

MODEL STUDY OF A SKI-JUMP TYPE ENERGY DISSIPATOR

Prof. S.K. Mazumder

General Manager (Hydrology)
Intercontinental Consultants and Technocrats
Pvt. Ltd. New Delhi-110 016
(Former Professor of Civil Engg.,
Delhi College of Engg.)

P.L. Patel,

Asstt. Professor of Civil Engineering,
Delhi College of Engineering, Delhi

ABSTRACT

A 1:100 Scale model of a ski-jump type energy dissipator on mobile sand bed was tested to find the applicability of design guidelines given in IS:7365(1985) code for rocky type river bed. Throw length and throw height and submergence of the jet were measured and compared with codal provisions. Scour depth and size of plunge pool were also measured for the various discharges and tailwater depths and compared with theoretical values. Energy dissipation due to air entrainment in the jet was measured and found to be much higher than that given in the IS code.

INTRODUCTION

Ski-jump bucket (also called Flip Bucket) type energy dissipators are in common use in India and abroad. In this type of dissipator, energy of the flowing water jet is dissipated partly through interaction of the water jet with air and mostly through friction and turbulent diffusion of the jet in the plunge pool formed at the point of impact where the ski-jump impinges on the tail water. Ski-jump dissipators are provided where there is deficiency in tail water to produce a hydraulic jump- a situation which arises in hilly terrain with steeply sloping river bed made of hard and sound rock. Where the bed is made of weak and jointed rocks or of loose sandy and gravelly material, the impinging jet forms deep scour holes adjoining the structure. This is not safe and may cause failure of the structure and slope failure of the adjoining banks. Under such circumstances, it is preferred to preconstruct a plunge pool artificially at the appropriate location for complete energy dissipation. The study reported herein is in regard to finding the location, size and depth of such artificial plunge pools required to avoid undesirable crater and to avoid unhealthy erosion near the dam site in the absence of plunge pool. Scouring potential of the jet in the absence of plunge pool has been demonstrated by Patel (1994) by measuring typical distribution of velocity and induced stresses developed by the jet causing erosion and formation of crater.

REVIEW OF PAST STUDY

Exhaustive experimental study was done by McPherson (1957), Elevatorski (1958, 1959) Jain (1965) Handa (1966), Lenau (1969), Lucon (1973), Martins (1975), Rajan (1980), Dhillon (1981), Mason (1984, 1985) for the development and improvement of performance of ski-jump spillway. Ski-jump bucket was constructed in several dams in France e.g. Narges Dam (100 m ht.) L' Aigle dam (90 m height), Chastang dam (72 m ht), Bort-les Orgues dam (115 m ht) for flood discharges varying from 500 to 1500 m³/sec. Craters of varying depth (15 to 20 m) were formed at varying distance from the bucket lip. For Kasmishiba arch dam (110 m height) in Japan, ski-jump dissipator is provided for a design discharge of 2160 m³/s. Observed

scour in 1955 flood of $1000 \text{ m}^3/\text{s}$ caused scour as predicted in the model. In cleave land dam (British Columbia), Ski-jump bucket was provided with splitter type lip for spreading the flow in air. Sub-atmospheric pressure on the lip (sharp edges of splitters) caused lot of cavitation damage. The cavitation was controlled by rounding and chamfering the edges of the splitters. Based on model and proto type observations in a number of ski-jump buckets in USSR (height varying from 80 m to 165 m), Russian engineers developed several equations for estimating maximum scour depth in the plunge pool, side slope of scour holes, energy dissipation etc. for rocky bed of varying strength for varying discharge intensities strength of rock, height of fall, tail water depth etc. One such equation is given below.

Ski -jump buckets have been provided in a number of dams in India (Varshney-1970) e.g. Gandhisagar, Hirakud, Matihon, Rana Pratap Sagar, Rihand, Ukai, Tilaiya etc. for different heights (varying from 30m to 90m) and discharge intensities (varying from 25 to $85 \text{ m}^3/\text{s}/\text{m}$). Scour holes observed close to the lip in almost all the dams were protected by lining with M-200 concrete, construction of apron upstream from the crater to the bucket lip, buttressing, anchoring, etc. Tarabela (Lowe-1979) dam in Pakistan located in the foothills of Karakoram on river Indus is an earthen dam provided with two chute spillways on the left hillside abutment each having a lip bucket at the end of long concrete chutes with bucket lip angle of 35° . Plunge pool with a bottom width of 138 m was excavated upto a level of about 6 m below lip level. In 1975 flood, there was scour of about 30 m, and there was a macro slide producing 40000 m^3 of talus. Based on hydraulic model (1:50) study, Groyens were constructed within the plunge pool to prevent circulating motion responsible for erosion. Concrete plugging and concrete buttresses were built up behind the lip within the affected areas. The overall idea was to provide barriers on the sides of the spillway jet to intercept recirculating eddies and stop peripheral flow to prevent erosion.

OBJECTIVE OF THE STUDY

Most of the flip bucket dissipators in India are designed as per IS code: 7365-1985 and their dimensions are finalised after scaled model study. Objective of the present model study was to verify the applicability of the various formulae given in the IS:code for mobile river bed consisting of loose materials and to evaluate the flow characteristics with variation of discharge and tail water depths. Following characteristics of the flip-bucket dissipator are investigated:-

- (i) Characteristics of jet profile - its horizontal throw (X) and vertical throw (a)
- (ii) Percentage energy dissipation through air entrainment
- (iii) Tailwater height above bucket invert, for which the jet gets submerged.
- (iv) Maximum stable scour depth in mobile bed and the location of maximum scour depth and the size of plunge pool.

MODEL STUDY AND EXPERIMENTS

A 1:100 scale model was made with brick masonry and cement plaster. The prototype spillway data are as follows:

- (i) Full Reservoir Level (FRL) = 75.33 m
- (ii) Crest RL = 66.35

- (iii) Tail Water Level = 13.80 m
- (iv) Design Flood Discharge = 3100 m³/s
- (v) Bucket invert RL = 10.53 m
- (vi) Length of spillway crest = 53.5 m

With the above data the different jet parameters were computed as follows:

- (i) Design bucket velocity = 35.27 m/s
- (ii) Bucket flow depth at invert $d_1 = 1.79$ m
- (iii) Froudes number of flow at bucket invert = 7.7
- (iv) Conjugate depth for jump formation at bucket invert (d_2) = 18.65 m

As per IS Code : 7365-1985 bucket dimensions were found as follows:

- (i) Bucket radius = 19.3 m
- (ii) Lip Angle (ϕ) = 35°
- (iii) RL of lip corresponding to the given angle (ϕ) = 15.83 m
- (iv) Mean dia of sediments of which bed was made (d_{50}) = 0.41 mm

Horizontal throw (X) from bucket lip and vertical throw (a) from lip level to tail water level and maximum depth of scour (T_{sc}) were determined using the equations 1, 2 and 3 respectively as follows:-

$$X/H_v = \sin 2\phi + 2 \cos \phi \sqrt{\sin^2 \phi + y/H_v} \quad (1)$$

$$a = V_a^2 \frac{2X \sin^2 \phi}{2g} \quad (2)$$

$$T_{sc}/h_{cr} = Z^{0.25} (\phi/\alpha_{uh}) \cdot f(w/K_r) \quad (3)$$

Where H_v is the velocity head at lip, V_a is the approach velocity at bucket invert, y is the difference between lip level and tail water level, Z is the difference between head water and tail water levels.

α_{uh} is the angle of upstream slope of scoured face with horizontal, η is coefficient of variation between bottom and surface velocities of the jet in the tail pool, K_r is the rock strength coefficient and w is the settling velocity of 1 m dia rock.

Fig. 1 shows the various parameters for the ski-jump type energy dissipator which was tested. The model was tested in a flume 10 m long and 1.2 m x 1.2 m in section. Due to limited space and to ensure that the side walls of the flume do not interfere with the full development of crater, only a sectional model of 13.4 m span (Corresponding model length = 13.4 cm) was tested. Corresponding model design discharge for the given head was found to be 7.5 litres per second with a model scale of 1:100. The sidewalls of spillway was made of Perspex sheet and the approach transition was made of GI sheet. Smooth approach transitions were used for eliminating vortices at the entry to spillway. Vortices were never stable and caused periodic swinging of the jet, resulting in unstable flow conditions downstream.

Besides design discharge of 7.5 lps, the model was tested also for two other discharges- one lower than the design discharge (5 LPS) and the other higher than the design discharge (10LPS). For each model discharge, the tail water elevations were also varied as explained in Tables 1 & 2. The Tail water levels corresponding

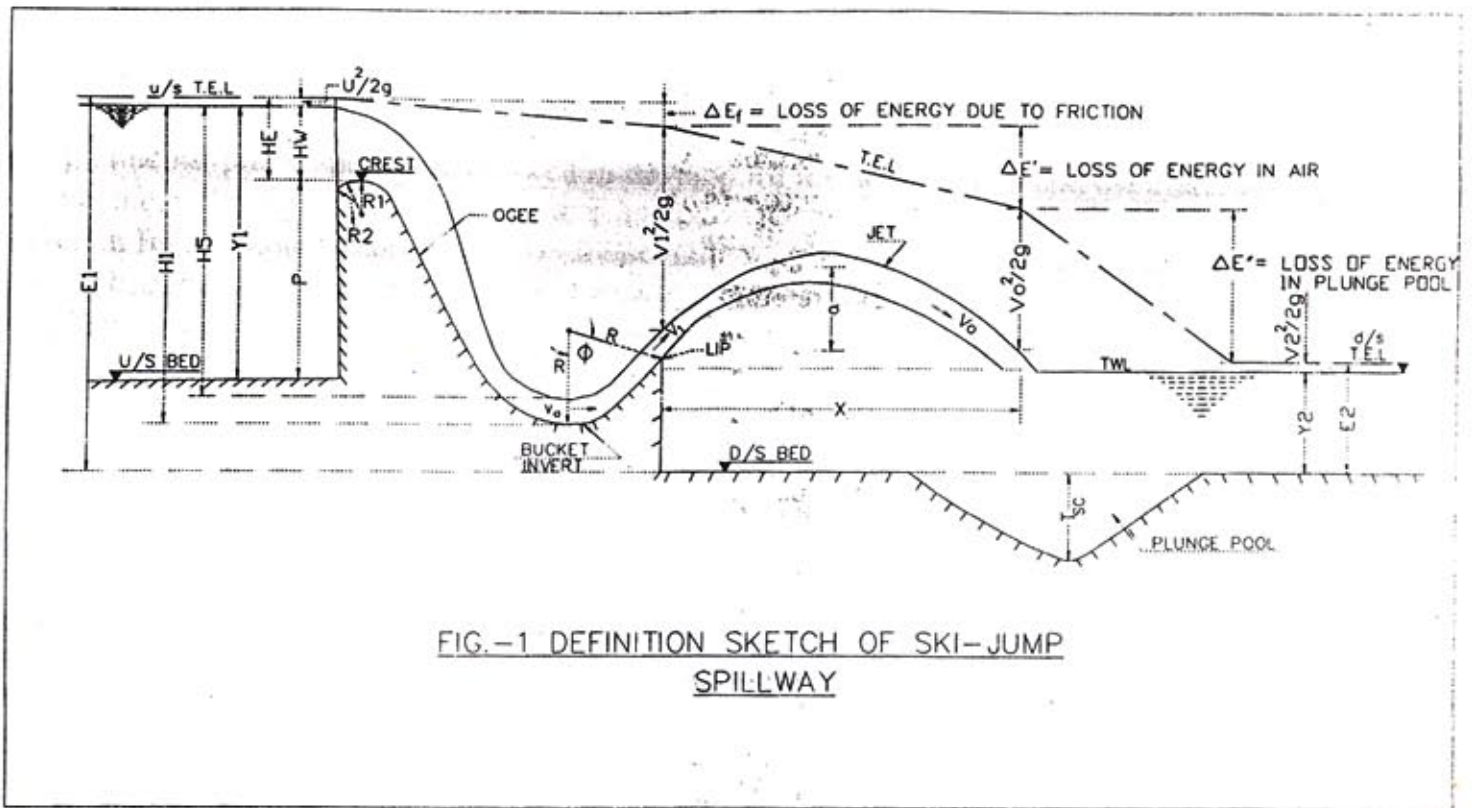


FIG.-1 DEFINITION SKETCH OF SKI-JUMP SPILLWAY

to critical submergence of the bucket (when jet gets just submerged) were also measured to find critical submergence of jet as indicated in Table-1.

DISCUSSION OF RESULTS

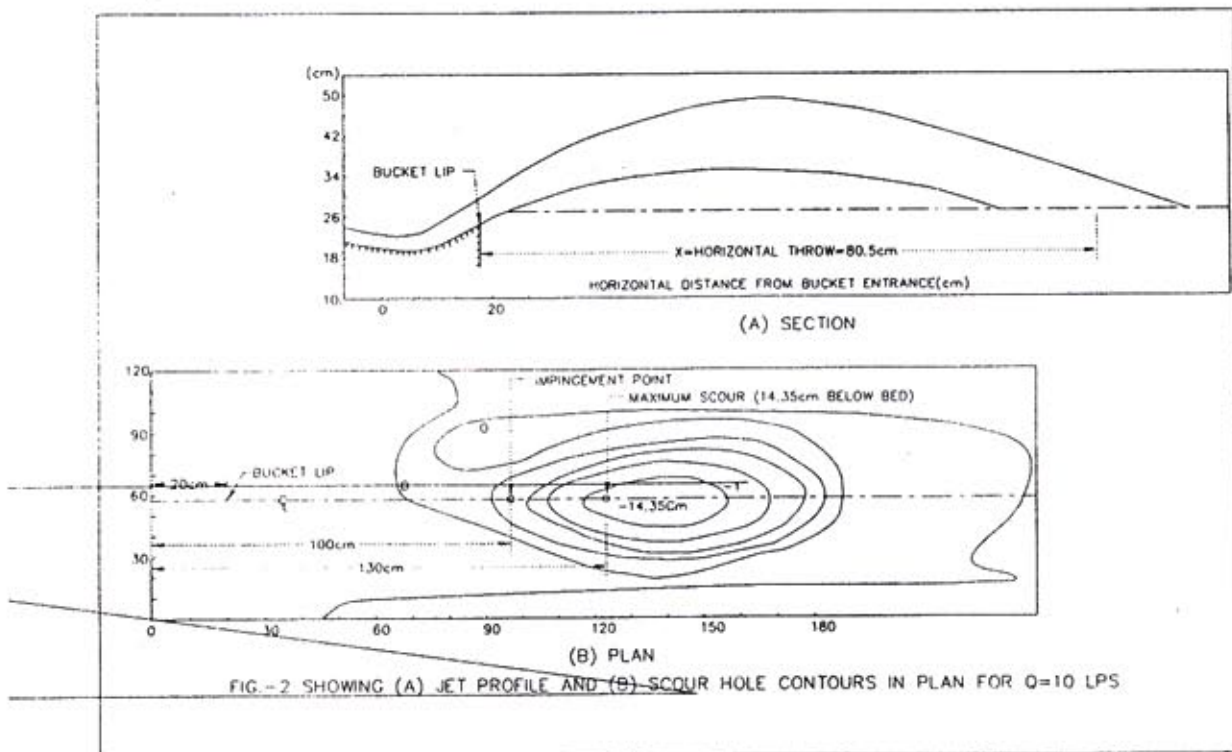
Jet Characteristics

Table- 1 shows the various jet characteristics namely horizontal throw length (x), vertical throw height (a), critical submergence limit of bucket (S_{cr}) and the percentage energy loss in the jet due to air entrainment. Measured values of throw length (x) and throw height (a) are found to be always higher than those given by the formulae (Equation 1 and 2). Percentage error between the measured value and that found from equation-1 varies from 12.2% to 31.6%. Similarly percentage error in throw height (a) found from equation 2 varies from 22.3% to 34.8% when compared with measured values. The error is minimum in case of design discharge (Expt No. 5) for which the bucket and the ogee spillways were designed. Critical submergence of bucket (S_{cr}) is defined as the ratio of actual depth of flow at which the jet gets just submerged (Y_{cr}) to the conjugate depth (d_2) for jump formation - both measured above the bucket invert level. $S_{cr} (= Y_{cr}/d_2)$ is found to vary from 0.68 to 0.72 almost the same as 0.7 as recommended by IS code. Energy loss in air entrainment was found after working out the energy levels at the lip and that just before the point of impingement of the jet with tail water. The Details of computations are given in reference (6). Percentage energy loss expressed as the ratio between energy loss in air entrainment ($\Delta E'$) and the total energy loss is found to vary from 24.8% to 54.5%- much higher than 20% given in IS code. It may again be seen that highest energy loss occurs for expt.5 i.e. for discharge 7.5 LPS for which the dissipator is designed. The errors may be due to model scale effect also.

PLUNGE POOL CHARACTERISTICS

In all the experiments, plunge pool was allowed to develop till the scour ended and the crater (or plunge pool) attained an equilibrium size. Typical scour contours and jet profile for experiment no. 7 i.e. $Q = 10$ LPS are given in fig 2. Scour occurred both upstream and downstream of the point of impingement. The upstream scour occurred due to clockwise eddy flow between the lip and the impingement points. Distance between impingement point and location of maximum scour depth was found to vary from 0.4 to 0.7 times the throw length. Table-2 gives the maximum scour depth and the average size of stable plunge pool. Maximum scour depth was found to be higher than the theoretical value in all the experiments. Percentage error between theoretical and measured values was found to vary from 22% to 42%. This is because of the fact that equation-3 for maximum scour depth is applicable for rocky bed whereas in the present case, bed was made of sand having d_{50} size equal to 0.41 mm. Rocky bed erodes due to jet impact and the drag due to viscous and turbulent shear. Dynamic pressure due to pressure fluctuations is also responsible for the development of uplift and pressure drag. When the rock is homogenous, free from joints and cracks, it erodes when the stress developed is more than its strength. As the rock erodes and the plunge pool develops, there is turbulent diffusion of the jet. Stress on the rock reduces as the jet loses much of its energy through turbulent diffusion. Erosion stops and a stable pool forms when the stress developed is equal to the strength of rock.

The maximum depth of scour and size of plunge pool are, therefore dependent on the nature of bed material. In the present study where bed is composed of sand, the scour equation developed by Russian Engineers for rocky strata is not applicable. However, the study is useful where the bed consists of loose boulders or jointed and fragmented rock and where it is decided to preconstruct the plunge pool. Fig. 3 gives the average size of the plunge pool which was formed in the present study with loose sandy bed.



CONCLUSIONS

- (i) Experimental values of horizontal throw (x) are found to be higher than the ones found by Eq.1 by 12.2 to 31%.
- (ii) Experimental values of throw height (a) are found to be higher than the one found by eq. 2 by 22.3% to 34.8%
- (iii) Percentage energy dissipation in air entrainment is found to vary from 26% to 54.4% which is higher than 20% prescribed in IS Code:7365-1985.
- (iv) Maximum depth of scour found from eq (3) is always less than the measured values. Percentage error varies from 22% to 42%.
- (v) Critical submergence of bucket varies from 0.68 to 0.72 i.e. almost same as 0.70 as prescribed by IS code
- (vi) The errors are due to the fact that the model bed is made of sand whereas equation 1, 2 and 3 are applicable for rocky bed. The error may be also due to model scale effect.

Table-1: Jet Characteristics - Comparison of Measured and Theoretical Values.

Expt. No.	Q (LPS)	Tail water Depth (cm)	Horizontal Throw (x) (cm)			Vertical throw (a) (cm)			Percentage loss of energy in air entrainment	Critical submergence ratio $S_{cr} = Y_{cr}/d_2$
			Theory (Eq.1)	Measured	Percentage Error	Theory (Eq.2)	Measured	Percentage Error		
1	5	11.5(TWL=NWL)	44.84	71	31	7.4	10.9	34.8	26	$S_{cr}=0.69$
2	5	15.9(TWL at lip level)	45	64	29.6	7.4	10.7	30.8	32.7	$S_{cr}=0.69$
3	5	21.5(TWL at 0.75 d_2 above bucket invert)	JET IS SUBMERGED							
4	7.5	14.9(TWL=NWL)	70.9	94	24.50	12.2	16.27	25	37.8	0.68
5	7.5	15.9(TWL at lip)	68.9	78.5	12.2	12.2	15.71	22.3	54.4	0.68
6	7.5	22.3 (TWL at 0.75 d_2) above bucket invert)	JET IS SUBMERGED							
7	10	17.9 (TWL at NWL)	63.5	80.5	21.1	11.1	16.5	28.4	26.3	0.72
8	10	24.3(TWL at 0.75 d_2)	JET IS SUBMERGED							

TWL
NWL
 d_2

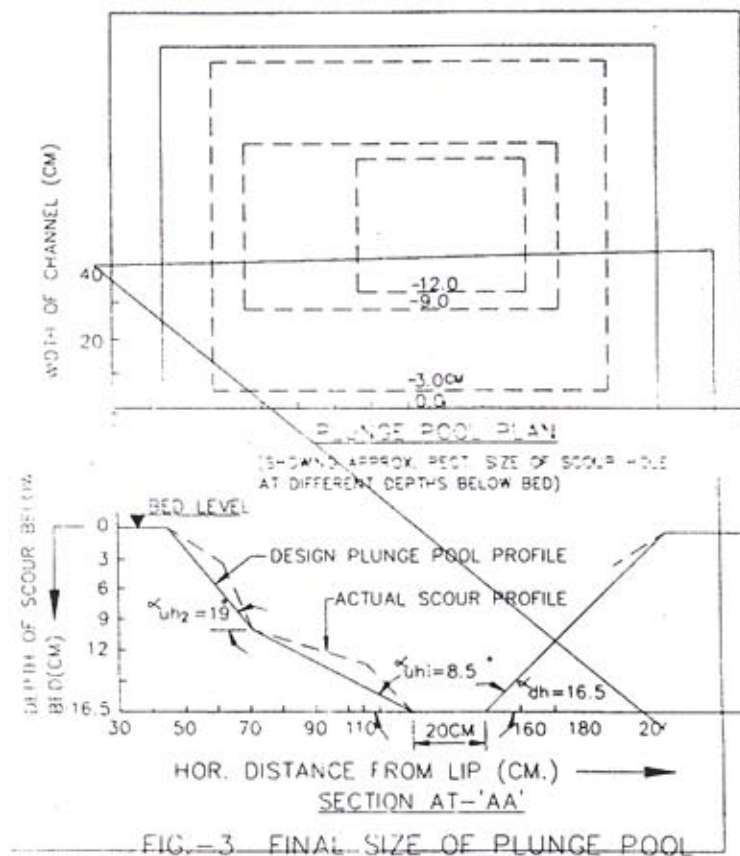
Tail water Level
Normal Water level corresponding to give discharge
Conjugate depth

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Table-2: Plunge Pool Characteristics: Scour and Plunge Pool Size

Expt. No.	Q(LPS) (cm)	TWD	Maximum Depth of scour (cm)				Location of maximum scour from bucket lip (cm)	Stable size of pool (cm)	
			Theory (Eq-3)	Measured	Percentage error	D/S		U/S	Length
1	5	11.5	8.1	14.0	42%	122	43	105	80
2	5	15.9	6.0	10.0	40%	110	59	95	60
3	5	21.5	Jet Submerged						
4	7.5	14.9	12.5	16.1	22.3%	130	48	110	90
5	7.5	15.9	10.0	14.2	29.5%	123	50	105	75
6	7.5	22.3	Jet Submerged						
7	10	17.9	9.7	14.3	32.1%	130	53	105	80
8	10	24.3	Jet Submerged						



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