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Assessment of ski-jump bucket parameters for sluice spillway of Himalayan dam by hydraulic model studies

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ABSTRACT

Ski jump buckets are a very popular type of energy dissipators for dam spillways. These ski jump buckets are provided where the tailwater levels downstream of the spillway are such low that stilling basins type of energy dissipator cannot be provided. The design of ski jump bucket for a spillway of a dam is very complex in nature, as it involves hydraulic variables such as discharge intensity, head over the spillway, lip angle, lip elevation, full reservoir level, tailwater level, velocity head of jet at bucket lip, bucket radius and frictional losses. Himalayan dams are mainly run- of- river schemes mainly meant for hydropower generation and where poundages are minimum and also serve dual purposes of disposing of flood and sediments. Many of Himalayan dam sluice spillways are provided with ski jump buckets as energy dissipators. Sometimes ski jump buckets are provided when the tailwater levels are higher and bucket lip is provided under submerged condition. Computing jet trajectory length and trajectory height of ski jump bucket are important as the throw distance play a decisive role in fixing downstream structures like downstream cofferdam, tailrace outfalls, diversion tunnels, etc. Also, throw height computation is important to factor in fixing the heights of divider walls and training walls of the spillway. Various empirical formulae are available in the literature for finding out the throw distance of trajectory buckets. But hydraulic model studies play a crucial role in assessing the performance of ski jump buckets. The hydraulic model is the best tool to design or modify the spillways and energy dissipators by making the model run for different discharges and gate operation schedules prior to the construction of the project. In these papers, authors compared the results of model studies with the BIS empirical formula in obtaining the throw distance and throw height of ski jump buckets.

Keywords*— Himalayan dam, Spillway, Ski-jump bucket, Trajectory bucket, Throw distance, Throw height, Lip angle, Tailwater level, Lip elevation*

1. INTRODUCTION

One of the key issues concerns the safety of any dam is the performance of spillway. The spillway is designed to dispose of design flood safely to downstream for which energy dissipator must be suitable. There are various types of energy dissipaters provided dam spillways and mostly used are stilling basins, roller buckets (solid or slotted), trajectory buckets. The suitability of energy dissipater is depended on prevailing tail water levels and geology downstream of the dam. Ski jump bucket type of energy dissipator is more suitable when, tail water depth at the dam site is much lower than the sequent depth of hydraulic jump above bucket invert, thus preventing the formation of the jump. Ski jump buckets are suited where the bed of the river channel downstream is composed of sound rock. The energy dissipater must be good enough in dissipating the energy of flood coming over the spillway to permissible levels to prevent erosion downstream, of the spillway and prevent the undermining of the spillway. Modifications to designed spillway or energy dissipator are required if the performance of spillway or energy dissipater is not proper.

Himalayan dams have spillways mostly of sluice or breast wall type, which are required to pass not only the design flood but also the enormous quantity of sediments usually carried by the Himalayan Rivers. Ski jump buckets type energy dissipaters are mostly provided for Himalayan dam spillways. Though tail water levels prevailing downstream of the spillway are to be very low for the effective functioning of ski jump bucket but sometimes for sluice/ breast wall spillways, where the tail water levels are found at higher levels, ski jump buckets may be provided by locating the invert of the bucket at a higher level. Himalayan dam spillways are built with breast wall/sluice spillways where the crest of spillway is the location at a minimum possible elevation above river bed level and breast walls are introduced to maintain the head of the order of 30- 50 m. In case of trajectory bucket, also known as a ski-jump bucket, an incoming jet of water leaves as free discharging upturned jet and falls into the river some distance downstream of toe of the spillway. The energy dissipation using trajectory bucket takes place because of (a) the resistance between the jet and air (b) diffusion of the jet in the tail water (c) impact of jet on the river bed and (d) internal friction within the jet. The important parameters which are to be assessed for ski jump bucket are the throw distance and throw height of the jump. Throw distance governs the location of downstream structures like coffer dams, tail race outfalls, etc. and throws height above the invert of the ski buckets decides the height of training walls and dividing walls. These are depended upon the hydraulic/ structural design of ski ump bucket.

Hydraulic model studies are the best tool to finalize the design of spillways and ski jump buckets as the studies can be carried out for various operating conditions before finalizing the designs, when the preliminary designs of the same may be based on empirical formulae.

2. DESIGN CRITERIA OF COMPONENTS OF SKI - JUMP BUCKET (BIS 7365: 2010)

Ski jump bucket is an upturn solid bucket that is used as energy dissipater for spillways when the tail water depth is insufficient for the formation of the hydraulic jump, the bed of the river channel downstream comprises sound rock and is capable of withstanding, without excessive scour, the impact of the high-velocity jet. The flood passing over the spillway is thrown away from the toe of the dam to a considerable distance downstream as a free discharging upturned jet which falls into the channel directly, thereby avoiding excessive scour immediately downstream of the spillway. There is hardly any energy dissipation within the bucket itself except that due to shear along the bucket surface. The device is used mainly to increase the distance from the structure to the place where high-velocity jet hits the channel bed, thus avoiding the danger of excessive scour immediately downstream of the spillway. Due to the throw of the jet in the shape of a trajectory, energy dissipation takes place by:

(a) Internal friction within the jet,
(b) Interaction between the jet and surrounding air,
(c) Diffusion of the jet in the tail water,
(d) Impact of the channel bed, and
(e) Pre-formed plunge pool.

Parameters such as radius of the bucket, invert elevation, lip angle, lip elevation and throw distance/trajectory lengths are needed to be considered for the design of any trajectory-bucket type of energy dissipaters. On the basis of theoretical as well as experimental data collected, many investigators have pro- posed equations for the computation of bucket radius. These equations involve one or all variable such as X_v, H_v, H, Y, A and Φ.

The fixation of the invert level depends on the site, tail water conditions and the expected performance of the bucket. If a pure flip action is desired at all the stages, the lip has to be kept above the maximum tail water level. However, from consideration of economy, the invert is generally kept as near as river bed level. If slightly higher than the bed level so that the tail-water does not build up above the lip near the toe, the jet is thrown out clearly into the air so that it meets the bed sufficiently downstream. Figure 1shows the definition sketch of ski jump bucket (IS 7365).

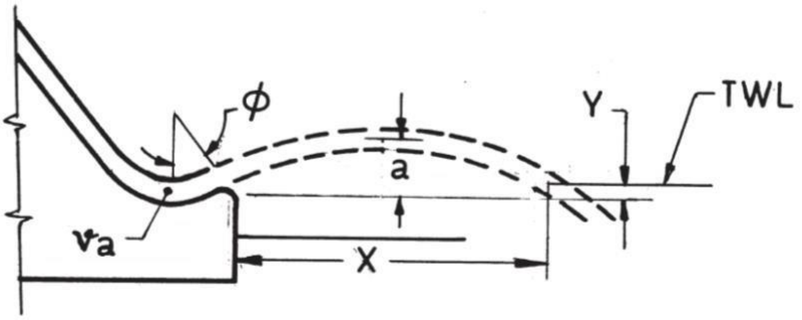

Fig. 1: Definition Sketch of ski jump bucket (IS 7365: 2010)

2.1 Trajectory length

The following expression may be used for calculating the horizontal throw distance (IS 7365):

$$\frac{X}{H_v} = \sin 2\phi + 2\cos\phi\sqrt{\sin^2\phi + Y/H_v}$$

2.2 Trajectory height

The vertical distance of throw above the lip level may be calculated from the following formula:

$$a = \frac{v_a^2 \sin^2\phi}{2g}$$

The height, slope, exit angle and the shape of the lip are of particular importance in deflecting the flow upward in the case of trajectory buckets. The shape of lip needs more careful attention in the design when the tail water is slightly above the bucket lip. In general, the shape of the lip is sought to be made flat for ease in construction. High sub-atmospheric pressure occurs in case of the flat lip when the tail water level is higher than the bucket lip it happens mainly in the Himalayan region.

3. HYDRAULIC MODEL STUDIES

A geometrically similar 1: 70 scale Froudian 3-D comprehensive spillway model was used to assesss the parameters of ski jump bucket and study the performance of ski jump bucket. The Himalayan project envisages construction of a 136 m high concrete gravity diversion dam to generate 1200 MW of power utilizing a net head of 343 m at an underground power house. The is designed to pass maximum discharge of 11,500 m^3/s and Glacial Lake Outburst Flood (GLOF) discharge of 4,300 m^3/s through 7 sluices at Full Reservoir Level (FRL) El.1202 m. The crest of the spillway is at El. 1166 m which is 16 m above river bed level. An auxiliary spillway in the form of ogee with a crest at El. 1198 m is equipped with vertical lift gate of size 4 m (W) x 4 m (H) at the centre of the main spillway. Ski jump bucket has been provided as energy dissipator for both the spillways. The water conductor system at the left bank comprises of four power intakes carrying a discharge of 462.65 m^3/s, a 9 km long 10 m diameter circular concrete lined head race tunnel carrying discharge of 385.54 m^3/s and a 128.5 m high, 24.5 m diameter underground restricted orifice type surge shaft. The tail race system comprises of a 1311 m long and 10 m diameter D-shaped tail-race tunnel. Figure 2 shows cross-section of spillway showing ski jump bucket as energy dissipator.

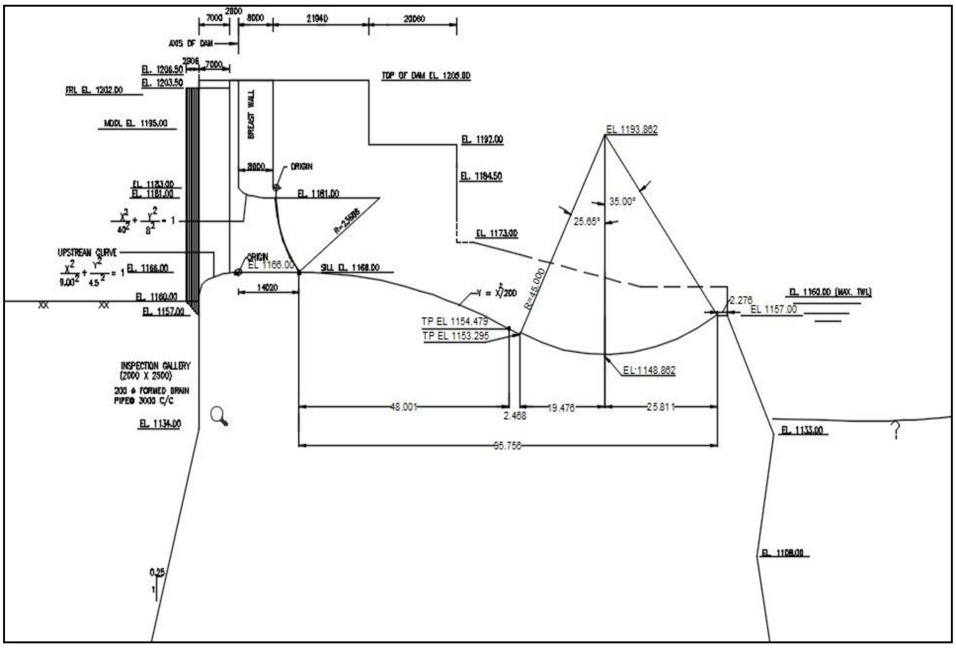

Fig. 2: Cross section of spillway showing ski jump bucket as an energy dissipator

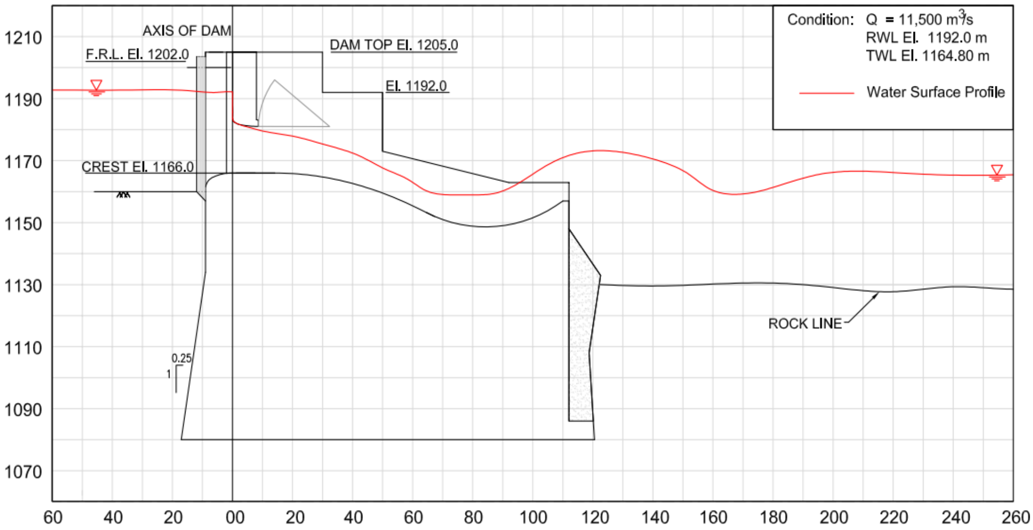

Fig. 3: Typical Water surface profile

Hydraulic model studies (HMS) were conducted on 1: 70 scale geometrically similar Froudian 3-D comprehensive model. The studies carried out for various discharges from 25% of Probable Maximum Flood (PMF) to 100% PMF under different reservoir water levels (RWL) with all gates fully open and partially open conditions. The tail water levels were maintained downstream of the dam axis as per G-D curve. Observations of ski jump bucket parameters like throw distance and throw height were made for different operating conditions. For all these conditions, the discharge intensity varies from 50 to 200 $m^3/s/m$ and differential head from RWL to Lip elevation varies between 18 m to 45 m. Figure 3 shows typical water surface profile showing throw distance and throw height of ski jump bucket for passing discharge of 11500 m^3/s at RWL El. 1192 m. Photo 1 shows the ski jump bucket performance for the same condition.

Fig. 4: Performance of ski jump bucket (Q=11500 m^3/s, RWL El. 1192 m)

3.1 Presentation and analysis of data

The observed throw distances from Hydraulic Model Studies (HMS) were compared with computed throw distances using BIS equation and presented in Table 1. The values are plotted as shown figure 4. A typical calculation for finding throw distance and height is shown as Annexure. The values obtained from model studies are not fully in agreement with the values computed from the BIS equation. It can be seen from data that the observed throw distance was less than computed throw distance but observed throw height was more than computed throw height. However, for the ungated operation of the spillway, the observed throw distance was nearly matching with computed throw distance. The reasons that can be attributed to this variation are the intensity of flow, Froude number, submergence of bucket lip in prevailing tail water levels, head causing flow, bucket radius and lip angle. The intensity of flow considered for the spillway model studies was in the range of 50 - 200 $m^3/ s/ m$ and head causing flow above bucket lip were in the range of 18- 45 m. It was seen that the submergence of the lip above tail water was 7.8 m for different conditions of the study. The higher tail water levels prevailing downstream of ski jump bucket may be the factor influencing the formation of clear ski action of the jump (Ramarao et al, 2015). Table -2 shows submergence levels at the lip of a ski jump bucket for various operating conditions**.** The maximum velocity under consideration for the study was in the range of 27 m/s. The air resistance affects the throw distance considerably and the effect of air resistance is small whenever velocity of the jet is less than about 20 m/s but it reduces the throw distance by about 30% when the velocity is about 40 m/s (Khatsuria, 2005). Figure 5 shows the Comparison of observed and theoretical values for varying Froude Number.

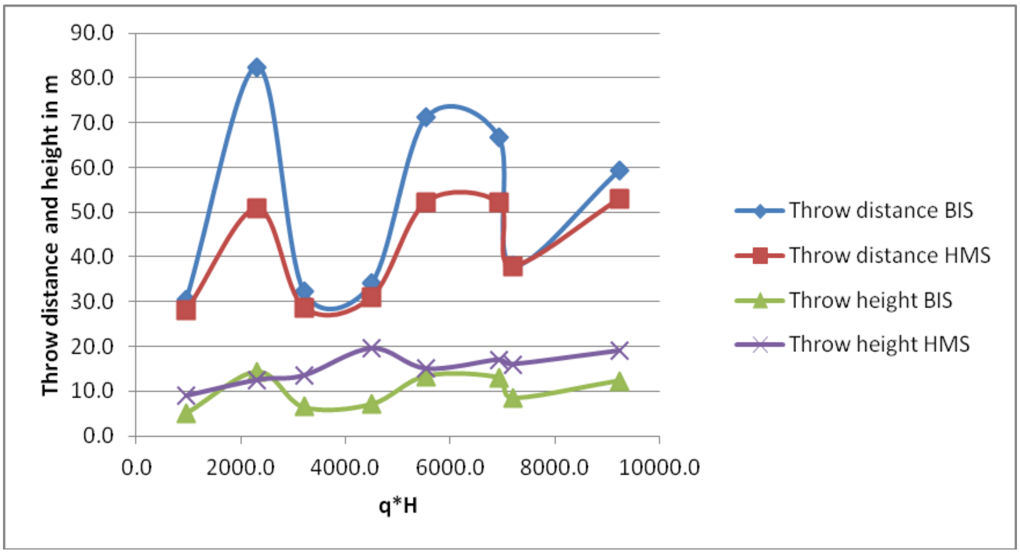

Fig. 5: Comparison of observed and theoretical values for varying qH_v Table-1

Table 1: Comparison of Observed and Computed Throw Distances

q*Hv	Observed Throw distance (Hydraulic Model studies)	The theoretical value of throw distance (BIS)	Observed throw height (Hydraulic model studies)	The theoretical value of throw height (BIS)
9241.1	52.9	59.4	19	12.3
7187.5	37.9	38.2	16	8.5
6930.8	52.1	66.8	17	13.0
5544.6	52.2	71.1	15	13.4
4497.3	30.9	34.1	19.5	7.2
3203.6	28.6	32.4	13.5	6.5
2310.3	50.8	82.5	12.5	14.2
954.9	27.9	30.5	9	5.2

Table 2: Submergence levels at the lip of ski jump bucket

$q*H_v$	Depth of TWL above the lip	Submergence ratio	Froude No.
9241.1	7.80	0.83	3.1
7187.5	7.80	0.78	2.4
6930.8	5.30	0.88	3.8
5544.6	3.80	0.92	4.3
4497.3	5.30	0.82	2.4
3203.6	3.80	0.85	2.5
2310.3	-0.90	1.02	7.0
954.9	-0.90	1.05	3.3

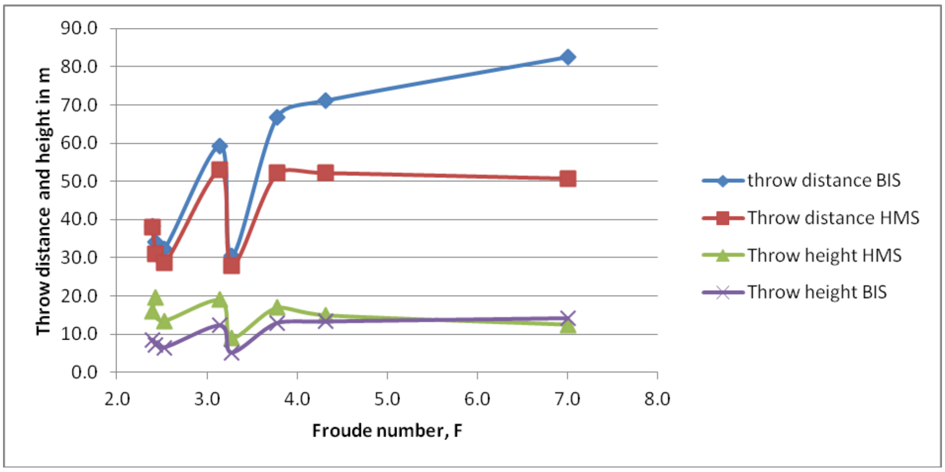

Fig. 6: Comparison of observed and theoretical values for varying Froude Number

4. CONCLUSION

Ski jump buckets are a popular type of energy dissipators provided even for sluice spillways of Himalayan dams where the tail water levels are higher than the lip of the bucket. Ski jump bucket performance of and its efficiency as an energy dissipator for a spillway are functions of discharge intensity, prevailing tail water levels, the radius of the bucket, lip angle, invert elevation, design head. These factors influence the performance of ski jump bucket by providing clear ski action with adequate throw distance and throw height for proper energy dissipation of outflow flood. The BIS has developed equations for computing trajectory length and height based on the theory of path of the projectile. It was found to be giving varied results with the observed values from hydraulic model studies when applied to sluice spillways of Himalayan dams with higher tail water levels. For carrying out the model studies, various flow intensities considered for the spillway model studies were in the range of 50 - 200 m^3/ s/ m and head causing flow above bucket lip were in the range of 18- 45 m. The maximum velocity under consideration for the study was in the range of 27 m/s. The higher tail water levels prevailing downstream of ski jump bucket may be the factor influencing the formation of clear ski action of the jump. It was seen that the submergence of the lip above tail water was 7.8 m for different conditions of the study. The air resistance also seems affecting the throw distance considerably and it reduces the throw distance by about 30% when the velocity is about 40 m/s.

5. ACKNOWLEDGEMENT

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APPENDIX

Notations

a= Vertical distance from lip level to the highest point of the centre of the jet in m.

F_1= Froude number of jet entering the bucket g= Acceleration due to gravity in m^2/s

H_v= Velocity head of jet at the lip in m

q= Discharge intensity per meter of bucket width in m^3/ s/ m Q= Total discharge in m^3/ s

R= Radius of the bucket in m

X= Horizontal throw distance from bucket lip to the centre point of impact with tail water in m
y= Difference between the lip level and tail water level, sign taken as positive for tail water below the lip level and negative for tail water above the lip level in.

Annexure

Typical calculation for finding throw distance and height:

Given data: Discharge, Q = 11500 m^3/s
FRL = 1202 m
Lip Level = 1157 TWL = 1164.8

Aim To calculate:
X_v (Horizontal Throw Distance) a (Vertical Throw height)

Step 1: To Calculate throw distance, X_v

$$H_v = \{FRL - (Lip\ level + thickness\ of\ jet\}$$
$$= \{1202-(1157 + 7.6)\}$$
$$= 37.4\ m$$

$$Y = (Lip\ level - TWL)$$
$$= (1202 - 1157)$$

Y = -7.8 m (since lip is submerged)

$$\frac{X}{H_V} = \sin 2\phi + 2\cos\phi\sqrt{\sin^2\phi + Y/H_V}$$

$$X= (Sin^2 (35) + 2 \cos (35) [\sin^2 (35) + (-7.8/45)]^{0.5}) * 37.4$$

X= 59.4 m

Step 2: To Calculate the height of throw, a

$$V = \sqrt{2gh}$$
$$V= (2* 9.81* 37.4)^{0.5}$$
$$V=27.1\ m/s$$

$$a = \frac{v_a^2 \sin^2\phi}{2g}$$

Putting values of
V = 27.1 in “a”

$$a = (27.1)^2 * \sin^2 (35) / (2 * 9.81)$$

a= 12.3 m