Using of Stepped Shape Rock filled Weir as Squandering Energy Structure in Rectangular Channels : A Laboratory Study

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***Abstract*—Measuring the ability of hydraulic structures on works performing may be consider as a definition of the flow energy. The current study goal is to know the dispersed energy of flow in the steps-shaped, rockfill weir. A set of twenty five laboratory experiments and one hundred seventy five operation tests were carried out by using a laboratory handled metal channel with multiple discharge values. The tested hydraulic models has a different five lengths, and the filling material used was natural quarry crushed stone with five different median diameters. The results of analysis showed that the energy dissipationincreases by increasing the discharge value, and decreases by increasing both the length ratio of the rockfill weir, and the diameter of the rockfill sample used. The resulted equation for energy dissipation refers toa positive agreement between the predicted and measured energy dissipation values.**

***Keywords*—Dissipation energy of flow, Flume channels, Rockfill structure, Statistical analysis.**

I. INTRODUCTION

Mostly, the dissipated amount of energy in the flow con be considered as one of the important objects and a noticeable matter in water engineering. Whereas it classified as a practical problem in most of cases in field, and can be measured in many ways as in [1] and [2], whereas they used the stepped shape of the weir in both solid and pervious states to investigate the dissipated energy of flow, [1] illustrated that choosing the suitable statistical method is important to understand how the structure deal with the energy, and [2] found that modifying the step shape has a noticeable effect on the energy dissipation of flow comparing with the classical step shape. The material that the hydraulic structure (dissipater) is made from consider as an important variable, whereas [3] tried to modify the traditional type of stepped gabion weir by using locally available media as a filling material such as porcelnite and limestone. The results of his study showed that using of limestone gives maximum energy dissipation at low and high values of flow-rate, whereas it equal to 26.35% at high flow rate compared with weirs of flat slope, 16.35% compared with no additions stepped weir, and 10% more than traditional stepped weir. In addition, the dissipation structure can be classified into solid or pervious and each one have a different hydraulic behavior (e.g. [4] and [5] performed a series of laboratory experiments to investigate the interaction between the open channel and a specified gabion weir, and compares it with a solid one, the downstream scouring, the upstream sedimentations, the discharge coefficients, the profile of water surface, and the seepage around the weir and below its foundation. [4] in their investigation illustrated that application of solid weir equation on gabion weir has a large deviation, despite of the similarity in dimensions between them. While [5] found that the sedimentation in the upstream and the scouring in the downstream were high in concrete weirs as compared with gabion weirs due to the fact that some sediments has an ability to pass through the body of the gabion type. In addition, the seepage beneath the foundation and around the body of the gabion weir can be lowered by 95% if it replaced by a concrete weir with reinforcement. Also, the results showed that the elevation of water surface of the concrete weir is much higher than the gabion weir, and as a conclusion the concrete weirs are more efficient in raising water levels and reducing seepage effect, and durable if it arranged well to control scouring and sedimentation). Weirs in multiple forms, shapes, and figures can be used efficiently for dissipating energy of flow with a clear affection and performance [6], calculating the flow related variables and equation coefficients [7], [8], [9],and [10], …. etc. This paper goal is to know the dispersed flow energy using the steps-shaped, rockfill weir.

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II. THE LABORATORY WORK

The tests were experimented in a laboratory of hydraulics in the College of Engineering of Babylon university in Iraq. The flume of work has dimensions of (10.0 m length * 0.3 m width * 0.5 m height). The hydraulic models that used have total lengths of 0.88, 0.96, 1.04, 1.12, and 1.20 m respectively, and they named as Stepped Rockfill Weir F, S.R.W.F, S.R.W.G, S.R.W.H, S.R.W.I, and S.R.W.J respectively. Figure 1. displays the general sketch of the tested rockfill weir. The dimensions of the hydraulic models have been listed in table 1. The rockfill samples that used as filling material for the hydraulic models were five "crushed stone type" samples with median diameters 11.75 mm, 16.5 mm, 22 mm, 31.25 mm, and 43.75 mm, and they numbered as Gravel Sample F, G.S.F, G.S.G, G.S.H, G.S.I, and G.S.J respectively. The frame of stepped weir was made of standard steel plated bars, covered by a metal mesh, and fixed inside the flume using the adhesion glue. Figure 2 shows a photo of S.R.W.F with G.S.G. A centrifugal pump having a rated capacity of 40 l/s was used to deliver flow to the flume. Two movable carriages with point gages were mounted on a rail at the top of flume sides which have accuracy of 0.1 mm to measure the depths of water.. A total of 175 operation tests were carried out and varied between minimum and maximum values of discharges recorded from 0.0007 to 0.0150 m3/s respectively.

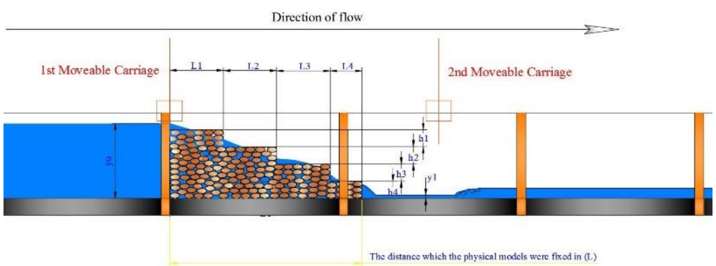

Fig. 1. *General sketch of the tested stepped-shape, rockfill weir*

TABLE I
STEPS DIMENSIONS OF THE TESTED ROCKFILL WEIRS

Steps rockfill weir	Step dimensions							
	1st step dimensions		2nd step dimensions		3rd step dimensions		4th step dimensions	
	h1 cm	L1 cm	h2 cm	L2 cm	h3 cm	L3 cm	h4 cm	L4 cm
F	15	40	5	20	10	20	10	8
G	15	40	5	20	10	20	10	16
H	15	40	5	20	10	20	10	24
I	15	40	5	20	10	20	10	32
J	15	40	5	20	10	20	10	40

Note A : h1, h2, h3 and h4 are the step height distance.

Note B : L1, L2, L3 and L4 are step length effective distance.

Fig. 2. Caption of Stepped-shape, Rockfill Weir F with Gravel Sample G

III. FORMATION OF EQUATION OF ENERGY DISSIPATION IN STEPPED ROCKFILL WEIRS

There are many ways to represent the relationships between parameters that used to discuss the hydraulic problems such as:

1- The standard equations,

2- The empirical formulas,

3- The direct relationships, or

4- The correlation using the dimensionless analysis.[1], [2],[7], [8], from [10] to [27], [30] and [31].

For the four steps stepped-shape rockfill weir, the relationship that combine parameters may be as [1] :

$$f\ \{q, y_{up}, y_{dw}, L_4, L, \mathbf{d}, \rho, g\} = 0 \quad (1)$$

Where, q is the discharge per unit width (L3/T/L), yup is the weir upstream water level (L), ydw is the weir downstream water level before the formed hydraulic jump (L), L4 is the weir forth step length (L), L is the weir total length (L), d is the median diameter of the used gravel sample (L), g is the gravitational acceleration (L/T^2), and ρ is the Mass density (M/L3).

The general definition of the specific energy, E, can be expressed as in equation (2) by taking the channel bed as a reference[32].

$$E = y + \frac{q^2}{2gy^2} \quad (2)$$

So, the weirupstream side energy equationis:

While, the weir downstream side energy equation is :

$$E_{dw} = y_{dw} + \frac{q^2}{2gy_{dw}^2} \quad (4)$$

$$E_{up} = Z_{up} + y_{up} + \frac{q^2}{2gy_{up}^2} \quad (3)$$

The difference in energy between both sides of the rockfill weir, ΔERW, is:

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$$\Delta E_{RW} = E_{up} - E_{dw} \quad (5)$$

From equations (3), (4), and (5), the final parameters of equation (1) that use in this study will be as :

$$f_1 \{q, \Delta E_{RW}, L_4, L, \mathbf{d}, \rho, g\} = 0 \quad (6)$$

IV. RESULTS AND DISCUSSION

Effect of the hydraulic parameters on the energy dissipation in rockfill weirs

Using of dimensionless analysis represented by the Buckingham "Π" Theorem, to generate a general equation, that bond the parameters of equation (6) leads to the following equation :

$$\frac{\Delta E_{RW}}{L} = f_2 \{\frac{q}{L^{1.5} g^{0.5}}, \frac{L_4}{L}, \frac{\mathbf{d}}{L}\} \quad (7)$$

where the left hand side dimensionless parameter of equation (7) will represent the energy dissipation in this study, and can be re-written as an abbreviation as in equation (8). While the parameters on the other side of equation (7) will be named, from left to right, as PRW1, PRW2, and PRW3respectively. Where PRW1 is the unit discharge dimensionless parameter, PRW2 is the weir length ratio dimensionless parameter, and PRW3 is the rockfill median diameter dimensionless parameter.

$$\frac{\Delta E_{RW}}{L} = E_L\% \quad (8)$$

Accordingly, equation (7) will be :

$$E_L\% = f_3\{ P_{RW1}, P_{RW2}, P_{RW3} \} \quad (9)$$

A. Discharge effect on the energy dissipation, (EL% - PRW1)

The rapport of the discharge and the energy dissipation can be represented as dimensionless relation as in figures 3, 4, 5, 6, and 7.These figures show that the power form was the best to represent the equation of the trend lines.

$$E_L\% = x_1 P_{RW1}^{\ x2} \quad (10)$$

where x1 and x2 are constants. From these figures it's clear that the dissipated energy value increases by increasing the value of flow-rate, because of the retard process that the filling material of the rockfill weir has. Besides, the energy dissipation value decreases by increasing the value of diameter of filling material, because of the ratio of voids between gravel particles that increases accordingly. This results agreed with[18], [25], [27], and [29], and disagreed with[7], [12], [13], [15], and [17] were they illustrated the dissipated energy of flow get increment by decreasing the discharge values in steps-shaped spillway. Table II contains thex1 and x2 values.

B. L4/L ratio effect on the energy dissipation, (EL% - PRW2)

Figure 8 displays a dimensionless relation that bond the dissipated energy of flowwithL4/L ratio. In this figure, it's obvious that the energy dissipation value decreases slightly by increasing the value ofL4/L. This behavior is expected when the flow transform from through-flow state to transient or over-flow state, because the roughness that affect the flow over the weir is less than that exist in the voids between rockfill particles. Also, this figure shows that the logarithmic form was the best to represent the equation of the trend lines.

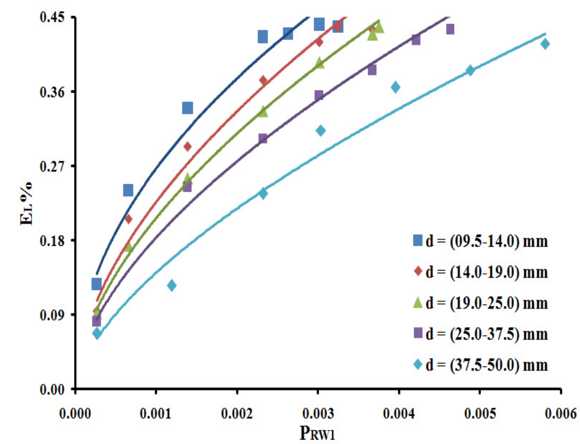

Fig. 3. The discharge-energy dissipation dimensionless relation for S.R.W.F.

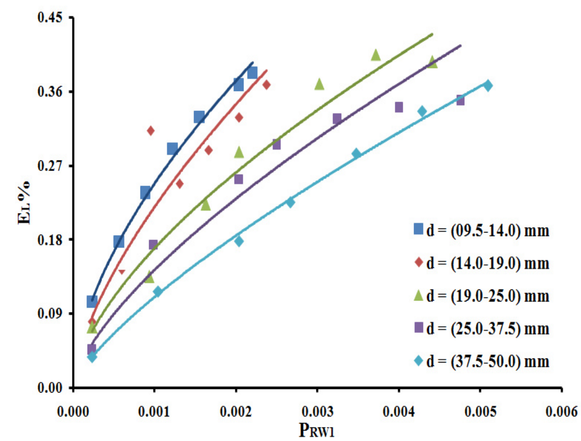

Fig. 4. The discharge-energy dissipation dimensionless relation for S.R.W.G.

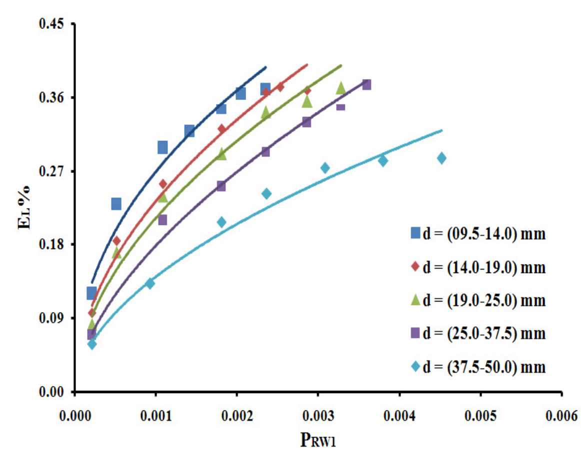

Fig. 5. The discharge-energy dissipation dimensionless relation for S.R.W.H.

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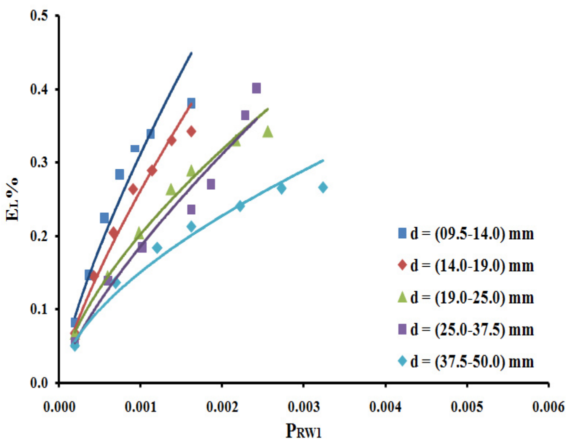

Fig. 6. The discharge-energy dissipation dimensionless relation for S.R.W.I.

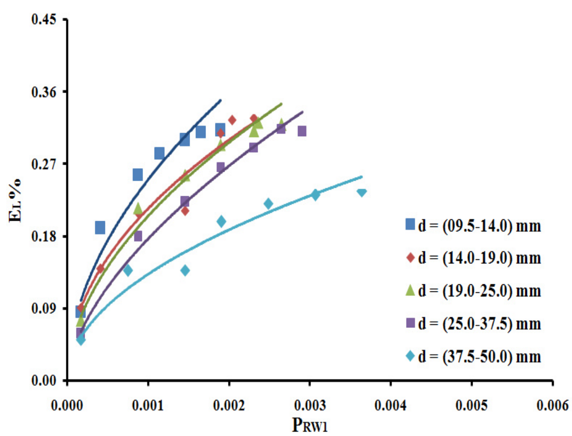

Fig. 7. The discharge-energy dissipation dimensionless relation for S.R.W.J.

TABLE II

X1 AND X2VALUESOF EQUATION (10)

Rockfill sample diameter mm	x_1	X2	R^2
9.5-14.0	8.126	0.494	0.971
14.0-19.0	11.77	0.572	0.973
19.0-25.0	11.34	0.579	0.995
25.0-37.5	10.75	0.589	0.993
37.5-50.0	11.22	0.633	0.972
9.5-14.0	14.59	0.589	0.996
14.0-19.0	19.65	0.650	0.905
19.0-25.0	12.91	0.627	0.974
25.0-37.5	16.30	0.685	0.962
37.5-50.0	19.14	0.746	0.998
9.5-14.0	6.060	0.450	0.958
14.0-19.0	8.061	0.512	0.981
19.0-25.0	8.180	0.528	0.973
25.0-37.5	10.36	0.587	0.992
37.5-50.0	6.010	0.543	0.986
9.5-14.0	50.03	0.749	0.963
14.0-19.0	47.56	0.767	0.983
19.0-25.0	15.92	0.646	0.993
25.0-37.5	28.29	0.742	0.983
37.5-50.0	8.087	0.591	0.974
9.5-14.0	9.107	0.520	0.935
14.0-19.0	6.118	0.485	0.965
19.0-25.0	8.152	0.533	0.984
25.0-37.5	10.93	0.597	0.991
37.5-50.0	4.221	0.500	0.959

$$E_L\% = x_3\,\mathrm{LIN}(P_{RW2}) + x4 \quad (11)$$

This results agreed with[14], [21], and [25]. Table 3 contains the x3 and x4 values. Also figure confirm that the dissipated energy of flow has an inverse proportion with increasing the diameter of the used rockfill sample.

C. d/L ratio effect on the energy dissipation, (EL% - PRW3)

Figure 9 obtains the dimensionless relation that bond the dispersed flow energy by the d/L ratio. The figure also confirm the fact of decrease the dissipated energy by increment the diameter of the used rockfill sample, and there is an undular behavior in the arraignment of weir filling material, because its response with the dissipated energy differ for each sample. This result agreed kindly with [14], [16], [21], [23] and[25] where they illustrated that increasing the rockfill particles will dissipate more energy in case of high values of discharge, while for low values of discharge, the smaller sizes will do the same behavior. Besides, this figure shows that the exponential form was the best to represent the equation of the trend lines.

$$E_L\% = x_5\mathrm{EXP}(x6\,(P_{RW1})) \quad (12)$$

where x5and x6 are constants, see Table IV.

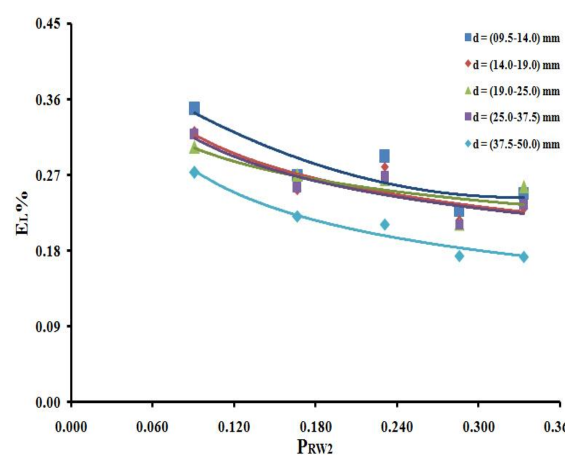

Fig. 8. The length ratio-energy dissipation relationships for all hydraulic models tested in this study

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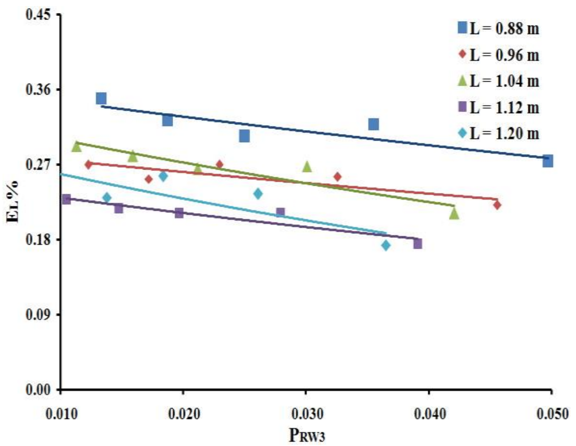

Fig. 9. The rockfill diameter-energy dissipation relationships for all hydraulic models tested in this study

TABLE III
VALUES OF CONSTANTS X3 AND X4OF EQUATION (11)

Rockfill sample diameter mm	x3	X4	R^2
09.5-14.0	-0.08	0.148	0.789
14.0-19.0	-0.07	0.146	0.757
19.0-25.0	-0.05	0.178	0.643
25.0-37.5	-0.07	0.146	0.799
37.5-50.0	-0.07	0.085	0.964

TABLE IV
VALUES OF CONSTANTS X5 AND X6OF EQUATION (12)

Total length of rockfill weir m	x5	X6	R^2
0.88	0.365	-5.53	0.779
0.96	0.289	-5.20	0.717
1.04	0.329	-9.49	0.860
1.12	0.250	-8.35	0.856
1.20	0.291	-12.0	0.678

Using of multi-linear regression to correlate the dependent and independent parameters of this study as previously followed by[1], [7], [8], [10], [11], [12], [14], [15], [16], [20], [22], [26], [29],[30] and [31 equation (7) can re-written as:

$$E_L\% = \left[\, 3.62517 + 2.77156\left(\frac{q}{L^{1.5}g^{0.5}}\right)^{0.25} - 3.51106\left(\frac{L4}{L}\right)^{0.01} - 1.44653\left(\frac{d}{L}\right)^{0.5} \right]^2 \quad (R^2 = 0.95) \qquad (13)$$

Also, 80% of data were determined for the regression analysis, the data of tests of the 1st, 2nd, 4th, and 5th lengths of rockfill weir, while 20% were determined for the confirmation of the illustrated equation, the data of test runs of 3rd length of the rockfill weir. The relationship combines the measured and the calculated energy dissipation values was plotted as in [7], [15], [18], [21], [23], [24], [25], [30] and [31] Figure 10, for the third length of the rockfill weir, and represented as:

$$(E_L\%)_{calculated} = 1.082((E_L\%)_{measured})^{1.103} \quad (R^2 = 0.974) \qquad (14)$$

From figure 10, it's clear that the resulted agreement between these values is good. While equation (15) was used to determine the percentage of error between these values, it was with6.13% as compared with [19] :

$$E_L\% = \frac{(EL\%)_{Calculated} - (EL\%)_{Measured}}{(EL\%)_{Calculated}} \qquad (15)$$

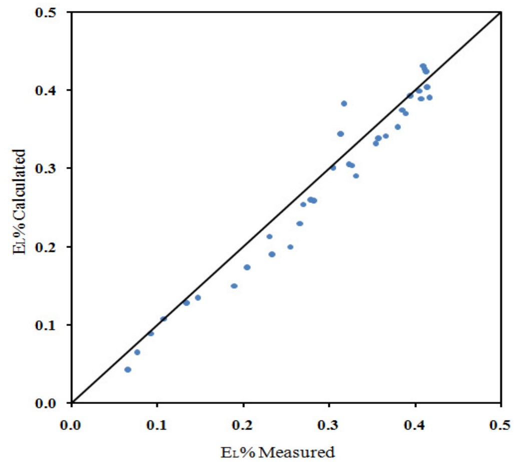

Fig. 10. The sketch of the (measured – calculated energy dissipation) relationship of the third length of the rockfill weir

CONCLUSION

The current study goal is about knowing the dispersed energy that happen between both sides of the 4 steps stepped rockfill weir, by knowing the parameters that effect on the energy dissipation using rock-filled structure. According to the study limitations :-

1- As the discharge increases, the dissipated energy of flow increases.

2- As the length ratio of the weir decreases, the dissipated energy of flow increases slightly.

3- As the median diameter of the used rockfill sample decreases, the energy dissipation increases.

4- The general equation of the energy dissipation, that created by the other parameters has R2 value equal to 0.95.

5- The equation that connect between both values of the measured-calculated energy dissipation has R2 value equal to 0.97, while the percentage of errors in this equation has average value approach to6.13%.

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