Estimation of Throw Distance in the Design of Ski-Jump Bucket

B.M. Simpiger, Dr. A. R Bhalerao

Abstract— The design of ski-jump bucket for a particular dam is very complex in nature, as it involves variables such as discharge intensity, head over spillway, lip angle, bucket radious and frictional losses. Prototype jet trajectory length is found significantly shorter than the theoretical distance computed using various empirical equations. Throw distances computed using equations such as BIS, USBR, Kawakami (1973) are compared with those observed in the model studies conducted in the present studies. On the basis of path of trajectory, new equation for computing throw distance has been developed. Throw distances computed by using new equation compared with the throw distances observed in model studies. The developed equation is also applied for computing Prototype jet trajectory length.

Keywords — Dam, Spillway, Ski-jump Bucket, Throw Distance, Lip angle, Tail Water Level, Lip Elevation, Design Discharge, Energy Dissipation.

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1 INTRODUCTION

Dissipation of excess energy of the water flowing from the crest of the spillway is essential in order to protect the erosion of bed downstream the foot of the spillway. Depending on relative position of jump height curve and tail water rating curve, arrangements are made to form the hydraulic jump for the same. However, if tail water depth is either too small or too large and downstream bed conditions are favorable, bucket type of energy dissipaters are preferred. These can be either trajectory bucket type energy dissipater or roller bucket type of energy dissipater.

In case of trajectory bucket, also known as ski-jump bucket, incoming jet of water leaves as free discharging upturned jet and falls in to the river some distance downstream of toe of 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 river bed and (d) internal friction within the jet.

2 Design of Trajectory Bucket

Parameters such as radius of the bucket, invert elevation, lip angle, lip elevation and throw distance / trajectory lengths are need 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 proposed equations for the computation of bucket radius. These equations involve one or all variable such as V, H_d, H, F and ρ.

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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 considerations 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.
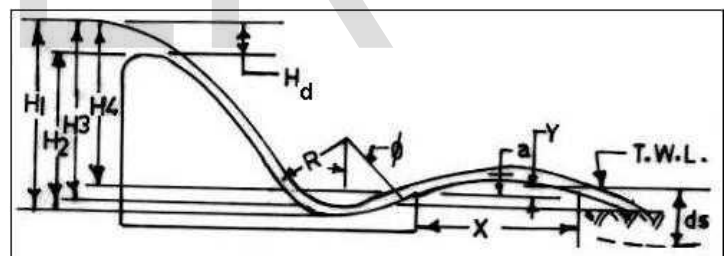

Fig No. 1: Definition Sketch

Joglekar and Damle (1961) mentioned that the maximum throw distance is not affected much, if the lip angle is reduced from 45° to 35° (only 6 percent loss is expected). When it is further reduced to 30°, the loss was found of the order of 13 percent. However, on the basis of experimental studies Rouse, Howe and Metzler (1978) have found that maximum horizontal throw occurs with 30° instead of 45°.

Joglekar and Damle (1961) observed that if a high exit angle is provided, negative pressures just before the edge of the sill would occur due to the turning of the jet in the downstream direction as it leaves the bucket. Analytical studies have also indicated the same.

The height, slope, exit angle and the shape of 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 bucket lip. In general, the shape of lip is sought to be made flat for ease in construction. High sub-atmospheric pressure occurs in case of flat lip, when the tail water level is higher than the bucket lip.

The throw distance is also one of the main parameter in the design of the plunge pool in trajectory bucket. It depends on initial velocity of the jet, bucket lip angle and difference in elevation between the lip and the tail water. Various empirical equations are available in literature for computing the trajectory length.

3 Model Studies

A geometrically similar physical model of rock fill dam (scale 1:70) was constructed in the present study in order to optimize the parameters of the trajectory bucket. The river portion about 2 km upstream and 1 km downstream of the dam has been reproduced. The spillway consists of three spans ,6.0 mx10 m high separated by 6.0 m thick piers and equipped with radial gates. The 3.0m thick breast walls are provided between the piers with upstream face flush with the dam axis . The spillway is designed to pass the maximum design discharge of 3200 m^3/sec at MWL EL.1348.5m and would also be used for flushing the reservoir almost every year, in addition to disposal of floods. The spillway with crest at El. 1307.0 m has 6 m long downstream curved crest profile followed by 120 m long chute having a slope of 1:11 (V: H) and the FRL is at El. 1345.0 m. A ski-jump bucket with lip 38 angle of is provided at the end of the chute for energy dissipation. Piezometers were provided on the crest profile along the center of span and along pier for observing pressures. Froudian criteria were used to express the mathematical relations between the dimensions and hydraulic quantities of model prototype. The general relations of the hydraulic quantities are expressed in terms of 1;70 model scale. Fig -2-& Fig-3-show the plan and section of the spillway.

Experiments were conducted for various discharges and observed flow conditions in the model. The performance of the trajectory bucket has been studied with lip angles of 30°, 35° in addition to the originally provided 38°. It was observed that at lip angle 30° and 38°, the ski-action was prevailing only for the reservoir water level above El. 1340 m. For reservoir water level El. 1340 m and below, the jet issuing from the bucket was seen just gliding over the bucket lip. This may be due to the smaller lip angle of the bucket witch could not effectively deflect thick jet upwards for a proper ski-action. After studies

with 35° lip angle, the performance of ski-jump bucket was satisfactory as a clear ski-action and was prevailing for entire range of discharge and reservoir water levels. Hence, an optimum lip angle of 35° has been selected. Also, the chute slope has been modified to 1:7.734 for the satisfactory performance of the chute and trajectory bucket.
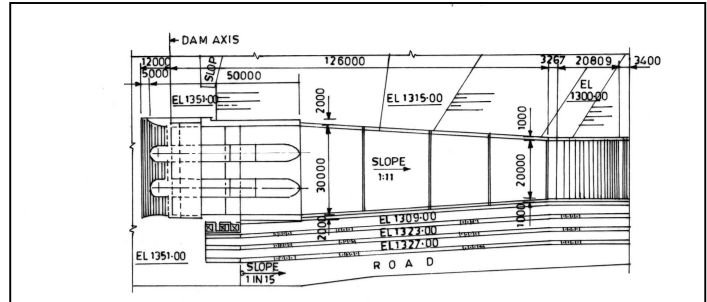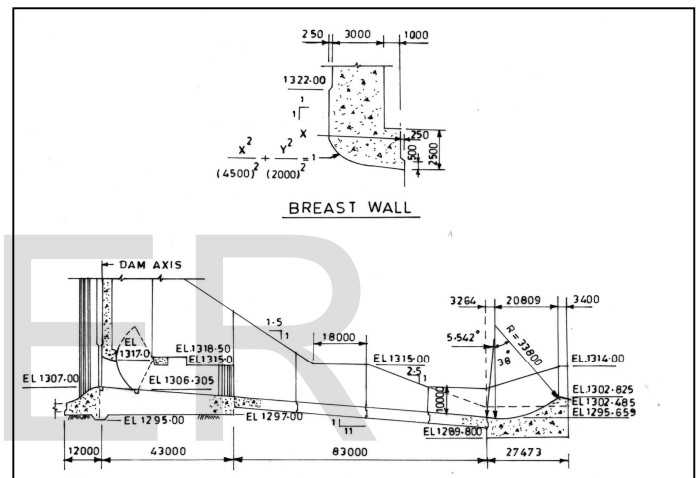

Fig.2 : Plan of Spillway

Fig. 3 : Section of Spillway

The experimental studies have shown that the performance of the trajectory bucket was found to be satisfactory for a lip angle of 35° as against the originally designed 38° and a chute slope of 1:7.734 instead of originally provided 1:11. Photo 1 show performance of the ski-jump bucket, Q=2,000 cumec, FRL EL. 1345.0M.

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The prevailing of ski-action has been considered for studying the performance of the trajectory bucket and hence, throws distances for various discharges for different lip angles of the bucket have been experimentally measured on the model. These are compared with the throw distances computed using various equations.

4   Presentation and Analysis of Data

The observed throw distances were compared with throw distances computed using various equations and presented in Table- 1.

Table 1

Comparison of Observed and Computed Throw Distances

Sr. No.	Equation	Discharge in m³/sec	RWL in mtrs	Computed throw distance		
				$\phi = 38^o$	$\phi = 35^o$	$\phi = 30^o$
1.	BIS 7365 : 1985	1000	1345	97.00	90.21	85.90
		3200	1345	91.00	89.52	84.70
2.	USBR-1987	1000	1345	76.53	74.30	68.80
		3200	1345	83.30	80.74	74.80
3.	Kawakami (Nov 1973)	1000	1345	81.84	87.10	80.30
		3200	1345	81.90	87.10	80.30

Sr. No.	Equation	Discharge in m³/sec	RWL in mtrs	Observed throw distance		
				$\phi = 38^o$	$\phi = 35^o$	$\phi = 30^o$
1.	BIS 7365 : 1985	1000	1345	50	47	40
		3200	1345	60	80	63
2.	USBR-1987	1000	1345	50	47	40
		3200	1345	60	80	63
3.	Kawakami (Nov 1973)	1000	1345	50	47	40
		3200	1345	60	80	63

A graph is plotted for observed versus computed throw distance values for a lip angle of 38º maintaining full reservoir level El. 1345 m and depicted in Fig.-4. It can be seen from the above table -1 that the throw distances computed using above mentioned equations are 27 to 34 percent higher than that of observed throw distances for lip angle 38º and a chute slope of 1:11. When the lip angle is changed from 38º to 30º and chute slope to 1:7.734, the variation was observed in the range of 13 to 23 percent. Hence, attempt has been made to develop new equation for the computation of throw distance with maximum accuracy.
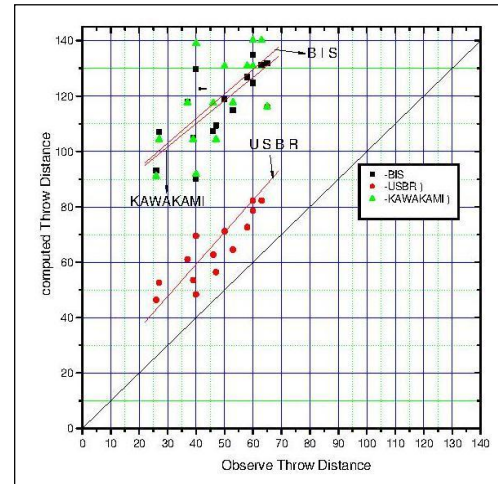

Fig.4: Comparison of computed vs. observed throw distance using different equations

New Equation

Hence, on the basis of path of the trajectory, the equation for the computation of throw distance is derived and is as presented below.

$$X = \frac{2V^2 \sin\phi}{g}\left(\sqrt{\sin\phi - Y/H_v}\right) \qquad ---- \qquad (1)$$

Where X is the throw distance, V is velocity, H_v is the velocity head and ϕ is bucket lip angle. The detail derivation of this equation is given in the appendix I. Henceforth, the said equation is called here as (Bhalerao and Simpiger) BS equation. Throw distances are computed using the BS equation and compared with those observed in model studies of the projects such as Dhauliganga, Jhakkam Dam, Mahi Bajajsagar, Ranganadi, Chandil, Parbati etc. conducted for the present studies. Figure - 5 shows this comparison and good agreement between computed and observed throw distances and all the data points collapse in the error brand of ±5%.
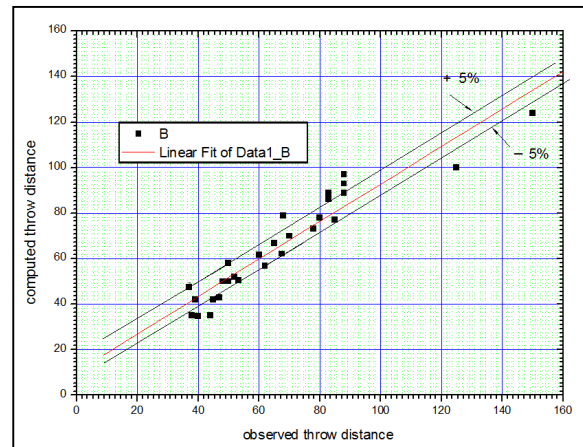

Fig 5: Comparison of observed and computed throw distance using BS equation

Table - 2 shows the throw distance computed using BS equation and other existing equations for different projects. Further, for simplicity and quick computation of throw distance attempt has also been made to relate the throw distance with velocity of jet using data collected in model studies conducted in the present study and presented in the Fig. 5.
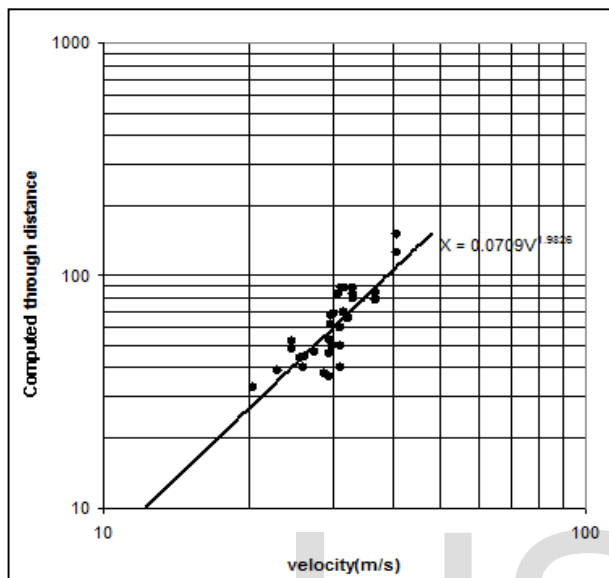

Fig. 6: Velocity versus throw distance (Data collected from model studies of different projects)

Throw distances using velocity of the jet of water in the ski jump buckets provided for the spillways of various projects were obtained using the Fig.6 and compared with throw distance computed using BS equation and other existing equations. The table -2 shows this data.
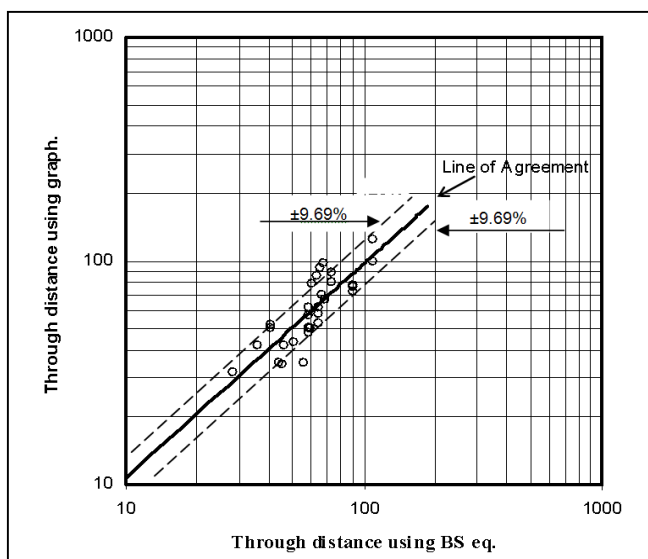

Fig.7: Computed throw distance using BS equation versus throw distance obtained using graph (Fig. 6)

Figure-7 shows this comparison and indicates good agreement between throw distances computed using BS equation and those of obtained using Fig.6. All data points fall in error brand of ± 9.69%. This analysis indicates that BS equation can be applied for field data also.

Table 2
Comparison of Throw Distance of Ski-Jump Bucket Using Various Formulae (MKS Units)

Name of Dam and Location	Tail Water Level	Bucket lip elevation	Radius of the bucket (m)	Lip angle	Velocity $V_A = \sqrt{2gh}$ m/s
Girna, Maharashra	370.0	366.00	15.24	35°	26.05
Gandhisagar, Rajasthan	354.0	347.50	30.48	30°	33.35
Banas, Gujarat	158.20	145.00	21.95	35°	29.94
Hirakud, Orissa	163.10	156.00	15.24	40°	27.91
Maithon, Bihar	112.80	115.60	10.67	43°	28.29
Panchet Hill, Bihar	109.70	102.80	18.29	43°	27.67
Ranapratap sagar, Rajasthan	326.50	322.50	16.76	40°	26.35
Rihand, U.P.	207.90	193.00	18.29	30°	39.04
Salandi, Orissa	45.70	48.90	13.72	30°	26.65
Ukai, Gujarat	65.00	58.30	27.43	40°	32.84
Vaitarna, Maharashtra	108.00	96.80	24.38	35°	37.69
Nagarjuna sagar, A.P.	86.80	76.80	21.34	34°	46.01
Srisailam, A.P.	186.00	178.00	21.34	20°	43.06
Mayurakshi, West Bengal	95.00	97.10	13.72	40°	23.98

Name of Dam and Location	Depth $d = \dfrac{q}{V_A}$	BIS-7365-(1985	USBR 1987	Kawakami N0V-1973	BS Equation
Girna, Maharashra	1.589	58.72	61.19	65.00	53.8

Gandhisagar, Rajasthan	1.616	84.95	90.90	90.20	70.4
Banas, Gujarat	1.430	57.60	79.60	85.88	55.97
Hirakud, Orissa	2.322	68.70	70.95	78.20	69.54
Maithon, Bihar	3.029	87.70	78.70	81.4	87.00
Panchet Hill, Bihar	2.819	69.80	75.00	77.84	75.45
Ranapratapsa-gar, Rajasthan	2.323	64.21	66.80	69.70	66.2
Rihand, U.P.	1.470	100.50	123.00	134.50	104.0
Salandi, Orissa	1.099	67.92	58.00	62.70	46.4
Ukai, Gujarat	2.972	94.00	102.70	108.30	101.9
Vaitarna, Ma-harashtra	1.162	89.30	124.60	136.00	107.5
Nagarjunasa-gar, A.P.	2.000	184.60	183.00	200.00	164.0
Srisailam, A.P.	2.819	94.60	112.00	64.00	65.6
Mayurakshi, West Bengal	1.435	59.85	54.00	57.70	56.94

5 Conclusion

The radius of the bucket, lip angle, invert elevation, design head, discharge intensity and throw distance are the factors that govern the satisfactory performance of a trajectory bucket.

The BS equation developed for trajectory length based on path of projectile is found to be appropriate for computing the throw distance, in addition to the other established empirical formulae. On the basis of the hydraulic model studies conducted and analysis of the throw distance computed using various equations, it is inferred that the optimum lip angle is most important factor for the satisfactory functioning of the trajectory bucket, which ultimately governs the throw distance value. Knowledge of the magnitude of the throw distance will be of great use in locating and designing the geometry of the plunge pool.

Optimum lip angle of 35° and a chute slope of 1:7.734 have been arrived for the satisfactory performance of the trajectory bucket.

6 Acknowledgement

Notations: The symbol used in standard are given below

a	=	Vertical distance from lip level to the highest point of the centre of jet in m.
d_c	=	Critical depth in m
d_s	=	Depth of scour below tail water level in m
F_1	=	Froude number of jet entering the bucket

$$= \frac{\mathbf{V\,a}}{\sqrt{\mathbf{g\,h_1}}}$$

g	=	Acceleration due to gravity in m^2/s
H_d	=	Depth of overflow over spillway in m
H_1	=	Reservoir pool elevation minus bucket invert elevation in m
H_2	=	Spillway crest elevation minus bucket invert elevation in m
H_3	=	Reservoir pool elevation minus top of water jet at bucket invert
H_4	=	Reservoir pool elevation minus bucket lip elevation in m
P	=	Pressure on the bucket in t/m^2
H_v	=	Velocity head of jet at lip in m
q	=	Discharge intensity per meter of bucket width in $m^2/s/m$
Q	=	Total discharge in m^3/s
R	=	Radius of 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 m
ϕ	=	Bucket lip angle with horizontal in degree
P	=	1000 KG/ M^2
FRL	=	Full Reservoir Level
MWL	=	Maximum Water Level
MDDL	=	Minimum Drawdown Level

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<u>Appendix - I</u>

New Equation

An equation has been developed for the computation of throw distance based on the path of projectile equation. The definition sketch for the same is depicted in Fig. 3.
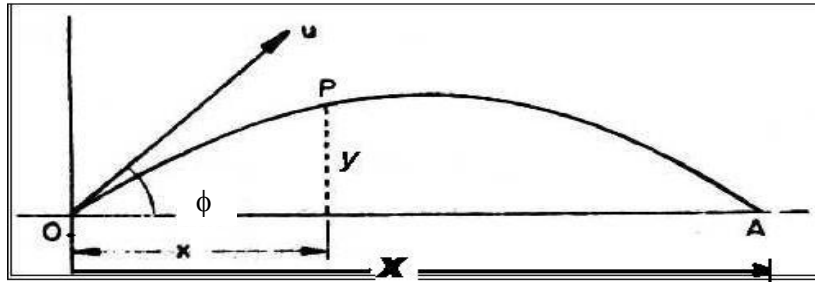
Definition Sketch: Path of a Projectile

The equation for the path traversed by a projectile is given by

$$y = X \tan \phi - \frac{g\, X^2}{2\, V^2 \cos^2 \phi}$$ ..... (1)

When y = 0

$$\therefore \quad X \tan \phi - \frac{g\, X^2}{2\, V^2 \cos^2 \phi} = 0$$

$$\therefore \quad \frac{2\, V^2 \cos^2 \phi \tan \phi}{g} = \frac{X^2}{X}$$

$$\therefore \quad \frac{2\, V^2 \cos^2 \phi}{g} \times \frac{\sin \phi}{\cos \phi} = X$$

$$\frac{2\, V^2 \cos \phi \sin \phi}{g} = X$$ ..... (2) Y = H

$\sin^2 \phi$

where   y = height above tail water level (+ve)
         height below tail water level (-ve)

H = RWL - lip elevation

$$\frac{y}{H} = \sin^2 \phi$$

$$\cos \phi = \sqrt{1 - \sin^2 \phi}$$ .... (3)

But $\sin^2 \phi = \dfrac{y}{H_v}$ substitute the value of $\sin^2 \phi$ in the above equation (3)

$$\therefore \quad \cos \phi = \sqrt{1 - \frac{y}{H_v}}$$ then substituting the value of $\cos \phi$ in equation (2)

$$\therefore \quad X = \frac{2\, V^2 \sin \phi}{g} \times \sqrt{1 - \frac{y}{H_v}}$$ ..... (4)

The equation (4) is the developed equation for computing the trajectory length of trajectory bucket.

For a given velocity of projectile, the range will be maximum when ϕ = 45°. Since sin 90 = 1 and as ϕ varies from 0 to 45° the above equation can be written as

$$X = \frac{2KV^2 \sin \phi}{g} \times \sqrt{\sin \phi - \frac{y}{H_V}}$$
 ….. (5)

where K= 0.78

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