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Experimental Study of Flow Regimes of Stepped Weir

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Abstract

A stepped weir, a type of weir featuring steps on the weir chute to help disperse the kinetic energy of the descending water, is a frequently used construction. Depending on the discharge and the stepped weir's dimensions, flow over a stepped weir can be primarily divided into three different flow regimes: nappe, transition, and skimming. Five-stepped weir models have been used in experiments to determine the flow regime limits for these weirs. The models were made with various numbers of steps (3, 5, 7, 10, and 14) and a downstream slope angle of 30˚. The configurations of steps were flat step, fully pooled step, and zig-zag pooled step. The results show that the sills on the end edges of the steps have a significant effect on determining the type of flow regime. In addition, they dissipate more energy than flat steps. Based on the experimental data for flow regimes (nappe flow, transition flow, and skimming flow), a new set of empirical equations was proposed, with a determination coefficient R^2 for these regimes (0.87, 0.71, 0.7), respectively.

Keywords: Regimes of flow, stepped weir, nappe flow, transition flow, skimming flow.

1. INTRODUCTION

The transmission of water flow to the dam downstream is one of the goals of weir design. The transfer of water flow downstream generates a significant amount of kinetic energy. If this energy is not reduced, it may cause damage to the weir downstream. Stepped weirs, which have been in operation for 3500 years [1], can minimize this energy and the size of the stilling basin downstream [1-4]. The flow patterns created by the river traveling over stepped weirs are nappe, transition, and skimming flows [5]. The height and length of the steps, as well as the flow discharge, influence the formation of these three patterns on stepped weirs [6-8].

The fact that stepped weirs perform admirably in terms of energy dissipation has prompted researchers to investigate the flow characteristics of stepped weirs experimentally. Most studies on stepped weirs have traditionally concentrated on the quantity of energy dissipation [9-11]. Many scholars have looked into how geometry affects energy dissipation. According to Sorensen [2], energy dissipation in spillways is determined by four factors: (a) discharge, (b) weir slope, (c) step shape, and (d) the number of steps. Furthermore, for a given discharge with a constant step height, energy dissipation increases as the number of steps increases. The flow patterns created by the river traveling over stepped weirs are nappe, transition, and skimming flows [5]. The height and length of the steps, as well as the flow discharge, influence the formation of these three patterns on stepped weirs [6-8].

This study aims to improve the hydraulic performance of the stepped weirs and increase the energy loss by using zig-zag sills and fully pooled water on the edge of the steps. In addition, this study aims to know the limits of the flow regimes on the stepped weir and the effect of the discharge on them, as well as to develop equations to find the energy dissipation of these regimes.

2. REGIMES OF FLOW

There are three types of flow regimes on stepped weirs. Nappe flow is for low discharges, skimming flow is for high discharges, and transition flow is for medium discharges. Researchers in the hydraulic area regard the nappe flow regime to be the most efficient [12]. According to Chanson and Toombes [13], with large volumes of discharge, the flow in stepped weirs can become a skimming flow, and with low-volume discharges, it can become a free-falling nappe. However, there is a variety of transition flows that occur between nappe flow and skimming flow, each with its own set of characteristics, such as the disturbed flow motion associated with severe splashing. The flow characteristics of the regimes are noticeably different. The discharge rate, as well as the geometry of the steps (height, slope, and length), determine the regimes [14].

2.1.Nappe flow regime

When fluid flows from one step to the next, it is referred to as a nappe flow regime. For example, Free-falling down the steps with air spaces beneath you. The step, with or without a complete hydraulic jump, affects the free-falling nappe. The flow regime is nappe flow, which occurs when discharge rates are low. It is created by a flat slope with enormous, awkward step heights [15]. More energy is dissipated by nappe flows over stepped weirs than by the other two regimes. There are three sources of energy dissipation:

1. In the air, a jet breaks up;
2. The jet's impact on the step;
3. Constructing a hydraulic jump (completely or partially) [16].

2.2.The transition flow regime

In some steps, this flow regime shares hydraulic features with nappe flow, whereas in others, it appears as a skimming flow [17]. Re-evaluated a huge number of data points and proposed equations for predicting the maximum and lower limits of nappe and skimming flow [1].

The other category is transition flow, which includes:

The lower limit of transition flow

$$\frac{y_c}{h_s} = 0.89 - 0.4\left(\frac{hs}{l_s}\right) \tag{1}$$

The upper limit of transition flow

$$\frac{y_c}{h_s} = 1.2 - 0.325\left(\frac{h_s}{l_s}\right) \tag{2}$$

For horizontal steps, the restrictions of Equation 1 are applied. The gradient of the canals ranges from 3.4 to 60 degrees. Outside of the gradient range, it is legitimate between nappe and skimming flow regimes. There are considerable changes in flow properties. The unstable flow conditions are in a transition flow regime, which could lead to a fluctuating hydrodynamic load, which could cause vibration in the hydraulic structure [18].

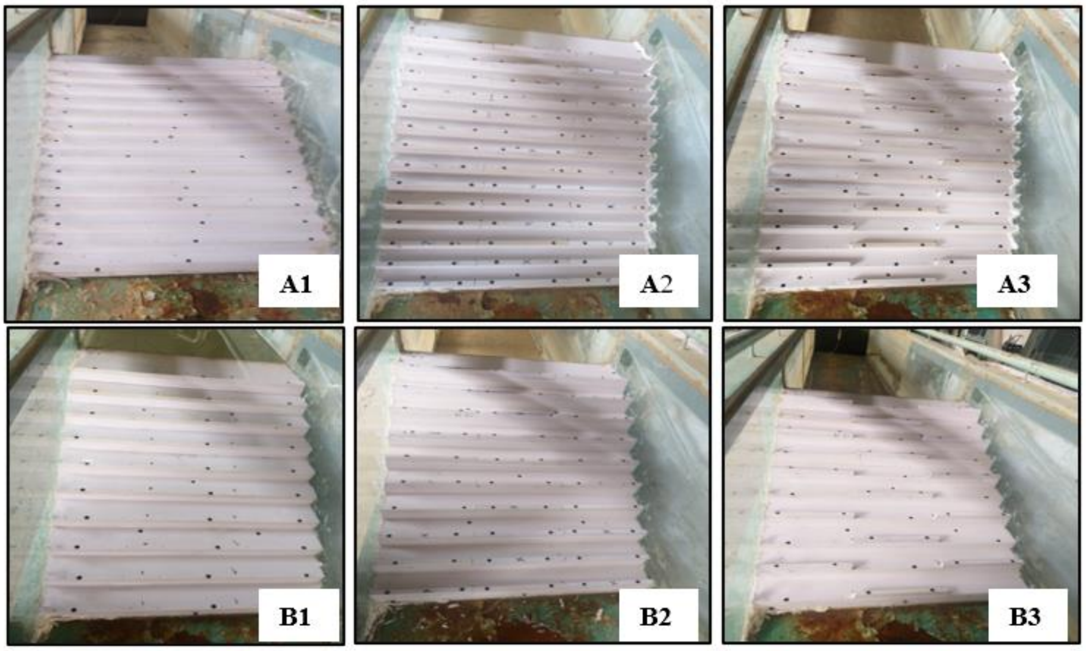
2.3.Skimming flow regime

At a high flow rate, skimming flow regimes occur. In the steep slope of the stepped weir, the flow depth is large as compared to the step height. The water travels down the weir without touching the steps, and the flow characteristics are suitable for energy dissipation and aeration. Aerated water flows through the triangular area between the steps and the main flow. When the water collides with the edges of the steps and is directed back up, vortex energy is created. The water returns to the main flow after passing through the vortex [12].

3. MATERIALS AND METHOD

Each experiment was carried out in the hydraulic laboratory of the Middle Technical University, Kut Technical Institute, Iraq, using a 12 m long, 50 cm wide, and 50 cm high laboratory flume, as shown in Figure 1. At the entrance of the channel's glass wall, there is a 90-degree V-notch. This tool, which features a movable gate for managing the depth of the tail water, is used to measure the water outflow on the downstream side. The stepped weir models under examination were made using a CNC machine, which offered excellent accuracy for reaching the model's required dimensions. It was foam, as shown in Figure 2 of this article. Each model has a similar overall height, width, weir slope, and crest length (35 cm, 60.6 cm, 50 cm, 30°, and 10 cm, respectively). There were variations in step height, length, and number. Seventy-five tests were performed with five discharges (7, 12, 15, 20, and 25 L/sec) for each model under the free flow condition, as shown in more detail in Table 1.

Figure 1 The flume that was employed in this investigation.



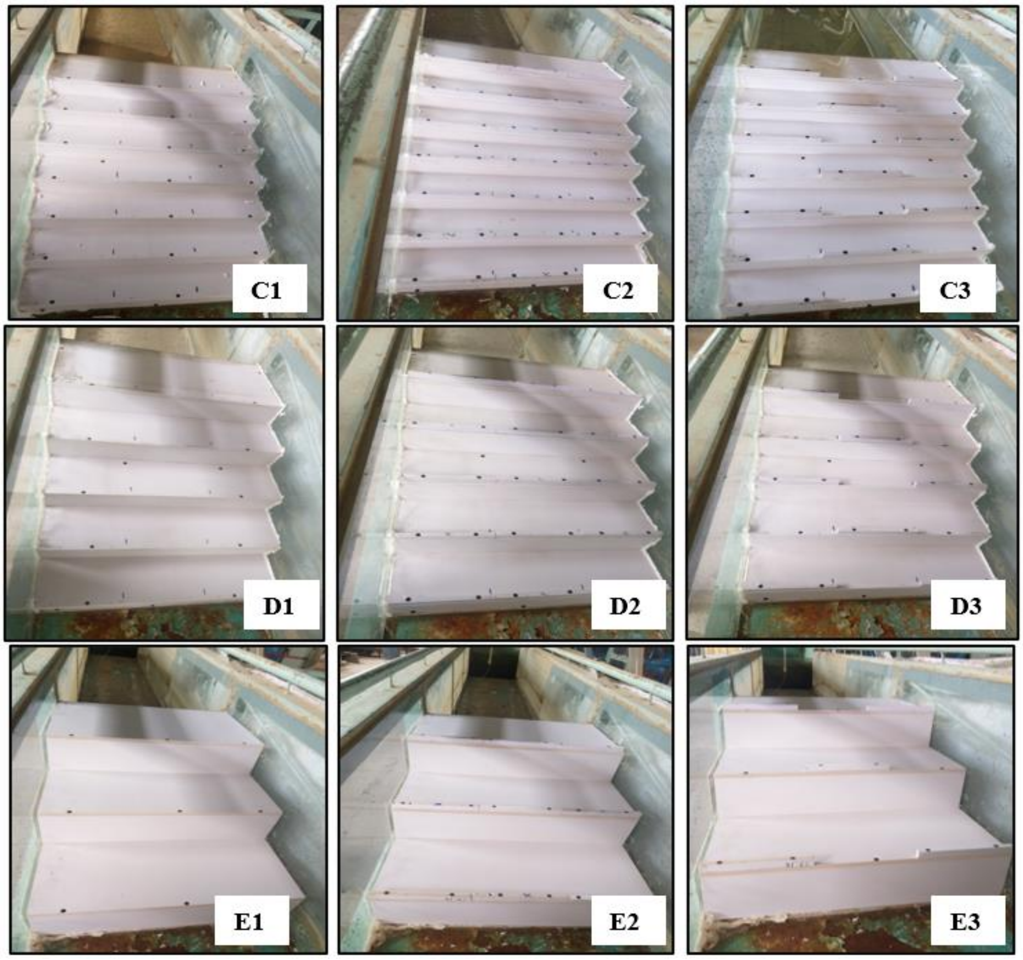


Figure 2 The experimental models (θ =30˚).

4. DIMENSIONAL ANALYSIS

Geometric characteristics of the stepped weir, such as the height (H_{dam}), the width (W), and the slope of the weir (θ), as well as the number, height, and length of steps ($N_s, h_s,\ l_s$) respectively, affect on energy dissipation of hydraulic jump downstream stepped weir. Flow parameters can also have an impact on kinetic flow properties, such as velocity (V), gravity acceleration (g), mass density (ρ), surface tension (ơ), dynamic viscosity (μ), and critical flow depth (y_c).

Thus, the energy dissipation of flow is a function of these variables:

$$f(E, H_{\mathrm{dam}}, W, \quad \theta, N_{\mathrm{S}}, h_{\mathrm{S}}, l_{\mathrm{S}}, V, \quad g, \rho\ , ơ , \mu, y_{\mathrm{C}}) \tag{3}$$

The above variables can be lowered by multiplying the non-dimensional parameters following Buckingham's theory, and Equation 3 can be written as follows:

$$E\% = f\ (l_s/y_c\ , y_c/\ h_s\ \ , Ns\ \ , F_r\ \ , \theta) \tag{4}$$

For the examination of energy dissipation in weirs, dimensionless properties are required

. **Table** 1 Models stepped weir (All dimensions in cm)

Model Type of	Model	No. of steps	Dimension of steps			Dimension of pooled steps		
			h_s	l_s	w_s	h_p	l_p	w_p
Flat step	**A1** **B1** **C1** **D1** **E1**	**3** **5** **7** **10** **14**	**11.7** **7** **5** **3.5** **2.5**	**20.0** **12.12** **8.65** **6.1** **4.3**	**50**	/	/	/
Fully pooled step	**A2** **B2** **C2** **D2** **E2**	**3** **5** **7** **10** **14**	**11.7** **7** **5** **3.5** **2.5**	**20.0** **12.12** **8.65** **6.1** **4.3**	**50**	**1.5**	**1**	**50**
Zig-zag pooled step	**A3** **B3** **C3** **D3** **E3**	**3** **5** **7** **10** **14**	**11.7** **7** **5** **3.5** **2.5**	**20.0** **12.12** **8.65** **6.1** **4.3**	**50**	**1.5**	**1**	**16.5**

5. RESULTS

The flow of water over the stepped weir is divided into three regimes, depending on the discharge and the dimensions of the steps, where the step height is important in determining these regimes, as shown in Table 2.

Nappe flow (NA) occurred at low discharges (7, 12) L/s, as well as when the critical depth is small, and this is in step numbers (3 and 5), where the step height is large. The nappe flow is clearly observed when the sills are at the end edge of the step, as shown in Figure 3. The highest energy dissipation rate for this regime reached (90%).

(a) (b)

Figure 3 Nappe flow regime; (a) Nappe Flow, Fully Pooled Step, Ns= 5, Q = 7 L/s and (b) Nappe Flow, Fully Pooled Step, Ns= 3, Q = 12 L/s

The transition flow (TRA) occurred at medium discharges at the (12, 15) L/s and in the number steps (5 and 7). The transition flow was turbulent, causing a lot of water to spray on the glass wall. The sills at the edge of the step increased the flow turbulence, especially in the case of the zig-zag pooled step, more than the fully pooled step, as shown in Figure 4. The highest energy dissipation rate for this regime reached (88%).

Figure 4 Transition flow regime Zig-Zag Pooled Step, Ns= 7, Q = 12 L/s.

In the case of skimming flow (SK), it occurs at high discharges (20, 25) L/s, and the critical depth is higher than the rest of the flow regimes at the numbers of steps (10, 14), and the flow is smooth towards the bottom of the weir, as shown in Figure 5(a). The highest energy dissipation rate for this regime reached (89%).

There is no effect of the sills at the end-edge of steps in both cases (fully pooled step and zig-zag pooled step) on this regime, as shown in Figure 5 (b), (c).

(a)

(b)

(c)

Figure 5 Skimming flow regime; (a) Skimming Flow, Flat Step, Ns= 10, Q = 20 L/s, (b) Skimming Flow, Fully Pooled Step, Ns= 14, Q = 25 L/s and (c) Skimming Flow, Zig-Zag Pooled Step, Ns= 14, Q = 20 L/s.

Energy dissipation increases in the few discharges and decreases with the increase in the discharge, as the increase in the discharge turns the nappe flow into a skimming flow, which reduces the effect of the gradient on the flow, and thus, the energy dissipation will decrease. By increasing the number of steps, the amount of energy dissipation increases, and the results showed that the largest amount of energy dissipation in the fully pooled step is more than in other cases (flat step, zig-zag pooled step).

Table 2 The flow regimes over the stepped weir.

Type of Step	Ns	Q (L / S)	h_s / l_s	y_c / h_s	Flow Regime
Flat Step	14	7	0.58	0.92	TRA
	14	12	0.58	1.2	SK
	14	15	0.58	1.44	SK
	14	20	0.58	1.96	SK
	14	25	0.58	2.4	SK
Fully Step Pooled	14	7	0.58	1.72	SK
	14	12	0.58	2.08	SK
	14	15	0.58	2.4	SK
	14	20	0.58	2.68	SK
	14	25	0.58	3.4	SK
Zig-Zag Step Pooled	14	7	0.58	1.56	SK
	14	12	0.58	2	SK
	14	15	0.58	2.2	SK
	14	20	0.58	2.6	SK
	14	25	0.58	3.36	SK
Flat Step	10	7	0.58	0.83	TRA
	10	12	0.58	0.91	TRA
	10	15	0.58	1.03	TRA
	10	20	0.58	1.4	SK
	10	25	0.58	1.6	SK
Fully Step Pooled	10	7	0.58	1.4	SK
	10	12	0.58	1.6	SK
	10	15	0.58	1.68	SK
	10	20	0.58	1.88	SK
	10	25	0.58	2.4	SK
Zig-Zag Step Pooled	10	7	0.58	1.1	SK
	10	12	0.58	1.5	SK
	10	15	0.58	1.9	SK
	10	20	0.58	1.94	SK
	10	25	0.58	2.25	SK
Flat Step	7	7	0.58	0.6	NA
	7	12	0.58	0.78	TRA
	7	15	0.58	0.92	TRA
	7	20	0.58	1.1	SK
	7	25	0.58	1.3	SK
Fully Step Pooled	7	7	0.58	0.96	TRA
	7	12	0.58	1.24	SK
	7	15	0.58	1.28	SK
	7	20	0.58	1.48	SK
	7	25	0.58	1.74	SK
Zig-Zag Step Pooled	7	7	0.58	0.86	TRA
	7	12	0.58	1.1	SK

	7	**15**	**0.58**	**1.12**	**SK**
	7	**20**	**0.58**	**1.36**	**SK**
	7	**25**	**0.58**	**1.4**	**SK**
	5	**7**	**0.58**	**0.36**	**NA**
	5	**12**	**0.58**	**0.49**	**NA**
Flat Step	**5**	**15**	**0.58**	**0.54**	**NA**
	5	**20**	**0.58**	**0.73**	**TRA**
	5	**25**	**0.58**	**0.88**	**TRA**
	5	**7**	**0.58**	**0.71**	**TRA**
	5	**12**	**0.58**	**0.81**	**TRA**
Fully Step Pooled	**5**	**15**	**0.58**	**0.86**	**TRA**
	5	**20**	**0.58**	**0.89**	**TRA**
	5	**25**	**0.58**	**0.93**	**TRA**
	5	**7**	**0.58**	**0.54**	**NA**
	5	**12**	**0.58**	**0.61**	**NA**
Zig-Zag Step Pooled	**5**	**15**	**0.58**	**0.71**	**NA**
	5	**20**	**0.58**	**0.83**	**TRA**
	5	**25**	**0.58**	**1.11**	**SK**
	3	**7**	**0.58**	**0.21**	**NA**
	3	**12**	**0.58**	**0.32**	**NA**
Flat Step	**3**	**15**	**0.58**	**0.34**	**NA**
	3	**20**	**0.58**	**0.4**	**NA**
	3	**25**	**0.58**	**0.5**	**NA**
	3	**7**	**0.58**	**0.37**	**NA**
	3	**12**	**0.58**	**0.47**	**NA**
Fully Step Pooled	**3**	**15**	**0.58**	**0.5**	**NA**
	3	**20**	**0.58**	**0.6**	**NA**
	3	**25**	**0.58**	**0.64**	**NA**
	3	**7**	**0.58**	**0.33**	**NA**
	3	**12**	**0.58**	**0.46**	**NA**
Zig-Zag Step Pooled	**3**	**15**	**0.58**	**0.5**	**NA**
	3	**20**	**0.58**	**0.52**	**NA**
	3	**25**	**0.58**	**0.6**	**NA**

6. DEVELOP NEW FORMULA

The function of many of the variables that were already studied is the energy dissipation of flow regimes. The non-dimensional functional connectivity Equation 4 should be submitted as an empirical form using IBM SPSS Statistics V23. 70% of the experimental data is used in the multiple regression analysis process to establish an experimental relationship and validate that relationship using the remaining 30% of the experimental data. The indicated level of confidence in the relationship was evaluated using the coefficient of determination (R^2).

6.1.For Nappe flow regime

The coefficient of determination R^2 and the correlation coefficient R are (0.87, 0.93), respectively.

$$E\% = 81 + 0.259\,\theta + 2.973\,N_s - 15.285\,{}^{y_c}/_{h} + 1.732\,{}^{l_s}/_{y_c} - 11.848\,F_{r1} \tag{5}$$

The predicted and measured values of energy dissipation are shown in Figure 6.

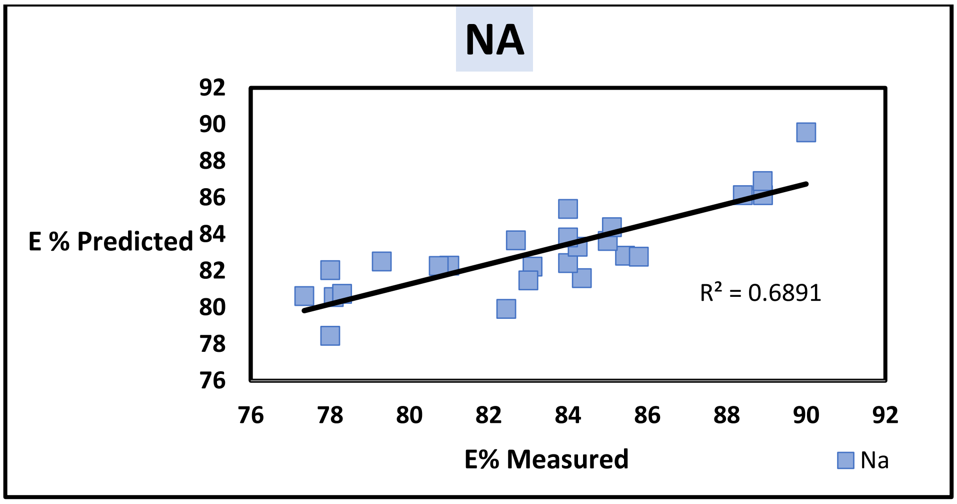


Figure 6 Comparison of Equation 5 with experimental data.

6.2.For transition flow regime

The coefficient of determination R^2 and the correlation coefficient R are (0.71, 0.84), respectively.

$$E\% = 56.991 + 0.531\,\theta + 1.391\,N_s - 0.224\,{}^{y_c}/_{h} + 5.677\,{}^{l_s}/_{y_c} - 8.18\,F_{r1} \qquad (6)$$

The predicted and measured values of energy dissipation are shown in Figure 7.

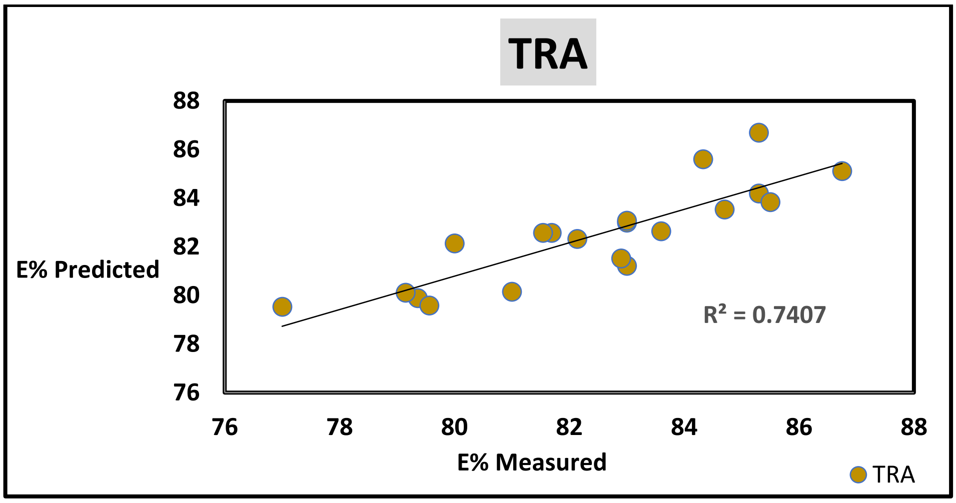


Figure 7 Comparison of Equation 6 with experimental data.

6.3.For skimming flow regime

The coefficient of determination R^2 and the correlation coefficient R are (0.7, 0.82), respectively.

$$E\% = 77.11 + 0.234\,\theta + 1.227\,N_s - 5.523\,{}^{y_c}/_{h} + 4.528\,{}^{l_s}/_{y_c} - 9.325\,F_{r1} \qquad (6)$$

The predicted and measured values of energy dissipation are shown in Figure 8.

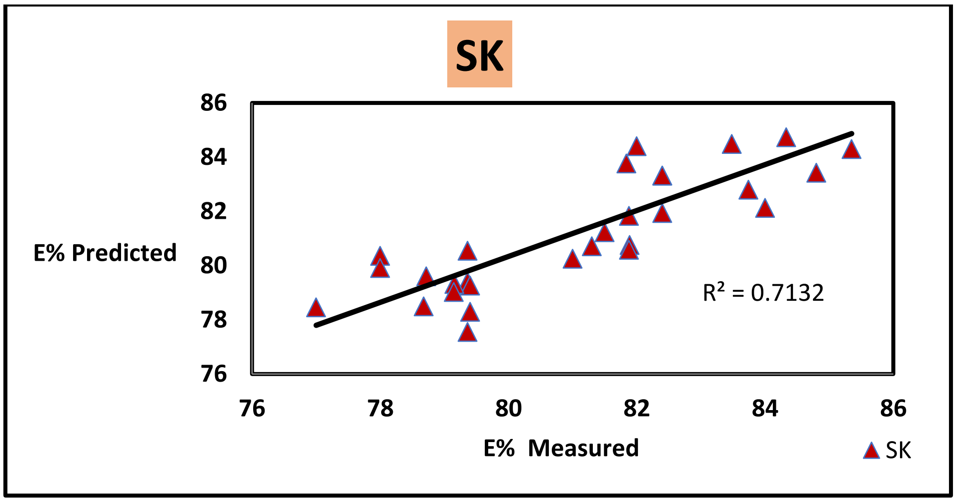


Figure 8 Comparison of Equation 7 with experimental data

7. CONCLUSION

Due to the various characteristics of each flow regime, determining the flow regime on the stepped weir is an important component in the design of the stepped weir. The dimensions of the steps and discharge flow rate have an impact on the type of regime. Three flow regimes were identified by the experiments: the nappe flow (NA), the transitional flow (TRA), and the skimming flow (SK). For these systems, the maximum energy dissipation rates were (90, 88, and 89) %, respectively. NA occurs with few discharges (7–12 L/s) at high step heights (5–11.7 cm); TRA occurs with medium discharges (12–20 L/s); and SK occurs with high discharges (25 L/s) and short step height (2.5–5 cm). The sills at the end edge step influence the type of flow regime. Fully Pooled steps affect nappe flow clearly. The zigzag pooled steps lead to an increase in the scope of the transition flow regime, in addition to increasing the instability that occurs in this regime, but in the skimming flow, the effect of these sills does not appear since the flow is smooth towards the downstream. Using the results of the experimental work to form new experimental equations to calculate the energy dissipation rate for each of the aforementioned flow regimes using the SPSS program and with a determination coefficient (R^2) (0.87, 0.71, and 0.7), respectively.

SYMBOLIZATIONS

Parameters		Unit
H_{dam}	Height of weir	m
W	Width of Weir	m
y_c	Critical depth	m
h_s	Step height	m
l_s	Length step	m
W_s	Width of step	m
h_p	Height of pooled	m
l_p	Length of pooled	m
W_p	Width of pooled	m
N_s	Number of steps	/
θ	Slope of weir	/

g	Acceleration gravity	m/ s^2
F_r	Froude number	/
Q	Discharge Flow	m^3 / s

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