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STEEPED SPILLWAY AS A MEAN FOR ENERGY DISSIPATION – A REVIEW

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Abstract:
Stepped spillways are spillways provided by steps that are used to dissipate energy and reduce the scour and erosion that occur at the end of the hydraulic structures. Since the spillway is one of the parts of the dam used to get rid of excess water during floods, spillways can be constructed in various forms and sizes depending on the geology of the dam site and the hydraulic conditions of the flow. The stepped type was chosen because it dissipates energy and reduces the size of the basin at the end of the structure. The aim of the research is to review most of the studies that dealt with the subject of stepped spillways as energy dissipaters. This study collected much research on stepped spillways, some of which used physical models and others numerical models. These studies were performed to determine energy dissipation, flow properties, or type of flow in the stepped spillways and to study the effect of the shape of the steps on energy dissipation. The results showed that some studies indicated that when the flow over the stepped spillways is in the form of jet or free flow, it increases the efficiency of energy dissipation and reduces the length of the hydraulic jump. It is worth mentioning that some studies used software such as ANSYS, while others used artificial intelligence (AI) techniques like genetic programming and fuzzy logic.

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1. INTRODUCTION

Energy dissipaters are structures intended to protect areas downstream from scour and erosion. A significant consideration in the design of canals, bridges, and dams is the creation of these structures, which lower the flow rate. Thus, the safety of hydraulic structures - such as spillways - is required to achieve sustainable power production [1]. Although the structure of stepped spillways dates back at least 3,500 years, they were no longer in use at the start of the 20th century due to innovations in the construction of hydraulic jump-stilling basins [2]. The Al-Khawsar River dam in Iraq is considered one of the oldest stepped spillways in the world. The Khosr River dams were built around B.C. 694 by the Assyrian King Sennacherib. The dams were designed to supply water to the capital city of Assyrian, Nineveh (near Mosul) [3]. Because of its excellent energy dissipation function, a stepped spillway is a significant hydraulic structure that is frequently utilized in hydraulic projects. The stilling basin at the dam's toe needs less space than a smooth spillway because of the increased energy dissipation rate [4,5]. It is difficult to predict the erosion and energy dissipation process in hydraulic structures [6]. Dams include many hydraulic structures for irrigation, drinking, and hydroelectric power generation [7]. The air entrainment affects a stepped spillway's performance. Since cavitation frequently happens in the non-aerated flow zone, recognizing the precise position of air entrainment is essential to identifying the cavitation-affected area. The location of the inception point indicates the length of the non-aerated flow zone. Therefore, the aerated and non-aerated flow zones can be anticipated by precisely locating the inception

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point [8,9]. The location of the inception point is vital in the energy dissipation in a stepped spillway and in calculating the stilling basin's length. The energy dissipation upstream of the inception point is much less than that downstream. The inception point is located farther downstream in a smooth spillway than a stepped spillway. The step height, geometry, and discharge affect the position of a stepped spillway's inception point [10,11]. Weirs, blasts, dams, and other water-powered constructions are used for electric power generation, flood control, and irrigation, among other things. Consequently, despite the numerous ways to dissipate Stream Energy, including hydraulic jumps, roller buckets, stilling basins and free jets, hydraulics researchers and engineers' application importance was placed on reducing the flow velocity that causes the formation of the hydraulic jump at the end of the channel when designing hydraulic structures [12]. In this research, a review will be conducted on the stepped spillways as energy dissipaters.

2. MATERIALS AND METHODS

2.1. Spillways

A spillway is a construction that regulates the amount of water released from a dam into a downstream region [13]. The purpose of spillways is to prevent floodwaters from overflowing and damaging the dam. Spillways may have installed gates to regulate water flow downstream and, in turn, reservoir level [14]. Typically, a spillway is only crossed by water during flooding, when the reservoir's level rises over emergency levels. Several spillways are currently used worldwide, and a few more prevalent kinds are briefly covered. Free Over-Fall Spillway: This spillway's flow easily falls from the crest of the spillway. This spillway is used for an arch dam with an approximately vertical downstream face [15,16]. Ogee (Overflow) Spillway: An ogee spillway has a downstream profile that coincides closely with the profile of water dropping easily from the weir of a sharp-crested. In general, for concrete and masonry dams, the Ogee spillway is more appropriate [17]. Chute Spillway: In a chute spillway, an open channel conveys the spillway discharge from the dam reservoir to the downstream [18]. Siphon Spillway: A closed duct system with an inlet end at the level of the dam emergency reservoir, shaped like an inverted U with uneven legs [19]. When using a cascade spillway in a very high dam, the downstream river water depth might not be able to support a single-fall hydraulic jump due to the large kinetic energy at the dam's toe [20]. Tunnel Spillway: A tunnel spillway is a vertical or inclined shaft that releases water through tunnels. Steeped spillway A cascade spillway's typical design is a stepped spillway. Dissipating excess kinetic energy is the primary purpose of stepped spillways. To improve energy dissipation and hence reduce stilling basin building costs, a variety of technologies are utilized in conjunction with it [21].

2.2. Types of Flow in Stepped Spillways

When studying the flow over the stepped spillway, it is necessary to know the flow types; thus, it can be divided into three types based on the discharges such as Nappe, transition, and skimming [22]. At Nappe, water falls in the form of a jet that hits the step and then the step that follows it. Thus, energy is dissipated during the mix of the air with the jet, whether a hydraulic jump is formed or not. When designing, transitional flow must be avoided as it is the cause of failure of many structures and occurs in medium discharge. The skimming, during this type, the flow is continuous along the steps, thus enhancing energy dissipation and occurring at high discharges [23]. The transmission of shear stress from the mainstream sustains these recirculation eddies, which play a crucial role in energy dissipation down the tiered spillway. The nappe flow is thought to be the most effective at dissipating energy in small dams, whereas the skimming flow works best in huge dams and long spillway chutes [24].

2.3 Theory of Energy Dissipation

The energy conservation law must be understood before we can comprehend energy dissipation. The physics phenomenon that energy cannot be created or destroyed is referred to as the conservation of energy. It is limited to being transformed from one form to another. With this, that energy can be transformed into various forms, even if it cannot be created or destroyed. Dissipation can occur when energy is changing from one form to another.

2.4 Applications Studies

According to research, [25] and [26], energy dissipation efficiency must be considered when designing stepped spillways to reduce the dissipation basin's cost. The purpose of the structures determines the shape of the stepped spillway, as shown in Figure (1), by using a model with a slope of 0.78H: 1V and the two circumferences that make up the curved form upstream from the crest. Numerical models are used to study interface behavior, air concentrations along the flow interface behavior, air concentrations along the flow, dependency between the bed profile properties and the location of the inception point. The result showed that when using skimming flow simulation, significant results were obtained in air entrainment in stepped spillways. The pressure, velocity, and void fraction profiles along the simulated spillways were provided.

Fig. 1. Three samples of dam structures are shown here: 1) smooth waterfall; 2) flow over a stepped waterfall; and 3) a labyrinth [25]

In research [27], a physical study was conducted in a moderate slope-stepped chute (*1V:3.5H*) to *1V:2H* where the angle of slope (15.9^{o} - 26.6^{o}) was used to study energy dissipation performances of stepped spillways. Experiments with Reynolds numbers ranging from 5×10^{4} to 1×10^{6} for large discharge showed a notable rate of energy dissipation on the steps in addition to significant free-surface aeration. Curiously, the experimental results supported previous discoveries that a slope of 1V:2.H tended to be the highest for the energy dissipation rate. The fundamental results revealed little variations among all designs and suggested that the energy dissipation rate for uniform and nonuniform stepped configurations was almost the same. However, the findings indicated that, at lower flow rates, the nonuniform stepped arrangements might cause some flow instabilities.

In research [28], comparative studies are carried out to investigate the flow features by numerical modeling. 3D distributions can be seen in pressures above the step surfaces of the nontraditional designs. Pool weirs are necessary to raise the minimum and maximum pressure loads. For V-shaped and reversed V-shaped models, the downstream bed pressures exhibit a distinct pattern, with the highest pressures occurring along the sidewalls in the former case and the middle plane in the latter. Figure 2 illustrates how symmetrical secondary flows arise for V- and reversed V-molded situations with varying patterns. Several variations are made to examine the impact of the step. In all circumstances, distributions of turbulent kinetic energy indicate variations in flow movements. Moreover, flat setups have a relative energy loss of approximately 5.4% less than pooling configurations with the same step face angle; there is no discernible difference when the face angle is reversed.

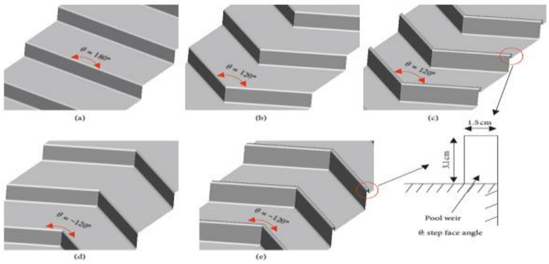

Fig. 2. Spillway models: (a) traditional stepped spillway; (b) V-shaped stepped spillway; (c) pooled V-shaped stepped spillway; (d) inverted V-shaped stepped spillway; and (e) pooled inverted V-shaped stepped spillway [28]

Research [29] conducted five turbulence models to estimate the pressure distribution for skimming flow types. The realizable *K - ε* model demonstrated superior accuracy for evaluating distribution pressure compared to the physical value. The flow pattern of V-shaped and a conventional stepped spillway was presented to show the distinct distribution of pressure using a turbulence model. Fluent software was utilized to carry out these simulations using the finite volume technique (*FVM*). The numerical model of the stepped spillway shown in Figure 3 consists of a press slope section, a smooth section, a stepped section, and a tailwater section. Compared to previous turbulence models, the outcome demonstrated that the realizable K-ε model somewhat more accurately mimics the pressure distribution of a V-shaped stepped spillway, even if all numerical findings show good agreement with empirical values. The negative pressure is higher than in regular steps, but the order of magnitude is still the same. Thus, there is no discernible difference between the traditional and V-shaped steps along the sidewalls, despite the traditional steps' greater resistance to cavitation damage. Several potential applications exist due to the improved energy dissipation rate and aeration qualities, particularly in ecological water conservation and aeration tanks.

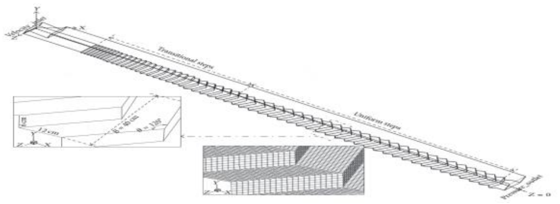

Fig. 3. The numerical model layout [29]

In research [30], the tests were conducted in the University Sulaimani's College of Engineering hydraulics lab in a rectangular flume with 10 mm thick walls. Utilizing three wooden physical models, each model was composed of a broad crested weir. Figure 4 illustrates the stepped models used in the study. The initial model, the *M1* configuration, used 16 steps as a flat reference model. Several transverse slopes were applied to each of the next *12* steps for the two additional models, the *M2* and *M3* models. It was decided to keep the first step flat because the dam crests cannot have a transverse slope. The research focused on a stepped spillway's capacity to dissipate energy, using the angle of slope 26.6°, a typical slope for embankment dams and concluded that three types of flow nappe, transition, and skimming flows when using flat stepped spillway . Nevertheless, nappe flow and transition flow are the only two possible flow forms on a stepped spillway with steps with transverse slopes.

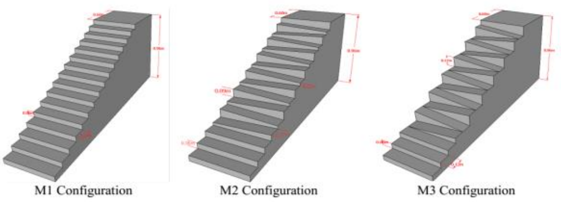

Fig. 4. Illustration of the stepped models (configurations) [30]

Research [31] investigated the impact of the stepped spillway's height and design on the position of the inception point. Table 1 lists the six types of stepped spillway models utilized for numerical modeling. The models vary in step size and configuration. Figure 2 displays models with flat, pooling, and round stairs that vary in step height. All six models were simulated sequentially, with the turbulence model being the realizable *k* model and the multiphase model being *VOF*. All models have the same slope. The inception point of a flat-stepped spillway is further away from the spillway crest, but under identical discharge and step count conditions, it is closest to the spillway crest in a round-stepped spillway. The stepped height causes both the non-aerated flow zone and the likelihood of cavitation to diminish. With identical boundary conditions, the flat shape exhibits the largest non-aerated flow zone, and the round-stepped spillway the least. Therefore, the circular stepped spillway has a lower chance of causing cavitation damage, making it preferable to employ it to avoid cavitation.

Table 1. Different Variables of different stepped spillways used in numerical simulation [31]

Model	Step Geometry	Step Hight (m)	Step Length (m)	Slope (°)
M1	Flat	0.1	0.45	12.52
M2	Flat	0.09	0.37	13.67
M3	Flat	0.05	0.21	13.39
M4	Flat	0.04	0.17	13.24
M5	Pooled (hp =0.01 m)	0.04	0.15	14.93
M6	Round	0.04	0.16	14.03

The current study [32] predicts the free-surface profile over a stepped spillway with non-uniform step sizes using the 2D ANSYS-CFX code with one extruded unit. For this reason, four flow discharge configurations with a range of *dc/hs* from 1 to 2.2 are investigated in eight combinations of two slopes *(1V:2H and 1V:2.5H)*. A wavy pattern is visible in the free surface profile over the stepped spillway. The results show that the free surface is evident at high discharges, and the effect of the free surface decreases with increasing channel slope. The effect of the step size is also found to be small. Further investigations into the pressure distribution and energy dissipation are recommended.

In research [33], the test was carried out laboratory of hydraulics in the college of Engineering as display in Figs. 5 and 6. This study used standard gabion stepped weirs composed of gravel medium and modified gabion stepped weirs built of limestone and porcelain to educate the hydraulic performance, relation energy dissipation, and removal accuracy for flow.

As a result, relation energy dissipation increased by 26.35% when compared to a flat sloped spillway and 16.35% compared to a stepped spillway without any addition. The results indicated that limestone (*MGSW*) exhibited the maximum energy dissipation at small (nappe) and high (transition) flow rates. However, at high flow rates (transition flow), the relation energy dissipation of porcelain rock was low, comparable to 10%. The copper metal (*Cu*) may be effectively removed by the porcelain immersed weir; the removal efficiency was 90% during the first six hours of system operation and 58% after that. Ineffective for removing copper metal (*Cu*), with a RE% of 20% at low flow, was the gravel media (*TGSW*).

Fig. 5. Inside channel with model was used in tests [33]

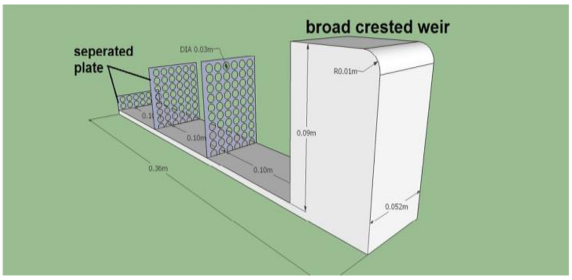

Fig. 6. Illustration of the soaked weir mold's details [33]

Research [34] used computational fluid dynamics (*CFD*) to assess how flow rate, step angle, and step count affect where a stepped spillway's inception point is located. To achieve this goal, the fluid volume combined with a *CFD-FLUENT* code that utilizes the Finite Volume Method is utilized to capture the characteristics of free-surface flow. The outcome shows that the inception point has a bigger step height under the same discharge and is closer to the spillway crest when steps are flat and flow rates are high. However, when steps are sloping, the effect increases as step slope increases, and the consequences move in the opposite direction. The results for every stepped spillway configuration demonstrate that the inception point's length also does when the flow rate increases. If significant flows and large step slopes are simultaneous, rising α will not alter the inception length. However, decreasing step height has a greater effect on lengthening the inception point than increasing the steep slope. The location of the inception point in the flat stepped spillway model is closer to the spillway crest than the sloping stepped spillway model, which has the same flow. The inception point length of a flat and sloping stepped spillway is the same for a particular flow, but as the discharge increases in size, the difference becomes more noticeable. If steps are taken at the same slope and discharge but with a different number or height, the inception length will rise.

In research [35], an experimental investigation of the impact of the orifice plate on the flow characteristics of the stepped spillways using the physical model shown in Figure 7, which includes a drainage channel, a basin for feeding, a stepped spillway physical model, and a flow return system. The flow of water from the orifice plate will be in the form of a jet, thus creating cavitation at the sides and ends of the structure, but it works to supply the lower part with air, and the amount of aerator larger than *1-2%*. Here, the importance of reducing the risk of damage to the stepped spillways appears. According to the research, the orifice plate can enhance the stepped spillways' ability to dissipate energy while simultaneously producing a jet to entrain air, particularly for large unit discharges. When *hc/t* (critical depth/step height) = 3.5, the energy dissipation can be increased by approximately 8% compared to conventional stepped spillways.

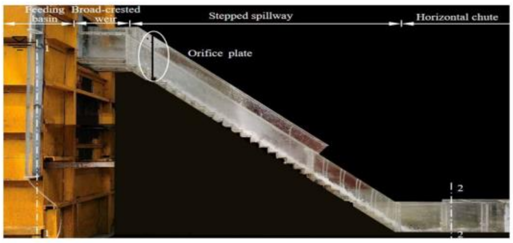

Fig. 7. Experimental set-up [35]

In research [36] investigating energy dissipation, the flow by a cylindrical stepped weir using a physical model. The main channel is 24.6 m in length, 76 cm in height, and 81 cm in width beyond the end of the straight portion, as shown in Figure 8. Three distinct weir heights, 60, 45, and 30 cm, with one slope angle in the end equal to 45°, and three diameters, 7.5, 5, and 2.5 cm, were employed. The steps are *Fc*, *Fc* & *Hc*, and *Hc*, where *Fc* - all steps in a circle without cutting (Fig. 8-a); *Fc* & *Hc* - circular step and the other cut in half, respectively (Fig. 8-b); and *Hc* - all steps are cut in half (Fig. 8-c). The outcome shows that as the weir's height grows, the flow energy dissipates, with the flow energy at height *P* = 60 cm having the highest share of dissipation. The ratio of flow dissipation energy increases when the step geometry is changed, for example, when a step takes on a circular form. The form of all the steps in a circle without cutting (*Fc*) is inferior to the other cut in half (*Fc* & *Hc*). The two forms are inferior to the characteristics of steps (*Hc*), which is the weir's entire set of stairs divided in half. The former characterizes the flow's percentage dissipation energy across all study diameters. The energy dissipation rate in stepped cylindrical weirs was 67.27%, while conventional stepped weirs were 57.84%.

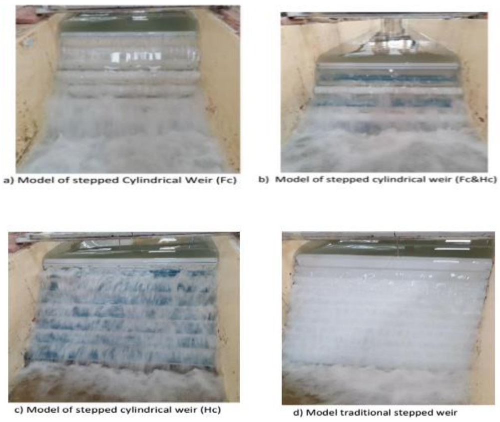

Fig. 8. The models for stepped weir [36]

In research [37], this experimental program was carried out in the technical institute of Mosul's hydraulic laboratory. Four models were used to study the hydraulic flow characteristics of the stepped spillway. The models are divided into A and B, where A was for the conventional spillway without stepping, and B was for the semicircular stepped spillway. Rubber tubing was used for pressure measurement, as shown in Fig. 9. The result showed that three different types of flows happen when water flows over stepped spillways. The research shows that the areas with negative readings are toward the end of the spillway's sloping straight line at low flow and the crest when the discharge is large. These negative readings decrease as the discharge increases. Increasing the flow rate reduces energy dissipation in all models. Compared to the conventional shape and other sizes and numbers of steps 5 and 7, the dissipated energy of flow over the model with a large size and a few step numbers of step 3 is greater. ($\Delta E/E0$)% value increases with (d_0/d_c) value for both regular spillways and varied *D/S* step spillway.

Fig. 9. A) The channel used in the experiments has triangular Sharp, B) stepped spillway model, and C) a piezometer board [37]

In research [38], a stepped model with different step sizes placed in a channel with glass sides, a channel with dimensions 6.0 m long, 30.4 cm wide, and 40.0 cm deep flume was used to study the effect of the model on energy dissipation and reducing the length of the hydraulic jump as figure 10. The results showed that when comparing traditional stepped with stepped spillways, the inserted extinguishers are more effective in dissipating energy and increasing the number of steps increases energy dissipation. It also showed that stepped spillways are an excellent alternative when designing a dam. However, there are some disadvantages, such as noise and erosion of steps when the flow changes from nappe to skimming, so they require high quality in design and implementation.

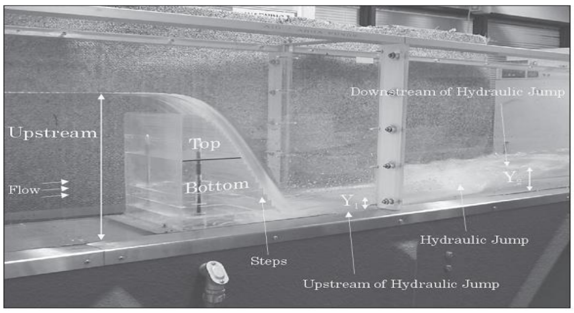

Fig. 10. Testing Setup with Flow across a Stepped Spillway Model [38]

In research [39], based on the outcomes of the simulation, experimental data for a flat stepped spillway was obtained by [40] using Flow-3D software for circular stepped spillways (*CSS*). According to Fig. 11, three different discharges (0.0121, 0.00831, and 0.00684 m^3/s) were used for the numerical investigations. The numerical results obtained using the RNG k–ε turbulence model accord with the experimental data [40], with the maximum error being 5.88%. These are the study's results. In general, energy dissipation rates rise in all models when the discharge falls. The energy dissipation rates in all models generally rise as the discharge lowers. Maybe the *CSS* releases more energy than the flat-stepped spillways with the same flow conditions. The depth of flow is greater than that of the flat stepped spillway because of the large flow variability over the *CSS*, even with the increased air entering the flow. Therefore, the *CSS* is also negatively impacted by the weir sidewall height and labor expenses. These can be used for chute channels designed in tourist areas for a stylish aesthetic or in spots downstream without topographical restrictions.

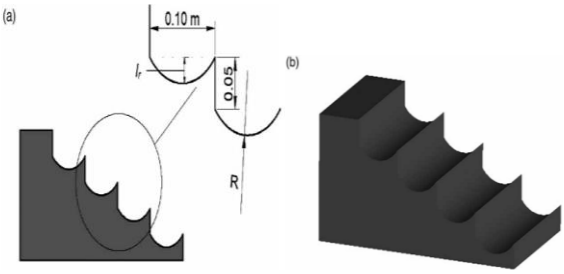

Fig. 11. The model was used in study: a) two-dimensional and b) three-dimensional [39]

In research [41], this study deals with an experimental test of a new type of geobag stepped spillway that can be used in the case of small dams. The geobag stepped spillways are constructed from bags filled with soil compressed with cement. The geobag stepped spillway model test site was the Yellow River Water Conservancy Commission's Suide Soil and Water Conservation Scientific Investigational Position in Shaanxi Province, China. The results indicate that in the case of high flow velocities, the geobag stepped spillway overflow constructed on small dams is considered safe. The strengthened chute and side slopes of the spillway construction remained stable and unbroken during the more than thirty overflow tests conducted for more than five minutes each. Using this model, the water head above the spillway crest was placed between 35 and 55 cm. The discharge was between 0.64 and 1.41 m^3/s, and the flow speed into the stilling basin ranged from 3.16 to 6.68 m/s. The energy dissipation rate for the weir flow was between 92.8% and 73.8%.

Research [42] used a genetic algorithm for the geometric optimization of stepped spillways, and data from laboratory models were utilized. The study's objective is to compute the maximum energy consumption based on the overflow height and the flow rate into the stepped overflow by determining an equation with minimal error. Additionally, a formula to forecast the amount of energy consumption was obtained using powerful statistical tools, specifically WEKA and MATLAB. The result summarized that the most significant energy consumed reduces as the flow rate increases. It is possible to increase the number of perfect steps for equivalent energy consumption by increasing the slope of the small head at a constant flow rate. The conclusion that arises from the many steps that lead to low energy consumption is that the high step reduces the influence of the step's existence. The little head is inclined towards the smooth bottom head, reducing the proportion of energy lost.

In research [43], Fuzzy logic was used to determine energy dissipation above stepped spillways by utilizing IF and a logical rule base depending on the flat-stepped spillway's three laboratory test results [44-46]. In fuzzy logic, input and output variables analyze the complex flow. Variables entered into the program include the number, height, and length of steps and discharges. The result showed good outcomes are represented by fuzzy logic, its mean percentages (-1.69%) and absolute errors (2.00) are modest. The Python function created by the fuzzy inference system is easily adaptable to various flow conditions and stepped spillways.

In research [47], numerical modelling of the spillway flow was conducted using the Open FOAM model and depended on the typical laboratory results of stepped spillway obtained [44] to study circular stepped-labyrinth spillway configuration with varying cycle counts and its three-dimensional hydraulic performance assessment. C++ is the programming language used to create these 170 models. The volume of fluid approach is the basis for developing the Inter FOAM solver, which is used to solve the two-phase flow. Using the finite volume technique, momentum and continuity equations in the solution domain were achieved. Therefore, flow velocity and pressure are controlled by the usual Navier-Stokes equations. The result summarized Flow velocities downstream of the spillway are reduced by circular labyrinth layouts compared to traditional form of stepped spillways. The circular labyrinth layouts were compared, and the 346 three-cycle version yielded the maximum reduction in flow velocity. In comparison to the traditional 348 stepped spillway configuration, the 2CSS, 3CSS, and 4CSS configuration 347 forms have decreased flow velocity by 15.6%, 36.5%, and 23.1%, respectively.

In research [48], three physical models were used to study the impacts of step transverse slopes on where flow across stepped spillways originate, as shown in Figure 12. Each model consisted of a broad-crested weir measuring 0.605 m in width and *Lcrest* = 0.6 m in length. It had an upstream sharp corner and thirty-two uniform steps. The steps measured 0.03 meters in height and 0.06 meters in length, while the spillway's longitudinal slope (*ϑ*) was 26.6 m. The experiment was conducted in a prismatic flume at the Hydraulics Laboratory at the University of Sulaimani's College of Engineering. The result summarized It was discovered that for the stepped spillways with steps with a transverse slope of 2.84°, the average distances between the inception sites and the downstream border of the spillway crest were reduced by 37%. Additionally, it was shown that the skimming flow started at more significant discharges, precisely *yc/h* ≥ 2.06 for stepped spillways with steps that have a transverse slope.

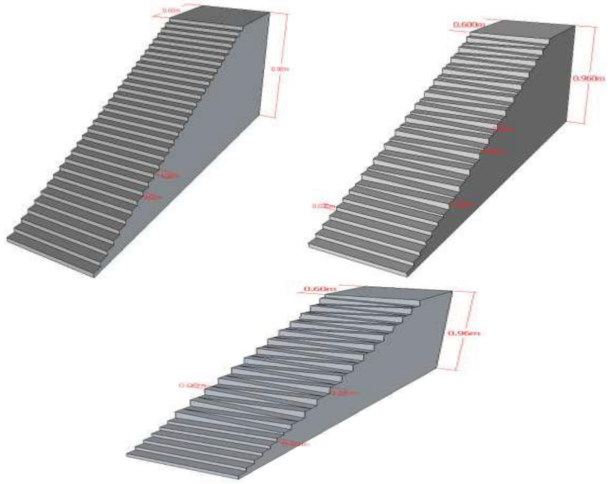

Fig. 12. Illustrate the Physical (S1, S2, and S3) in this study [48]

In research [49], using data from the literature review, flow characteristics and energy losses on step pools were studied, and the results were simulated using the software ANSYS-CFX. The result showed three different flow regimes, nappe, transition, and skimming, could be distinguished for a particular step-pool channel as the flow rate rose from low to high. Energy loss is reduced with increasing flow rate. The energy loss was essentially unchanged at 0.15 m; therefore, this drop was only slight. Energy loss increased range (0.18 m - 0.55 m) when the flow regime changed from transition to skimming. The recirculation zone's size, velocity, vorticity and the area over which it is very vortices are all positively connected with energy loss in step pools. Additional research is necessary to comprehend this behavior. A study of the Darcy Weisbach friction factor parameter and the amount of slope affects the amount of energy dissipation, as the amount of energy dissipation is equal to 31.6% if the slope is 2-10 and equals 58.6% and 75% if the slope increases from 40-70.

In research [50], two physical models were used in this study to investigate losses of energy and flow types by using different steps. The experiment constructed by the Water Research Institute (WRI) on Iran's hydraulic structures, a physical model of the Khansar Dam and Spillway (Yazd, Iran), examined the spillway's energy losses and flow patterns. According to the results, the 23-step plan used less energy than the 12-step model. But compared to the 12-step model, the flow regimes found in the 23-step model were thought to be more appropriate. The investigations demonstrated that in both scenarios, energy loss at lower flow rates was comparable. Nonetheless, energy dissipation in the skimming flow regime at greater discharges was approximately 12% lower in the 23-step model compared to the 12-step model.

The following research [51] deals with the skimming flow and the theoretical solution for the air-water mixture during flow over a stepped spillway. The investigation focuses on the numerical aeration of flows along stepped chutes with consistent steps. Mesh generation and CFD computations were performed using the open softwares Salome and OpenFoam®, respectively. Since the flows are intrinsically turbulent, the properties of the flows were examined here with the use of an appropriate wall function for the wall borders and a two-equation K-ε turbulence model.

In research [52], numerical model verification was performed using experimental data from [44]. They made use of 10-step, 52-cm-wide stepped spillways. The stairs measured 10 cm in height and 20 cm in breadth. There were 1.5 cm thick and 3.1 cm high ponds on each step. The stepped spillway's schematic design is depicted in Figure 13. Commercial cod FLOW-3D was utilized in this investigation. With stepped hydraulic structures, in particular, this software can simulate flow patterns. The FAVOUR approach has achieved more accurate obstacle simulation in this CFD program. Comparing the dimensions of the used pooled steps to the step and crest geometries, they were incredibly small. The capacity to replicate the tiny dimensions of obstacles is a benefit of the FAVOR approach. The spillway in this study was constructed using a CAD file, but the entire geometry may also be integrated using AutoCAD or the solid modeler that is already included in FLOW-3D. The results showed that the flow velocity at the end of the spillway was reduced when the number of steps in pooled stepped spillways was reduced. The consistent result for using different numbers was an increase in energy losses with a decreased number of steps.

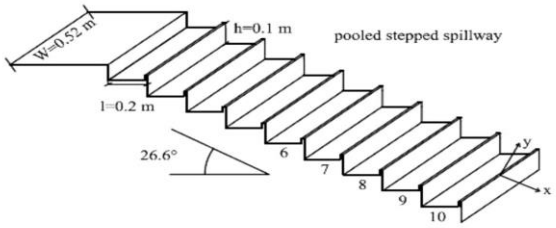

Fig. 13. Gabion stepped weirs with a slope of 1:2, without vertical impervious plate (left) and with vertical impervious plate (right) [52]

In research [53], the numerical simulation utilized in this work, which was accomplished by utilizing [54] experimental data, shows that the spillway's physical model is comprised of three steps by using a slope of *1V:2H* and a height of step 10 cm and in all models required the use of holes, convex half balls, baffles, and sills. It was positioned in a 9 m long by 0.25 m broad duct. At most, the unit discharged 0.0945 m3/s/m. The FLOW-3D program employed the *Klz* model for flow turbulence and the *VOF method* to estimate the free flow surface. The result summarized model A has higher energy dissipation for a maximum flow rate equal to 0.0945 m^3/s, especially when employing two, three, and four-half balls on steps. These variations increased the energy loss by 57%, and the energy dissipation was reduced when the half balls were moved to the inner and center edges of the step. The utilization of one, two, and four somewhat enhances the pace of energy dissipation, as seen by the convex half-ball results on the step. The most significant rise on steps was at one convex half ball, which was 15% higher than on flat steps. The positioning of the holes at the step's center, inner, and outer edges, as well as their diameter, are all considered when using holes in steps. Compared to the flat stepped spillway, the energy loss on the two holes at the outer border and the six-hole design on the step increased by 8%. However, there is no difference in energy loss between the other setups.

In research [55], was used Fluent software to numerically simulate four different types of stepped spillways to determine the position of the flow zone that is not aerated inception point and length. The slopes of stepped spillways range from gentle to high. Using the realizable *k*-turbulent model and the multiphase volume of fluid approach, test models used four samples with slope (12.5°, 20°, 29° and 35°) to simulate. The result showed a stepped spillway's increased flow rate on its slope could be the root cause of the skimming flow type. The discharge, step height, and step length determine the skimming flow regime in the stepped spillway. The discharge value for each discharge must be greater than the crucial value in order to identify the skimming flow regime. As the discharge rate rises, the location of air entrainment (the inception point) moves downward and the non-aerated flow zone's expanse grows. When the stepped spillway's slope changes from mild to severe and the inception point moves toward the crest, air entrainment happens close to the crest.

In the research [54], the study was carried out in the Krueng Baro River, Pidie District, Aceh Province, Indonesia, as part of the Krueng Baro irrigation plan. The purpose of this study was to ascertain how energy dissipaters vary and assess how that variation affects energy dissipation and the hydraulic jump. A two-step physical model was created using the current weir situation. Additionally, it was done on four different stepped-weir configurations: three-step, four-step, and six-step. The third configuration included extra baffle blocks at the end sills. The study demonstrates that a three-step leap has a substantially greater *Lj/y1* ratio, which is advantageous for the compaction of hydraulic jumps. When comparing the energy dissipation of all weir variations, it can be shown that the three-stepped weir wastes more energy than the other types. The three-step type's rise in energy dissipation is 20.41% greater than that of the current type and significantly greater than that of other types. The width-to-height ratio (*l/h*) of the three-step kind of stairs determines the dimensions of the energy dissipation basin (2.50).

In the research [56], a study aimed at analyzing the performance of gabion-stepped weirs for energy dissipation was conducted. Eight physical models with three different porosities (38, 40, and 42%) and two slopes (*1:1 and 1:2*) were used in the laboratory tests. As shown in Figure 14, the models were used to categorize the energy dissipation through the weir models, and if-then rules were constructed using a decision tree technique. The result findings indicate that a decision tree model can estimate the energy dissipation through a gabion-stepped weir utilizing various variables with an accuracy of 85%. This high level of accuracy in the estimation of energy dissipation through gabion-stepped weirs provides confidence in the reliability of the research findings.

Fig. 14. Sketch pooled stepped spillway was used in the study [56]

In research [57], five physical models were conducted to calculate the flow types above stepped spillways. The models had a downstream slope angle of 30 and were constructed with varying numbers of steps (3, 5, 7, 10, and 14). There were different step models: flat, fully pooled, and zigzag pooled. The investigations discovered three flow regimes: the skimming, nappe, and transitional flow. The highest energy dissipation rates for these systems were, in turn, (90, 88, and 89%). While transitional flow experiences medium discharges (12–20 L/s), skimming flow experiences large discharges equal to 25 L/s at short step heights (2.5–5 cm), and nappe flow experiences small discharges between 7–12 L/s at step heights between 5–11.7 cm. The flow regime is influenced by the sills at the terminal edge step. Nappe flow is obviously affected by fully pooled stages. The zigzag pooling steps broaden the extent of the transition flow regime and amplify its instability; however, in the skimming flow, these sills have little influence because the flow is smoother as it approaches the downstream.

Research [58] to study how well stepped weirs aerate, concentrating on the effects of adding labyrinths to the steps, varying the weir's slope, the tailwater level, and DO concentration upstream. Nineteen physical models using three distinct slopes (1:1, 1:2, and 1:3 V: H) for flat, stepped-labyrinth, and pooled-stepped weirs were evaluated. The samples, as Figure 15, were used in the tests. According to the data, the stepped-labyrinth weirs with slopes of 1:1 and 1:2 had the best configurations for the DO ratio; this was around 62% greater than that of the flat stepped weirs. On the other hand, compared to models with a slope of 1:1, the dissolved oxygen efficiency in the 1:3 models revealed a 15% decrease. in every instance showed that rising upstream DO concentrations or river discharges reduced dissolved oxygen efficiency.

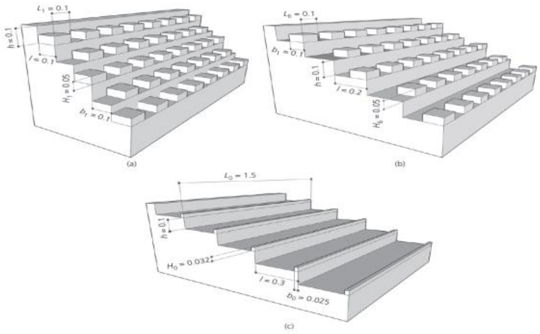

Fig. 15. Tests model was used in experimental: (a) M1 (S = 1:1), (b) M2 (S = 1:2), (c) M3 (S = 1:3)

In research [59], the study aimed to demonstrate a new technique that projected a water jet on the smooth bottom of the canal, created an energy dissipation basin involved, and reduced a hydraulic jump, as shown in Figure 16. To study the effect of the water jet on energy dissipation and the characteristics of the hydraulic jump below the skimming flow type, five rows of jets were created at the bottom of the canal downstream of the stepped dams. Compared to the non-jetted system, efficiency in dissipating energy could be increased by as much as 70.8%, and the lengths of the jumps could be lowered by as much as 48% by activating the middle three rows.

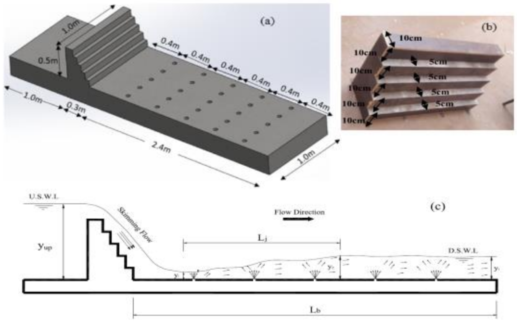

Fig. 16. Stepped spillway: (a) an illustration with Bed Water Jets, (b) stepped spillways (physical Model), (c) Flow Pattern after the model [59]

In research [47], a detailed comparison was conducted to assess the energy dissipation and residual energy of the traditional stepped spillway in contrast to a circular labyrinth configuration. The study also investigated the hydraulic properties of the flow downstream of the stepped spillway, particularly with varying cycles of steps.

The outcomes of the physical model were used to validate the numerical model. The OpenFOAM, an open-source program, was employed to study skimming flow type using four three-dimensional models of stepped spillways, such as conventional stepping, two--, three--, and four-cycle circular labyrinths. The numerical model's findings demonstrated that, for a constant discharge and yc/h = 1.68, the combination of the circular labyrinth and the stepped spillway enhances energy dissipation in two, three, and four cyclic circular forms by 7.4, 28, and 18.3% relative to its classical type. As a result, the three-cycle form has the highest dissipation rate among the circular labyrinth topologies. In addition, they compared to others.

3. CONCLUSION

The following stand out as significant results of this research subsequent statements:

- There are many types of spillways, such as Ogee (Overflow), Chute, Siphon, Cascade, Tunnel and Stepped spillway.
- Three different flow regimes can be distinguished in the flow over a stepped spillway: the nappe, transition, and skimming flow regimes.
- The design-phase characteristics, such as step height, length, slope, and shape, that must be changed for stepped spillways.
- Most studies used CFD tolls as numerical models, and fuzzy logic and genetic algorithms were used to study energy dissipaters.
- Most studies conclude that as the number of steps rises, the amount of energy lost by the flow increases.
- When determining air entrainment in stepped spillways, the inception point is the most critical parameter. The point at which air begins to permeate the water flow surface over the spillway is known as the inception point. It happens at the interface of the free surface and turbulent boundary layer. Numerous factors, including flow velocity, step size, geometry, and spillway slope, determine the location of the inception point.
- Compared to the non-jetted system, efficiency in dissipating energy could be increased by as much as 70.8%, and the lengths of the jumps could be lowered by as much as 48% by activating the middle three rows.
- The disadvantages of flowing in the form of a jet over the stepped spillway are the creation of cavities in the sides and the ends and the presence of air in the case of high discharges.
- The pressure distribution on the stepped spillway in the case of turbulence or skimming flow is studied.
- Using an Ansys program, CFX is preferable for predicting a free-surface profile over a stepped spillway with non-uniform step sizes.

Conflicts of Interest

The author declares no conflict of interest.

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