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Importance of model studies in finalizing the hydraulic design of energy dissipator and plunge pool downstream of spillway-A case study

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ABSTRACT

For number of decades the art of hydraulic modelling has been an important tool in solving complex hydraulic problems. It entails, with a degree of sophistication that varies with the objective of the investigation, the use of a scaled model for replicating flow and fluid transport processes in diverse natural flow systems and for evaluating the performance of hydraulic structures. A lack of understanding of physical processes or complex boundary conditions in many fluid mechanics/ hydraulics problems which are not amenable by numerical or analytical techniques are investigated by physical models. Physical model studies are indispensable tools to optimize various dam components and appurtenant structures. The present paper includes one case study of a dam project in which the importance of hydraulic model studies conducted on 1:70 scale 3-D comprehensive model for evolving the hydraulic design of spillway, energy dissipator arrangement and plunge pool downstream of ski jump bucket has been discussed.

Keywords— *Physical model, Ski-jump Bucket, Tail water levels, Water surface and Scour profile, Pre-formed Plunge Pool*

1. INTRODUCTION

Physical model studies are indispensable tools to optimize various components of reservoir and appurtenant structures. The hydraulic design of various components of a river valley project involves two types of problems viz. site specific problems and problems connected with complex hydraulic flow phenomena. The site-specific problems are due to topography at the site, availability of foundation, nature of soil and rock strata etc. The problems associated with complex flow phenomena are many viz. non uniform flow in the approach portion creating vortices, rapidly varied flow because of complex geometry, high velocities due to high heads leading to cavitation damages, high turbulence causing hydrodynamic forces on the structure and erosion of the river bed and banks downstream, flow induced vibration for wide range of operating conditions. These problems at present cannot be dealt analytically and therefore they have to be tackled by conducting studies on physical models of these structures.

Energy dissipators are devices designed to guard downstream areas from erosion by reducing the speed of flow to acceptable limits. Variety of devices namely, stilling basins, ski jump bucket and roller buckets etc., are used for energy dissipation at the base of spillways, the dissipation of energy is through internal friction and turbulence or impact and diffusion of the high velocity flow within the mass of water. The factors that govern the selection of the sort are hydraulic considerations, topography, geology, sort of the dam, layout of other associated structures, economic comparison, frequency of usage, as well as special and environmental considerations.

The project considered in this study is under construction as a run of river scheme on the river. The project envisages construction of an 86 m high (from deepest foundation level) concrete gravity diversion dam to generate 1020 MW of power utilizing a design head of 236 m at an underground power house. The main spillway consists of 7 sluices of dimensions 8 m (W) x 13.2 m (H) to pass probable maximum flood of 11,723 m3/s and Glacial Lake Outburst Flood (GLOF) of 4,300 m3/s. The MWL / FRL are at El. 843 m and the MDDL is at El. 825 m. The crest of the spillway is at El. 797 m. An auxiliary spillway in the form of ogee with crest at El. 839 m is equipped with vertical lift gate of size 4 m (W) x 4 m (H) at the centre of main spillway. A Ski -jump bucket has been provided as energy dissipator for both main and auxiliary spillways. A pre excavated plunge pool is provided downstream of the ski-jump bucket. The water conductor system at the right bank comprises of four power intakes carrying a discharge of 552 m3/s, four desilting basins of size 420 m (L) x 19 m (W) x 24.743 m (H) and an 8.52 km long, 11 m diameter circular concrete lined head race tunnel and a 137 m high surge shaft of 31 m diameter. The tail race system comprises of a 2895 m long and 11 m diameter D-shaped tunnels.

2. STATEMENT OF PROBLEM/OBJECTIVE

Main objective of the study is to investigate hydraulic parameters such as discharging capacity of spillway, water surface profile, pressure distribution over spillway surface and to finalize the plunge pool geometry based on scour studies for a dam project by means of physical model studies.

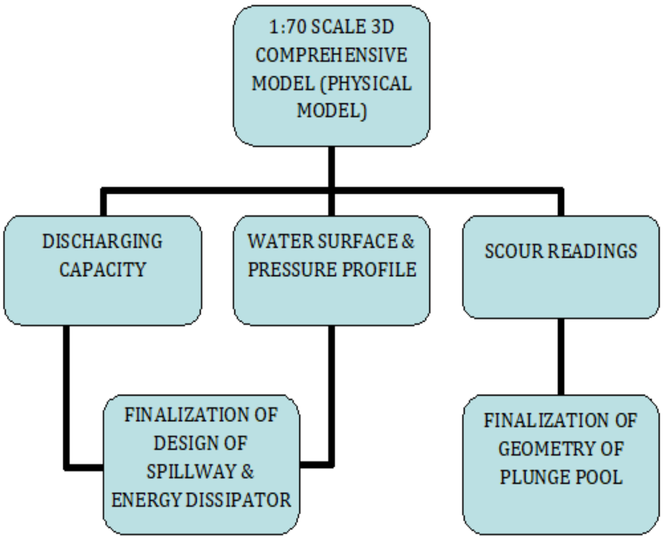
3. LITERATURE REVIEW

(Ninad Doke, et al. March 2019) They had experimented that, When the water is dispatched through the spillway the static energy gets converted in kinetic energy. This energy is in high magnitude due to the force which destroys the nearby area by flooding. Thus the kinetic energy is reducing to acceptable limits. They used Ski-jump energy dissipator to reduce the kinetic energy of Khadakwasla dam. (Dr. M.R. Bhajantri et al. 2018) They had experimented that, Dissipation of K.E. generated at the toe of spillway is important for bringing the flow velocity of the river back to normal in shortest possible distance. great deal of sediments entering the reservoir may be a significant issue in Himalayan region which reduces the capacity of the reservoir and damages the hydropower plants. Although no design procedures were readily available for designing the energy dissipators for orifice spillways, experience from the hydraulic model studies and prototype provides useful guidelines. (Dhaktode Asaram et al. June 2016) They studied to investigate the consequences of various slope of ogee spillway surface on energy dissipation. With slope of 1:1, 0.85:1, and 0.75:1 three ogee spillway models were prepared. 18 test runs were applied to analyze the energy dissipation downstream the three spillway models. (Sokchhay Heng et al. May 2012) They had studied that, Spillway is a major concern for stabilization of hydraulic structures and their downstream channel. The objective of this study were to select an appropriate movable riverbed material for reproducing scour hole in the physical model and to analyse the characteristics of its formation using the selected material. (Saiful Bahri Hamzah et al. June 2016) They had experimented that, Physical model was utilised to create an assessment of Batu Dam spillway, yet on make informed recommendations of its hydraulic performance and proposed alterations. optimum configuration was obtained from a model scale of 1:25. Simulations with reference to various reservoir levels and discharges to analyze effects of the various flow conditions were performed.

Physical hydraulic models are commonly used during design stages to optimize a structure and to make sure a secure operation of the structure.

(IS Code 10132: 1982) This code has guideline on selection of spillways and energy dissipators. (IS Code 7365: 2010) This code has guideline on Criteria for hydraulic design of bucket type energy dissipators.

4. METHODOLOGY



Physical model studies were conducted for discharging capacity, measurement of water surface profile, measurement of pressure distribution and performance of ski jump bucket.

For carrying out scour studies, the most common method of representing the geological features of river bed and banks in the vicinity of anticipated plunge pool scour in the physical model is the use of cohesionless erodible material to reproduce the river topography. The existing 1:70 scale 3-D comprehensive model of spillway was modified and river portion downstream of bucket lip was from chainage of 110 m to 330 m between contours El. 840 m on left and right banks were excavated as a scour pit with deepest level as El. 725 m. This river portion was reproduced erodible, by filling with cohesionless material (sand) of mean size (d50) of about 2 mm and the river banks above these elevations were kept rigid. The sides of scour pit were made rigid but vertical to avoid subsidence of loose cohesion less material from the sides into the scour hole. The accepted relationships of hydraulic similitude, supported Froudian criteria were wont to express the mathematical relations between the size and hydraulic quantities of the model and therefore the prototype. The general relations expressed in terms of model scale are as given in Table 1 below:

Table 1: Model Scale Relations for Various Dimensions

Parameter	Scale Relation
Length	1:70
Area	1:4900
Velocity	1:8.367
Discharge	1:40996.34
Time	1:8.367
Pressure in m of water head	1:70
Manning's 'n'	1:2.03

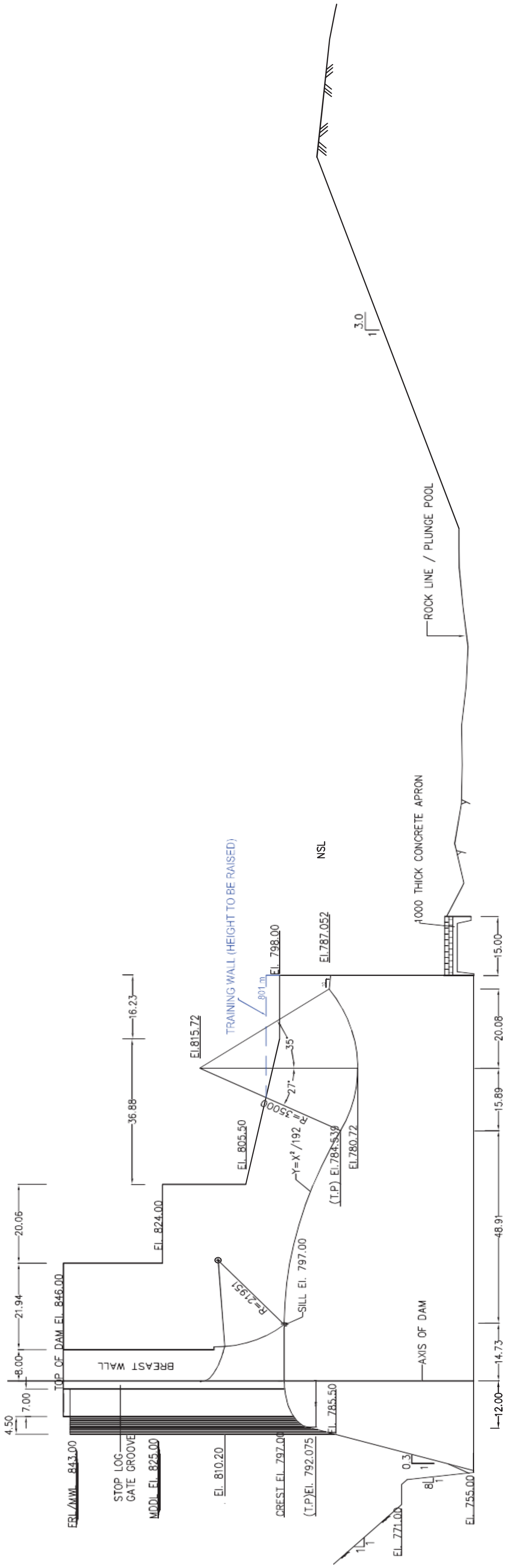


Fig. 1: Cross Section of Spillway

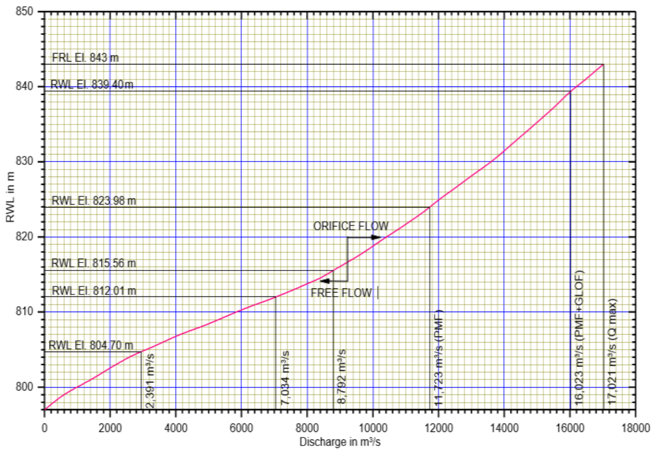
Fig. 2: Downstream Side of Dam

Fig. 3: Upstream Side of Dam

5. EXPERIMENTATION

5.1 Discharging Capacity of Spillway

The studies were conducted for assessing the discharging capacity of the spillway. For ungated (i.e. by keeping all the gates fully open) flow condition the maximum discharge of 17021 m^3/s can be passed at FRL El. 843 m. Probable Maximum Flood (PMF) combined with Glacial Lake Outburst Flood (GLOF) of 16023 m^3/s can be passed at RWL 839.40 m, whereas PMF of 11723 m^3/s can be passed at RWL El. 823.98 m, 8792m^3/s at RWL El. 815.56 m, 7034m^3/s at RWL El. 812.01 m, 2391m^3/s at RWL El. 804.70 m. Graph-1 shows the discharging capacity curve for the spillway for ungated operation of spillway. A discharging capacity of the spillway was considered to be adequate.



Graph 1: Discharging Capacity Curve

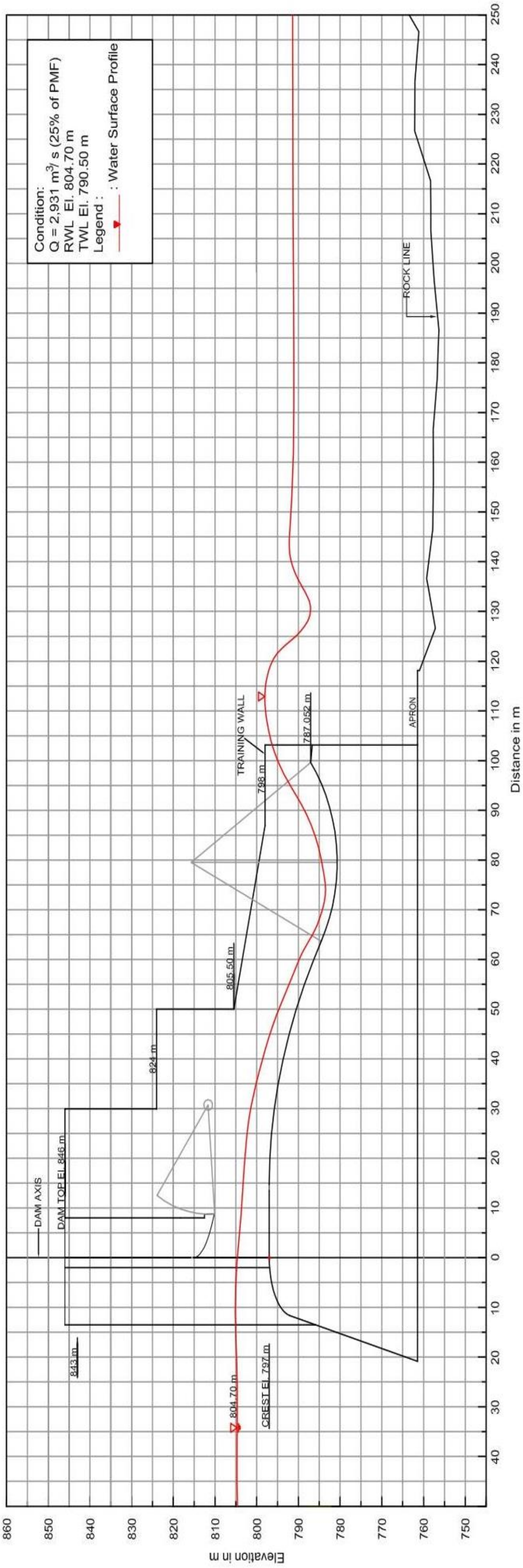
5.2 Water Surface Profiles and Pressure Profiles

Water surface profiles and pressure profiles were observed on the upstream side and the downstream side of spillway for entire range of discharges with ungated and gated operation. Graph 2 to 5 show the water surface profiles and pressure profiles of spillway. The flow conditions on upstream side of spillway are predominantly straight with high flow velocities, due to steeper gradient, for all the discharge conditions with gated and ungated operation of spillway. Trunnion of gate was well above water surface profiles for all the operating conditions, and is acceptable.

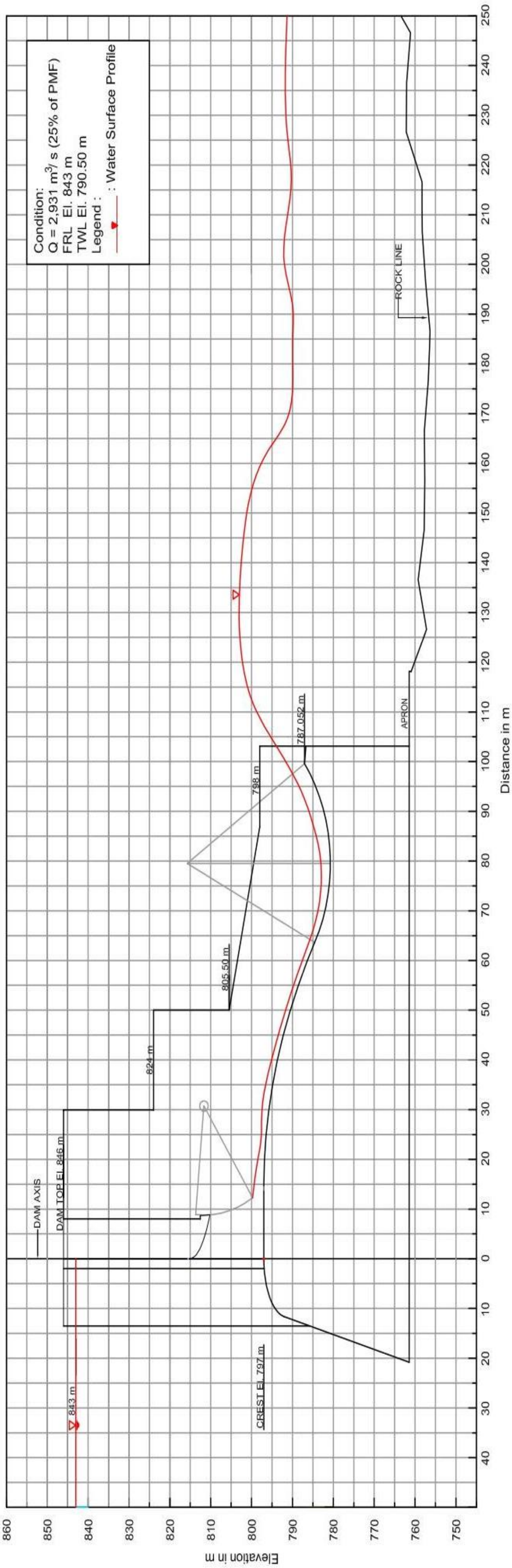
5.3 Performance of Ski Jump Bucket

Performance of modified ski jump bucket was observed for entire range of discharges and reservoir water levels for gated and ungated operation of spillway. The corresponding tail water levels at 286 m downstream of dam axis were maintained as per the tail water rating curve shown in graph-6. It was observed that for both gated and ungated operation of spillway, clear ski-jump action was forming for all the discharges. The modified design of ski jump bucket with raised invert and lip by about 4 m to that of original design was found satisfactory. However, the bucket lip was Observed getting submerged in tail water due to high tail water levels for all conditions but the high velocity ski jump jet was able to push the tail water levels allowing formation of clear ski jump action. Lip of auxiliary spillway was getting submerged for discharge of 60% of PMF allowing tail water to enter the bucket. The maximum throw distance of the ski-jump jet was about 76.5 m from bucket lip for 60% PMF with gated operation of spillway and minimum of 24 m for 25% of PMF with ungated operation of spillway. Thus, for all the operating conditions the performance of ski jump bucket was said to be satisfactory.

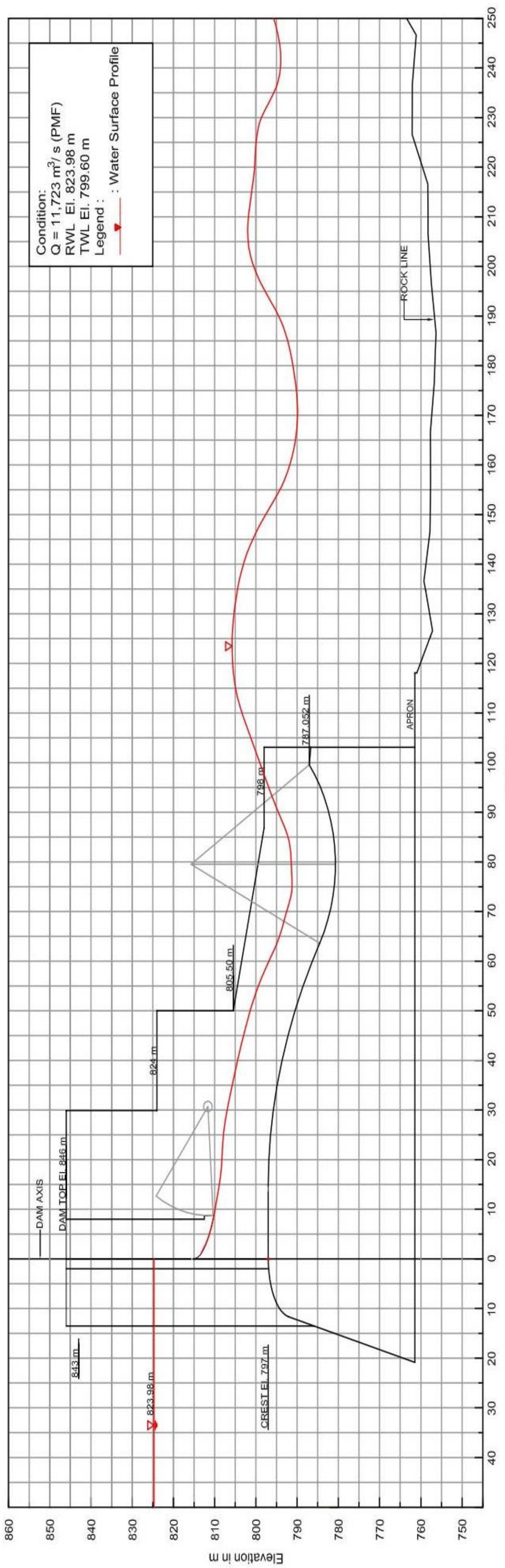
The minimum discharge required for forming ski jump in all spans was recorded as 1000 m^3/s (RWL El. 799.0 m) when lowered from MDDL. The jump was observed forming in different spans, when the water level was raised from crest level. The jump was recorded in span 3 and 5 at discharge of 1800 m^3/s and for span 2,4,6 and 7 for discharge of 5400 m^3/s and the jump for span 1 was recorded at discharge of 7400 m^3/s (RWL El. 812.6 m) which was highest of all spans discharge. It was attributed to the protrusion of left bank into the width of spillway at section 140 m upstream of dam axis, at the upstream coffer dam which was proposed. To avoid undermining of bucket a concrete apron is proposed of 15 m long and 1.5 m downstream of lip firmly anchored for providing cascading flows.



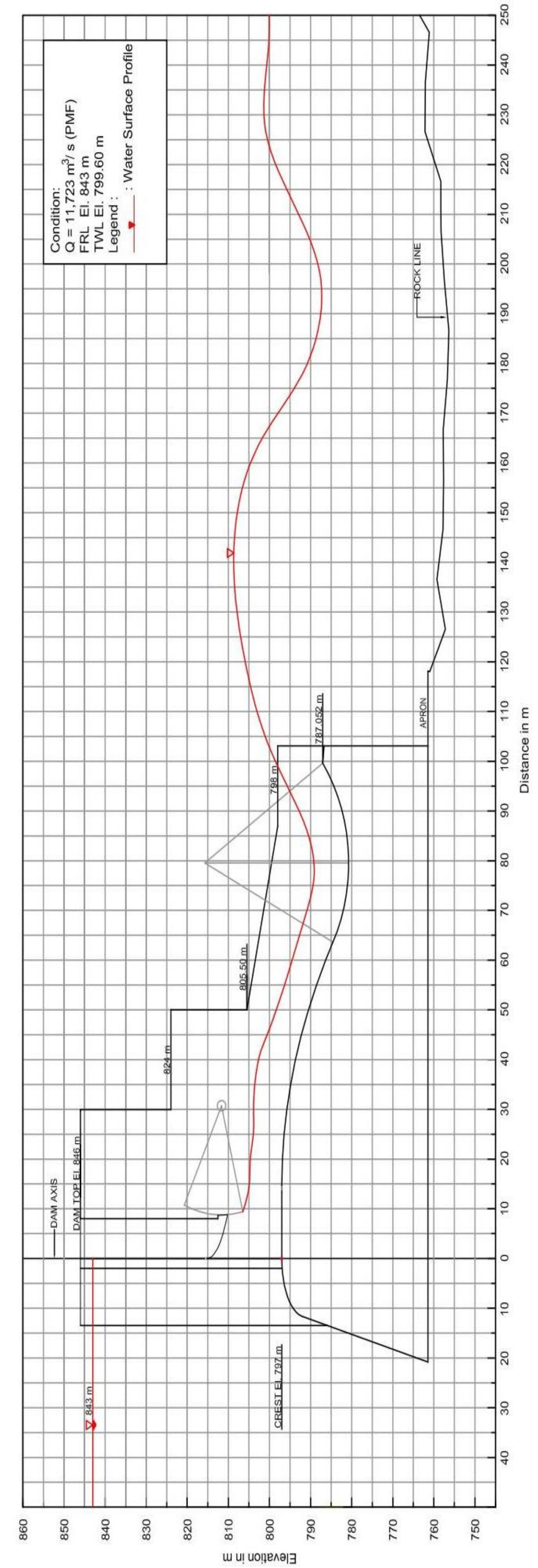
Graph 2: Water Surface and Pressure Profile at Q=2931 M^3/S (Ungated Operation)



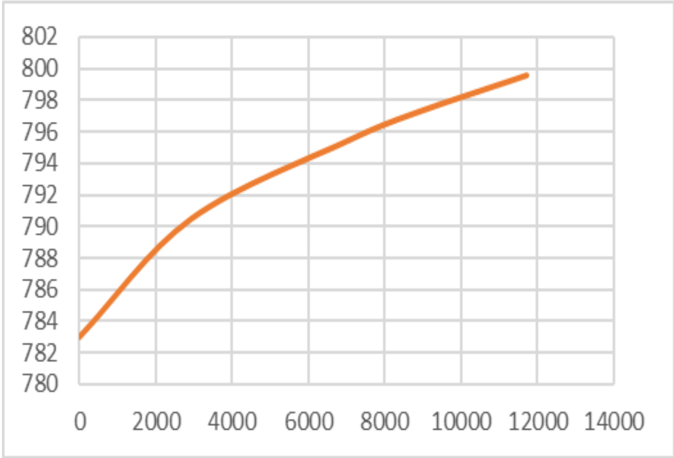
Graph 3: Water Surface and Pressure Profile at Q=2931 M^3/S (Gated Operation)



Graph 4: Water Surface and Pressure Profile at Q=11,723 M^3/S (Ungated Operation)



Graph 5: Water Surface and Pressure Profile at Q=11,723 M³/S (Gated Operation)



Graph 6: Tail Water Rating Curve

Table -2: RWL & TWL for Different Gate Operations

Sr. no	Discharge in m³/s	RWL m	Gate operation	TWL m
1	2931 (25% of PMF)	804.70	Fully Open	790.50
2		843.00	Partially Open	
3	7034 (60% of PMF)	812.00	Fully Open	795.45
4		843.00	Partially Open	
5	8792 (75% of PMF)	815.56	Fully Open	797.20
6		843.00	Partially Open	
7	11,723 (100% of PMF)	823.98	Fully Open	799.60
8		843.00	Partially Open	

5.4 Scour Downstream of Spillway

Experiments were conducted to assess the scour downstream of ski jump bucket and also to observe water surface profiles over the spillway and on downstream side for the entire range of discharges and reservoir water level. The tail water levels at chainage 286 m downstream of dam axis were maintained as per the tail water rating curve shown in graph 6.

The ultimate scour depth is the result of approach of cohesionless erodible bed which simulates fully disintegrated rock. The scour studies were conducted by reproducing cohesionless erodible bed material to assess the extent and pattern of scour so that the location, shape and size of plunge pool can be determined. The cohesionless bed was reproduced for assessment of depth of scour downstream of spillway and location of plunge pool.

Table 3: Observed Scour Values for Various Operating Conditions

Discharge In m³/s	RWL In m	Location & depth of scour			
		Gated		Ungated	
		Chainage (m)	Elevⁿ (m)	Chainage (m)	Elevⁿ (m)
2931 (25% of PMF)	804.70	---	---	160	772.5
	843.00	195	771	---	---
7034 (60% of PMF)	812.00	---	---	175	772
	843.00	215	770	---	---
8792 (75% of PMF)	815.56	---	---	180	770
	843.00	200	769	---	---
11,723 (100% of PMF)	823.98	---	---	195	769
	843.00	210	768	---	---

Fig. 4: Model View from Downstream

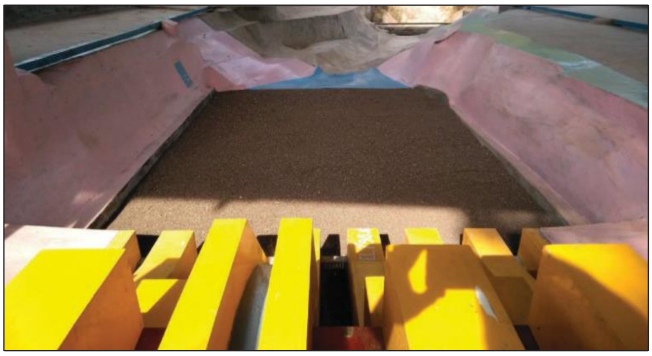


Fig. 5: Model View from Upstream

Fig. 6: Flow Conditions Q=2931 M^3/S (Ungated Operation)

Fig. 7: Scour at Q=2931 M^3/S (Ungated Operation)

Fig. 8: Flow Conditions Q=2931 M^3/S (Gated Operation)

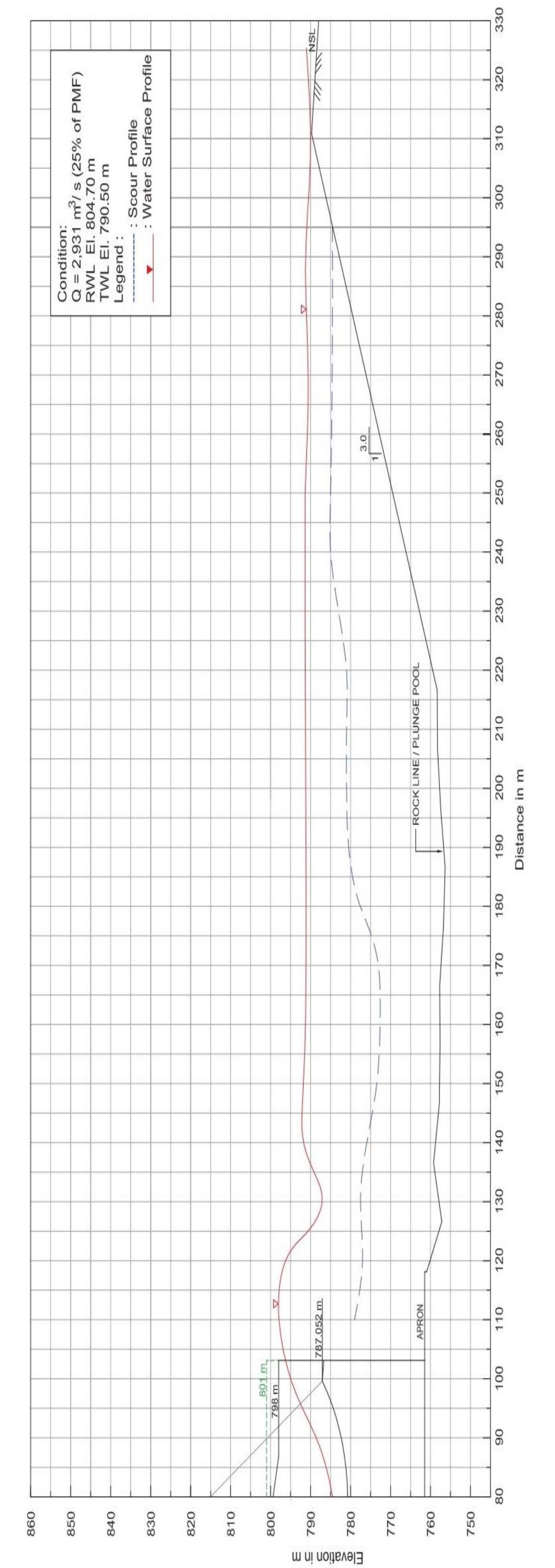
Fig. 9: Scour at Q=2931 M^3/S (Gated Operation)

Fig. 10: Flow Conditions, Q=11,723 M^3/S (Ungated Operation)

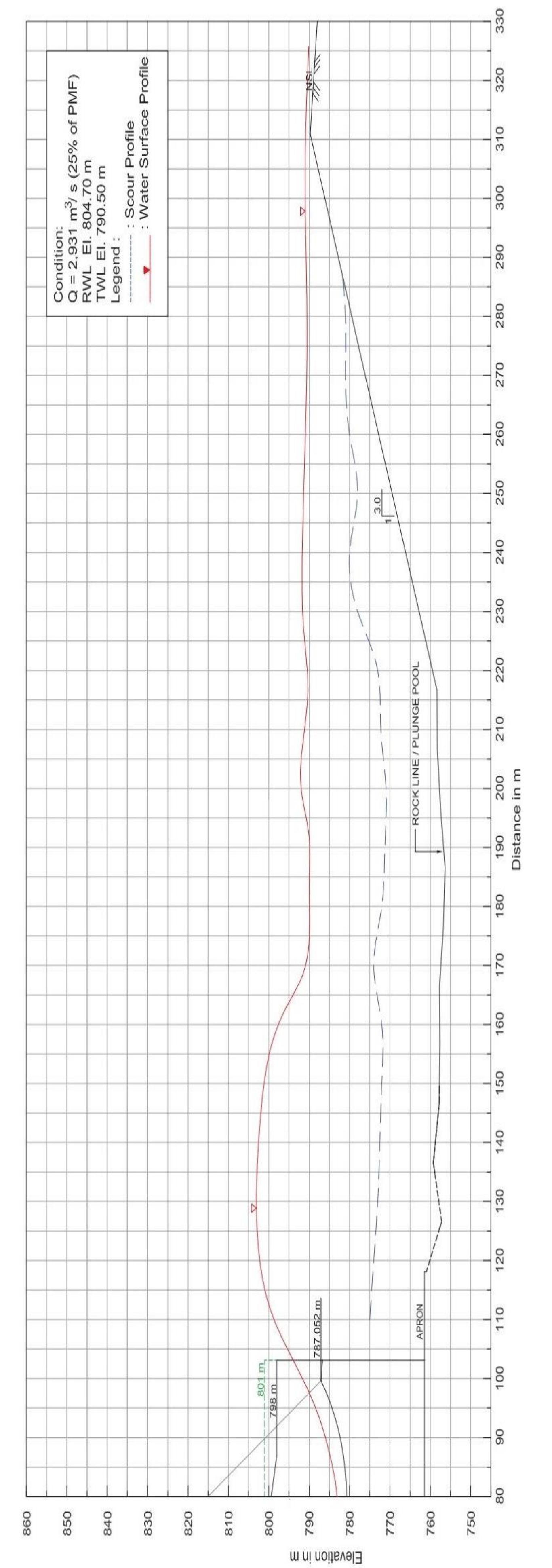
Fig. 11: Scour at Q=11,723 M^3/S (Ungated Operation)

Fig. 12: Flow Conditions Q=11,723 M^3/S (Gated Operation)

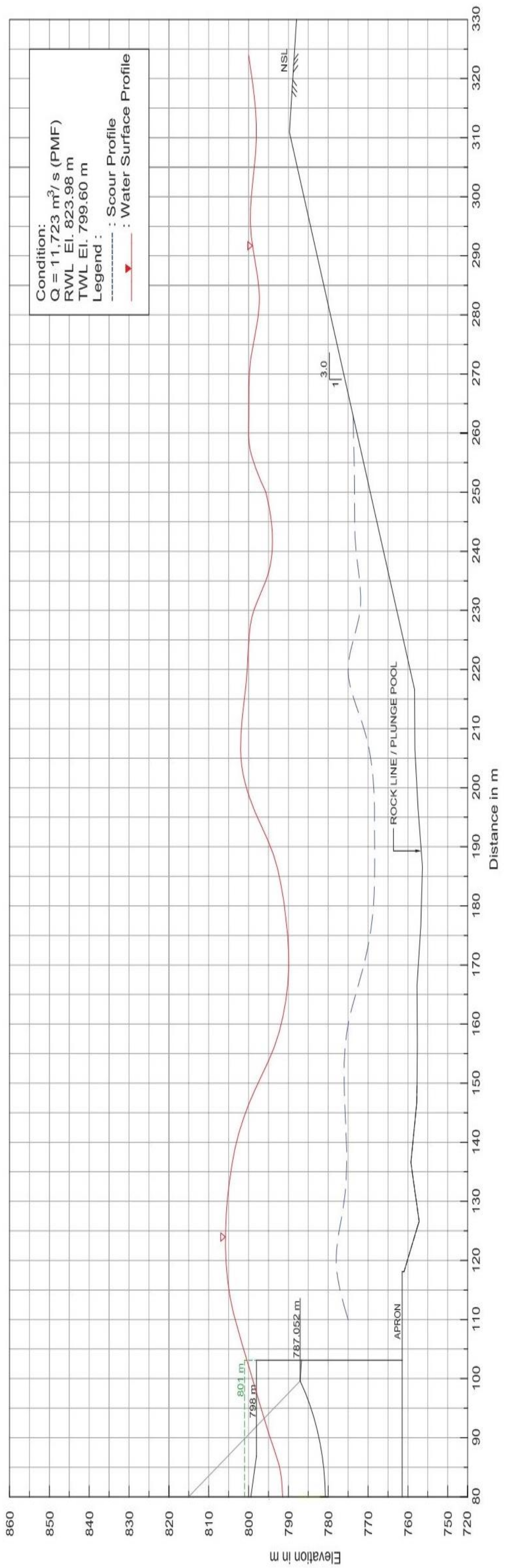
Fig. 13: Scour at Q=11,723 M^3/S (Gated Operation)



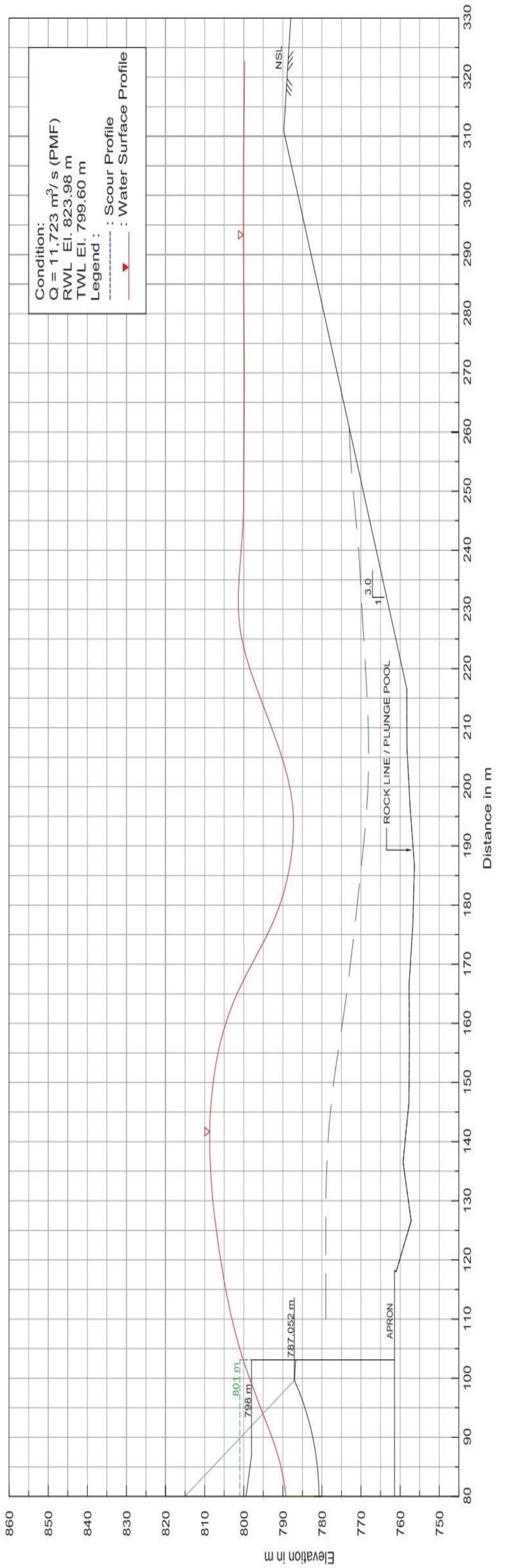
Graph 7: Water Surface and Scour Profile at Q=2931 M^3/S (Ungated Operation)



Graph 8: Water Surface and Scour Profile at Q=2931 M^3/S (Gated Operation)



Graph 9: Water Surface and Scour Profile at Q=11,723 M³/S (Ungated Operation)



Graph 10: Water Surface and Scour Profile at Q=11,723 M³/S (Gated Operation)

6. CONCLUSION

Water surface and pressure profile were observed for the entire range of discharges and performance of ski jump bucket was found satisfactory for the selected design.

The deepest scour reached up to El. 768 m at chainage 210 m downstream of dam axis for discharge of 11,723 m^3/s (PMF) passed with gated operation and with ungated operation of spillway, it reached upto El. 769 m at chainage 195 m. For 75% PMF with gated and ungated operation the deepest scour depth reached upto El. 769 m at chainage 200 m and El. 770 m at 180 m respectively. For 25% of PMF, scour depth reached upto El. 771 m at 195 m and El. 772.5 m at chainage 160 m for gated and ungated operation respectively.

The bottom elevation of pre-formed plunge pool is to be recommended same as existing rockline against the proposed plunge pool bed at El. 750 m. The apron downstream of bucket lip was firmly anchored to rockline beneath to avoid undermining of bucket for cascading flows. The downstream end of apron is the start of upstream slope of plunge pool. For bed level of pre-formed plunge pool the average elevation of rockline is El. 757m. This avoids excavation of rock of about 7 m for a distance of about 100 m for optimising cost and time. From Ch. 215 m, the downstream slope of pre-formed plunge pool with a slope of 1 (V): 3(H) was joined to the river bed. Thus, Physical model studies are important tools to optimize various components of dams and appurtenant structures.

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