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MODEL STUDY TO MINIMIZE SCOUR IN TAIL CHANNEL OF SKI-JUMP BUCKET ENERGY DISSIPATOR USING DEFLECTORS

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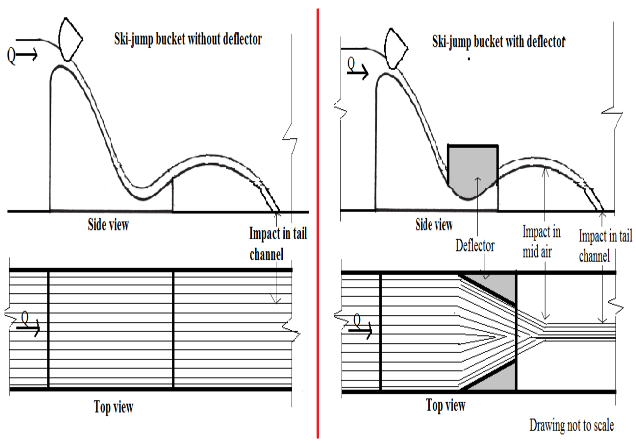
Graphical abstract



Abstract

In recent years, discharging flood water downstream of the dams by the use of ski-jump bucket has become increasingly common. However, due to impact of trajectory unexpected scour holes have occurred in the tail channel, leading to expensive remedial work. One of the threats is that scouring caused by the impact of trajectory, which not only affects the safety of the river bed or tail channel but it also affect the safety of the dam, spillway and bucket. To minimize this risk of scouring, a model studies using deflector along both sides of the ski-jump bucket is performed. The model is designed in the scale of 1:50. The experiments are performed in a flume of 20 m long, 0.7 m wide and 1.2 m deep. The work is carried out using prototype data of the Ukai dam Spillway. The experimental observations are taken with and without presence of deflector. In the current study, a convergent deflector arrangement on a bucket forces a water jet to impact in mid-air, allowing it to fall down with a downscale impact. The results show that using a deflector can minimize scour by 16.51% to 28.28%.

Keywords: Deflector, Energy dissipation, Scour, Ski-jump, Model study

1.0 INTRODUCTION

The Ski-jump bucket energy dissipator discharges the flow in the form of a trajectory. Ski-jump bucket energy dissipator was introduced in France on Dordogne hydraulic scheme in the mid of 1930s. Trajectory bucket, flip bucket, free jet spillways and free over-falls are the different names of Ski-jump bucket energy dissipator. Ski-jump bucket dissipates energy with the effects of air entrainment in combination with impact in tail channel. Ski-jump bucket energy dissipator structures consist of three main sections: 1.Ski-jump bucket, 2.Ski-jump/ Trajectory and 3. Plunge pool/Tail channel. The ski-jump bucket structures are relatively compact and inexpensive as they simply direct the jet to downstream. In the ski-jump bucket, there is a risk of scour damage occurring in the tail channel.

There are several cases for the scour development, as follows [1]: In 1945 under the bucket at M Alder Dam, there was a scour in the plunge pool (30 m × 45 m x 24 m deep). The Nacimiento Dam experienced substantial erosion in February 1969. A 20-meter-deep Scour pit was produced in Picote Dam after a flood in 1962. When the upper sound layer disappeared at Grand Rapids generating station, erosion of the lower soft layers occurred. At Kariba Dam, a surface bank slide occurred in 1962. The Tarbela Dam in Pakistan was eroded in 1975, particularly on the right-hand side of the plunge pool.

The summary of scouring in plunge pools for other dams are as follows [2]: For the Cabora Bassa dam in 1982, scour depth of 28 m was happened. In the period between 1983 to 1986 water jets falling near the toe of flip bucket developed scours in Keban dam. For the karakaya dam during spillway operation in 1986, 1987 and 1988 the scours was occurred at several cross sections along longitudinal profile of the river bed. A scour 22 x 60 m and 10 m depth was generated after spillway operation at different flow rates for Kilickaya dam. An example of substantial plunge pool erosion is Ukai dam. For Ukai dam a scour hole of approximately 29 m depth was formed.

Consequently, the minimization of scour of tail channel in ski-jump bucket energy dissipator is very important. Some researchers conducted research on scour minimization by varying angle of the ski-jump bucket [3] and changing bed material in tail channel [4]. This paper focuses on minimization of scour extent using novel approach. In novel approach conventional ski-jump is modified by fixing deflector along both side of the bucket. A study on the deflector in the ski-jump bucket was carried out using a simple triangular shape deflector on one side of the ski-jump bucket [5, 6]. In present study Indian Standards codes: IS 4623 (2000) [7], IS 6934 (1998) [8] and IS 7365 (2010) [9] is used for design of the model. The present research is, therefore, an important step forward in protection facility against tail channel scoure. Numerous empirical relations for determination of the scour depth at downstream of a ski-jump spillway are available [10]. In present study, to determine the scour depths, empirical formula given by Heng et.al.(2012) [11] is used. Researchers have used different factors in developing these relations. However, analyzing the correlation of the scour depth with the two dominant factors, namely, discharge per unit width (q) and the tail water depth (h), Heng et.al.(2012) [11] Specified to work out the depth of scour (Ds) by the equation (1) given below.

$$D_s = 7.4837 \frac{q^{1.4652}}{g\,h^{1.1972}} \quad (1)$$

Where

D_s = depth of scour in m below tail water level

q = discharge per unit width (m^3/s)/m and

h = Tail water depth, in m.

2.0 METHODOLOGY

For experimental analysis a hydraulic model of the gated ogee spillway with the ski-jump bucket energy dissipater is design with a scale of 1:50. The selected scale is based on the prototype spillway data and size and discharge capacity of the hydraulic flume. For design a prototype data of Ukai dam spillway is used. The prototype data of the Ukai dam spillway is given in table 1. Model dimensions are shown in Figure 1 and in Table 1. Photo of prototype and model of Ukai dam spillway is shown in Figure 2.

This paper focuses on minimization of scour extent using novel approach. In novel approach conventional ski-jump is modified by fixing deflector along both side of the bucket. The figure 3 shows the conceptual model of the present study. So in novel approach water jets force to impact in mid-air, and allow falling down with downscale impact. Mid-air impact of jet is done by using converging deflector along both sides of the bucket. Deflectors are the small blocks or element. The deflectors placed along both sides of the bucket will contract the flow from both side and promote impact of trajectory in mid-air. So in deflector ski-jump bucket some of the energy is lost in mid-air impact and jet reaches the riverbed, which has low scouring ability. In present study the experimental observations are taken with and without presence of deflector. The experiments were performed for the flow ranging between 0.045 m^3/s (maximum discharge) and 0.005 m^3/s (minimum discharge).

Table 1 Ukai dam spillway prototype and model dimension

Parameters	Ukai dam spillway	
	Prototype dimensions	Model dimensions
Discharge	Q_p= 1051.57 m^3/s	Q_m = 0.05948 m^3/s
Discharge per meter width	q_p=107.57 m^3/s/m	q_m=0.006086 m^3/s/m
Velocity of flow	v_p = 29.168 m/s	v_m = 4.125 m/s
Width of spillway	W_p = 9.775 m	W_m = 0.1995m
Height of spillway	H_p = 43.265 m	H_m = 0.865m
Width of bucket	B_p = 9.775 M	B_m = 0.1955 m
Radius of bucket	R_p = 17.85 m	R_m = 0.3570 m
Lip angle of bucket	Φ_p = 400	Φ_m = 400
Lip elevation	S_p =3.65 m	S_m = 0.073m
Bucket invert elevation	I_p = 1.5 m	I_m = 0.03m
Radius of gate	r_p = 16.485 m	r_m = 0.32975 m

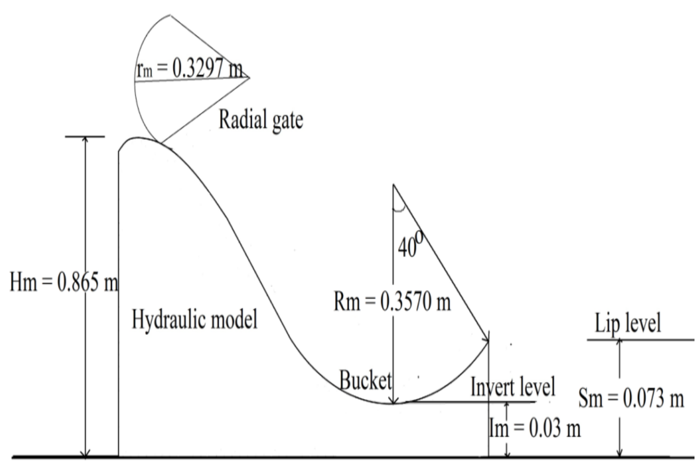


Figure 1 Hydraulic model dimensions

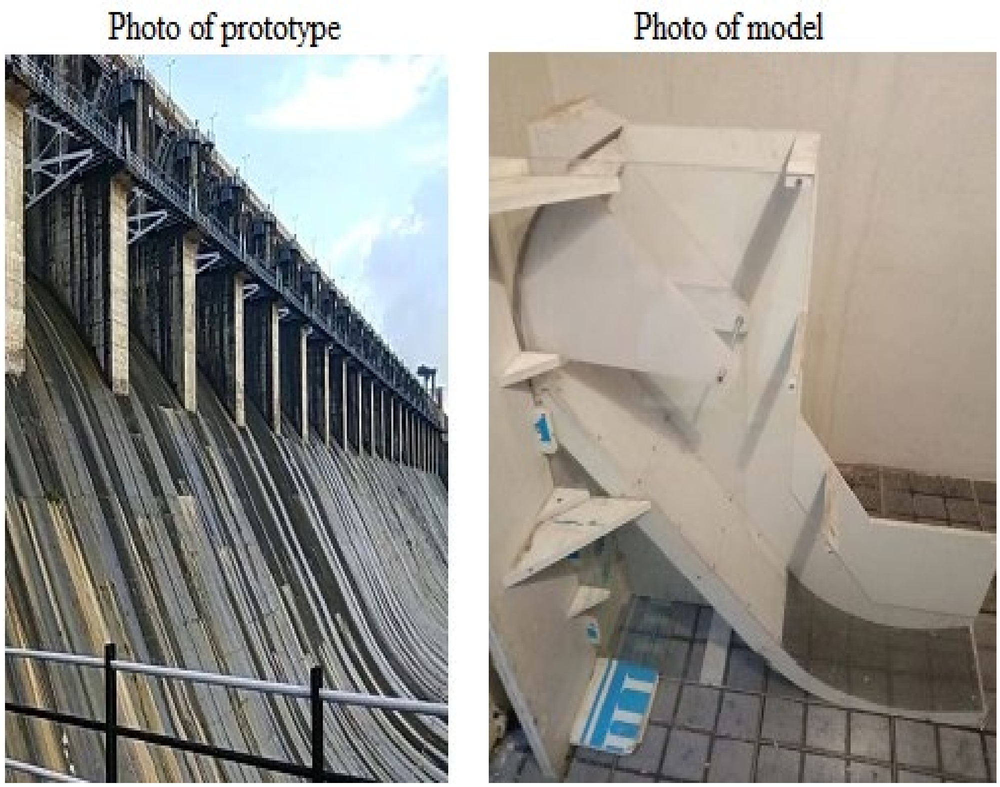


Figure 2 Photo of prototype and model of Ukai dam spillway

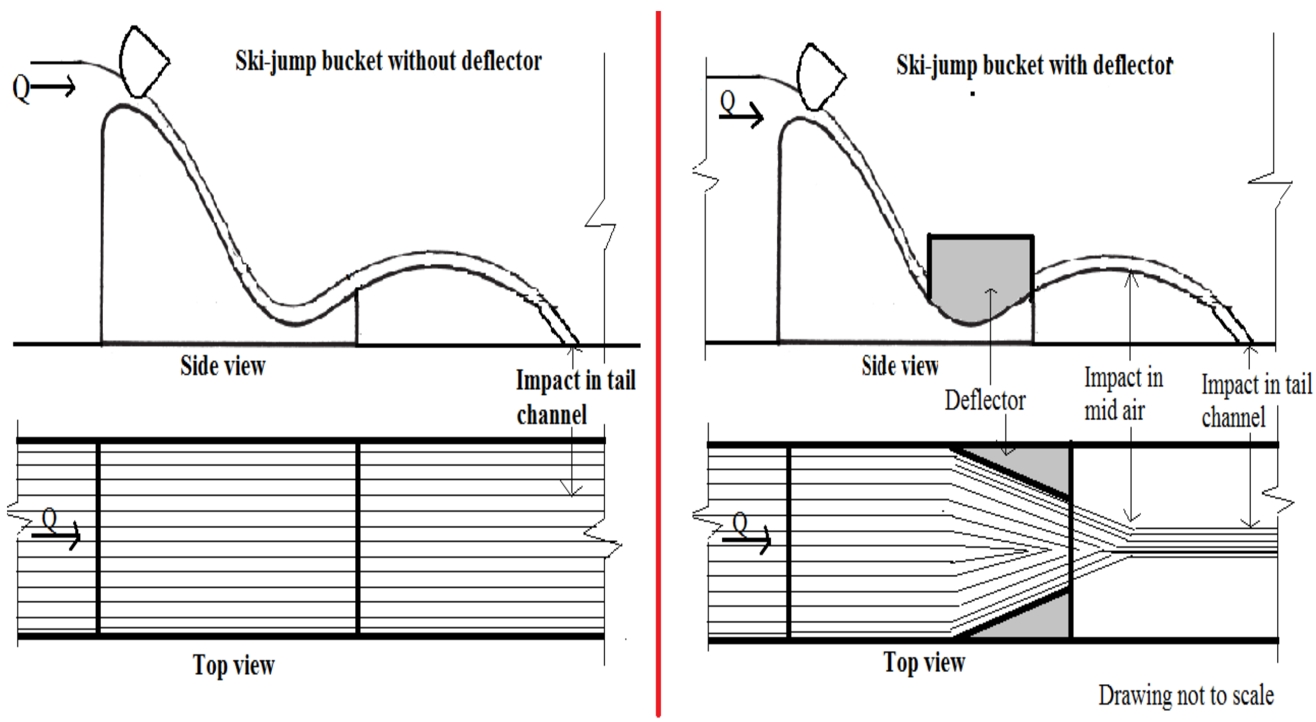


Figure 3 The figure shows the conceptual model of the present study.

3.0 DEFLECTOR

A deflector is a small block use on the ski jump bucket for spreading and deflecting the trajectory. The ski-jump bucket energy dissipator endow with deflector are [12]: Karakaya dam and Keban dam (Turkey), Pishin dam and Ago-Chai dam (Iran), Picote dam (Portugal), Oroville dam and Cleveland dam (USA), Slapy dam and Orlik dam (Czech), Chastang dam (France), Magat dam (Philippines), Stiegler dam (Norway) and Gutianxi dam (China).

The present model study is done by using triangular shape deflector on both side of the ski-jump bucket. In the present work, to reduce the scour of the tail channel water trajectory force to impact in mid-air with deflector arrangement and allowing to fall down in tail channel with downscale impact. For mid-air impact of trajectory with deflectors following points are considered (Fig. 4):

- The deflectors are place along both side of the ski-jump bucket i.e. two deflectors are used on bucket.
- The deflector is started at the beginning of the ski-jump bucket (i.e. at lower tangent point of spillway) and ended at its downstream crest (i.e. at lip).
- The transition between starting and end of deflector is finished with gradual conversion.

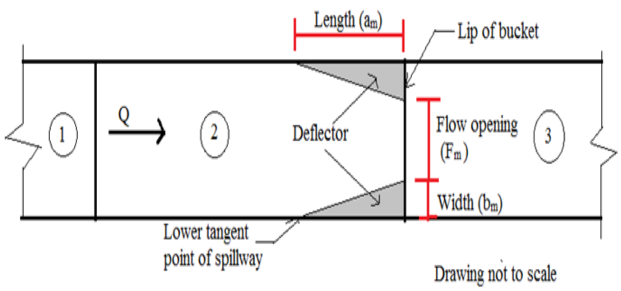


Figure 4 Schematic of deflector arrangement (With Notation as: (1) Upstream of model in a flume, (2) Hydraulic model, (4) Tail channel.

Deflector is designed with same scale i.e. 1:50. Design of deflector consists of determining length, width and height. The graphical representations of length, width and height and schematic of deflector setup is shown in figure 4. Length (am) - The length of deflector is decided by the distance between lower tangent point of the spillway and lip of bucket.

$\text{Length}\ (a_m) =$ Distance between lower tangent point of spillway and lip of the bucket.

$$\text{Length}\ (a_m) = 0.502\text{m} \quad (2)$$

Width (b_m) – The width of deflector is calculated by using equation (3).

$$\text{Width}\ (b_m) = \frac{W_m - F_m}{N} \quad (3)$$

Where - W_m is width of bucket, N is number of deflector and Fm is flow opening at lip. Width of bucket (W_m) is 0.1955 m as given in Table 1. In the present work two deflectors are used and hence N is taken as 2. In present work flow opening (F_m) is consider as 60% of width of bucket.

$$F_m = 60\%\ \text{of}\ W_m \quad (4)$$

$$F_m = 0.6 \times 0.1955$$

$= 0.1173$ m

Putting the values of W_m, F_m and N in equation 3.

$$\text{Width}\ (b_m) = \frac{0.1955 - 0.1173}{2}$$

$$\text{Width}\ (b_m) = 0.0391 \approx 0.04\ \text{m}.$$

Height (c_m) - The height of deflector is calculated by using equation (5).

$$\text{Height}\ (c_m) = \frac{Q_m}{v_m \times F_m} \quad (5)$$

Where- Q_m is discharge, F_m is flow opening at lip and v_m is velocity of flow. Putting the values of Q_m, F_m and v_m in equation 5.

$$\text{Height}\ (c_m) = \frac{0.05948}{4.125\ X\ 0.1173}$$

$$\text{Height}\ (c_m) = 0.1229\ \text{m}, \approx 0.13\ \text{m}$$

Photo of fabricated deflector is shown in figure 5.

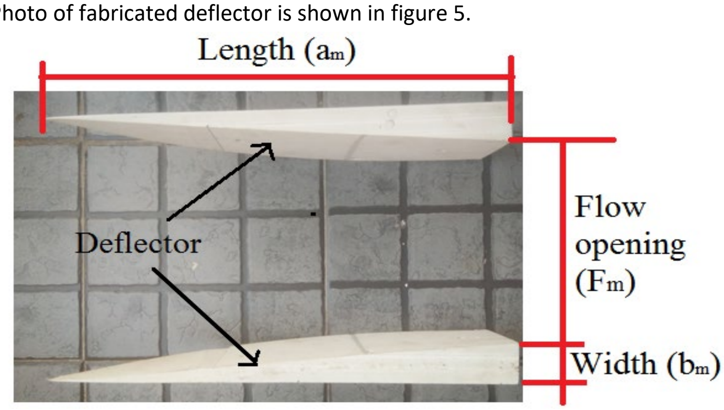


Figure 5 Photo of deflector

4.0 EXPERIMENTAL SETUP

Experimentation is carried out in a hydraulic flume at Bharati Vidyapeeth college of Engineering Pune.

Hydraulic Flume details:

- Tilting flume in the form of rectangular channel with test section portion which has acrylic side walls.
- Length of flume -20 m
- Width of flume - 0.70 m
- Height of flume –1.2 m
- Maximum discharge capacity-100 lps
- Motor Horsepower- 30 HP

Schematic of flume is shown in Figure 6. Figure7(a) shows photo of flume. Flume is having a V–notch arrangement for discharge measurement. For experimentation model is placed in the flume as shown in Figure 7 (b). Initially experiments with ski-jump bucket without deflector are done and then deflectors are fixed along both side of the ski-jump bucket by using nut and bolt.

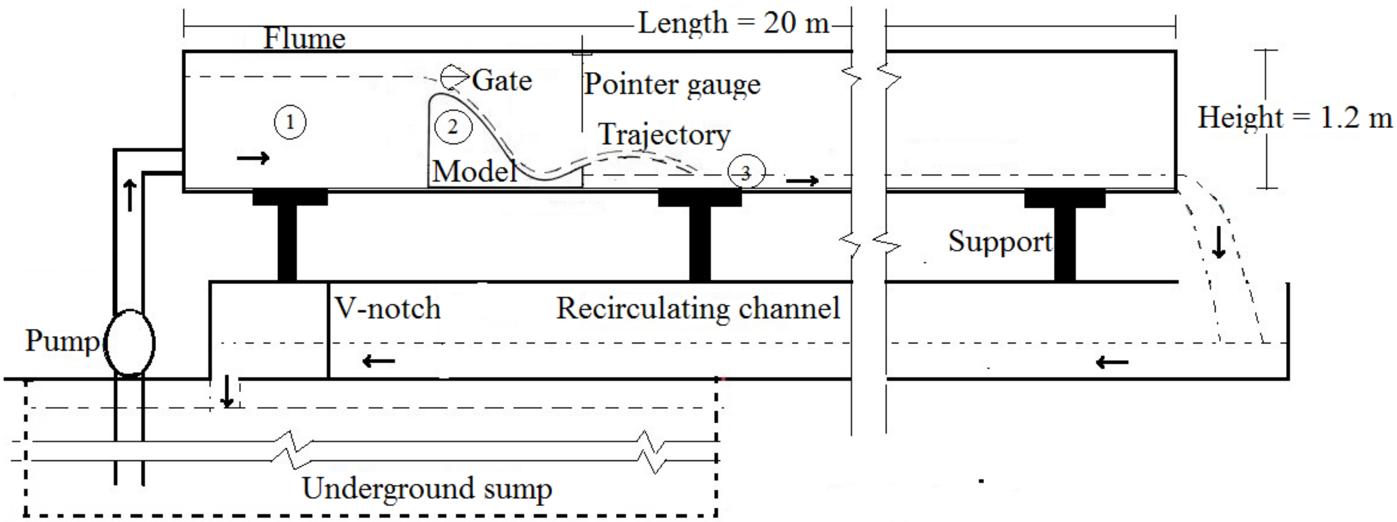


Figure 6 Schematic of experimental setup

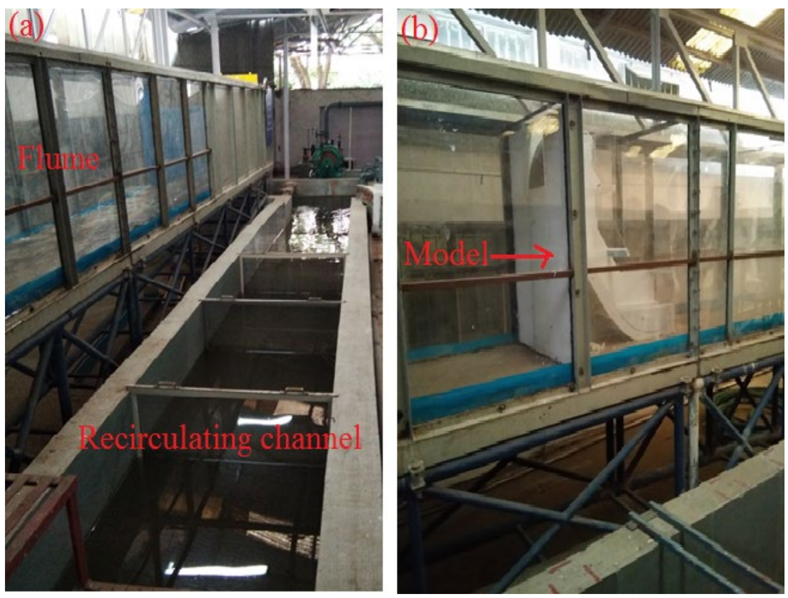


Figure 7 (a) Photo of flume and (b) Photo of model after fixed in flume

5.0 RESULTS AND DISCUSSION

Experiments are performed for seven separate discharges, range from 0.045 m3/s to 0.005 m3/s as shown in table 2. The tail water level (TWL) for each discharge condition is equal to the normal water level (NWL) corresponding to the given discharge. The pump is on to bring flow into the flume and the require discharge is adjusted by the valve and the partial opening of the radial gate. Figure 8 shows parameters measured during experiment.

The experimental work includes measurements of: Discharge and Flow depth. The discharge is measured by using V-notch arrangement provided in recirculating channel. For discharge measurement the water depth above crest (Z) is measured and then by using basic head-discharge equation of a V-notch, discharge is calculated. . Flow depths are measured at lip and in tail channel. The flow depths are measured by using pointer gauge arrangement provided in flume. Table 2 shows parameters measured during experiment.

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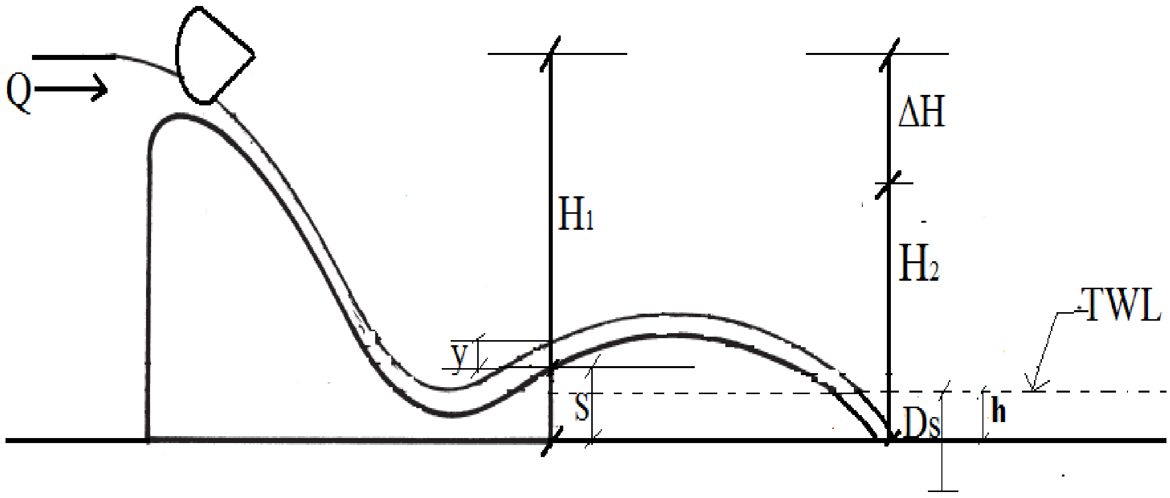

Figure 8. Parameters measured during experiment

Table 2 Details of parameters measured during experiment

Flow condition	Discharge (Q) m^3/s	Discharge per meter width (q) $(m^3/s)/m$	Water depth above crest of V-notch (Z) m	Ski-jump bucket without deflector		Ski-jump bucket with deflector	
				Depth of flow at lip (y) m	Tail water depth (h) m	Depth of flow at lip (y) m	Tail water depth (h) m
1	0.045	0.226	0.280	0.19	0.15	0.21	0.175
2	0.04	0.201	0.267	0.15	0.14	0.16	0.17
3	0.035	0.175	0.253	0.102	0.13	0.115	0.165
4	0.03	0.150	0.238	0.097	0.12	0.11	0.14
5	0.025	0.125	0.221	0.091	0.11	0.098	0.13
6	0.02	0.100	0.202	0.089	0.09	0.08	0.11
7	0.01	0.050	0.153	0.05	0.088	0.068	0.1
8	0.005	0.025	0.116	0.042	0.06	0.03	0.08

Results Of Energy Dissipation

The energy dissipation across the ski-jump is defined by equation (6) (Ref. Figure 8):

$$\eta = {}^{\Delta H}/_{H_1} \quad (6)$$

Where, $\Delta H = H_1 - H_2$

$H_1 = S + y + {}^{v_1^2}/_{2g}$ is the energy head on the lip of the bucket and

$H_1 = h + {}^{v_2^2}/_{2g}$ is the energy head in tail water channel.

Here y and h are the flow depth on lip and in tail water respectively, v_1 and v_2 are mean velocities on lip and in tail water respectively and S is the lip height. Velocity of flow on lip (v_1) and velocity of flow in tail channel (v_2) are calculated by using continuity equation.

Table 3 and Table 4 show results for energy dissipation. The energy dissipation for ski-jump bucket without deflector is found to vary between 52.41 % to 54.40 %. The energy dissipation of ski-jump bucket with deflector is found to vary between 59.30% to 60.22 %. Figure 9 shows comparison of energy dissipation with and without deflector. For all flow conditions the energy dissipation for ski-jump bucket with deflector are found to be higher than ski-jump bucket without deflector.

Table 3 Results of energy dissipation for ski-jump bucket without deflector

Flow condition	Discharge (Q) m^3/s	Discharge per meter width (q) $(m^3/s)/m$	Ski-jump bucket without deflector				
			Depth of flow at lip (y) m	Velocity of flow at lip (v_1) m/s	Tail water depth (h) m	Velocity of flow in tail water (v_2) m/s	Energy dissipation η %
1	0.045	0.226	0.19	1.187	0.15	0.429	52.41
2	0.04	0.201	0.15	1.337	0.14	0.408	52.72
3	0.035	0.175	0.102	1.720	0.13	0.385	57.78
4	0.03	0.150	0.097	1.550	0.12	0.357	56.75
5	0.025	0.125	0.091	1.377	0.11	0.325	55.74
6	0.02	0.100	0.089	1.126	0.09	0.317	58.03
7	0.01	0.050	0.05	1.003	0.088	0.162	48.72
8	0.005	0.025	0.042	0.597	0.06	0.119	54.40

Table 4 Results of energy dissipation for ski-jump bucket with deflector

Flow condition	Discharge (Q) m^3/s	Discharge per meter width (q) $(m^3/s)/m$	Ski-jump bucket with deflector				
			Depth of flow at lip (y) m	Velocity of flow at lip (v_1) m/s	Tail water depth (h) m	Velocity of flow in tail water (v_2) m/s	Energy dissipation η %
1	0.045	0.226	0.21	1.793	0.175	0.367	59.30
2	0.04	0.201	0.16	2.092	0.17	0.336	61.46
3	0.035	0.175	0.115	2.547	0.165	0.303	67.28
4	0.03	0.150	0.11	2.282	0.14	0.306	67.72
5	0.025	0.125	0.098	2.135	0.13	0.275	66.81
6	0.02	0.100	0.08	2.092	0.11	0.260	69.84
7	0.01	0.050	0.068	1.231	0.1	0.143	53.69
8	0.005	0.025	0.03	1.395	0.08	0.089	60.22

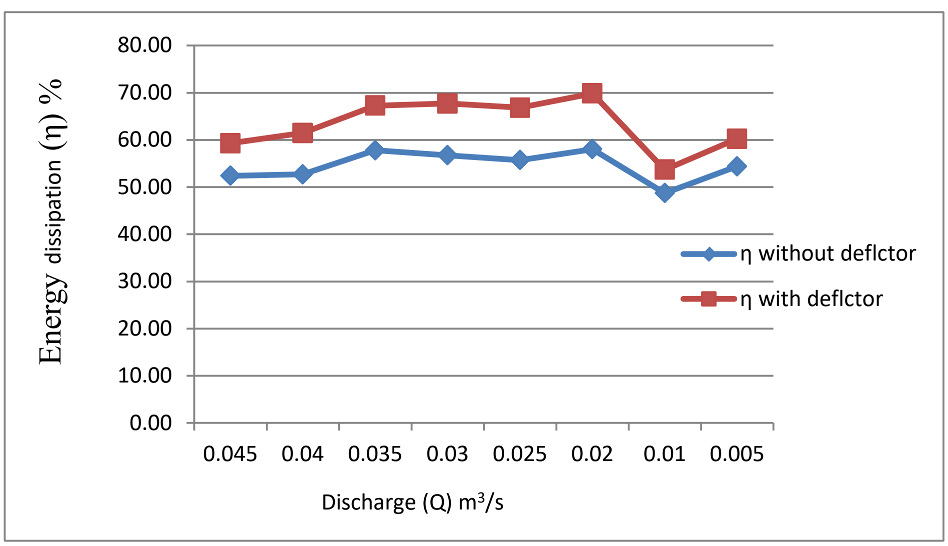

Figure 9. Comparison of energy dissipation

Results Of Scour Depth

The scour depths obtained after putting values of q and h in formula given by Heng et.al. (2012) are shown in Table 5. Figure 10 shows comparison of scour depth with and without presence of deflector. The scour depths for ski-jump bucket without deflector are found to vary between 0.836 m to 0.099 m. The scour depths for ski-jump bucket with deflector are found to vary between 0.698 m to 0.071 m. For all flow conditions the scour depth for ski-jump bucket with deflector are found to be lower because the deflectors placed along both sides of the bucket contracted the flow from both side and promoted additional impact of trajectory in mid-air as shown in Figure 11.

Table 5 Results for scour depth

Flow condition	Discharge (Q) m^3/s	Discharge per meter width (q) $(m^3/s)/m$	Ski-jump bucket without deflector		Ski-jump bucket with deflector		Percentage decrease in scour (E) %
			Tail water depth (h) m	Scour depth (D_s) m	Tail water depth (h) m	Scour depth (D_s) m	
1	0.045	0.226	0.15	0.836	0.175	0.698	16.51
2	0.04	0.201	0.14	0.766	0.17	0.611	20.23
3	0.035	0.175	0.13	0.684	0.165	0.514	24.85
4	0.03	0.150	0.12	0.600	0.14	0.499	16.83
5	0.025	0.125	0.11	0.509	0.13	0.417	18.07
6	0.02	0.100	0.09	0.468	0.11	0.386	17.52
7	0.01	0.050	0.088	0.174	0.1	0.149	14.36
8	0.005	0.025	0.06	0.099	0.08	0.071	28.28

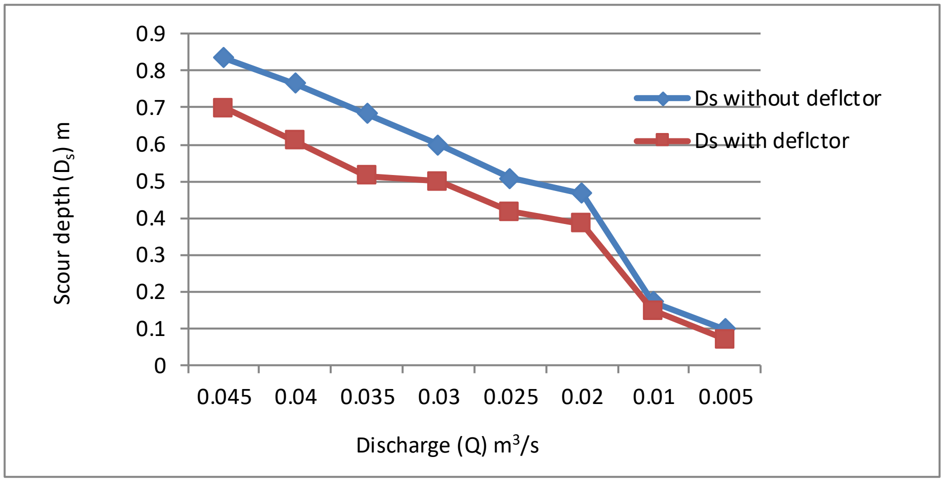

Figure 10. Comparision of scour depth

Figure 11 Photos of Ski-jump bucket without and with presence of deflector

6.0 CONCLUSIONS

The results obtained show that, by the use of deflector it is possible to increase energy dissipation. The findings show that the deflector used along both side of the ski-jump bucket is favorable. Scour is reduced by 16.51 % to 28.28 % when the deflector is used on both sides of the bucket.

In general, a higher grade concrete lining is used to protect the downstream of the ski-jump bucket energy dissipator to protect from the trajectory's impact. In ski-jump bucket with deflector provisions on both sides of the bucket, a mid-air impact happened, and the trajectory reaches downstream riverbed is having a downscale impact. As a result, the provision of deflectors could reduce the grade of concrete and ultimately cost is also decrease.

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References

[1] Mason, P. J. 1984. Erosion of plunge pools downstream of dam due to the action of free-trajectory jets. *Proceedings of the Institution of Civil Engineers.* 76(2): 523-537. https://doi.org/10.1680/iicep.1984.1257

[2] Yildiz, D., and Üzücek, E. 1994. Prediction of scour depth from free falling flip bucket jet. *International water power and dam construction.* 50-56. https://www.semanticscholar.org/author/E.-%C3%9Cz%C3%BCcek/101739384 Accessed on 15 June 2020.

[3] Machado, L. S., Lima, M. M. C. L., Aleixo, R., and Carvalho, E. 2020. Effect of the ski jump bucket angle on the scour hole downstream of a converging stepped spillway. *International journal of river basin management.* 18(3): 383-394.

[4] Movahedi, A. Kavianpour, M. and Yamini, O. A. 2017. Experimental and numerical analysis of the scour profile downstream of flip bucket with change in bed material size. *ISH Journal of Hydraulic Engineering.* 25(8):1-15. https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10 1080%2F09715010.2017.1398111 Accessed on 12 Aug 2020.

[5] Juon R., and Hager, W. H. 2000. Flip bucket without and with deflectors," *Journal of Hydraulic Engineering.* 126(11):837-845. http://tarjomefa.com/wp-content/uploads/2018/01/8529-English-TarjomeFa.pdf Accessed on 7 July 2016.

[6] Lucas, J., Hager W. H., and Boes, R. M. 2013. Deflector Effect on Chute Flow. *Journal of Hydraulic Engineering.* 139(4): 444-449. https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29HY.1943-7900.0000652 Accessed on 7 July 2016.

[7] Bureau of Indian Standards. IS 4623. 2000. Recommendations for structural design of radial gates. https://law.resource.org/pub/in/bis/S14/is.4623.2000.pdf

[8] Bureau of Indian Standards. IS 6934. 1998. Hydraulic Design of High Ogee Overflow Spillways-Recommendations. https://law.resource.org/pub/in/bis/S14/is.6934.1998.pdf Accessed on 10 June 2015.

[9] Bureau of Indian Standards. IS 7365. 2010. Criteria for hydraulic design of bucket type of energy dissipators. https://archive.org/details/gov.in.is.7365.2010 Accessed on 10 June 2015.

[10] Heng, S., Tingsanchali, T., and Suetsugi, T. 2012. Analysis of plunge pool scour hole formation below a chute spillway with flip bucket using a physical model. *ASEAN Engineering Journal Part C.* 1(1):88-101.

[11] Heng, S., Tingsanchali T., and Suetsugi, T. 2012. Prediction formulas of maximum scour depth and impact location of a local scour hole below a chute spillway with a flip bucket. *WIT Transactions on Ecology and The Environment.* 172:251-262. https://www.witpress.com/elibrary/wit-transactions-on-ecology-and-the- environment/172/24649 Accessed on 2 July 2020.

[12] Rahatabad, F. G. 2004. Effect of using dentate ski jump spillways on scouring profile. *Proceedings 2nd International Conference on Scour and Erosion*, *(ICSE-2)*, Singapore. https://izw.baw.de/publikationen/tc213/0/LS_20.pdf Accessed on 10 June 2015.