Effect of using stepped gabions on the distance of the hydraulic jump

Ali M Al-Fawzy1,*, Faiz H Al-Merib2, Fadhil M Al-Mohammed3, Ali H Hummadi4, and Riyadh Z Al-Zubaidy5

1Directorate of Water Resources in Kerbala, 56001, State Commission on Operation of Irrigation and Drainage Projects, Ministry of Water Resources, Iraq. Email: ali_alfawzy85@yahoo.com
2Civil Department, College of Engineering, University of Babylon, 11702, Babylon, Iraq. Email: Faiz_bh@yahoo.com
3Kerbala Technical Institute, Al-Furat Al-Awsat Technical University, 56001, Kerbala, Iraq. Email: fnhmjime@yahoo.com
4Al-Hindiyah Barrage Project, Babylon, 11702, State Commission of Dams and Reservoirs, Ministry of Water Resources, Iraq. Email: alihassan197950@yahoo.com
5Water Resources Department, College of Engineering, University of Baghdad, 10011, Baghdad, Iraq. Email: razzubaidy@yahoo.com
*Corresponding author

Abstract. The present study investigates the effect of using stepped gabion weir in a laboratory channel on the distance of the hydraulic jump. A set of 25 laboratory experiments and 175 operation tests were conducted using a laboratory flume with dimensions 10 m long by 0.3 m wide, and 0.5 m high. The tested gabion weir had different five possible lengths 0.88 m, 0.96 m, 1.04 m, 1.12 m, and 1.20 m, and the filling material used was natural quarry monograined gravel in five different sample sizes of average equivalent diameter 11.75 mm, 16.50 mm, 22.00 mm, 31.25 mm, and 43.75 mm. Operation discharge values ranged between 0.7 to 15.0 l/s. The data set was subject to dimensional analysis to generate dimensionless groups, and correlated using the Buckingham Pi-Theorem. The results of this study showed that in case of direct representation between the parameters, the distance of hydraulic jump has a direct relationship with discharge but both the gravel sample used and the overall length of the weir give an undular behaviour with its increment. While using of dimensional representation shows that both the gravel sample and weir length have an inverse relationship with the distance of the hydraulic jump. Many trials have been made to formulate the best equation which combine the studied parameters with good agreement.

1. Introduction

The general expression that may define the hydraulic jump occurrence in open channels is a phenomena in which transition from supercritical to sub-critical flow occurs [1], [2], [3], [4], [5] and [6]. The hydraulic jump characteristics have been studied to discuss and understand many problems related to management of water resources, such as the effect of relative pipe diameter on the jump occurs in the downstream side of a weir controlled by a sluice gate with different shape openings [7] and [8], or diverging open channel [9], its behavior in the presence of magnetic fields and electrical currents [10], investigating the change in spatial turbulence intensity and scales of turbulent eddies in a rectangular channel [11], analyze the occurrence of oscillatory flow conditions between different jump types.
characterized by Quasi-Periodic oscillation [12], investigating the effect of cross-sectional shape and bed friction on its formation [13], studying the air-water flow properties in hydraulic jump with partially developed inflow conditions [14]. Also, it's an important parameter taken into considerations within the construction of the downstream protection works [15], deciding the best stilling basin behind the hydraulic structures [16], and so many topics. The main aim of this study is to investigate the effect of using the stepped shape of gabions on the distance of the hydraulic jump formed in the laboratory standard channel.

2. Laboratory work
Conducting of tests was in the hydraulic laboratory of civil Engineering department at University of Babylon in Iraq. The laboratory has a tilting flume of 10 m length, with 0.3 m width and 0.5 m height. The bed of flume was fabricated from iron plates and the flume side walls were made of anti-crush glass supported by stainless steel bars. The physical models that used have overall lengths of 0.88, 0.96, 1.04, 1.12, and 1.20 m, and assigned as SGW.1, (Stepped Gabion Weir number 1), SGW.2, SGW.3, SGW.4, and SGW.5 respectively. Figure 1 displays the general sketch of the tested gabion weirs. All physical models have constant cross-section, (width of 0.3 m and Maximum step height of 0.4 m at upstream side of the weir), and steps of different heights and lengths as listed in table 1. While the gravel samples that used as filling material for the weir physical models were five mono-sized gravel samples with diameters ranged between (9.5-14), (14-19), (19-25), (25-37.5), and (37.5-50) mm, and numbered as GS.1, (gravel sample number1), GS.2, GS.3, GS.4, and GS.5 respectively. The frame of the gabion was made of thin steel plated bars, covered by a wire mesh, and fixed inside the flume by silicone glue. A photo of SGW.5 with GS.5 is provided in Figure 2. 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 brass rail at the top of flume sides which have accuracy of 0.1mm to measure the depths of water. The first was located at the upstream side of the gabion to measures the upstream water depth before it during each test run. The second was at the downstream side of the gabion and measures the downstream water depths before and after the hydraulic jump location during the test run too. A gross of 175 test runs were conducted and the discharges were ranged from 0.70 to 15.00 l/s respectively.

3. The hydraulic jump formula in stepped gabions
Generally, the relationships that governing multiple variables can be represented in many ways such as the standard formulas, empirical equations, direct relations, or subject to correlation by using the dimensional analysis [1], [2], [5], [6], [7], [15], [16], [17], [18], [19], [20], and [21]. Accordingly, the variables of the four steps stepped gabions which the hydraulic jump depends on it may be as below :

\[ f_1 (DHJ, Q, d_m, L_4, L, \rho_w, g) = 0 \]  

Figure 1. The general sketch of stepped gabions tested in this study, and a part of the laboratory flume shows the general position of the hydraulic jump and depths of water.
Table 1. Step dimensions details for all steps of the tested gabions.

| Stepped gabion weir | Step dimensions | 1st step dimensions (cm) | 2nd step dimensions (cm) | 3rd step dimensions (cm) | 4th step dimensions (cm) |
|---------------------|----------------|--------------------------|--------------------------|--------------------------|--------------------------|
|                     |                | h1 | L1 | h2 | L2 | h3 | L3 | h4 | L4 |
| A                   |                | 15 | 40 | 5  | 20 | 10 | 20 | 10 | 8  |
| B                   |                | 15 | 40 | 5  | 20 | 10 | 20 | 10 | 16 |
| C                   |                | 15 | 40 | 5  | 20 | 10 | 20 | 10 | 24 |
| D                   |                | 15 | 40 | 5  | 20 | 10 | 20 | 10 | 32 |
| E                   |                | 15 | 40 | 5  | 20 | 10 | 20 | 10 | 40 |

Note 1: h1, h2, h3 and h4 present the effective distance of step height.

Note 2: L1, L2, L3 and L4 are divided according to maximum weir length tested in this study, which is equal to 1.2 m where:
L1 has a percentage of 33.33% of the maximum weir length.
L2 has a percentage of 16.67% of the maximum weir length.
L3 has a percentage of 16.67% of the maximum weir length.
L4 has a percentage of 6.67% of the maximum weir length, for SGW.1, and the percentage of L4 increases accumulatively by 6.67% of maximum weir length with every physical model tested according to their arrangement in the table above.

where DHJ is the distance of the hydraulic jump formed at the downstream side of the gabion (L), q is discharge per unit width, (L³/T), d_m is the equivalent diameter of the used gravel sample, (L), L4 is the length of the forth step of the gabion, (L), L is the overall length of the gabion (L), ρ_w is mass density of water (M/L³), and g is the gravitational acceleration (L/T²).

Figure 2. Photo of stepped gabion weir number 5 with the used gravel sample number 5.

4. Dimensional analysis

Using of Buckingham Pi – Theorem consider as an effective way to represent the relationships of parameters functionally in dimensionless mode, [1], [5], [6], [7], [15], [17], [19] and [21]. The representation of the hydraulic jump with the other parameters can be expressed in non-dimensional formula as follows:
5. Results and discussion: Parameters affecting the hydraulic jump in stepped gabions analysis

5.1. Effect of discharge on the distance of the hydraulic jump

The relationship between the discharge and the distance of the hydraulic jump may be represented and drawn in xy-plane style [6], [15], [18], and [20], and the figures 3, 4, 5, 6, and 7 display this relationship. In these figures, the preferable equation form of trend lines to represent this relationship was varied between two forms, either exponential or power.

\[ \frac{DHJ}{C} = c_1 e^{c_2 q} \]  \hfill (3)

\[ DHJ = c_3 q^{c_4} \]  \hfill (4)

Where \( c_1, c_2, c_3 \) and \( c_4 \) are constants, and table 2 presents their values. Generally, for all figures, the discharge is directly proportional to the distance of the hydraulic jump.

5.2. Effect of the gravel sample on the distance of the hydraulic jump

From the figures mentioned in the above, it's obvious that there is no clear effect of increasing the diameter of the used gravel sample on the distance of the hydraulic jump at low discharge values, this leads to the possibility of use any available sample within the limitations of this study in field, where the water flow through the pores of different gravel particles in laminar state, and there is no formation of the hydraulic jump in most of case. But increasing of discharge value, this behavior transforms to an undular effect on the formed distance of hydraulic jump. Using of dimensional analysis after combining the data of these figures, and draw the relationship between the parameters \( \left( \frac{DHJ}{d_m} \right) \) and \( \left( \frac{q}{g^{0.5} d_m^{1.5}} \right) \) as shown in figure 8, changes this undulation to an inverse proportion to the distance of the hydraulic jump. From figure 8 it's clear that the preferable equation form of trend line to represent this relationship was the exponential form, equation (5), and the equations resulted from this figure use for design purposes.

\[ \frac{DHJ}{d_m} = c_6 e^{c_0 \left( \frac{q}{g^{0.5} d_m^{1.5}} \right)} \]  \hfill (5)

5.3. Effect of the gabion overall length on the distance of the hydraulic jump

The figures 9, 10, 11, 12, and 13 view the relationships of discharge – distance of the hydraulic jump for each gravel sample used in all gabion weir lengths. From these figures it's obvious that there is also an undular effect of increasing the length of the gabion weir on the distance of the hydraulic jump. But using of dimensional analysis and draw the relationship between the parameters \( \left( \frac{DHJ}{L} \right) \) and \( \left( \frac{q}{g^{0.5} L^{1.5}} \right) \) as shown in figure 14, also change this undulation to an inverse proportion to the distance of the hydraulic jump. From this figure it's clear that the preferable equation form of trend line to represent this relationship was the exponential form, equation (6), and the equations resulted from this figure use for design purposes.

\[ \frac{DHJ}{L} = c_8 e^{c_0 \left( \frac{q}{g^{0.5} L^{1.5}} \right)} \]  \hfill (6)

Table 3 lists the values of constants of equations (5) and (6).

To Use the multi-linear regression for the data set to correlate the dependent and independent parameters [6], [19], and [21], 80% of data were chosen for this process, (data recorded of test runs of the 1st, 2nd, 4th, and 5th overall lengths of the gabions), and 20% of data were used for confirmation of the resulted formula, (data recorded of test runs 3rd overall length of the gabion weir).
Figure 3. The discharge-distance of hydraulic jump relationships in stepped gabion weir No.1.

Figure 4. The discharge-distance of hydraulic jump relationships in stepped gabion weir No.2.

Figure 5. The discharge-distance of hydraulic jump relationships in stepped gabion weir No.3.

Figure 6. The discharge-distance of hydraulic jump relationships in stepped gabion weir No.4.

Figure 7. The discharge-distance of hydraulic jump relationships in stepped gabion weir No.5.

Figure 8. The gravel sample-distance of hydraulic jump non-dimensional relationship.
Table 2. Values of constants c₁ and c₂ in equation (3), and c₃ and c₄ in equation (4).

| SGW | GS | q (m³/s/m) From | To | DHJ (m) From | To | c₁  | c₂  | c₃  | c₄  | R²  |
|-----|----|----------------|----|-------------|----|-----|-----|-----|-----|-----|
| 1   | 1  | 0.00233        | 0.02800 | 0.0290 | 121.5 | -   | -   | 0.919 |
|     | 1  | 0.00233        | 0.03168 | 0.0120 | 162.6 | -   | -   | 0.947 |
|     | 1  | 0.00233        | 0.03237 | 0.0080 | 148.3 | -   | -   | 0.890 |
|     | 1  | 0.00233        | 0.03990 | 0.0040 | 157.4 | -   | -   | 0.994 |
|     | 1  | 0.00233        | 0.05000 | 0.0070 | 125.8 | -   | -   | 0.934 |
| 2   | 1  | 0.00233        | 0.02167 | 0.13   | -     | 0.0363 | 0.866 | 0.998 |
|     | 2  | 0.00233        | 0.02333 | 0.22   | -     | 23.87 | 1.229 | 0.990 |
|     | 2  | 0.00233        | 0.04333 | 0.235  | -     | 35020.00 | 2.959 | 0.974 |
|     | 2  | 0.00233        | 0.04667 | 1.15   | -     | 490.00 | 2.012 | 0.980 |
|     | 2  | 0.00233        | 0.05000 | 2.58   | 0.0060 | 118.3 | -     | 0.975 |
| 3   | 1  | 0.00233        | 0.02600 | 0.46   | 0.0100 | 150.5 | -     | 0.951 |
|     | 2  | 0.00233        | 0.03168 | 1.41   | 0.0120 | 147.8 | -     | 0.981 |
|     | 3  | 0.00233        | 0.03633 | 1.93   | 0.0010 | 206.2 | -     | 0.950 |
|     | 4  | 0.00233        | 0.03990 | 2.76   | 0.0030 | 181.5 | -     | 0.952 |
|     | 5  | 0.00233        | 0.05000 | 2.47   | 0.0070 | 124.6 | -     | 0.907 |
| 4   | 1  | 0.00233        | 0.02000 | 0.35   | 0.0090 | 188.7 | -     | 0.950 |
|     | 2  | 0.00233        | 0.02000 | 0.61   | 0.0050 | 237.2 | -     | 0.971 |
|     | 3  | 0.00233        | 0.03168 | 1.03   | 0.0020 | 199.5 | -     | 0.968 |
|     | 4  | 0.00233        | 0.03000 | 1.61   | 0.0001 | 268.6 | -     | 0.952 |
|     | 5  | 0.00233        | 0.04000 | 2.36   | 0.0001 | 236.1 | -     | 0.946 |
| 5   | 1  | 0.00233        | 0.02600 | 0.13   | -     | 3.469 | 0.836 | 0.902 |
|     | 2  | 0.00233        | 0.03168 | 1.60   | 0.0001 | 235.7 | -     | 0.953 |
|     | 3  | 0.00233        | 0.03237 | 2.13   | 0.0340 | 139.2 | -     | 0.961 |
|     | 4  | 0.00233        | 0.03990 | 1.90   | 0.0130 | 134.5 | -     | 0.993 |
|     | 5  | 0.00233        | 0.05000 | 2.33   | -     | 3E+10 | 7.584 | 0.897 |

\[
\frac{\text{DHJ}}{L} = (-0.2984824) + 117696.411 \times \left( \frac{q}{g^{0.5} \cdot L^{1.2}} \right)^2 + 30.3295093 \times \left( \frac{L_d}{L} \right)^3 - 14839.929 \times \left( \frac{d_m}{L} \right)^3 \quad R^2 = 0.70 \quad (7)
\]

After many trials, equation (2) can be re-written as,

Figure 15 displays the calculated - measured distance of the hydraulic jump relationship [1], [4], [5], [16], [17], and [18], and the equation (8) expresses this relationship,

\[
\text{DHJ}_{\text{Calculated}} = 1.058 \ln(\text{DHJ}_{\text{Measured}}) + 1.095 \quad R^2 = 0.803 \quad (8)
\]

According to this figure, an accepted agreement was achieved. The percentage of errors for both values of distance of the hydraulic jump, calculated and measured, was reached by equation (9) with an average value of 52.4797%. May be this value becomes lower and more accurate if a separation has been made between the data of through flow and the over flow,

\[
E\% = \frac{(\text{DHJ}_{\text{Calculated}} - \text{DHJ}_{\text{Measured}})}{\text{DHJ}_{\text{Calculated}}}\]
Figure 9. The relationships of discharge-distance of the hydraulic jump for all gabion lengths and gravel sample No.1.

Figure 10. The relationships of discharge-distance of the hydraulic jump for all gabion lengths and gravel sample No.2.

Figure 11. The relationships of discharge-distance of the hydraulic jump for all gabion lengths and gravel sample No.3.

Figure 12. The relationships of discharge-distance of the hydraulic jump for all gabion lengths and gravel sample No.4.

Figure 13. The relationships of discharge-distance of the hydraulic jump for all gabion lengths and gravel sample No.5.

Figure 14. The total length-distance of hydraulic jump non-dimensional relationship.
Table 3. Values of constants $c_5$ and $c_6$ in equation (5), and $c_7$ and $c_8$ in equation (6).

| SGW | GS | $c_5$  | $c_6$  | $c_7$ | $c_8$ | $R^2$ |
|-----|----|--------|--------|-------|-------|-------|
| All | 1  | 1.405  | 01.641 | -     | -     | 0.763 |
| All | 2  | 0.716  | 03.360 | -     | -     | 0.844 |
| All | 3  | 0.260  | 05.674 | -     | -     | 0.899 |
| All | 4  | 0.190  | 08.350 | -     | -     | 0.847 |
| All | 5  | 0.074  | 13.680 | -     | -     | 0.934 |
| 1   | All| -      | -      | 0.021 | 1012.0| 0.787 |
| 2   | All| -      | -      | 0.022 | 0960.6| 0.836 |
| 3   | All| -      | -      | 0.010 | 1499.0| 0.852 |
| 4   | All| -      | -      | 0.007 | 1835.0| 0.699 |
| 5   | All| -      | -      | 0.004 | 1966.0| 0.754 |

Figure 15. The calculated - measured distance of the hydraulic jump relationship for the 3rd length of the gabion weir.

6. Conclusion
In this study, the aim was investigating the effect of put a stepped gabions consist of four steps inside a rectangular, Laboratory channel on the distance of the hydraulic jump. The relationships between the parameters were expressed either directly or in non-dimensional conditions, and finally the regression technique was used to correlate all the studied parameters. Within the limitations of the present study, the concluded results were:

- The discharge has a direct proportional with the distance of the hydraulic jump.
- The effect of increasing the diameter of used gravel sample and the gabions overall length on the distance of the hydraulic jump is little at the small discharge values.
- The diameter of the used gravel sample and the overall length of the gabions have an inverse proportional with the distance of the hydraulic jump.
• A general non-dimensional equation was evolved to correlate all the parameters of the present study.
• The calculated - measured distance of the hydraulic jump relationship has been drawn, and the fitness equation was with \( R^2 \) equal to 0.803.
• The percentage of errors was 52.4797\% for the relationship between the calculated and measured distance of the hydraulic jump.

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