Arabian Journal of Geosciences (2024) 17:70
https://doi.org/10.1007/s12517-024-11874-y

ORIGINAL PAPER

The investigation of energy dissipation in ogee profile spillway model

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Received: 31 March 2023 / Accepted: 11 January 2024

Abstract

Major failures of spillway occur due to the inadequate or inefficient design of the spillway. In the Khadakwasla dam spillway, Pune (Maharashtra) has erosion and scouring on the spillway bed. The roller bucket is the alternative to reduce the kinetic energy and minimize the length of the hydraulic jump. Hence, there is an urgent need to develop appropriate energy dissipators to intend for high discharges. To address these concerns, the current study concentrates on resolving them by implementing plain and slotted roller buckets for the ogee profile stepped spillway. The proposed approach involves combining roller buckets and stilling basins, integrating appropriate steps designed for the ogee profile stepped spillway. This is achieved through the creation of a physical hydraulic model in the laboratory, with a scale ratio of 1:33. A comprehensive model study was conducted and the performance was validated using the Froude model law and continuity equation for a design discharge rate of 900 m^3/s. Performance evaluation of plain and slotted roller bucket for ogee and stepped spillway illustrated that 82% of specific energy is eliminated by a plain roller bucket and 78% by a slotted roller bucket. In a stepped spillway, 58% of specific energy is eliminated by a plain roller bucket and 57% by the slotted bucket. Hence, in this device, the ogee spillway with a plain bucket is more reliable than the stepped spillway and helpful in reducing the intensity of specific energy over the chute surface of the spillway at a low head of 4 m.

Keywords Ogee spillway · Roller buckets · Ogee stepped spillway · Type II stilling basin · Non-dimensional parameter · Energy dissipation

Introduction

To safely manage the surplus water in the reservoir, a hydraulic structure known as a spillway is built to play a pivotal role. Its primary function is to dissipate the specific energy of floodwater, safeguarding both the waterway and the structures downstream. Specifically, an ogee spillway is employed to facilitate the controlled release of floodwater and the safe discharge of excess water from a dam into the downstream river (Abbasi and Kamanbedast 2012). The release of water from the reservoir results in a substantial kinetic energy buildup at the base of the spillway, which can lead to erosion and scouring of the channel bed (Ali and Mohamed 2010). Given the high kinetic energy levels at the spillway's base, it is imperative to transition the flow into a stable condition to ensure the safety of the dam and adjacent structures such as powerhouses and canals (Ali et al. 2014). To effectively dissipate this energy, large-scale energy dissipators are utilized, including various hydraulic jump types and several forms of stilling basins, with stepped spillways being a less common choice (Bhosekar et al. 2012). Notably, the stepped spillway stands as the sole option for energy dissipation directly within the spillway chute itself (Chatiola and Jurdi 2004). In the case of an ogee spillway, water attains its maximum kinetic energy as it reaches the spillway's toe, with energy dissipation devices coming into play downstream (Felder and Chanson 2011). Various energy dissipators are employed to minimize their impact on the structure, including roller buckets and stilling basins (Gupta et al. 2013). Among these, the hydraulic jump type of stilling basin is favored for energy dissipation beneath spillways and outlets due to its well-documented characteristics and extensive research (Goel 2016).

Responsible Editor: Broder J. Merkel

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Published online: 26 January 2024

It allows for the use of a relatively shorter structure, offering economic benefits over sloping aprons or horizontal stilling basins. However, the Khadakwasla dam in Pune, equipped with an ogee spillway and stilling basin type II as an energy dissipator, has been grappling with scouring and erosion issues since 1993 (Habib et al. 2012). Two significant incidents in 2013 and 2018, involving erosion, ponding of water, and friction pile damages in the stilling basin, disrupted the surrounding area and were attributed to energy dissipation (Doke et al. 2019). The second incident, in 2018, resulted in a canal breach and flooding of the low-lying areas adjacent to it. Both incidents underscore the need for effective energy dissipation strategies (Doke et al. 2019). To address these challenges, a design involving a ski-jump type of bucket was proposed to reduce the velocity on the ogee spillway of the Khadakwasla dam (Al-Zubaidy et al. 2014; Hassan et al. 2014). The study aimed to assess the effectiveness of transitioning from a smooth crest profile to a stepped profile in stepped spillways for quantifying energy dissipation (Agoubi and Kharroubi 2019, Abdelkarim et al. 2023). The research revealed that incorporating steps into the profile eliminates the deflection of a water jet (Hsin-Fu Yeh et al. 2019, Bilel et al. 2022, Missaoui et al. 2023). However, this design requires a higher tailwater depth and may still result in scouring and erosion of the stilling basin (Rashwan 2013; Wuithrich and Chanson 2014). The ineffectiveness of the terminal structure's design and analysis has been identified as a key factor in the spillway's failure. This has led to the scouring and erosion of the chute block and downstream bed at the Khadakwasla dam in Pune, Maharashtra, India.

Considering these challenges, the present work proposes to conduct a comprehensive study of the dam and develop a physical working model of a stepped ogee spillway integrated with steps, a plain roller bucket, and stilling basin type II as an energy dissipator for the Khadakwasla dam spillway.

Material and methodology

The Khadakwasla dam was constructed in the Pune district of Maharashtra (India) in 1875. Khadakwasla dam is located at latitude 18° 26′ 30″ N and longitude 73° 46′ 5″ E on the Mutha river basin (Fig. 1). It has a cultivable commanded area of 677.43 km^2, an annual irrigation capacity of 621.46 km^2, and supplying 280.3 Mm^3 of water to Pune city. The parameters of the ogee spillway are a crest height of 23.75 m, a design head of 4.29 m, 14 spans having 10-m width, and 900 m^3/s design discharge. The location of the Khadakwasla dam is shown in Fig. 1. The features of the dam are shown in Table 1.

Methodology

The present methodology aims to attain the energy dissipation on the spillway chute and reduce the velocity of flow before reaching the base of the spillway. The proposed

Fig. 1 Location of Khadakwasla dam (source: www.googlemap.com)

Table 1 Salient features of Khadakwasla dam

Sr. no	Titles	Values	Units
	Area of catchment	501.8	km^2
	Mean annual runoff	1088.45	m^3
	Mean annual rainfall	800	mm
Dam	Type of dam	Composite dam	-
	Bed rock	basalt	-
	TBL	586.13	m
	MWL	583.38	m
	FRL	582.47	m
	Spillway crest	578.37	m
	Lowest river bed	554.45	m
	Minimum drawdown level	574.30	m
	Height of dam	31.76	m
	Length at top of dam	1539	m
	Number of gates	12 m × 5 m	14 nos
Spillway (seismic zone III)	Type of spillway	Ogee crested spillway	-
	Length of spillway	169	m
	Energy dissipator	Stilling basin type II	-
	Design discharge	900	m^3/s

methods are developed with the design of an ogee spillway, stepped spillway, roller bucket, and stilling basin. The limitations of discharge on stepped spillway as 30 l/s/m and nappe flow ($y_c/h < 0.8$) for steeped spillways are considered in this study. The stepped spillway is the proposed device to achieve energy dissipation on the chute itself. Plain and slotted roller bucket is studied and designed as per I.S. 7365 (2010). The design philosophy is applied to the hydraulic parameters and suggests modifications in the existing ogee spillway (Yadav et al. 2015). The plain roller bucket and slotted roller bucket are functioning properly with tailwater depth in the order of 1.1 to 1.4 times sequent depth and maintain Froude number should be less than 4.5. The current research aims to reduce velocity on spillway chute by the provision of different steps on the ogee profile with y_c/h and h/l parameters. This is achieved in the design of a stepped spillway by maintaining the non-dimensional parameter below 0.8 (Chamani and Rajaratnam 1999; Hamedi et al. 2014). Thus, the existing ogee spillway profile has been replaced by steps, considering 12 steps and 9 steps with step height to step length ratio (h/l) ranging from 0.90 to 1.20 and non-dimensional parameter (y_c/h) less than 0.8. The velocity of water reduces on each step and reaches the base of the spillway with the lowest intensity for fulfilment of roller bucket requirements.

To construct the hydraulic model of the ogee profile stepped spillway, a combination of materials including foam sheet, a 6-mm thick acrylic sheet, and polyvinyl chloride (PVC) was employed. The acrylic sheet was elevated by 300 mm on both sides of the spillway chute to guide floodwater downstream effectively. For measurement purposes, 20 piezometers were strategically placed along the spillway chute. These piezometers, equipped with 6-mm-diameter brass holes, were positioned at 45-mm intervals, allowing for the measurement of static head using a multitube manometer. In order to prevent the ingress of silt-laden water, the invert level of the roller bucket was maintained above the riverbed level. The entire setup, representing the ogee profile stepped spillway model, was affixed to a tilting hydraulic flume. This flume featured dimensions of 6 m in length, 300 mm in width, and 300 mm in depth. A series of experiments were conducted using both ogee and stepped spillway hydraulic models, with options for plain and slotted roller buckets, as depicted in Fig. 2. These laboratory experiments took place within the tilting hydraulic flume, subject to varying hydraulic heads, including 4 m, 5.5 m, and 6 m.

The laboratory experiments were carried out within a tilting hydraulic flume, covering a range of hydraulic head conditions, specifically at 4 m, 5.5 m, and 6 m. These experiments were conducted at discharge rates of 0.0053 m^3/s for the low head condition (4 m) and 0.00649 m^3/s for the high head

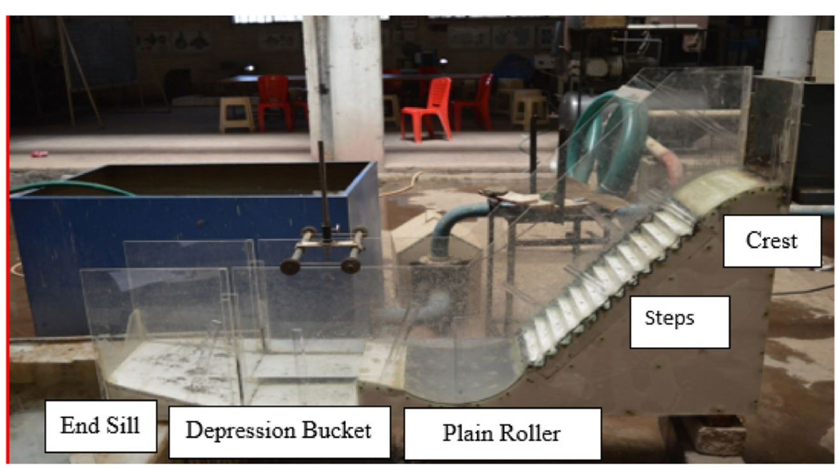

Fig. 2 Hydraulic model of ogee profile stepped spillway

condition (6 m). To maintain a continuous flow of 0.0053 m^3/s and 0.00649 m^3/s within the tilting flume, an orifice meter was employed, and the flume was maintained in a horizontal position throughout the observations. Water was pumped into the system using a 3 HP motor, and the total head on the model was measured by a pressure gauge affixed at the inlet of the tilting flume. Within this model setup, provisions were made to interchange different components, including the plain roller bucket, slotted roller bucket, and steps, as needed. The performance of each model was evaluated based on specific energy and energy dissipation, with assessments conducted across various head and discharge conditions. Subsequently, the experimental results from all the model configurations were compared against hydraulic parameters, accounting for both low and high head conditions of water flow.

Results and discussion

Design of an ogee profile spillway

The ogee spillway is designed on the basis of I.S. 6934 (1998), the design steps of ogee spillway are as mentioned below.

Input data of the Khadakwasla dam spillway is as follows:

Design discharge = 900 m^3/s.

Span = 10 m (assume single span).

Design height of spillway crest = 23.75 m.

Full reservoir level (FRL) = 28.02 m.

Design head (H_d) = 4.29 m.

Pier width = 2.5 m.

Maximum water level = 28.93 m.

Maximum head of water = 5.18 m.

Assume $C_d = 2.2$, $Q = C_d\, L_e\, H_e^{3/2}$

Number of span (N) = 14 nos.

Length of single span = 10 m.

The length and number of spans are decided on the basis of the tilting hydraulic flume width, the width of the flume is 30 cm. Thus, the model scale is selected as 1:33 in the proposed model.

Design steps

Effective length of overflow crest, assume $L_e = L - 2\,(N.\,k_p + k_a)H_e = L$.

where L is the length of single span, N is the number of piers, H_e is the effective head, k_p is the pier contraction constant, and k_a is the abutment constant.

Assume radial gates, considering gate is open or no gate.

$$L = L_e = 10 \times 14 = 140m$$

$$Q = C_d L_e H_e^{3/2}$$

Hence, $900 = 2.2 \times 140 \times He^{3/2}$

$H_e = 2.846\ m\ satisfactory\ (H_e < H_d)$

$H_e \approx H_d,\ He/H_d = 0.664 < 1$ - no effect on C_d.

$P/H_d = 5.59 \geq 1.7$ - it is a high spillway (P = crest height)

Hence, the coefficient of discharge is not affected by downstream apron interference, tailwater conditions, and the effect of approach velocity. Check for actual effective crest length (L_e).

$$L_e = L - 2H_e\ (N.\ k_p + k_a)$$

where for rounded pier nose, $k_p = 0.01$, for 14 spans, $N = 13$, and for rounded abutment, $k_a = 0.1$.

$\therefore L_e = 166.76$ m.

$H_e = 4.29$ m, hence the design is safe.

Design head, H_d = 4.29 m (neglecting velocity of approach)

Velocity of approach, $V_a = 0.19$ m/s

$\therefore$ Velocity head, $H_a = 0.0018$ m.

Determination of downstream profile

The downstream profile of the proposed ogee spillway is determined by using IS code.

The point of tangency for ogee profile with the downstream slope is 0.75 H:1 V.

Hence, coordinates of a lower tangent point are identified as $x = 6.5976$ m and $y = 4.755$ m.

Determination of upstream slope

Keep upstream slope is vertical, hence $k = 2.00$ and $n = 1.85$ (constants).

The downstream crest profile is given by $x^{1.85} = 2.\ H_d^{0.85}\ y$ (I.S. 6934, 1998).

Determination of x and y coordinates for ogee profile spillway

The downstream profile of ogee spillway is determined with the following methods.

IS code method, according to I.S. 6934 (1998) assumptions, the following data were calculated.

To determine x and y coordinates of the working model and plot the crest profile for the vertical *u/s* face. Spillway having vertical *u/s* face, the *d/s* crest is given by

Table 2 Design of downstream profile for ogee spillway

H_d $(m) \rightarrow x$ (m)	0.5 Y_1 (m)	1 Y_2 (m)	1.5 Y_3 (m)	2 Y_4 (m)	2.5 Y_5 (m)	3 Y_6 (m)	3.5 Y_7 (m)	4 Y_8 (m)
0.2	0.045893	0.025461	0.018038	0.014125	0.011685	0.010007	0.008778	0.007837
0.4	0.165446	0.091787	0.065028	0.050922	0.042124	0.036077	0.031646	0.028251
0.6	0.350288	0.194334	0.13768	0.107814	0.089187	0.076383	0.067003	0.059813
0.8	0.596433	0.330892	0.234428	0.183574	0.151858	0.130057	0.114085	0.101844
1	0.90125	0.5	0.354236	0.277392	0.229467	0.196525	0.17239	0.153893
1.2	1.262789	0.700576	0.496338	0.388669	0.321519	0.275361	0.241545	0.215628
1.4	1.679509	0.931766	0.66013	0.51693	0.42762	0.36623	0.321254	0.286785
1.6	2.150144	1.192867	0.845112	0.661784	0.547448	0.468855	0.411277	0.367148
1.8	2.67362	1.483283	1.050864	0.822903	0.68073	0.583003	0.511407	0.456534
2	3.24901	1.802501	1.277021	1	0.82723	0.708472	0.621466	0.554785
2.2	3.875497	2.150067	1.523261	1.192824	0.986741	0.845082	0.7413	0.661761
2.4	4.552357	2.525578	1.7893	1.401152	1.159076	0.992676	0.870769	0.777338
2.6	5.278934	2.928672	2.074881	1.624782	1.344069	1.151112	1.009748	0.901404
2.8	6.054633	3.359018	2.379769	1.863532	1.54157	1.320259	1.158123	1.033859
3	6.878913	3.816316	2.703751	2.117234	1.75144	1.5	1.31579	1.174609
3.2	7.751272	4.300287	3.046631	2.385734	1.973551	1.690225	1.482653	1.323569
3.4	8.671246	4.810675	3.408226	2.668889	2.207786	1.890832	1.658625	1.480659
3.6	9.638404	5.347239	3.788367	2.966567	2.454034	2.101728	1.843622	1.645806
3.8	10.65234	5.909757	4.186895	3.278643	2.712193	2.322826	2.037567	1.818941
4	11.71269	6.498019	4.603662	3.605002	2.982167	2.554041	2.240388	2.0
4.2	12.81907	7.111827	5.038527	3.945533	3.263865	2.795298	2.452016	2.188922
4.4	13.97118	7.750995	5.49136	4.300134	3.557201	3.046522	2.672389	2.385649
4.6	15.16867	8.415346	5.962034	4.668706	3.862095	3.307645	2.901444	2.590127
4.8	16.41125	9.104714	6.450431	5.051156	4.17847	3.578601	3.139124	2.802304
5	17.69864	9.818938	6.956438	5.447397	4.506252	3.859326	3.385374	3.022133
5.2	19.03057	10.55787	7.479949	5.857344	4.845373	4.149761	3.640142	3.249565
5.4	20.40676	11.32136	8.020859	6.280916	5.195764	4.44985	3.903378	3.484556
5.6	21.82696	12.10927	8.579071	6.718036	5.557364	4.759538	4.175034	3.727064
5.8	23.29095	12.92147	9.154491	7.168632	5.93011	5.078772	4.455064	3.977048
6	24.79849	13.75783	9.747029	7.632632	6.313945	5.407503	4.743424	4.234468
6.2	26.34936	14.61822	10.3566	8.109968	6.708812	5.745682	5.040073	4.499286
6.4	27.94335	15.50254	10.98311	8.600574	7.114657	6.093263	5.344968	4.771467
6.6	29.58025	16.41067	11.62649	9.104389	7.531427	6.450201	5.658072	5.050976
6.8	31.25986	17.34249	12.28666	9.62135	7.959073	6.816453	5.979346	5.337778
7	32.98199	18.29791	12.96355	10.1514	8.397546	7.191977	6.308753	5.631841

$x^{1.85}=2.0\ H_d^{0.85}*y$

$$x^{1.85} = 2.0\ H_d{}^{0.85} x\ y$$

where H_d is the design head, x is the horizontal distance, and y is the vertical distance.

The design of downstream profile for ogee spillway is mentioned in Table 2.

US Army Corps method

According to the latest studies of US Army Corps, the upstream curve of the ogee spillway having a vertical upstream face should have the following equation:

$$y = \frac{0.724(x + 0.27Hd)\hat{}1.85}{Hd\hat{}0.85} + 0.126H_d - 0.4315H_d^{0.375}(x + 0.27H_d)^{0.625}$$

x and y coordinates calculated from US Army Corp method (Table 3).

Performance evaluation of ogee spillway with plain and slotted roller bucket

Experiments were conducted on both plain and slotted roller buckets for an ogee spillway, involving different head levels.

Table 3 × and *y* coordinates calculated from US Army Corp method

x (m)	Y_1 (m)	Y_2 (m)	Y_3 (m)	Y_4 (m)	Y_5 (m)	Y_6 (m)	Y_7 (m)	Y_8 (m)
0.1	0.017965	0.00926	0.006155	0.004533	0.003521	0.002819	0.002296	0.001886
0.2	0.067587	0.03593	0.024491	0.01852	0.01483	0.01231	0.010472	0.009066
0.3	0.145016	0.078251	0.053896	0.041111	0.03319	0.02778	0.023841	0.020837
0.4	0.2482	0.135173	0.093717	0.071861	0.058276	0.048982	0.042208	0.037041
0.5	0.375796	0.205954	0.143466	0.110419	0.089826	0.075711	0.065407	0.057542
0.6	0.526833	0.290032	0.20276	0.156502	0.127621	0.107791	0.093298	0.082223
0.7	0.700565	0.386968	0.271287	0.209878	0.171477	0.145076	0.125756	0.11098
0.8	0.896388	0.4964	0.348789	0.270346	0.221237	0.187434	0.162675	0.143722
0.9	1.113801	0.618027	0.435049	0.337739	0.276762	0.234754	0.203958	0.180365
1	1.352379	0.751591	0.529877	0.411907	0.337933	0.286933	0.249519	0.220837
1.1	1.611751	0.89687	0.633109	0.492721	0.404642	0.343882	0.299281	0.265071
1.2	1.891591	1.053666	0.7446	0.580065	0.476794	0.40552	0.353174	0.313005
1.3	2.191608	1.221805	0.864219	0.673834	0.554303	0.471772	0.411136	0.364583
1.4	2.511541	1.401129	0.99185	0.773936	0.637089	0.542573	0.473106	0.419755

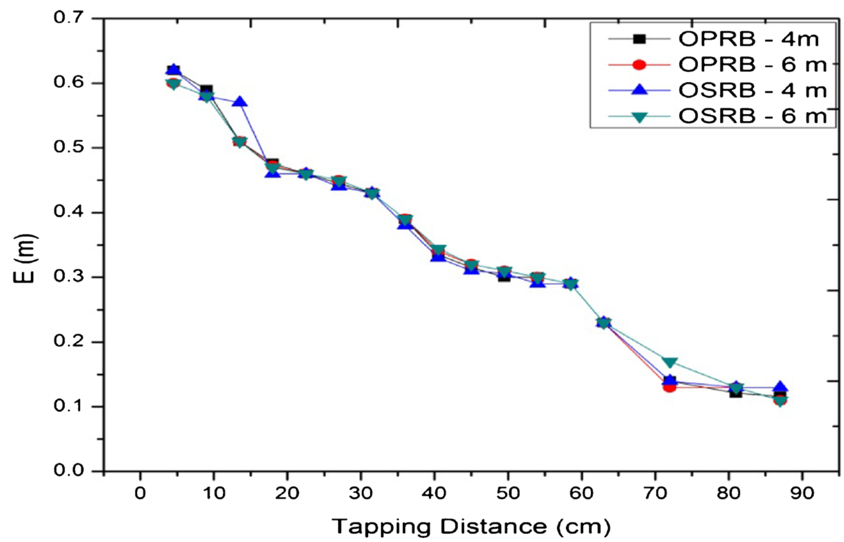

Fig. 3 Specific energy with plain and slotted roller bucket

The choice of head levels was based on the design head of the prototype, which stands at 4.29 m. The operational head was assumed to be 1.4 times the design head, leading to experiments being carried out at head levels of 4 m and 6 m. The objective was to assess the performance of these roller buckets for the ogee spillway and make any necessary modifications to the model. This model investigation served as the initial phase to identify potential issues with the prototype. Further adjustments to the prototype could be made to address any problems. The model was equipped with facilities to adapt both plain and slotted roller buckets for the ogee spillway. The results of these experiments were observed at the 4-m and 6-m head levels and compared using specific energy (E) and energy dissipation ($\Delta E/E_1$), as depicted in Figs. 3 and 4. The plain roller bucket (OPRB) and slotted roller bucket (OSRB) were found to effectively reduce kinetic energy on the ogee profile. Specifically, the slotted roller bucket outperformed the plain roller bucket in reducing kinetic energy for lower discharge rates (0.0052 m^3/s). However, the plain roller bucket also exhibited effective kinetic energy reduction across all discharge rates, with particular efficiency seen at higher discharges (0.0063 m^3/s). The greatest relative percentage of energy loss was observed with the plain roller bucket at the 4-m head, while the slotted roller bucket showed maximum energy loss at the 6-m head. During this initial stage, the performance of both roller buckets within the ogee spillway was effectively assessed using a horizontal rectangular channel located at the model's toe end. Significantly, the slotted roller buckets demonstrated superior effectiveness in terms of energy dissipation compared to plain roller buckets.

When the water flows on the ogee profile and reaches the roller bucket, the flow is drastically changed and creates a hydraulic jump on the roller bucket. The roller buckets are functioning properly for all discharges, and it is observed that the enhancement of energy dissipation is about 50% on the surface

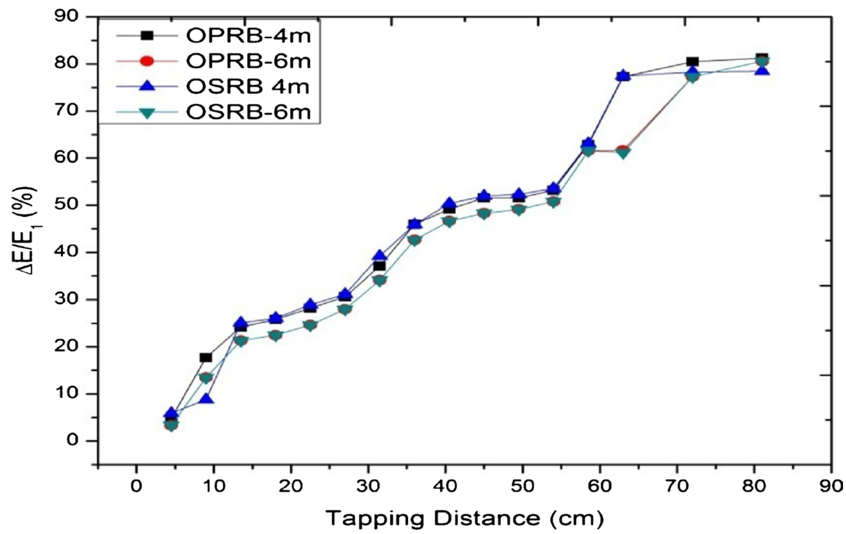

Fig. 4 Energy dissipation with plain and slotted roller bucket

of the roller bucket as shown in Fig. 3. In a slotted roller bucket, it is observed that for higher discharge, the hydraulic jump is thrown away from the structure at a longer distance. The throw distance of the hydraulic jump increases with an increase in discharge; especially, high jump is created with a slotted roller bucket and thrown away from the structure at a distance of 0.85 m from the roller bucket as shown in Table 4. The flow regime in the rectangular channel did not change but has the chance of causing erosion due to a falling high jump in the downstream channel. Therefore, the roller bucket of the ogee spillway is a suitable option to dissipate energy on the chute but needs to improve tailwater depth in a rectangular channel. In comparison with all heads and discharges, the plain roller bucket is a suitable energy dissipator for the ogee spillway but needs to stabilize the flow in the stilling basin.

Performance evaluation of plain and slotted roller bucket for ogee and stepped spillway

In this model, the experiments are performed ogee spillway with a plain, slotted roller bucket, and stepped spillway. Ogee plain roller bucket (OPRB), ogee slotted roller bucket (OSRB), stepped plain roller bucket (SPRB), and stepped slotted roller bucket (SSRB). The specific energy and energy dissipation are checked and tested with these mentioned models for the low head of 4 m and high head of 6 m. The performance of a stepped spillway having 12 steps, step height (h) 4.0 cm, and step length (l) 3.3 cm is evaluated with specific energy and energy dissipation. Figure 5a shows that in the ogee spillway, 82% of specific energy is eliminated by a plain roller bucket (OPRB) and 78% by a slotted roller bucket (OSRB). In a stepped spillway, 58% of specific energy is eliminated by a plain roller bucket (SPRB) and 57% by the slotted bucket (SSRB). Hence, in this device, the ogee spillway with a plain bucket is more reliable than the stepped spillway and helpful in reducing the intensity of specific energy over the chute surface of the spillway at a low head of 4 m.

In Fig. 5b, it is evident that OPRB, OSRB, and SPRB models collectively contribute to an 80% reduction in specific energy, primarily due to the presence of steps and a plain roller bucket. Notably, the SPRB model achieves a 57% reduction in specific energy. For the SSRB model, a stilling basin downstream of the spillway is required for the higher 6-m head. In this assessment, the ogee spillway equipped with a slotted bucket (OSRB) proves to be more dependable than other models, effectively eliminating 82% of energy in the spillway chute at a high 6-m head. The energy dissipation on the spillway chute, attributed to the stepped spillway itself, ranges between 32 and 79.79%. In the initial part of the slotted roller bucket on the model, the stepped spillway achieves a 69% energy dissipation due to increased turbulence and flow transition. Energy dissipation with the ogee spillway gradually increases by 5% along the chute and reaches 81.26% at the toe portion, as depicted in Fig. 5c. It is worth noting that the ogee spillway, whether equipped with plain or slotted roller buckets, attains an impressive 80% energy dissipation even before reaching the roller bucket on the spillway chute at the lower 4-m head.

It is observed that the stepped spillway with a slotted roller bucket gave better performance and was observed consistently on the chute of the spillway. The energy dissipation observed by the stepped spillway is 65 to 80% from crest to toe of the spillway at a head of 6 m as shown in Fig. 5d. It has been observed that in combination with a plain roller bucket dissipates maximum energy dissipation on its chute surface only. Hence, the stepped spillway with a plain roller bucket is found efficient than other devices for energy dissipation. Therefore, the plain roller bucket is selected as an energy dissipator for both spillways and tested with a modified stilling basin.

Table 4 Location of hydraulic jumps on hydraulic model

Stages	Types of spillways	Head (m)	Discharge (m^3/s)	Description of model	Location of hydraulic jump	
					Model (m)	Prototype (m)
1	Ogee spillway	5	0.059	Plain roller bucket	0.80	26.66
2				Slotted roller bucket	0.83	27.66
3		6	0.064	Plain roller bucket	0.83	27.66
4				Slotted roller bucket	0.85	28.33
5	Stepped spillway	4.0	0.052	Plain roller bucket (Set 1)	0.79	26.33
6				Plain roller bucket (Set 2)	0.77	25.66
7		5.5	0.062	Plain roller bucket (Set 1)	0.80	26.60
8				Plain roller bucket (Set 2)	0.79	26.33
9		6.5	0.067	Plain roller bucket (Set 1)	0.85	28.30
10				Plain roller bucket (Set 2)	0.83	27.66

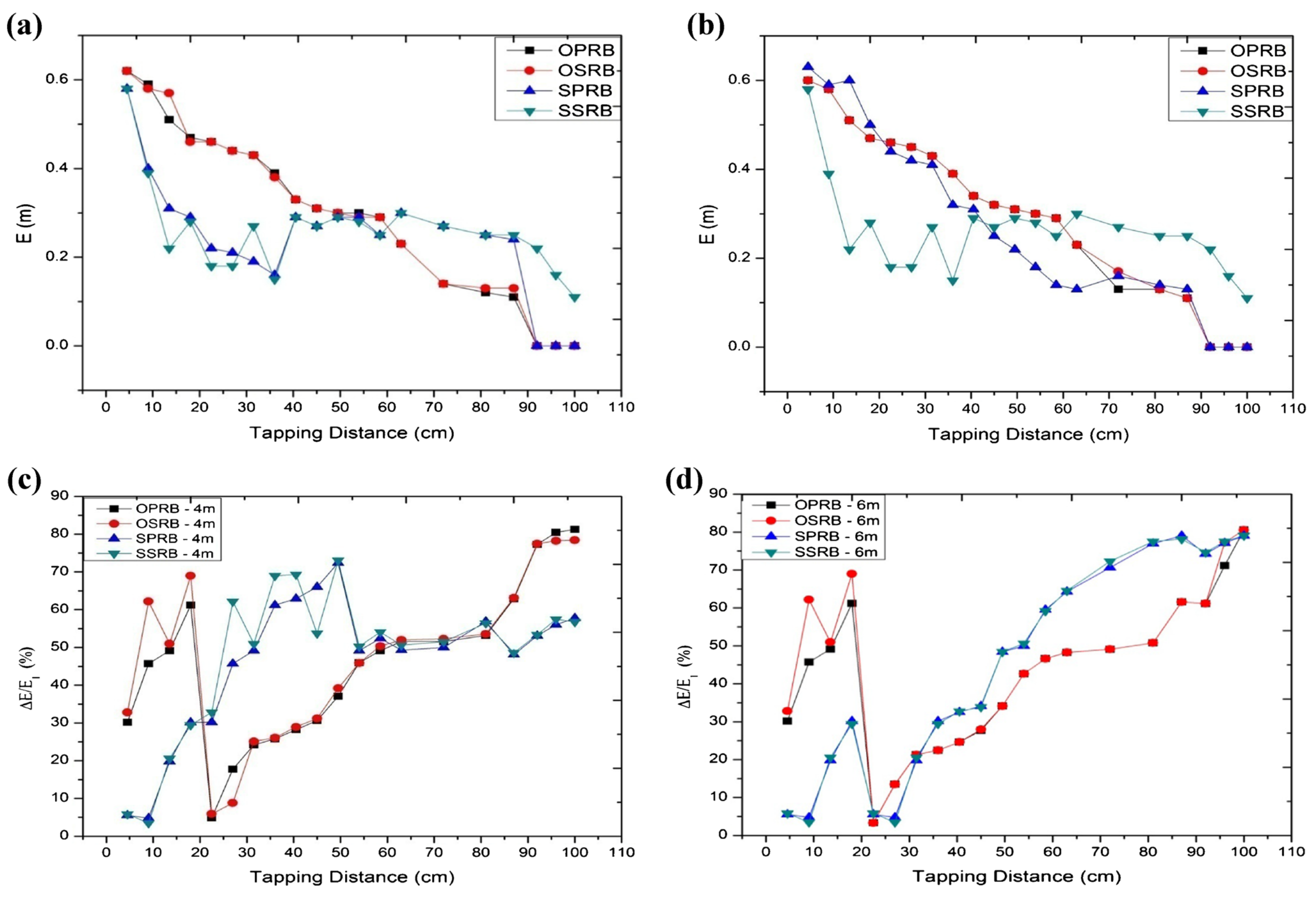

Fig. 5 **a** Specific energy for ogee and stepped spillway at 4-m head. **b** Specific energy for ogee and stepped spillway at 6-m head. **c** Energy dissipation for ogee and stepped spillway at 4-m head. **d** Energy dissipation for ogee and stepped spillway at 6-m head

Performance evaluation of plain roller bucket with modified stilling basin for ogee and stepped spillway

In this model, the plain roller bucket is the preferred choice, given its superior performance as evidenced in prior studies across various head levels. As a result, the plain roller bucket is subjected to further testing at head levels of 4 m, 5 m, and 6 m for both spillway configurations, featuring a modified stilling basin. These configurations are denoted as the ogee spillway with a plain roller bucket (OSPRB) and the stepped spillway with a plain roller bucket (SSPRB). Stilling basin type II is

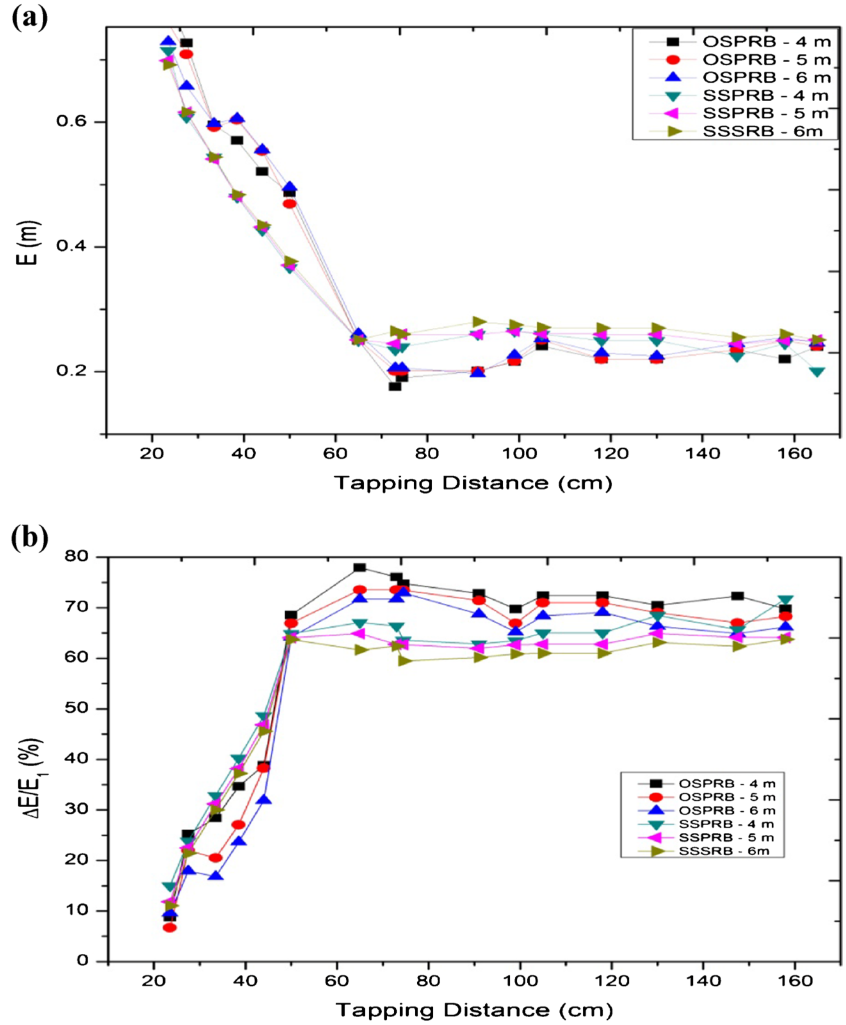

Fig. 6 **a** Specific energy with plain roller bucket and modified stilling basin. **b** Energy dissipation with plain roller bucket and modified stilling basin

selected, which incorporates a depression bucket and an end sill (sloping apron). This design leads to an increase in tailwater depth within a range of 1.1 to 1.4 times the sequent depth (y_2) downstream. The specific energy and energy dissipation for all head levels are compared and presented in Fig. 6a, b.

In the previous evaluations, the plain roller bucket consistently demonstrated superior energy dissipation performance, making it the preferred choice for both ogee and stepped spillways. Consequently, experiments were conducted by combining the plain roller bucket with a stilling basin at head levels of 4 m, 5 m, and 6 m. Subsequently, the results were compared in terms of specific energy and energy dissipation, as detailed in Table 5. The findings reveal that the stepped spillway significantly outperforms the ogee spillway in enhancing energy dissipation, and this improvement is consistently observed along the spillway chute. The presence of steps on the stepped spillway reduces the flow velocity, resulting in the most significant reduction observed on the spillway chute. Notably, the ogee spillway model (OSPRB) achieves maximum energy dissipation, precisely 77.90%, right at the location where the flow transitions from supercritical to subcritical flow. It is noteworthy that the percentage of energy dissipation decreases as head and discharge increase. On average, the energy loss observed is 68.05% for the ogee spillway and 64.00% for the stepped spillway. The flow conditions in the ogee spillway models are appropriate, as indicated by Froude numbers ranging from 5.61 to 4.46 (Fr1 > 4.5). In contrast, the stepped spillway exhibits Froude numbers ranging from 3.05 to 1.74, signifying a more favorable and stable condition in the model. This reduction in Froude number is a result of the reduced velocity on the spillway chute.

Ogee spillway with plain roller bucket and modified stilling basin

The experiments were conducted using an ogee spillway in conjunction with a plain roller bucket and a modified stilling basin to achieve controlled tailwater conditions. Specifically, the tailwater depth in the stilling basin was carefully maintained within a range of 1.1 to 1.4 times the sequent depth. To

Table 5 Comparison of ogee and stepped spillway with hydraulic parameters

Sr. no	Types of spillways	Head (m)	Froude number (Fr_1)	Total Energy (E) (m)		Energy loss (ΔE) (m)	Relative energy loss (%)	Energy dissipation ($\Delta E/E_1$) (%)
				E_1	E_2			
1	Ogee spillway	4	5.61	0.798	0.221	0.577	72.30	77.90
2		5	4.46	0.760	0.251	0.509	66.97	73.54
3		6	5.23	0.729	0.256	0.473	64.88	72.95
4	Stepped spillway	4	3.05	0.715	0.246	0.469	65.59	71.76
5		5	2.21	0.699	0.251	0.448	64.09	64.90
6		6	1.74	0.693	0.261	0.432	62.33	63.74

Table 6 Comparison of ogee spillway with plain roller bucket and modified stilling basin

Provisions	Head (m)	Discharge (m^3/s)	Froude number (Fr_1)	Total energy (E) (m)		Energy loss (ΔE) (m)	Energy dissipation ($\Delta E/E_1$) (%)
				E_1	E_2		
Controlled end sill (C)	4	0.0052	5.53	0.796	0.195	0.601	75.50
	5.5	0.0062	5.02	0.785	0.194	0.591	75.28
	6.5	0.0067	4.81	0.787	0.247	0.54	68.61
Uncontrolled end sill (UC)	4	0.0052	5.53	0.796	0.189	0.607	76.25
	5.5	0.0062	5.02	0.785	0.221	0.564	71.84
	6.5	0.0067	4.81	0.787	0.235	0.552	70.14

Table 7 Stepped spillway with combination of plain roller bucket and stilling basin

Provisions	Discharge (m^3/s)	Head (m)	Froude number (F_{r1})	Total energy (E) (m)		Energy loss (ΔE) (m)	Energy dissipation ($\Delta E/E_1$) (%)	Non-dimensional parameter (y_c/h)
				E_1	E_2			
Controlled end sill	0.0052	4	5.53	0.795	0.175	0.62	77.98	0.78
	0.0062	5.5	5.01	0.783	0.178	0.606	77.39	0.87
	0.0067	6.5	4.68	0.787	0.179	0.607	77.12	0.92
Uncontrolled end sill	0.0052	4	5.53	0.796	0.173	0.623	78.26	0.78
	0.0062	5.5	5.02	0.784	0.173	0.611	77.93	0.87
	0.0067	6.5	4.75	0.787	0.176	0.611	77.63	0.92

assess performance, the tailwater depth in the stilling basin was adjusted by a 0.10-m height using a V-notch. The ogee spillway's performance was evaluated at head levels of 4 m, 5.5 m, and 6.5 m. The results were then compared under both conditions, specifically with and without the end sill, as presented in Table 6.

The combination of a stilling basin and a solid (plain) roller bucket effectively dissipates approximately 76.25% of the specific energy in the absence of control at the downstream end. The flow conditions within this range are favorable, with observed Froude numbers falling between 5.53 and 4.81. However, it is noteworthy that, at a high head of 6.5 m, the roller bucket faced operational issues, and no ground roller formation was observed in the stilling basin. Furthermore, there is a clear trend where the percentage of energy dissipation decreases with increasing discharge and head. In this model, the ogee spillway combined with a modified stilling basin demonstrated the highest energy dissipation at a lower head of 4 m. This condition aligns with favorable Froude numbers, facilitating enhanced energy dissipation within the ogee spillway.

Performance evaluation of stepped spillway with plain roller bucket and modified stilling basin

The experiments were conducted on a stepped spillway with a modified stilling basin to control tailwater conditions at head levels of 4 m, 5.5 m, and 6.5 m. This configuration consisted of 12 steps with a step height (h) of 4 cm, step length

Table 8 Stepped spillway with combination of plain roller bucket and stilling basin for V-notch position

Provisions	Discharge (m^3/s)	Head (m)	Froude number (F_{r1})	Total energy (E) (m)		Energy loss (ΔE) (m)	Energy dissipation ($\Delta E/E_1$) (%)	Non-dimensional parameter (y_c/h)
				E_1	E_2			
Controlled end sill	0.0052	4	5.53	0.797	0.157	0.639	80.17	0.69
	0.0062	5.5	5.02	0.785	0.177	0.608	77.45	0.78
	0.0067	6.5	4.76	0.787	0.179	0.608	77.25	0.82
Uncontrolled end sill	0.0052	4	5.53	0.805	0.173	0.632	78.50	0.69
	0.0062	5.5	5.02	0.784	0.175	0.609	77.67	0.78
	0.0067	6.5	4.76	0.786	0.179	0.607	77.22	0.82

(l) of 3.3 cm, and an h/l ratio of 1.20. The stepped spillway consistently proved to be an effective method for energy dissipation, with energy being dissipated consistently along the spillway chute. The percentage of energy dissipation on the stepped spillway is influenced by the non-dimensional number, the number of steps, and the h/l ratio. To explore its performance, two sets of steps were employed. The tailwater depth in the stilling basin was carefully maintained within a range of 1.1 to 1.4 times the sequent depth. The results were analyzed at head levels of 4 m, 5.5 m, and 6.5 m for both scenarios, with and without an end sill, as detailed in Table 7.

The design of the stepped spillway relies on a non-dimensional parameter, which should be less than 0.8 to maintain nappe flow on the stepped spillway model. For the first trial, under uncontrolled tailwater depth in the stilling basin at a head of 4 m, approximately 78.26% of energy dissipation was achieved. In the second trial, a total of 9 steps were used, with a step height (h) of 4.5 cm, step length (l) of 5.0 cm, and an h/l ratio of 0.90. The stilling basin was equipped with a V-notch, and downstream water depth was maintained at 1.1 times the conjugate depth, resulting in an energy dissipation of approximately 80.17%. The outcomes associated with different heads are presented in Table 8.

Conclusion

In the current investigation, employed a combination of steps, roller buckets, and stilling basins to augment energy dissipation in a spillway model featuring an ogee profile. The effectiveness of a stepped spillway becomes evident when the operational head is less than 1.4 times the design head. The plain roller bucket proved to be effective for higher discharge rates when used in conjunction with the modified stilling basin type II. When a stepped spillway is combined with plain roller buckets and stilling basin type II, it exhibits superior performance in terms of energy dissipation, especially at the lowest value (0.69) of a non-dimensional parameter. The ogee profile stepped spillway model achieved maximum energy dissipation under a 4-m head. Energy dissipation percentages increased with longer step lengths but decreased as the step slope became steeper. By utilizing a combination of steps, roller buckets, and stilling basins, we managed to reduce the length of the stilling basin, thereby minimizing the footprint in the downstream channel. This innovative model is suitable for various spillway types, especially for high discharge scenarios, and is effective in enhancing energy dissipation. Combination of plain roller bucket (PRB) energy dissipating energy model in stepped spillway attained 80.17% energy dissipation. Stepped spillway showed that the energy dissipation occurred only on the chute and increased consistently and intensity of kinetic energy reduced till flow reached up to the roller bucket for higher discharges. A plain roller bucket eliminates 82% of specific energy, whereas a slotted roller bucket removes 78%. In the case of a stepped spillway, a plain roller bucket dissipates 58% of specific energy, while a slotted bucket dissipates 57%. As a result, for this application, the ogee spillway with a plain bucket stands out as the more reliable option compared to the stepped spillway, effectively reducing the specific energy.

Declarations

Competing interests The authors declare no competing interests.

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