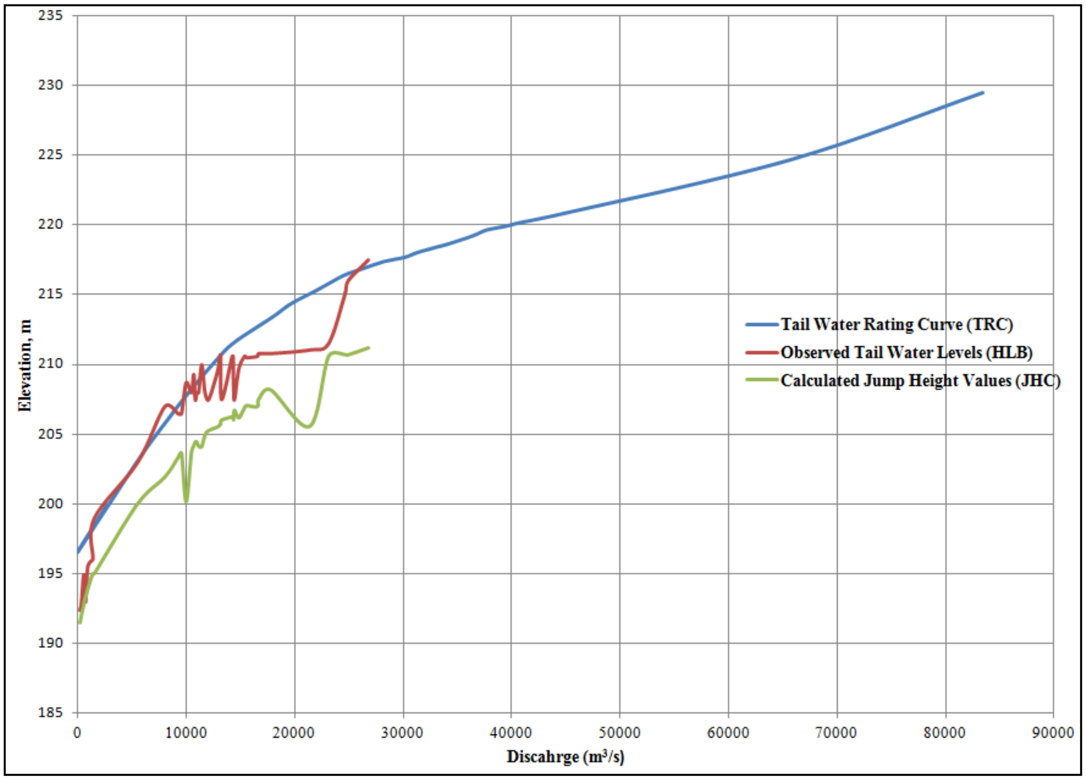

Figure 3. Plot showing tailwater depth and sweep out depth for floods occured

3. Remedial measures suggested

As it was experienced that slotted the roller bucket does not function satisfactorily during the last few years of operation due to its inherent limitations, it was felt that the ski jump bucket is a better long term solution. It has the advantage that it will have the same footprint as the roller bucket and also downstream apron's footprint will remain the same. This will enable the construction of ski jump bucket raising the already existing downstream coffer dam constructed during dam construction.

4. Modified energy dissipator in the form of ski jump bucket

Ski jump bucket is a widely adopted form of energy dissipator which is an upturn solid bucket that is recommended when the tailwater depth is insufficient for the formation of roller action/ hydraulic jump, or when the downstream river bed comprises of sound rock and capable of resisting the high velocity scouring jets released from the bucket. In this form, the flow released from spillway glacis is thrown away from the toe of the dam to a considerable distance downstream as a free discharging jet that falls into the plunge pool, avoiding excess scour caused to the downstream bed. The energy of incoming flow is dissipated in this formation by internal friction within the jet, interaction between the jet and the surrounding air, the diffusion of jet in the tailwater and the impact of jet in the plunge pool. The hydraulic design of ski jump bucket consists of determining bucket shape, its invert elevation, its radius, lip elevation and exit angle, trajectory length and elimination of scour downstream of spillway (IS 7365, 2010).

For the Indira Sagar spillway, the original energy dissipator in the form of slotted roller bucket with invert at El. 189 m and lip at El. 195.73 m was modified to the form of ski jump bucket with a radius of 50 m, invert at El. 199.75 m, lip at El. 210 m and the lip angle is 37º which was recommended by CWC in consultation with CWPRS. The radius of bucket was increased from 23 m to 50 m to accommodate the ski jump bucket profile. Fig 4 shows the cross

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section of ski jump bucket superimposed on a slotted roller bucket type energy dissipator. Photo 5 shows downstream view of spillway with ski jump bucket.

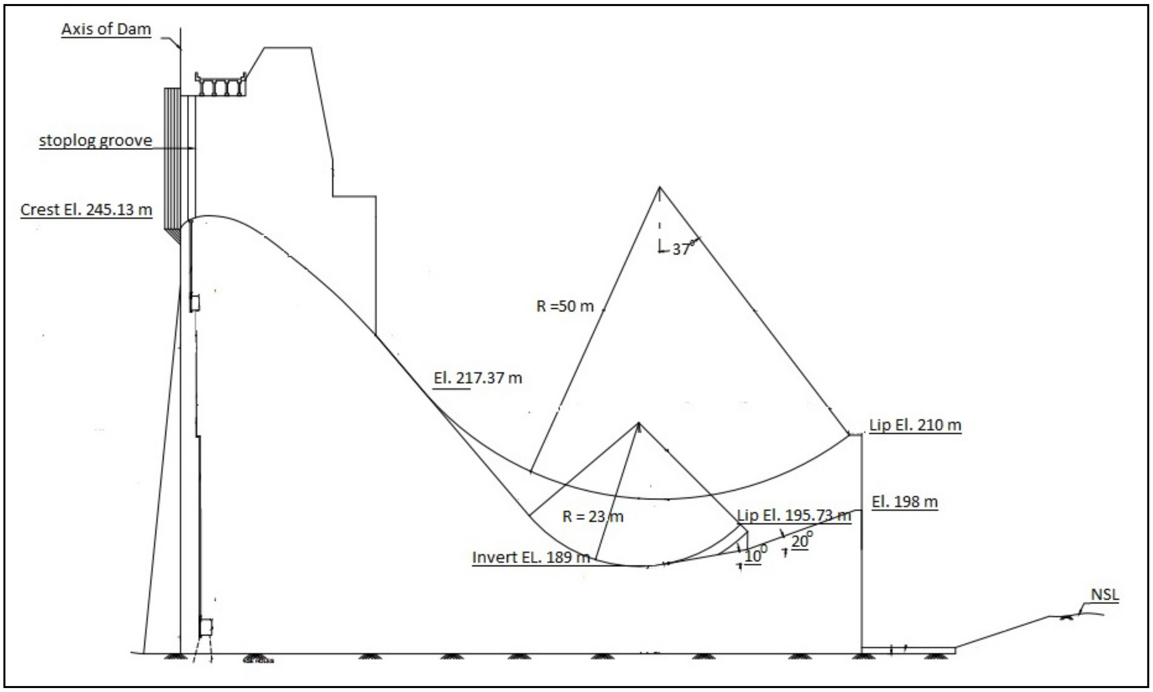

Figure 4. Cross section of modified energy dissipator

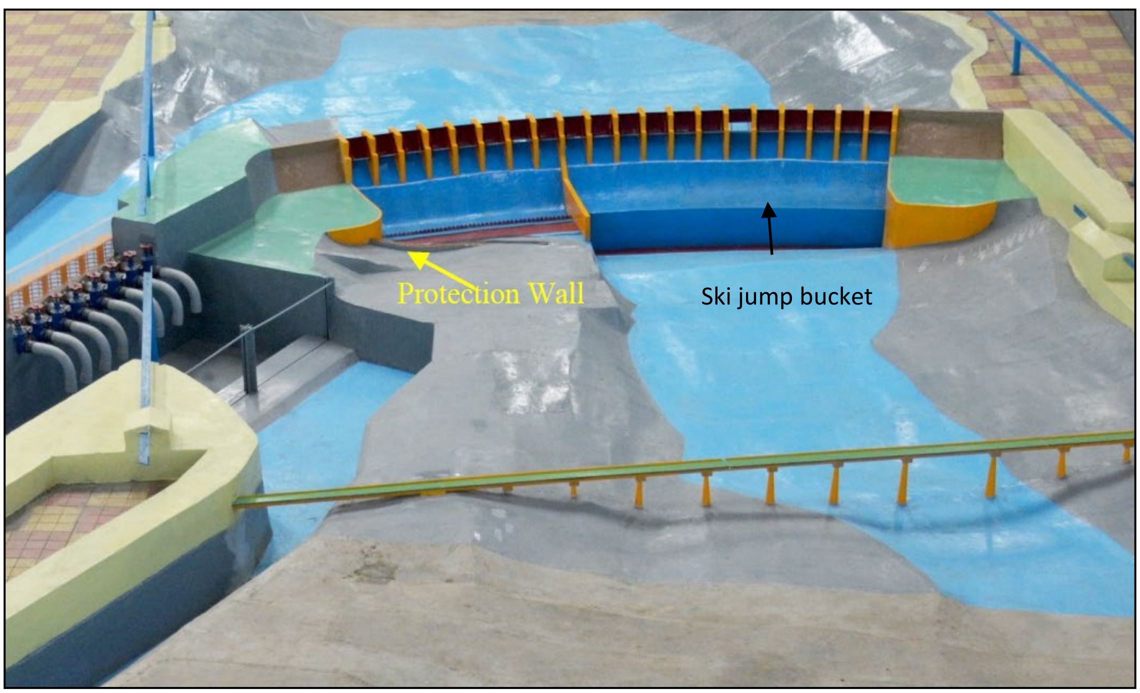

Photo 5. Downstream view of spillway with ski jump bucket

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5. Performance of ski-jump bucket of main spillway (CWPRS TR No. 5579, 2018)

Hydraulic model studies were carried out on a 1: 130 scale geometrically similar 3-D comprehensive model for assessing the performance of ski-jump bucket for various operating conditions of spillway. Studies indicated that the discharges of 55,727 m^3/s and 62,566 m^3/s could be passed with the ungated operation of main and auxiliary spillways keeping the reservoir water level at Full Reservoir Level (FRL) at El. 262.13 m and MWL El. 263.35 respectively and at Full Reservoir Level (FRL) El. 262.13 m, the discharge of about 32872 m^3/s could be passed through the main spillway. Performance of ski-jump bucket of the main spillway was satisfactory as the clear ski action was seen forming in the bucket. The throw distance was found to be about 86 m from the lip of the bucket. Photo 6 shows the performance of ski jump bucket while passing discharge of 32,872 m^3/s at Full Reservoir Level (FRL) El. 262.13 m with all 12 gates fully open.

Photo 6. Performance of ski jump bucket, Q= 32872 m^3/s at Full Reservoir Level (FRL) El. 262.13 m

6. Conclusions

The building up of tailwater levels plays a crucial role in the effective functioning of slotted roller buckets. If the tailwater levels are insufficient to form roller action in the bucket, there is a possibility of sweeping out of the jump causing cavitation of bucket surface and teeth and erosion of the same. For Indira Sagar dam spillway, a major portion of bucket and teeth of energy dissipator has been remarkably eroded/ uprooted due to unsatisfactory functioning of slotted roller bucket for insufficient building up of tailwater levels. From the analysis and site observations it could be concluded that the damage to the energy dissipation arrangement was due to both hydraulic as well as structural reasons. It was opined that roller bucket may not be a suitable arrangement for energy dissipation for the spillway of Indira Sagar dam and must be replaced with ski jump bucket type of energy dissipator for main spillway where major damage has occurred. Hydraulic model studies were carried out in CWPRS for the modified energy dissipator as ski jump type bucket and found satisfactory. The project was completed and the ski jump bucket has been performing satisfactorily.

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