CASCADING HYDROPOWER PROJECTS ON TEESTA RIVER BASIN

MRS. S. R. PATNAIK, MRS. V.P. GADHE, B.S. SUNDARLAL,
DR. M.R. BHAJANTRI AND DR. (MRS.) V.V. BHOSEKAR
MoJS, DoWR, RD & GR, Central Water and Power Research Station, Pune, India

ABSTRACT

In Teesta River Basin construction of a series of cascade dams for hydropower generation is the most significant development activity in the state of Sikkim and West Bengal. Hydraulic model studies play a vital role in finalizing the design of spillway and energy dissipator of the hydro-power projects. The paper describes the hydraulic model studies of the cascading hydropower projects on Teesta River Basin namely, Teesta-IV, TLDP-IV and TLDP-III conducted at Central Water and Power Research station, Pune, India for evolving the optimum design of spillways, energy dissipators and layout of power intake structures.

1. INTRODUCTION

Teesta River originates from the Pahunri glacier and flows southward through deep and narrow gorges and rapids in the Sikkim. Throughout its course the river is turbulent and flows with high velocity with a steep gradient of the order of 1:125. The rapid descent of the river from high elevations makes it ideally suited for hydropower development. The most significant development activity on the 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 West Bengal and Sikkim includes TLDP-III (132 MW), TLDP-IV (160 MW), Teesta -II (330 MW), Teesta -III (1200 MW), Teesta -IV (520 MW), Teesta-V (510 MW), Teesta-VI (500 MW). Figure 1 shows the Cascade Development of Hydropower Projects of Teesta River Basin. Hydraulic model studies of many of the above completed and proposed hydro-projects are conducted at Central Water and Power Research Station (CWPRS), Pune, India

The paper describes the hydraulic model studies of the cascading hydropower projects on Teesta River Basin namely, Teesta-IV, Teesta Low Dam Project (TLDP), Stage-IV and Teesta Low Dam Project (TLDP), Stage-III conducted at CWPRS for evolving the optimum design of spillways, energy dissipators and layout of power intake structures and shows how physical model studies play an important role in enhancing the overall performance of spillway and energy dissipator arrangement which ultimately helped the projects in optimizing a techno-economic design of spillway and associated appurtenant structures of dam complex.

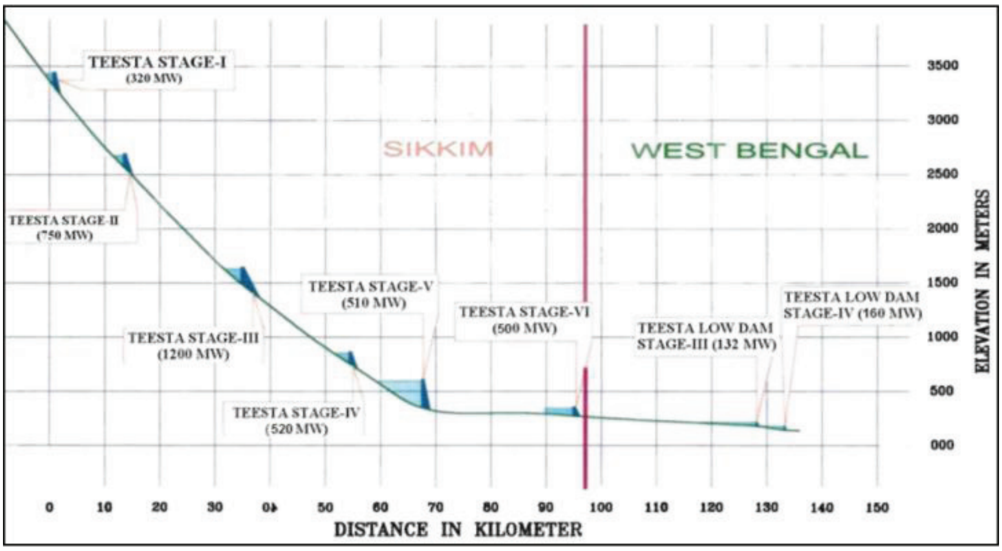

Figure 1 : Cascade development of Teesta River Basin

2. TEESTA-IV DAM SPILLWAY, SIKKIM

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 envisages construction of 65 m high and 197.2 m long concrete gravity dam with top at El. 760 m. The breast wall spillway has been provided to pass the design flood of 13,000 m^3/s through 6 orifice openings of size 9 m wide x 14.5 m high with crest level at El. 716 m. The ski-jump bucket with 35 m radius and 350 lip angle and its invert at El. 697 m is provided for energy dissipation. An underground powerhouse has been provided on the right bank, with an installed capacity of 520 MW (4x130 MW) with design discharge of 480 m^3/s.

Hydraulic model studies were conducted on 1: 60 scale geometrically similar 3D comprehensive model for assessing the discharging capacity of spillway for ungated and gated operation, water surface profiles for entire range of discharges, pressures on the spillway surface and bottom of breast wall profile, performance of the spillway and energy dissipator for entire range of discharges and flow conditions in the vicinity of power intake. Photos 1 and 2 show the downstream and upstream view of the model respectively.

Photo 1 : Downstream View of Model

Photo 2 : Upstream View of Model

2.1 Studies for the Original Design of Spillway and Energy Dissipator

Studies were conducted for discharging capacity of spillway for all the spans operating with full gate opening for entire range of discharges for ungated operation of spillway. It was observed that with one span inoperative, the design discharge of 13,000 m^3/s could be passed at RWL El. 755.91 m as against FRL El. 755.0 m. Thus, the encroachment on the free board is only by 0.91 m as against the available free board of 6 m. At FRL El. 755.0 m, a discharge of 12,800 m^3/s could be passed for one gate inoperative, which is 1.5% less than the design discharge of 13000 m^3/s. As simultaneous occurrence of one gate inoperative and PMF in the river would be a very rare event, this small deficiency of discharging capacity can be accepted. As such, discharging capacity of the spillway is considered to be adequate. It was observed that submerged ski-action was taking place for the discharges higher than 3250 m^3/s with gated and ungated operation of spillway. It was also seen that the flow was concentrated towards the right bank in the plunge pool and the jet issuing from span no. 6 was also hitting the right bank. In order to avoid uncontrolled erosion of the right bank, it was suggested to provide curved dam axis and tilt the dam axis anti-clockwise by about 3^0 to improve the performance of ski-jump bucket, uniform flow distribution across the river valley downstream of spillway and would also economize to great extent the excavation of steep right bank required for providing pre-formed plunge pool. It was also revealed that the upper nappe of the jet was not following the breast wall bottom profile for entire range of reservoir water levels with orifice flow. Therefore, it was suggested to modify the bottom profile of the breast wall so as to make it effective as there is a scope for further improvement in the discharging capacity of spillway. Mild vortices were observed in front of all the 4 units of power intake for the entire range of discharges with and without operation of ungated and gated operation of spillway at MDDL El. 740 m. Therefore, it was recommended that the design of the intake needs to be revised. Photo 3 shows the performance of energy dissipator for the discharge of 13000 m^3/s.

Photo 3 : Performance of energy dissipator for the discharge of 13000 m^3/s

2.2 Studies for the Revised Design of Spillway and Energy Dissipator

Taking the due cognizance of the result of the model studies, the modification which includes the tapering of the pillway span, curvature in the dam axis and tilting by 3^0, revision in the design of intake and modification in breast wall bottom profile were incorporated in the existing 1:60 scale 3-D comprehensive model. It was observed that the discharging capacity was improved with C_d increasing from 0.78 to 0.84. Submerged ski-action was observed for the discharges higher than 3250 m^3/s with gated and ungated operation of spillway. Photo 4 shows the performance of energy dissipator for the discharge of 13000 m^3/s. No vortices were observed in front of all the 4 units of power intake for the entire range of discharges with and without operation of ungated and gated operation of spillway at MDDL El. 740 m as the centerline elevation was lowered by 1 m. S/D ratio increased from 1.65 m to 2.61m eliminating the possibility of formation of vortices ensuring adequate submergence. Figure 2 shows the plot of non-dimensional submergence versus Froude number. It was also observed that the ski-jump jet is impinging in the pre-formed plunge pool which was earlier hitting the right bank but it was recommended that the dam axis should be tilted to 5^0 instead of 3^0 so that the flow concentrated towards the right bank is further reduced.

Photo 3 : Performance of energy dissipator for the discharge of 13000 m^3/s

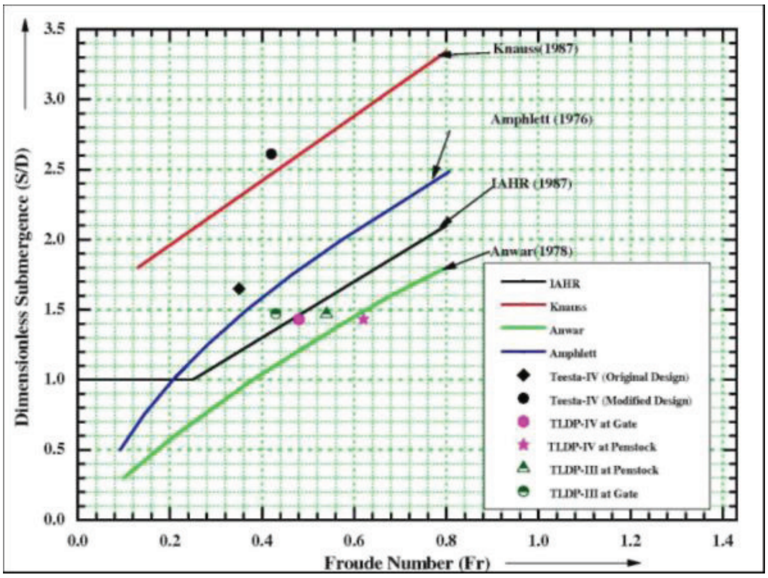

Figure 2 : Plot of Non-Dimensional SubmergenceVersus Froude Number

2.3 Scour Studies for the Revised Design of Spillway and Energy Dissipator

Hydraulic model studies were conducted for assessing the maximum depth of scour and scour pattern downstream of spillway for various discharges up to design maximum discharge of 13000 m^3/s. The river portion downstream of spillway up to chainage 420 m downstream of dam axis was reproduced with cohesionless erodible material (sand) of mean size (d_{50}) of about 1 mm and the river banks beyond chainage 420 m were reproduced. River banks beyond maximum tail water level of El. 715.26 m were reproduced rigid in the model which was not the actual site condition. The scour profiles in the river portion are indicative of depth of scour and location of deepest scour hole. It was observed from the model studies that the flow was concentrated towards the right bank due to the obliquity of the river course downstream of spillway, due to which the scour towards the right bank was maximum as compared to the left bank. Figure 3 shows the water and scour profile for gated operation of the spillway. Return flow was also observed which was taking the bed material towards the left bank thereby creating deposition in front of four spans. Photos 5 to 7 show the view of the scour pit, river bed with erodible bed material in the model and scour pattern for gated operation of the spillway for the discharge of 13000 m^3/s at FRL El. 755 m.

It was suggested to tilt the dam axis anti-clockwise by another 2^0 (Overall tilting by 5^0 in comparison to original layout) which would further improve the flow conditions in containing and guiding the ski-jump jet after the point of impingement towards the river course which was taking a left turn downstream of pre-formed plunge pool. It was also suggested to shift spillway layout towards left side by one span so as to improve the performance of ski-jump bucket and uniform flow distribution across the river width. This would also economize to great extent the excavation of steep right bank required for providing pre-formed plunge pool. The model studies for the revised design after incorporating shifting of dam complex towards left bank by one span and tilting of dam axis by 5^0 are in progress.

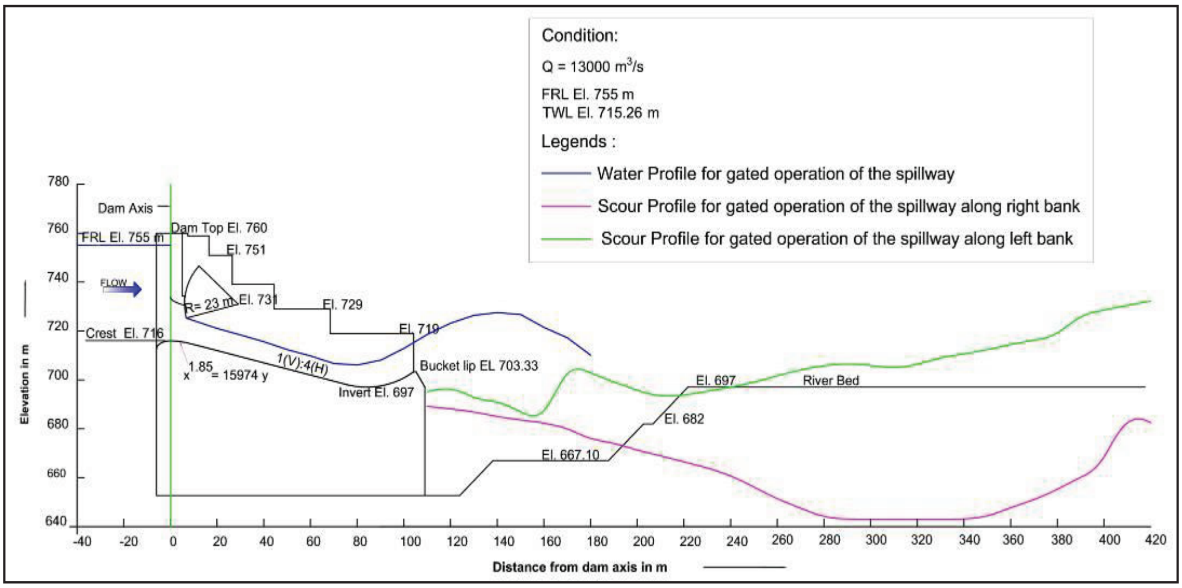

Figure 3 : Water and scour profile for gated operation of the spillway

Photo 5 : View of scour pit in model **Photo 6** : River bed (scour pit) with erodible bed material in model

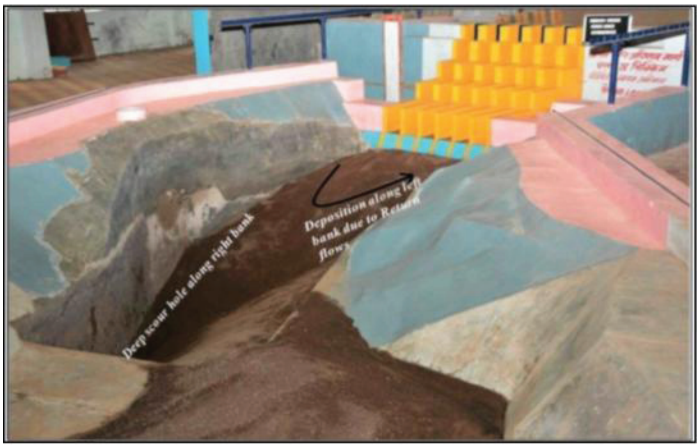

Photo 7 : Scour pattern for gated operation of spillway for the discharge of 13000 m^3/s at FRL El. 755 m

The model studies for the revised design after incorporating shifting of dam complex towards left bank by one span and tilting of dam axis by 5^0 are in progress. Figures 4 and 5 show the superimposed layout plan provided by Project Authorities & Recommended by CWPRS and General layout Plan provided by Project Authorities. Photos 8 to 11 show the downstream, upstream view of the model and performance of energy dissipator for the discharge of 6500 m^3/s and 13000 m^3/s respectively.

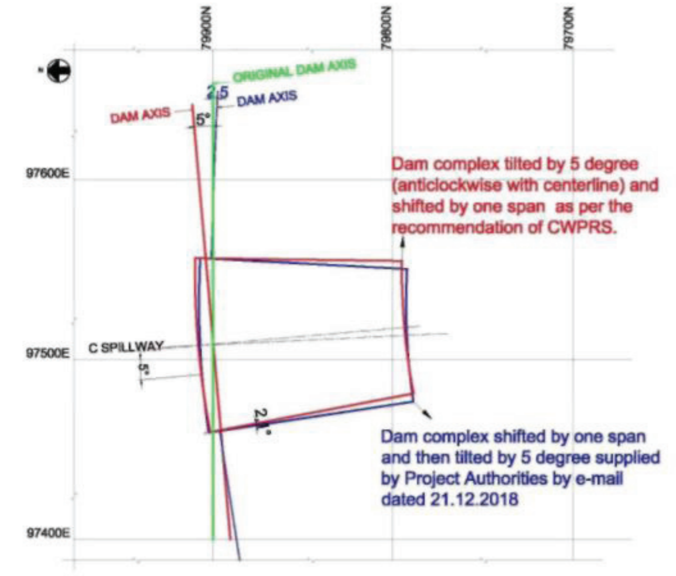

Figure 4 : Superimposed Layout Plan Provided by Project Authorities & Recommended by CWPRS

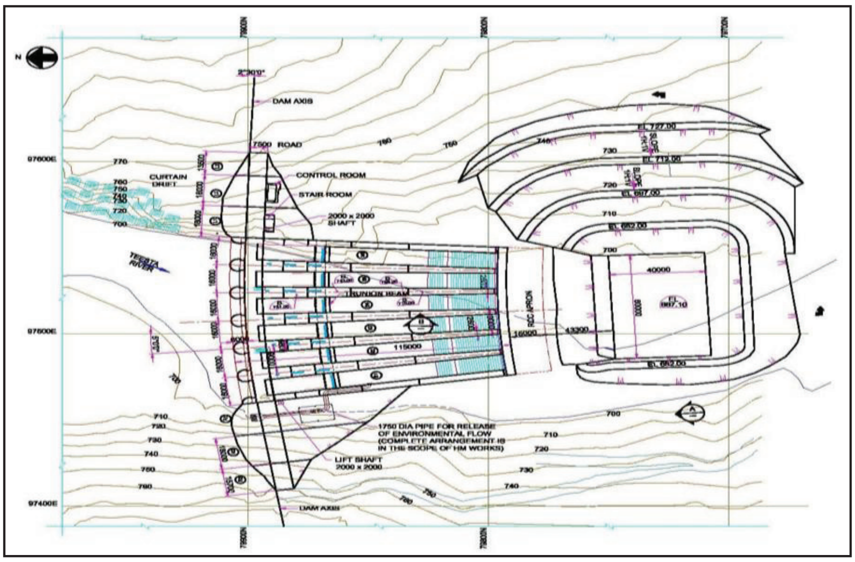

Figure 5 : General layout Plan provided by Project Authorities

Photo 8 : Downstream View of the Model

Photo 9 : Upstream View of the Model

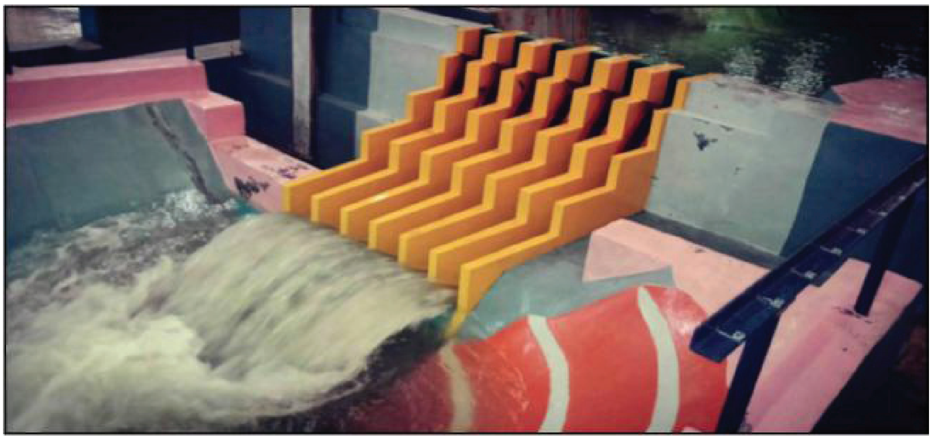

Photo 10 : Performance of energy dissipator for the discharge of 6500 m^3/s

Photo 11 : Performance of energy dissipator for the discharge of 13000 m^3/s

3. TEESTA LOW DAM PROJECT (TLDP) STAGE – IV, WEST BENGAL

Teesta Low Dam Project, Stage – IV is located on River Teesta in West Bengal, India. The project envisages construction of 30 m high concrete gravity dam above river bed level, 350 m upstream of the confluence of Kalikhola and River Teesta. The spillway consists of 7 spans of 11 m (W) x 17 m (H) with breast walls with the design discharge of 5,400 m^3/s at FRL El. 182.25 m. A surface powerhouse has been provided on the left bank, with an installed capacity of 160 MW, 4 units of 40 MW each with the design discharge of 787.60 m^3/s.

3.1 Selection of Energy Dissipator (Original Design)

As the tail water level of the dam was quite high, solid roller bucket type of energy dissipator was provided for energy dissipation. As the solid roller bucket was prone to damage due to accumulation of sediment lifted by the ground roller and its subsequent churning by the surface roller. It was, therefore, essential that the ground roller doesn't erode the river bed in the vicinity of the bucket. This was taken care by providing 15 m apron downstream of the bucket, 1m below the lip. The invert of the solid roller bucket in the original design was kept at El. 145.0 m, with a radius of 15 m and lip angle of 40 degree. The lip elevation was at El. 148.5 m. Figure 6 shows the original and alternative designs of solid roller buckets. Hydraulic model studies were conducted for finalizing the dimensions of the bucket based on its performance.

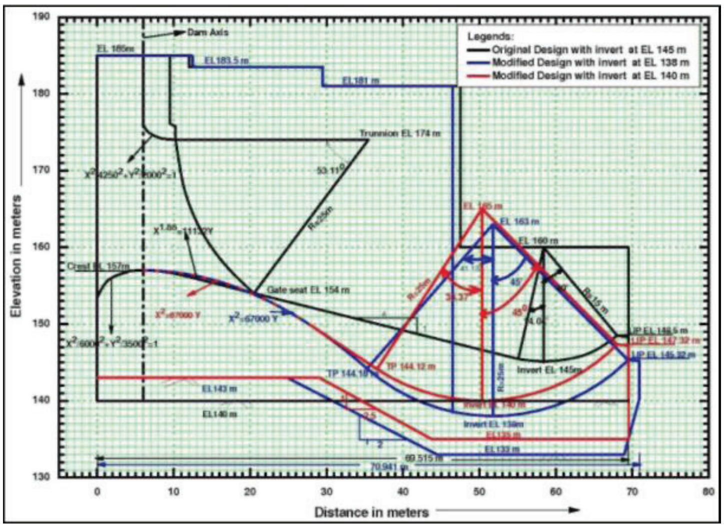

Figure 6 : Original and alternative designs of solid roller buckets

3.2 Studies for the Original Design of Spillway and Energy Dissipator

Hydraulic model studies were conducted for the original design on a 1:70 scale geometrically similar 3-D comprehensive model. Studies revealed that 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 back up of flow like a hydraulic jump in the bucket. The thickness of jet entering into the bucket for 50% of design maximum discharge i.e. 7850 m^3/s was of the order of 4 m, for which the energy dissipator was designed. The discharge intensity was of the order of 100 m^3/s /m and the incoming Froude number was 4.5. Due to these hydraulic parameters the incoming jet does not turn to form the roller. Therefore, it was felt that the design of the bucket could be revised by lowering the bucket by about 5 m, increasing the radius of bucket from 15 m to 25 m and increasing the exit angle from 40^o to 45^o. Accordingly, a design of roller bucket (Alt –1) was suggested as shown in Figure 6. A crest profile conforming to equation $x^2 = 67\ y$ was suggested in place of the original equation $x^{1.85} = 11132\ y$. This alternative was incorporated in the model and it was observed that further lowering of the bucket by 2 m was necessary. Another alternative design of bucket with invert at El. 138 m (Alt-2) was studied on a 1: 45 scale 2D Sectional model.

Studies indicated that for 40% of design discharge i.e. 6,160 m^3/s and below, the performance of the bucket was found to be satisfactory as roller action could be seen. The performance of the solid roller bucket was not satisfactory for the discharges above 6,160 m^3/s i.e. 40% of the PMF as no roller action could be seen due to high tail water level and weak submerged hydraulic jump was seen in the bucket. In view of the above observations and theoretical calculations, it was felt that improvement in the performance of the solid roller bucket could not be achieved due to high discharge intensity upto 200 $m^3/s/m$ and incoming velocities of the order of 20-25 m/s which did not ensure proper roller action for energy dissipation. Thus, the performance of the solid roller bucket was not acceptable. Also it was considered that excessive excavation was required for the roller bucket with invert at El. 138.0 m and churning of material in the roller bucket might cause abrasion damage. Photos 12 and 13 show the performance of solid roller bucket for the discharge of 15400 m^3/s and 3850 m^3/s respectively.

Photo 12 : Performance of solid roller bucket for gated operation of spillway for the discharge of 15400 m^3/s

Photo 13 : Performance of solid roller bucket for gated operation of spillway for the discharge of 3850 m^3/s

3.3 Studies with Stilling Basin as Energy Dissipator

In view of the observations on the 2D model and the jump height analysis carried out with stilling basin floor level at El 144 m, the stilling basin type energy dissipator was considered to be more suitable as energy dissiaptor. After incorporation of stilling basin as energy dissipator with its floor at El 144 m in 1: 70 scale 3-D comprehensive model, the studies indicated that the performance of the spillway and energy dissipator was satisfactory as energy dissipation was taking place in the form of hydraulic jump for entire range of discharges. Photos 14 and 15 show the performance of stilling basin for the discharge of 7700 m^3/s and 3850 m^3/s for gated and ungated operation of spillway respectively.

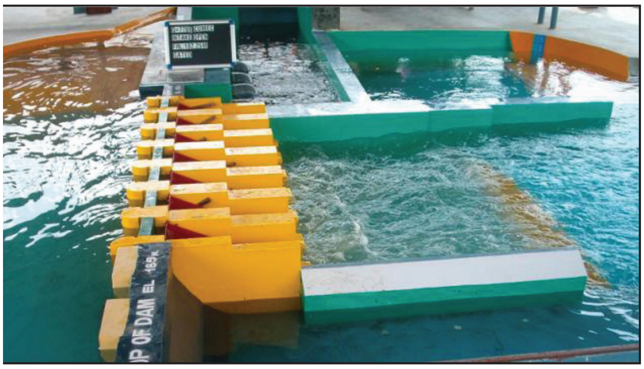

Photo 14 : Performance of stilling basin for gated operation of spillway for the discharge of 7700 m^3/s

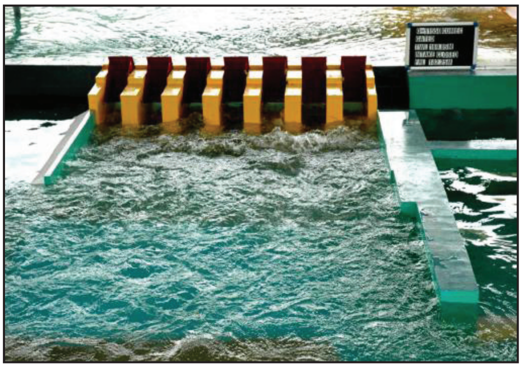

Photo 15 : Performance of stilling basin for ungated operation of spillway for the discharge of 7700 m^3/s

3.4 Raising of Power Intake

The submergence provided for the intakes was adequate, therefore, it was suggested that the intake could be raised so as to optimize the design of the intake. The MDDL was lowered by 1 m in the model and studies revealed that the flow conditions upstream of power intake were tranquil and no vortices were observed in front of intake for the entire range of discharges upto the design discharge of 787.6 m^3/s. Thus, the studies indicated that the intake level could be raised by 1 m. The Froude numbers at gate and penstock were 0.48 and 0.62 respectively which fall in the vicinity of IAHR curve as shown in Figure 2. In view of the model studies and theoretical analysis, raising of the intake level by 1.0 m was recommended as the submergence provided for the intake was found to be acceptable.

4. TEESTA LOW DAM PROJECT (TLDP) STAGE – III, WEST BENGAL

Teesta Low Dam Project Stage – III is the last but one at the fag end of the Teesta River. The project envisages construction of 32 m high barrage with total length of 140 m comprising of 7 bays each made up of about 200 m long RCC raft. The spillway consists of seven spans each with an opening size of 14 m (W) x 14 m (H) with breast walls and separated by a double pier each 3.5 m thick with design maximum discharge of 10430 m^3/s. The energy dissipator was provided in the form of a stilling basin. A surface powerhouse on the right bank has an installed capacity of 132 MW (four units of 33 MW each) with a design discharge of 693.6 m^3/s and water head of 21.34 m.

The original design of spillway consisted of a flat crest for a distance of 3.4 m on the upstream and downstream profile in the form of a slope of 1:3 up to stilling basin EL 178.0 m like a barrage. Since the head over the crest (30 m) is much more than that on the barrage, resulting in high velocity flow leading to separation, it was suggested that a crest profile conforming to the equation $x^2 = 72$ y downstream of barrage axis and an upstream profile in the form of an ellipse having an equation $X^2/3.4^2+Y^2/1.0^2=1$ may be provided. This design was accepted by the project authorities and adopted for the model studies.

4.1 Hydraulic Model Studies

Hydraulic model studies were conducted on 1:60 scale 3-D comprehensive model incorporating spillway, energy disssipator, power intake and river reach up to 725 m upstream and 675 m downstream of the dam axis. The Railey Khola nallah which meets the Teesta River just downstream of spillway was also reproduced in the model. Photos 16 and 17 show the upstream and downstream view of the model respectively. Studies revealed that the flow was free flow for the entire range of discharges with a low coefficient of discharge due to large orifice opening. The design maximum discharge of 10430 m^3/s could be passed through seven spans fully open with an upstream water level of EL 197.6 m as against the FRL EL 208 m. As such the discharging capacity of the spillway was found to be adequate. It was also suggested that the elevation of the trunnion may be raised by about 2 m and the height of left and right training walls (cellular wall) may also be raised considering bulking due to air entrainment and minimum free board required as the water profile was touching the trunnion of the radial gate and cellular walls for gated and ungated operation of the spillway. Photos 16 to 19 show the upstream and downstream view of the modeland performance of stilling basin for the discharge of 7822.5 m^3/s and 5215 m^3/s for gated operation of spillway respectively.

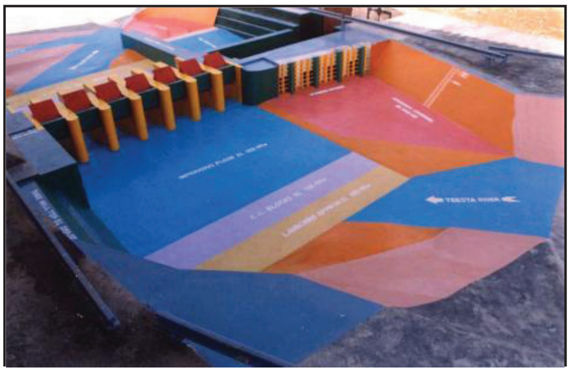

Photo 16 : Upstream View of the Model

Photo 17 : Downstream View of the Model

Photo 18 : Performance of stilling basin for the discharge of 7822.5 m3/s for gated operation of spillway

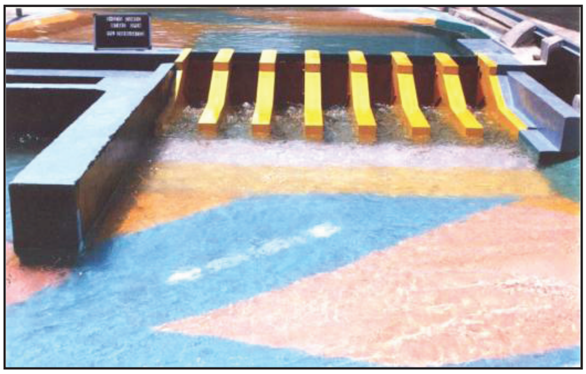

Photo 19 : Performance of stilling basin for the dis-charge of 5215 m3/s for gated operation of spillway

4.2 Tail Water and Jump Height Analysis

It was also observed that the tail water levels in front of the spillway are higher by about 2 to 3 m than those supplied by the project authorities when both the spillway and power house were operating. This rise in the tail water level was due to the deposited material brought by the Railley Khola and the subsequent high grounds in front of the spillway. The high ground in front of the spillway formed due to deposited material was dressed down varying from El. 186 m to El. 182 m resulting in reduction of about 0.5 m to 1.0 m in the tail water levels. The tail water level was also controlled by a rapid formed due to bend and constriction in the downstream. However, the water levels in the tail race channel were lower than the water levels in front of the spillway by about 2-3 m for the condition of both spillway and power house operating as the spillway and power house are separated by a divide wall. Figure 7 shows the tail water rating curves at 225 m downstream of barrage axis.

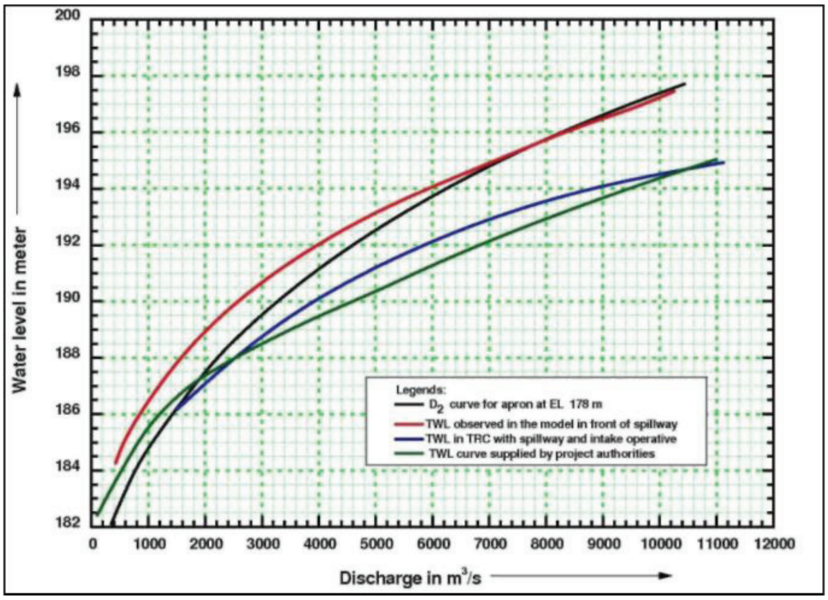

Figure 7 : Tail Water Rating Curves at 225 m downstream of barrage axis

4.3 Upstream Protection Works and Flow Condition in Tail Race Channel

As the structure was being constructed on alluvial reaches, therefore, heavy protection works were required to be provided on the upstream of the spillway as in the case of barrages. Velocities of the order of 1 m/s to 4 m/s were observed along the left bank upstream of spillway with ungated operation of spillway for the entire range of discharges. It was suggested that the protection works on the left bank beyond the left training wall may be designed for these velocities.

The right bank portion in front of the tail race channel with bed at EL 179.0 m was having a sharp curve and return velocities of the order of 0.5 m/s were prevailing at Ch. 210 m with both spillway and power house operating. This sharp curve was modified and a mild curvature with a radius of 330 m was incorporated in the model. With this modification the return velocities vanished and forward velocities of the order of 0.8 m/s were observed. Hence, it was recommended that the modified curvature of the right bank downstream of tail race channel may be adopted.

4.4 Flow Condition in the Vicinity of Power Intake

Studies conducted to optimize the design of intake indicated that the intake level may be raised by 0.5 m as there was no formation of vortices. Tranquil and satisfactorily flow conditions were observed upstream of spillway and power intakes for any combinations of intakes operating with corresponding discharges and with four units operating with a design discharge of 693.6 m^3/s. Theoretical analysis was also carried out for assessing the submergence over the centre line of intake considering the areas at the penstock and gate for calculation of Froude number. It was found that the Froude number varied from 0.43 to 0.54 with corresponding S/D ratios of about 1.5 which falls in the vicinity of IAHR curve (IAHR 1987) as shown in Figure 2. Therefore, it was recommended that the intake level may be raised by 0.5 m.

5. CONCLUSIONS

Hydraulic model studies are important for optimizing the efficient design of spillway and energy dissipator. The case studies of Teesta-IV, TLDP-IV and TLDP-III Projects indicated that the several modification were recommended for the original design of the spillway and energy disispator. All these modifications improved the overall performance of the spillway and energy dissipator and were very efficient and economical. Thus, the model studies played a crucial role in enhancing the overall performance of spillway, energy dissipator and other appurtenant structures based on techno-economic feasibility.

ACKNOWLEDGEMENT

The authors are thankful to the project and design engineers from NHPC Ltd. for constant interaction during the course of studies. The help of all the staff in conducting the studies and compiling the data is gratefully acknowledged.

REFERENCES

1. CWPRS Technical Report No. 5241 (2015). Hydraulic model studies for Teesta-IV Dam Spillway, Sikkim. 1:60 scale 3-D Comprehensive model
2. CWPRS Technical Report No. 5315 (2015). Hydraulic model studies for Revised Design of Teesta-IV Dam Spillway, Sikkim. 1:60 scale 3-D Comprehensive model
3. CWPRS Technical Report No. 5468 (2017). Hydraulic model studies for scour downstream of Teesta-IV Dam Spillway, Sikkim. 1:60 scale 3-D Comprehensive model
4. CWPRS Technical Report No. 4252 (July 2005) Hydraulic model studies for spillway and power intake of Teesta Low Dam Project, Stage - IV, 1:70 scale 3-D Comprehensive model.
5. CWPRS Technical Report No. 4343 (June 2006). Hydraulic model studies for spillway with stilling basin as energy dissipator Teesta Low Dam Project , Stage - IV, West Bengal, 1:70 scale 3-D Comprehensive model.
6. CWPRS Technical Report No. 4188 (2004). Hydraulic model studies for spillway and power intake of Teesta Low Dam Project, Stage –III, 1:60 scale 3-D comprehensive model”