FLOW THROUGH AND OVER GRAVEL GABION WEIRS

الجريان من خلال و فوق هدارات السلال الحصوية

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Abstract
Gravel and Rockfill gabions are commonly used in hydraulic structures such as self-spillway dams, cofferdams, and head regulators for water distribution or other purposes. A laboratory experiments were conducted to study the influence of gravel mean size, which consists of gabion, length and height of gabion on its upstream water depth. The present study included two cases of flow regimes, through and transient flow. In this study, different gravel gabion weir models were tested in horizontal laboratory flumes of 10m length, 0.3m width, and 0.5m depth, for various weir lengths and heights using a wide range of discharges. Monosized gravel was used as filling material for the weir models. The gravel samples used in this study were three monosized gravel samples with diameters (-14+10), (-20+14), and (-25+20) mm. The results showed that for throughflow regime; upstream water depth of the gabion weir increases by decreasing the gravel mean size for the same weir length. In addition, for same gravel size, upstream water depth of the gabion increases by increasing the weir length. The results indicated that the relation between upstream water depth and unit discharge passing through gabion weir is linear for through and transient flow regimes. A positive and significant correlation was found between upstream water depth and unit discharge with an average $R^2$ of 0.99 and 0.97 for through and transient flow regimes respectively. Based on dimensional analysis concept, multiple regression analysis equations were developed for computing the upstream water depth of the gabion weir at throughflow and transition flow regimes.

Keywords: Gabion; Throughflow; Transient flow; Hydraulic structures; Weir.

الخلاصة
تستخدم هدارات السلال الحصوية والرصفية بشكل شائع في المنشات الهيدروليكية كسد ذاتية المقطع أو كسد ترسيب أو كنظام رأسية للتحكم والتنظيم. أجريت التجارب المختبرية لدراسة تأثير معدل قطر الحصى لقوائم النسبة الحصوية وطول وارتفاع السلاسل على عمق الماء في مقسم السلة تحت تأثير جريان الماء. يضم البحث حاليتين لاستخدام الحصى في الدرجات. فبال연сте من الدرجات، فان العضو المائي في باب البندان التدريبي ما الحصى الخالص والجرام الغير الزيت. ففي هذا البحث لحصى نماذج سلال حصية باستخدام مواد حماية مختبرية مختلفة لإنتاج البتة بعد استخدام قناة مختبرية عميقة بطول 10m وعرض 0.5m وعمق 0.3m، حيث كونت النماذج المفسحة بطول وارتفاعات مختلفة وفوق حستة الدرجات مع استخدام مدى واسع للتصريف الماء من خلالها ووقفيات اتجاه التجارب المختبرية باختبار ثلاث نماذج من الحصى النهري الأحادي (-14+10) mm و (-20+14) mm و (-25+20) mm. بتبنت النماذج الدرجات الخالية بفتح وحدة التصرف وطول الدرجات الحصوي فان الارتفاع الماء في مقسم الدرجات زيد كم غل قطر الحصى المسموح به. كما أظهرت نتائج الدرجات الخالية بفتح نظام التصرف وقطر الحصى فان الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. بتبنت النماذج الدرجات الخالية بفتح نظام التصرف وقطر الحصى المسموح به. فان يكون الارتفاع الماء مقسم الدرجات زيد كم غل قطره. **R**4 0.99 و 0.97 لجهاز الحصى والمابع المستخدمة هي عتلة خليطية يتم محاكية ارتباط التوقع ب sean استعمال أساليب الإعداد الخطي والمعدل. واعتمادا على نظرية التحليل البدع، يمكن التوصل إلى معدلات خصاء لحصى المشاء في مقسم الدرجات الحصوي الحجريين الخالصي والانتقالي اعتمادا على التصرف المار عبر السلة الحصوية والقطر المثل للمواد الحصوية والابعاد الهندسية للهدار.
1. INTRODUCTION

Flow through gravel weirs is of fundamental importance to a wide range of disciplines including water resources engineering, hydrology, and chemical engineering. Generally, impermeable weirs that constructed of concrete, metal, rubber, etc. were used in various engineering applications, but nowadays alternative weirs made of porous media such as gravel gabion weir GGW are preferred since the latter can better meet natural and ecological requirements. The GGW consist of gravel aggregates enclosed with a wire mesh grid. Economically, the GGW is less expensive compared with other types of weirs in areas in which gravel is readily available. Depending on the nature of the site, gravel aggregates are manufactured by crushing solid rocks and are also commonly found among glacial and floodplain soil deposits. The main function of weir is to reserve water and to regulate river flow for various purposes. An impermeable weir usually prevents the longitudinal movement of aquatic life and transportation of physical and chemical substances in water. So this has a negative impact on the river environment. The GGW is permeable but it reserves amount of water and it allows the rest of water to pass through its body. This, however, allows streamwise migration of aquatic lives. In addition, physical and chemical substances such as suspended organic matter and sediments could pass downstream through the GGW permeable body which minimizes negative impact of the gabion on stream environment. In compared to traditional types of impermeable weirs, the GGW is considered as an ecologically friendly structure.

In gravel or rockfill gabions, due to the large size of pores, the flow is inherently turbulent and therefore not amenable to a classic seepage analysis on the basic of Darcy’s low, so a non-Darcy flow relationship must be used [1]. Few experiments conducted to study the hydraulic characteristics of flow through and over gravel and rockfill weirs have been reported because of the large apparatus required and of the physical difficulty handling the material. Those studies that are available generally indicate that the flow through gravel materials is not laminar and, therefore, does not obey Darcy’s law and the relationship between flow velocity \( v \) and the hydraulic gradient, \( i \), was of the form \( (v = mi^k) \), with \( m \) and \( k \) are constants for particular gravel [2 and 3]. Kells, [4] studied flow through and over rockfill models. He showed that the ratio of through to overtopping flow as a discharge was in the range from to 0.25 to 0.5 for the experiments in his model. Michioku et al., [5], examined the hydrodynamics of a rubble-mound weir theoretically and experimentally. By performing a one-dimensional analysis on a steady non-uniform flow through the weir, they found that the discharge may be described as a function of related parameters such as flow depths on the upstream and downstream sides of the weir, porosity, and grain diameter of rubble mound, weir length. They found that it is possible to apply the rubble mound weir for practical use as a discharge control system. Michioku et al., [6], investigated the flow field around rubble mound weirs and groins experimentally. They found that mass and momentum exchange between the main flow and the rubbles porous media was predominant around the upstream and downstream corners of the weir and the groin, where the streamline was rapidly contracted. Chinnarasri et al., [7] found that the energy dissipation rate in a gabion-stepped weir depends on filling material porosity and weir slope. Mohamed, [8] studied the flow over gabion weirs. He indicated that the nature of flow over the gabion weir is different than that of the solid weir where the flow is divided into two parts, one over the weir and the other through the weir. He also showed that for the same discharge, the head over the gabion weir is less than that over the solid weir and the head decreases by increasing gabion material particle size. Salmasi et al., [9] examined the behavior of gabion-stepped weirs for energy dissipation. They found that the decision tree technique can be used as a reasonable method for classification of different parameters involved in energy dissipation through a gabion-stepped weir.

This paper aims to formulate upstream water depth for gabion weirs as a function of flow regime, gravel mean size, discharge, length of gabion, and geometric dimension of the gabion, and compares the results with those in previous literatures.
2. TYPES OF FLOW REGIMES FOR ROCKFILL WEIR

Depending on a hydraulic conductivity of rockfill materials and gabion’s geometry for porous gabion weirs, five possible flow regimes can be observed [10]. As shown in Fig. 1, they are as below:
1. Non-overflow (throughflow): occur when the water flows only through the porous weir.
2. Non-overflow (throughflow) limit: is the state of flow that the free surface disappears from the upper edge of the weir crest.
3. Transient flow: is the state that the flow gets into the filling material over the weir.
4. Overflow flow limit: is the flow profile that the free surface reaches just the downstream edge of the weir crest.
5. Overflow flow: occur when the stream is running over the top of the weir.

In measurements and calculations, only throughflow and transition flow regimes are taken into consideration in this study.

Figure 1. Flow regimes for porous gabion weir.

3. LABORATORY EXPERIMENTS

All laboratory experiments were conducted in a glass-sided tilting flume with a fabricated stainless steel bed 10 m long, 0.3 m wide and 0.5 m deep as shown in Fig. 2.

Figure 2. View of flume used in the study.
Experiments were carried out at the fluid mechanics laboratory of the civil engineering department in al- Mustansiriya University (Iraq). Water was circulated through the flume by an electrically driven centrifugal pump providing a maximum flow of 28 lps. Water flow rates were measured by means of a triangular weir. The longitudinal flume slope fixed with 0° angle of inclination. In the present paper three monosized rounded gravel samples were chosen with nominal diameters (-14+10) mm, (-20+14) mm, and (-25+20) mm.

Porosity \( n \) of a porous media sample was defined as the volume of voids within a porous media divided by the bulk volume of the sample. It was evaluated for each sample by randomly dumping the test gravel into a tank, weighing the tank and gravel, filling the tank with water; weighing the tank, gravel and water; arithmetically determining the volume of water, which was equivalent to the volume of voids; \( n \) may be expressed as equation:

\[
\frac{V_v}{V_b} = n
\]

in which
\( V_v = \) voids volume in a sample, \((L^3)\), and
\( V_b = \) bulk volume of the sample, \((L^3)\).

For each gravel sample, the equivalent gravel diameter, particle density, porosity and shape factor were determined. To estimate the shape factor \( SF \) [11], three major axes were measured for the gravel particles using a vernier and the average axes lengths calculated for each sample. Shape factors were estimated using the relationship

\[
SF = \frac{c}{\sqrt{ab}}
\]

in which
\( a = \) length in longest direction, \((L)\), and
\( b \) and \( c = \) lengths measured in mutually perpendicular medium and short directions \((L)\).

Figure 3 shows the three dimensions \( a, b, \) and \( c \). Table 1 summarises the properties of the three samples randomly drawn from each of the three materials.

Figure 3. Gravel particle principal axes.
Table 1. Properties of the three gravel samples.

<table>
<thead>
<tr>
<th>Monosized sample mm</th>
<th>Gravel mean size mm</th>
<th>Particle Density (g/cm³)</th>
<th>Porosity</th>
<th>Shape Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-14+10)</td>
<td>12</td>
<td>2.69</td>
<td>39.16%</td>
<td>0.53</td>
</tr>
<tr>
<td>(-20+14)</td>
<td>17</td>
<td>2.72</td>
<td>40.7%</td>
<td>0.48</td>
</tr>
<tr>
<td>(-25+20)</td>
<td>22.5</td>
<td>2.75</td>
<td>41.06%</td>
<td>0.57</td>
</tr>
</tbody>
</table>

In this paper, the gravel samples were tested in a rectangular section contained in a wire mesh gabion with vertical upstream and downstream faces as shown in Fig. 4 with two flow regimes throughflow and transition flow.

Figure 4. Definition sketch of models used in the experiments.

The experiments were conducted for various ranges of gabion height and two weir lengths 30 cm and 60 cm. The experimental conditions for the flume experiments are listed in Tables 1 and 2, respectively. The total number of experimental runs or data points was 63 runs for through and transient flow experiments.

Table 2. Experimental condition for through flow regime.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel mean size</td>
<td>dₘ</td>
<td>Various</td>
<td>12 to 22.5</td>
<td>mm</td>
</tr>
<tr>
<td>Gabion length</td>
<td>L</td>
<td>30,60</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Gabion height</td>
<td>H</td>
<td>18</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Gabion width</td>
<td>W</td>
<td>30</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Unit discharge</td>
<td>q</td>
<td>Various</td>
<td>1.59E⁻³ to 7.35E⁻³</td>
<td>m³/s/m</td>
</tr>
</tbody>
</table>
Table 3. Experimental condition for transition flow regime.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel mean size</td>
<td>(d_m)</td>
<td>17</td>
<td>-------</td>
<td>mm</td>
</tr>
<tr>
<td>Gabion length</td>
<td>(L)</td>
<td>30,60</td>
<td>-------</td>
<td>cm</td>
</tr>
<tr>
<td>Gabion height</td>
<td>(H)</td>
<td>Various</td>
<td>10 to 18.5</td>
<td>cm</td>
</tr>
<tr>
<td>Gabion width</td>
<td>(W)</td>
<td>30</td>
<td>-------</td>
<td>cm</td>
</tr>
<tr>
<td>Unit discharge</td>
<td>(q)</td>
<td>Various</td>
<td>4.2E(^{-3}) to 13.3E(^{-3})</td>
<td>m(^3)/s/m</td>
</tr>
</tbody>
</table>

The laboratory work included the examination of the gravel samples for the two regimes, through and transient flow according to experimental conditions shown in Tables 2 and 3. This work was carried out according to the following steps:

1. Manufacturing a metal frames with a wire mesh with various dimensions of gabion height and length as shown in Tables 2 and 3.
2. Putting the first metal frame \((L=0.30 \, m)\), 3 m from the flume head as the gabion dimensions (height and width) shown in Table 2.
3. Constructing the gabion for throughflow regime experiments by randomly dumping the test gravel with a monosized diameter 12 mm in the metal frame as shown in Fig. 5.
4. Establishing a flow rate by adjusting a control valve in the flume supply line.
5. Waiting 30 min so that upstream water depth equilibrium is established.
6. Recording the discharge, flow depth at the gabion upstream face, and water depth at the gabion downstream face.
7. Changing the value of the discharge as in step 4.
8. Repeating steps 5 to 7 several times.
9. Repeating steps 3 to 8 for other test gravel sizes and lengths shown in Table 2 for throughflow regime experiments.
10. Repeating steps 2 to 9 for other gabion length \((L=0.60 \, m)\) as shown in Table 2.
11. Repeating steps 2 to 8 using gravel of 17 mm diameter only according to the gabion dimensions as in Table 3 for all gabion heights (10, 12, 16.5, 17, 18, 18.5 cm), producing transient flow experiments.
4. DIMENSIONAL ANALYSIS

The upstream water depth for the GGW depends on many variables such as the properties of the filling material, discharge, and geometric of the weir. A physically pertinent relation between the upstream water depth and other variables may be found by dimensional analysis. The nondimensional relationship is also useful for checking the sensitivity of the different parameters which affect the phenomenon [11]. The functional relationships of the water depth upstream the gabion weir \( h_u \) for through and transient flow may be expressed as below:

4.1 Throughflow regime

The relationship for this condition can be expressed as follows:

\[
\begin{align*}
  h_u &= f(\rho, g, q, L, d_m) \\
  \text{in which} \\
  h_u &= \text{upstream water depth (L)}, \\
  L &= \text{gabion length, (L)}, \\
  d_m &= \text{mean gravel size used in gabion construction, (L)}, \\
  \rho &= \text{water density, (ML}^{-2}\text{)}, \\
  g &= \text{gravity of acceleration, (LT}^{-2}\text{), and} \\
  q &= \text{discharge per unit width of the flume (unit discharge), (L}^2T^{-1}\text{).}
\end{align*}
\]

4.2 Transition flow regime

In general the relationship for this condition can be expressed as follows:

\[
\begin{align*}
  h_u &= f(\rho, g, q, L, H, d_m) \\
  \text{in which} \\
  h_u &= \text{upstream water depth (L)}, \\
  L &= \text{gabion length, (L)}, \\
  H &= \text{height of the weir, (L)}, \\
  d_m &= \text{mean gravel size used in gabion construction, (L)}, \\
  \rho &= \text{water density, (ML}^{-2}\text)}, \\
  g &= \text{gravity of acceleration, (LT}^{-2}\text{), and} \\
  q &= \text{discharge per unit width of the flume (unit discharge), (L}^2T^{-1}\text{).}
\end{align*}
\]
For a particular gravel size the relationship for transition regime can be written as follow:

\[ h_u = f(\rho, g, q, L, H) \]  

(5)

Depending on the relationships (3) and (5), some transformations lead to the non-dimensional relations (6) and (7) for throughflow and transition flow respectively.

\[ \frac{q}{g^{0.5}h_u^{1.5}} = \Phi\left(\frac{L}{h_u}, \frac{d_m}{h_u}\right) \]  

(6)

\[ \frac{q}{g^{0.5}h_u^{1.5}} = \Phi\left(\frac{L}{h_u}, \frac{H}{h_u}\right) \]  

(7)

In the following section the dimensionless groups in the relations (6 and 7) will be correlated to give an explicit equation for computing the water depth upstream the GGW at the throughflow and transition flow regimes.

5. RESULTS AND DISCUSSIONS

This paragraph describes the presentation and discussion of the results for throughflow regime and transition flow regime as follows:

5.1 Throughflow regime

Figure 6 shows the relation between upstream water depth and unit discharge passing through the gravel gabion weir with different filling material sizes and two gabion lengths 30 cm and 60 cm. It is obvious that the relation between \( h_u \) and \( q \) is linear for all gravel sizes and for same discharge and gabion length, \( h_u \) value increases by decreasing the mean gravel size of the gabion weir. For \( q=0.005 \, m^3/sec/m \) and \( L=30 \, cm \), the \( h_u \) values at \( d_m \) of 12, 17, and 22.5 mm are 0.143 m, 0.125 m, and 0.115 m respectively. This result agreed with the results of previous studies [8, 12, and 13]. It can be shown that for same discharge and mean gravel size, \( h_u \) value increases by increasing the length of the gabion. For \( q=0.004 \, m^3/sec/m \) and \( d_m=17 \, mm \), the \( h_u \) values at \( L \) of 30, and 60 cm are 0.108 m, and 0.141 m respectively.
Regression analysis with a linear function was used to obtain a formula to estimate $h_u$ values. Table 4 shows the formulas for estimating $h_u$ under throughflow regime with different conditions, in which $h_u$ in m and $q$ in $m^3/sec/m$. 

Table 4. Formulas for estimating $h_u$ of throughflow regime.

<table>
<thead>
<tr>
<th>$d_m$ (mm)</th>
<th>L (m)</th>
<th>$h_u$ formula</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.3</td>
<td>$h_u=19.411q+0.0462$</td>
<td>0.99</td>
</tr>
<tr>
<td>17</td>
<td>0.3</td>
<td>$h_u=16.865q+0.041$</td>
<td>0.98</td>
</tr>
<tr>
<td>22.5</td>
<td>0.3</td>
<td>$h_u=15.169q+0.0389$</td>
<td>0.999</td>
</tr>
<tr>
<td>12</td>
<td>0.6</td>
<td>$h_u=31.833q+0.0334$</td>
<td>0.999</td>
</tr>
<tr>
<td>17</td>
<td>0.6</td>
<td>$h_u=25.397q+0.0395$</td>
<td>0.999</td>
</tr>
<tr>
<td>22.5</td>
<td>0.6</td>
<td>$h_u=19.965q+0.0391$</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Table 4 shows that for the same length of the weir gabion, effect of $q$ on $h_u$ increases by decreasing gravel mean size and for the same gravel mean size, the effect of $q$ on $h_u$ increases by increasing the length of the GGW. The slope of the linear relationships for throughflow regime between $h_u$ and $q$ of different states for gabion length of 0.3 m and gravel mean size 12 mm, 17 mm, and 22.5 mm are 19.41, 16.86, and 15.6 respectively.
In addition the slope of the linear relationships for throughflow regime between $h_u$ and $q$ for different states for gabion that consist of gravel of 12 mm average diameter with a length 0.3 m and 0.6 m are 19.41 and 31.833 respectively.

A multi-linear regression analysis is used to correlate the different dimensionless parameters shown in relation (6) and develops an empirical equation for computing the upstream water depth at the throughflow regime. The developed equation was found with the correlation coefficient $R^2 = 0.94$ can be expressed as follows:

$$h_u = 1.607 \frac{q^{0.66} L^{0.349}}{d_m^{0.34}}$$

in which $h_u$ in m, $L$ and $d_m$ in m, and $q$ in m$^3$/sec/m.

Figure 7 shows values of the computed $h_u$ in dimensionless form from the regression analysis Eq. (8) versus the measured $h_u$. As shown from this figure, there is good agreement between the computed $h_u$ and the measured one.

![Graph showing computed and observed upstream water depth](image)

**Figure 7.** Computed value of upstream water level using Eq. (8) versus observed value at throughflow regime.

### 5.2 Transition flow regime

Figure 8 shows the measured values of $h_u$ for transition flow regime versus the measured discharge at $d_m$ of 17 mm with different lengths and heights of GGW. It is obvious that for same gabion length, the upstream water depth for each discharge increases by increasing gabion weir height. For $q=0.008$ m$^3$/sec/m and $L=30$ cm, the $h_u$ values at heights of 0.1, 0.165, 0.18, and 0.185 m are 0.125 m, 0.175 m, 0.188 m, and 0.197 m respectively.

Regression analysis with a linear function was used to obtain a formula to estimate $h_u$ values. Table 5 shows the formulas for estimating $h_u$ with different conditions, in which $h_u$ in m and $q$ in m$^3$/sec/m.
Table 5. Formulas for estimating $h_u$ of transition flow regime.

<table>
<thead>
<tr>
<th>H (m)</th>
<th>L=0.3 (m)</th>
<th>L=0.6 (m)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.185</td>
<td>$h_u=3.7261q+0.167$</td>
<td>--------</td>
<td>0.90</td>
</tr>
<tr>
<td>0.180</td>
<td>$h_u=4.1755q+0.1542$</td>
<td>--------</td>
<td>0.96</td>
</tr>
<tr>
<td>0.165</td>
<td>$h_u=4.5016q+0.1394$</td>
<td>--------</td>
<td>0.98</td>
</tr>
<tr>
<td>0.100</td>
<td>$h_u=3.4745q+0.0975$</td>
<td>--------</td>
<td>0.97</td>
</tr>
<tr>
<td>0.170</td>
<td>--------</td>
<td>$h_u=3.3011q+0.1551$</td>
<td>0.99</td>
</tr>
<tr>
<td>0.120</td>
<td>--------</td>
<td>$h_u=4.1453q+0.113$</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Tables 4 and 5 illustrate that the slope of $h_u$-$q$ relationship for throughflow regime is high great compared with that of transition flow regime.

A linear regression analysis is used to correlate the different dimensionless parameters shown in Eq. (7) and develops an empirical equation for computing the upstream water depth at the transient flow condition. The developed equation can be expressed as follows:

$$ h_u = 1.624q^{0.196}H^{0.704}L^{-0.002} $$  (9)
in which $h_u$ in $m$, $H$ and $L$ in $m$, and $q$ in $m^3/sec/m$. The correlation coefficient $R^2$ was found to be 0.79.

Figure 9 shows values of the computed $h_u$ in dimensionless form from the regression analysis Eq. (9) versus the measured values of $h_u$. As shown from this figure, there is good agreement between the computed $h_u$ and the measured one.

Figure 9. Computed value of upstream water level using Eq. (9) versus observed value at transition flow regime.

6. CONCLUSIONS

In this paper, a series of laboratory experiments were conducted to investigate the flow through and over the GGW. According to the results of the laboratory experiments, the following conclusions were found:

1. For throughflow regime, the relation between upstream water depth of the gabion and unit discharge through it is linear for all gravel sizes.
2. For same throughflow discharge and gabion length, upstream water depth value increases by decreasing the mean gravel size of the gabion weir.
3. For same through flow discharge and mean gravel size, upstream water depth value increases by increasing the length of the gabion.
4. Strong linear relationships were found between upstream water depth of the gabion and unit discharge through it for the three gravel sizes (12mm, 17mm, 22.5mm) with average $R^2$ equal to 0.99.
5. In transition flow regime, for same gabion length, the upstream water depth for each discharge increases by increasing gabion weir height.
6. In transition flow regime, strong linear relationships were found between upstream water depth of the gabion and unit discharge for the two lengths 0.3 m and 0.6 m with average $R^2$ equal to 0.96.
7. The slope of $h_u$-$q$ relationship for throughflow regime is high great compared with that of transition flow regime.
8. Based on dimensional analysis concept, multiple regression analysis equations were developed for computing the upstream water depth of the gabion at throughflow and transition flow regimes.
Notation

The following symbols are used in this paper:

- \( a, b, \) and \( c \) = particle axes lengths;
- \( d_m \) = gabion filling material mean size;
- \( g \) = gravity of acceleration;
- \( H \) = weir height;
- \( h_u \) = upstream water depth;
- \( i \) = hydraulic gradient;
- \( k \) = constants for particular gravel;
- \( L \) = weir length;
- \( m \) = constants for particular gravel;
- \( n \) = porosity;
- \( Q \) = discharge;
- \( q \) = unit discharge;
- \( V \) = flow velocity;
- \( V_b \) = bulk volume of the gravel sample;
- \( V_v \) = void volume in a gravel sample;
- \( W \) = weir width; and
- \( \rho \) = water density.

7. REFERENCES