Hydraulic Characteristics and Discharge of Canal Sluice Gate: Practical Approach

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ABSTRACT

Simplifying formulas that are used for calculations and design are the aim of researchers. For present work, the approach to distinguish the flow under sluice gate was conducted in a laboratory. The extensive experimental program was done to collect fifty-four data points for both free and submerged flow conditions. The data included different discharges, gate openings, flow depths at upstream as well as the flow depths represent a tail water and at a contracted section for downstream. The collected data are analyzed according to a problematic that may encounter in the field, to present a more straightforward (but with acceptable accurate) practical features equations and charts. Based on the proposed formulas, five methodologies were introduced as a guide for site engineers and beneficiary farmers. As results, necessary calculations should be followed for the purpose of the successful management of surface irrigation project by an investment of the available water to be delivered with minimizing or preventing head losses to ensure acceptable irrigation efficiency up to the farthest outlets.

Keywords: sluice gate, free flow conditions, submerged flow condition, tailwater depth, contracted section.

أقتراب تطبيقي للخصائص الهيدروليكية والتصريف للبوابة المنزلقة في القنوات

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الخلاصة

أن تبسيط المعادلات والصيغ المستخدمة لأغراض الحسابات والتصميم هي غاية الباحثين. تعتبر الدراسة الحالية مدخل لغرض تمييز الجريان تحت البوابات المنزلقة والتي أجريت عن طريق برنامج مختبري موسع جمعت من خلاله أربعة وخمسون حالة من البيانات للجريان الحر (free) والجريان المغمور (submerged) متضمنة قيما مختلفة للتصريف وفتحة البوابة وعمق الجريان في المقدم وعند المؤخر ممثلا بعمق الجريان الذيلي وكذلك الأعماق عند المقطع الأقلص. أن البيانات المستحصلة تم تحليلها طبقا للمشكلات التي يمكن أن تصادف موقعيا لغرض تقديم صيغ تطبيقية جديدة من المعادلات والأشكال تعتبر مبسطة بالأستخدام ولكنها بنفس الوقت يمكن أن تعطي نتائج مقبولة الدقة. طبقا للمعادلات والأشكال المقترحة في هذه الدراسة فقد تم تقديم خمسة أساليب يمكن

أتباعها كدليل لمهندس الموقع والمستفيد للحصول على الحسابات الضرورية لغرض الأدارة الناجحة لمشروع الأرواء وذلك باستثمار المياه المتوفرة وأيصالها الى أبعد منفذ بأعلى منسوب ممكن وأقل الخسائر وبالتالي الحصول على الكفاءة المقبولة للري.

الكلمات الرئيسية: البوابة المنزلقة، الجريان الحر، الجريان المغمور، عمق الجريان الذيلي، المقطع المقلص.

1. INTRODUCTION

A sluice or vertical gates are widely used for controlling the flow of irrigation projects. Depending on the upstream water depth (headwater), the gate opening, and the downstream water depth (tailwater) the flow is classified as free (modular) or submerged (non-modular). To distinguish the flow condition is free or submerged by indicating the hydraulic dependability between headwater, tailwater, and the gate opening, thereby the discharge through a sluice gate is affected accordingly. Similarly, for a given discharge the upstream depth is subjected to increase when the flow conditions at downstream become submerged. Submerged flow occurs when the hydraulic jump below the sluice gate drown in conjunction with grawing the tail water. Pertinent hydraulic characteristics previously investigated by numerous researchers, for the distinguishing between free and submerged flow based on the theoretical approach using energy and momentum principles via the experimental program. In the present study, the proposed formulations were related to the consideration of hydraulic phenomenon termed “vena-contracta” besides to the influence of water stages at upstream and downstream the gate. The distinguish condition was found to be powerful functions of the contraction coefficient. However, among the pertinent hydraulic affected parameters is a discharge coefficient, where it is the most important parameter to introduce for discharge calculations. Due to the existence of boundary layer growth and the energy loss upstream of the gate, the experimental values of the contraction coefficient may be higher than the theoretical ones **Scunic, 2006**. This coefficient as stated by previous investigators ranged between 0.6 - 0.75. In submerged flow, however, the section at which the vena-contracta to obtain has not been recognized. Much fewer researchers have worked under submerged conditions. In fact due to the lack of theoretical and experimental background, a common assumption is that the contraction coefficient is the same for both flow conditions. Accordingly, the dependability of this coefficient will be questionable. By using numerical methods via experimental data, the effect of the gate opening and a contraction coefficient in free flow condition was demonstrated by different researchers such as; **Marchi, 1953**, **Larock, 1969**, and recently **Montes, 1997** (cited by **Belaud, et al., 2009**). However, **Rajaratnam,** and **Subramanya, 1967** performed a detailed analysis of the flow structure under submerged sluice gates. They pointed out the experimental difficulties in determining the contracted section in submerged flow. Using these observations and via field information, **Clemmens et al., 2003** introduced an energy correction to account the change in contraction coefficient just at initial submergence. In more recently work, **Belaud et al., 2009** had proposed a new theoretical framework for the calculation of contraction coefficient. The approach is based on momentum and energy conservation between upstream the gate and the contracted section relies on an analytical calculation of pressure field upstream. More complex details for influences of the value of a contraction coefficient restricted to submerged condition. The authors concluded to present more than one value that depends on a partially submerged (occur when a vena-contracta drowned but the next water body does not touch the downstream side of the gate), submerged flow with relatively small gate opening, and with large opening, its value will no longer valid where it is much higher. Due to the dependence of discharge coefficient on contraction coefficient, the deficit in the accuracy of the later will certainly often lead to significant over or under prediction of discharge accordingly. Certainly, it is hard to lie in front of site engineer to choose the appropriate method and use it in precise calculations. The site engineer is usually looking for the easiest ways for both data collection and methodology for calculations. In practice at yet the facilities that used for finding necessary results are formulas, figures, and tables. The simplest form with an acceptable accuracy of any of these three formulations is an attractive target for site engineer. Thus, to move away from as much as possible the use of formulas that which are includes coefficients not to agreed with the specified values presented by the researchers is considered the right decision by the site engineer. In present work the collected data are analyzed to get practical methodologies without the need to follow the traditional methods in an attempt to get specified values of contraction and discharge coefficient.

2. EXPERIMENTS

The present experiments were conducted in the hydraulic laboratory at the University of Technology-Baghdad. A glass side horizontal flume 5m long, 10cm width, and 30cm depth was used. The water entered the working section after passing through the laminar screen, and discharge was measured by a flow meter with ± 1% accuracy. An adjustable tailgate was used to set desired tailwater depth. The upstream and downstream depths were measured using digital point gauges. A thin plate 2mm in thickness and sharp in edge was used as a vertical sluice gate and installed at 3m from the inlet of the flume to ensure getting a uniform flow at the upstream of the gate.

Seven gate openings ranged between 0.5 to 2cm, consisted 27 runs with different discharges for free flow and the same number of submerged flow conditions have adopted. The depth upstream of the gate taken at five locations along a center line of the flume and the average value was used as a depth of flow (headwater) before the gate and denoted as (yu). The location of vena-contracta was considered to occur not to exceed 2-times the gate opening as proposed by many previous studies (e.g., **Wahl,** and **Clemmense, 2005**). Via the tailgate, the initial depth of a hydraulic jump fixed at this location and a representative depth measured for free flow and denoted as (yf). The submerged flow was defined to occur when adjusting the tailgate for the same discharge of free flow to drown the vena contracta just to touch the downstream side of the gate, then depth is measured at the same location (i.e., twice gate opening) and denoted as (ys). It is worth to note that to accommodate the change in tail water (yt) and headwater (yu) for the submerged flow condition the measurements were repeated and distinguished in the data sheet. A schematic definition for both flow conditions is illustrated in **Fig.1**.

3. ANALYSIS FOR FIELD APPLICATIONS

Accurate flow measurements are a fundamental necessity for efficient and economical delivery of irrigation water. Many modern methods for operating canals in a more efficient manner depend on knowledge of flow rates throughout the canals system. This knowledge allows easy adjust the gates of the check, bifurcations, and turnouts structures to the desired opening to get the specific water stages both at upstream and downstream of the structure. The arrival of this aim required to adopt an easy (but with accurate results) format of deterministic formulas. In the present study, a new look for collected measured data has been focused on formulating more easy features of equations and graphs to help a site engineer in calculations which are needs for successful management and operation. It should be emphasized here that the dimensionless ratios have been adopted to overcome the scale effect between physical models and prototype.

4. PROPOSED EQUATIONS AND GRAPHS

The experimental data has been invested in analysis procedures to find a design and calculation formulas as equations and graphs. Firstly, Eq.(1) and Eq.(2) with a related graph, **Fig.2** have correlated the tail water depth with contracted depth as dimensionless ratios related to gate opening for both free and submerged flow. The determination coefficients for these equations are respectively; R^2=0.55 and R^2=0.983 refer to reliability. In site, these equations or related graph (as seen in **Fig.2**) can easily be employed to determine the flow depth at contracted section, (yf) or (ys) when the instrumentation of the tail water measurement is available, where;

$$\frac{yf}{G} = -0.0015\left(\frac{yt}{G}\right)^3 + 0.0366\left(\frac{yt}{G}\right)^2 - 0.227\left(\frac{yt}{G}\right) + 1.1647 \qquad (1)$$

Used for free flow, and for submerged flow condition the following form has high reliability (R^2=0.983);

$$\frac{ys}{G} = 0.8927\left(\frac{yt}{G}\right) + 0.0241 \qquad (2)$$

Another important parameter that should be known either by direct calculation or by measurement is the headwater depth, yu. When there is not the ability to measure this depth and also the regime of flow unrecognized, the following proposed formulas can be used to calculate the upstream depth for both free and submerged flow regime respectively when the tailwater depth and gate opening recorded.

$$\frac{yuf}{G} = 0.898\left(\frac{yt}{G}\right)^{1.592} \qquad (R^2=0.98) \qquad (3)$$

$$\frac{yus}{G} = 0.925\left(\frac{yt}{G}\right)^{1.515} \qquad (R^2=0.949) \qquad (4)$$

The high value of determination coefficient ensures the reliability. Thus, any of these equations can be easily used by a beneficiary with an acceptable error.

The experimental data are also employed to correlate another feature of the relations between headwater and tailwater for both flow conditions are recommend to used when the headwater can accurately be measure in site, these formulas for free and submerged flow respectively are;

$$\frac{yt}{G} = 1.15\left(\frac{yuf}{G}\right)^{0.6} \qquad (R^2=0.937) \qquad (5)$$

$$\frac{yt}{G} = 1.136\left(\frac{yus}{G}\right)^{0.626} \qquad (R^2=0.949) \qquad (6)$$

Eq.(5) and Eq.(6), can be invested, however, to know the type of flow as will mentioned later.

From the experimental results, a design curve (as shown in **Fig.3)** has been prepared to use for distinguishing the kind of flow when both the tail water and headwater depths are measured on the site directly, and it could be known from the database. The flow condition is to be submerged when the intercept point located exactly at the curve.

The correlation between headwater, yu, and the flow depth at a contracted section, yf, for free flow and, ys, for submerged flow, have also worked out and the resulting in the following formulas;

$$\frac{yf}{G} = -0.00003\left(\frac{yuf}{G}\right)^{3} + 0.0022\left(\frac{yuf}{G}\right)^{2} - 0.0349\left(\frac{yuf}{G}\right) + 0.9079 \qquad (R^2=0.96) \qquad (7)$$

$$\frac{ys}{G} = 1.0184\left(\frac{yus}{G}\right)^{0.628} \qquad (R^2=0.953) \qquad (8)$$

Figs.4 and **5** are a presentation of these equations as a solution by using a profile chart. The data also have been analyzed to obtain relationships between upstream depth and tail water depth and are presented as the following equations or as a graph as shown in **Fig.6**.

$$\frac{yuf}{ytf} = 0.3061\left(\frac{ytf}{G}\right) + 0.7829 \qquad (R^2=0.919) \qquad (9)$$

$$\frac{yus}{yts} = 0.925\left(\frac{yts}{G}\right)^{0.515} \qquad (R^2=0.683) \qquad (10)$$

The tailwater depth, yt, and the contracted depth, yf, in free flow, can be employed to present the following relationship from which the ratio between upstream flow depth, yu, and gate opening, G, can calculate.

$$\frac{yt}{yf} = 2.798ln\left(\frac{yuf}{G}\right) - 0.4879 \qquad (R^2=0.863) \qquad (11)$$

As will be seen later, yuf/G can be used to calculate the discharge corresponding to free flow without the need to know the gate opening previously.

The raising of tail water is the case that can expect when one or more outlets and/or check structures those located downstream the gate under considerations, have been partially or wholly closed. For this situation the hydraulic jump was drowned towards the gate, thereby lead to raising headwater and the flow conditions will become submerged. The knowing of (yus) is a practical need when raising above the limiting free board, it will escape over the bank, and an appreciable amount of water lost beside the occurrence of bank damage. The available data from present work was treated to extract a suitable formula for this practical situation. The analysis was concluded to introduce two equations with their design curves. The first form of these equations is used when the discharge at free flow and the gate opening are available, then the ratio of upstream water depth at free flow condition to gate opening could be calculated by;

$$\frac{yuf}{G} = 1.472\left(\frac{q}{\sqrt{gG^3}}\right)^{1.676} \qquad (R^2=0.988) \qquad (12)$$

Instead of Eq.(12), **Fig.7** is used as a design curve. After that, the following equation or related design curve, **Fig.8** is employed to find the headwater depth that should be for the same discharge when the flow becomes submerged.

$$\frac{yus}{G} = 1.322\left(\frac{yuf}{G}\right)^{0.976} \qquad (R^2=0.985) \qquad (13)$$

However, it should be emphasized here, that when the available documented data for free flow are, the upstream water depth and the gate opening, then Eq.(13) can be used directly to find the expected (yus) in the case when need for the same discharge for the two flow regimes.

The contracted flow depth for submerged flow regime could be easily calculated when both the flow depth at upstream and tailwater at downstream measured. **Fig.9**, illustrates the curved relation between, yt/yu, at submerged flow with the relative parametric ratio (ys/G) as a dependent. The R^2-value refers to an acceptable reliance of this curve and the related formula as listed herein;

$$\frac{ys}{G} = 18.184e^{-2.901\left(\frac{yt}{yus}\right)} \qquad (R^2=0.735) \qquad (14)$$

5. DISCHARGE CALCULATIONS

The major aim of gate operation is to regulate a discharge that should supply downstream. As mentioned earlier, this study focused on finding simplified formulas that it is possible to use on the site without the need to find precisely related discharge and contraction coefficients. Since no charts and/or equation that are presented previously having precise results which could use with reliance beside a heavy usage in projects sites. Accordingly, a discharge that the site engineer needs to find out can be calculated via a recorded data of upstream flow depth and gate opening when the flow condition known. The following two dimensionless formulas are the outcome of the analysis conducted on the laboratory data, being deterministic equations for discharge that should supply when the flow conditions could distinguish;

$$\frac{q}{\sqrt{gyf^3}} = 2.0974ln\left(\frac{yuf}{G}\right) - 0.1714 \qquad (R^2=0.948) \qquad (15)$$

$$\frac{q}{\sqrt{gys^3}} = 0.5255 - 0.093ln\left(\frac{yus}{G}\right) \qquad (R^2=0.808) \qquad (16)$$

The above equations show that the downstream flow depth at a contracted section for both flow conditions should be known to find the discharge. This depth regardless of the flow condition, if it is not simply measured it could be calculated by using Eq.(1) or Eq.(2) after the tail water related to gate opening, yt/G, was found from Eqs.3 or 4 in the case of free or submerged flow conditions respectively. The reliability of these equations has been examined with different statistical indicators as will explained later. For a practical situation, in case when the recorded facilities equipped by which just the tail water depth and gate opening can accurately measure, the discharge then can be calculated by the following equations based on free or submerged flow;

$$\frac{q}{\sqrt{gyf^3}} = 3.425ln\left(\frac{ytf}{G}\right) - 0.565 \qquad (R^2=0.972) \qquad (17)$$

$$\frac{q}{\sqrt{gys^3}} = 0.55 - 0.152ln\left(\frac{yts}{G}\right) \qquad (R^2=0.895) \qquad (18)$$

For confirmation, to calculate the depth of flow at a contracted section it needs to use Eq.(1) or Eq.(2) after application of Eq.(3) or Eq.(4). This procedure is for finding the upstream water depth based on the flow condition under gate when its actual measurements are difficult to measure precisely or are unavailable. **Figs.10-13**, are prepared to be used instead of the proposed four formulas.

6. RELIABILITY OF PROPOSED FORMULAS

To show the validity and reliability of the derived formulas for use in calculations and design, the acceptable value of the, R^2 may be inadequate for a final decision. Accordingly, it becomes necessary to the adoption of some statistical indicators that are often used in engineering applications. The results of indices give the good feature to decide the reliability of equation at hand. In the present study, the; Root Mean Square Error (RMSE), Mean Bias Error (MBE), Percent Bias (P-BIAS), and Nash-Sutcliff Efficiency Coefficient (NSEC), have been adopted. These indices are valuable because its resulted values indicate to the extent of approaching or moving away between the calculated and measured effectively. The first two indicators are widely used for putting reasonable decision, where the zero values indicate a perfect fit. **Nash,** and **Sutcliffe**, **1970** firstly presented the last indicator and then as recommended by **ASCE, 1993** to be a dimensionless indicator. The value of NSEC when located between zero and one, that viewed as an acceptable performance level, whereas if it is worth less than "zero" it indicates an unacceptable performance of formula. However, the percent bias (P-BIAS) also recommended by **ASCE, 1993** which measures the general tendency of simulated data to be larger or smaller than the observed values. **Tariq,** and **Latif, 2011** referred that, the percent bias can indicate clearly the poor or better model performance. The optimal value of this indicator is "zero" thus; the near zero values indicate to better simulation or calculation by formula. On the other hand, a positive value indicates a tendency to the underprediction while a negative value is an inducement to overestimation (**Morias et al., 2007**), cited by **Tariq,** and **Latif, 2011**. The deterministic forms of these statistical indices are listed in the appendix. **Table 1** presents the results of the statistical analysis, as apparent from the tabulated results of indices all are approaching the best target values. The P-BAIS for all proposed equations having negative values, thus these equations induced to over prediction, is preferred for more safety. Moreover, the errors due to this overprediction are located within a good fit performance. Similarly, the model performance is considered good for $0.75 \leq NSEC \leq 1$, thus a confidence level for all proposed formulas exist, where the NSEC values lie between 0.855 and 0.946. However, the near zero values of RMSE and MBE enhances the concept of the reliability of these equations in calculations and design considerations. Since the results of the four indicators located near the best, the differences of errors are insignificant between the four proposed formulas. Thus, there is no preference to the equation on the others.

7. VERIFICATION OF PROPOSED FORMULAS

Some data in the literature are available on free flow under sluice gate invested for verification. Seventeen data points were taken from Francesco **Carollo et al., 2007** and thirteen data points were extracted from the work of **Hughes, and Flack, 1984**. The available measured depth from these works are; the tailwater, yt, and the initial jump depth at a contracted section, yf. Because the proposed four equations have the nearly same reliability as previously concluded, it could take Eq.(15) as a representative verification for the other formulas. Moreover, the available data allow using Eq.(11) to get the data which enable to use Eq.(15) for discharge calculation. The calculated discharge then is compared with the measured for each database. **Fig.14** and **Fig.15** illustrate the results of these comparisons. As shown in these figures, the spreading of data points near the perfect line indicates the acceptable usage of Eq.(15) as a deterministic equation for discharge in free flow condition. It should emphasize here that, the exclusion of the use of Eq.(17) directly goes due to lack of gate opening within the data used for verification. The measured discharges that are recorded in experiments of the present study are also used to verify the calculation results from the four proposed equations. **Fig.16** and **Fig.17** illustrate the trend agreement between measured and calculated discharges when the headwater depth, gate opening, and the depth of a contracted section for both free and submerged flow are available. Whereas, **Fig.18** and **Fig.19** illustrate the spread of predicted results around perfect lines when the tailwater instead of headwater depth beside other flow depths and gate opening are known. The good agreements also hold as it sounds in those figures.

8. PRACTICAL APPLICATIONS

The methodology of how to use the developed equations should be presented step by step includes how necessary information that may be missing can be got or cannot be measured due to infield difficulties and/or limitations. The aim of the proposed deterministic equations is to determine the required discharge that should be supplied to channel to reach located downstream of the sluice gate. However, the tail water depth and headwater depth must be controlled to deliver a suitable amount of flow to the outlets which are located at downstream and to prevent undesired water stage from occurring upstream the gate. As previously mentioned, the site engineer often needs to use simple formats of equations, charts, and/or tables for the purpose of accessing the required flow properties. The cases those are frequently present in site and methodologies to get appropriate solutions are list herein.

- When tail water depth and gate opening can be measured with unknown flow condition; the method is restricted firstly to indicate the flow condition, then arriving at the amount of discharge that must be delivered by using appropriate equations and figures as listed in the following steps:-
  1- The parameters yf/G and ys/G, are calculated by using Eq.(1) and Eq.(2).
  2- Using **Fig.7** and **Fig.8** to find the parameters yuf/G and yus/G.
  3- The yt/G (at free flow) and yt/G (at submerged flow) then re calculated by using Eq.(5) and Eq.(6) respectively. Any of the resulted values of these parameters when nearly equal to this measured from the site, the flow condition will be distinguished.

4- Then a relative headwater depth to gate opening, yu/G could be calculated by using Eq.(3) or Eq.(4) based on the state of flow condition.
5- From **Fig.2** or using the results of step 1 to find yf or ys.
6- When the flow is free either Eq.(15) or Eq.(17) can be used for discharge calculations that need to deliver downstream. Instead of this, Eq.(16) or Eq.(18) should be used when the submerged flow exists.

- When the upstream headwater depth and gate opening can be measured, and the flow conditions are not recognized; the methodology will be:-
  1- Calculation of yt by using Eq.(5) and Eq.(6), each value of the calculated tail water corresponds to the state of flow condition once at free, and other is under submerged condition.
  2- From Eq.(9) and Eq.(10) or **Fig.6**, the upstream flow depth related to tailwater depth (yu/yt) can be found for each flow condition and get, yu (calculated). These two calculated values of headwater depth compared with measured (available from site measurements), the compatibility between measured and any of the two calculated will indicate and recognize the flow condition.
  3- After the flow condition is indicated, then using **Fig.3** to get the flow depth at a contracted section after using suitable yt from step 1.
  4- Any form of Eq.(15) to Eq.(18), will become suitable for discharge calculation based on flow condition.
- When the flow depths at upstream, yu and downstream, yt can be exactly measured and gate opening known; the steps followed to get a discharge are:-
  1- By using **Fig.6**, the flow condition can be distinguishing.
  2- **Fig.3** or either Eq.(1) or Eq.(2), then are used to find a depth of flow at a contracted section, yf or ys.
  3- Finally**,** any proposed discharge equation can be adopted for calculation based on at hand flow condition.
- In some practical situations, the user has information about the discharge, gate opening, and flow condition. At the same time, however, the user is unable to make flow depths measurements because of the lack of appropriate instruments. The data from present work have been invested in finding a practical solution to this site problem. The derived equations from the current study can be used to calculate a corresponding depth at upstream that should be with at hand discharge and gate opening. Firstly using Eq.(12) to calculate the relative flow depth at upstream when the flow condition is free at downstream. Secondly, it could employ this relative depth in Eq.(13) to find the increasing in a stage that will occur when the flow becomes submerged at downstream for the same delivered discharge as with free flow condition.
- The final methodology is restricted to know the gate opening when the flow below it is at the submerged condition with the ability to measure both upstream and downstream depths. For this methodology, firstly using Eq.(14) or **Fig.9** to calculate the relative flow depth at a contracted section is related to the gate opening for submerged flow, ys/G, then by using Eq.(2) it will be easy to calculate the gate opening. After that, it could use either Eq.(16) or Eq.(18) to get a discharge.

9. CONCLUSIONS

The present approach of sluice gate hydraulics aims to simplify formulas and charts without the need to use the equations or charts from which a contracted and discharge coefficient should know. Besides the different forms of equations and/or related figures, it has mainly significant errors based on the flow environments and boundary conditions those from which implemented, as well as the error arises with the estimated value from a related curve. The extensive experimental program has been conducted to collect 54 data points for both free and submerged flow conditions included different discharges, gate openings, flow depths at upstream as well as the flow depths representing tail water and at contracted section. The collected data analyzed with different problematic may be ncountered in the field, and a numerous simple, practical features of equations and charts have been presented accordingly. Based on the proposed deterministic equations and graphs, five methodologies were been introduced as a guide for site engineer, designer, and even beneficiary farmers to get a calculation of discharges and/or stages of water those miss-recorded or couldn't be measured due to unavailability of the appropriate measuring means on site.

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NOMENCLATURE

G=gate opening, m.

g=acceleration due to gravity, m/s^2.

q=unit discharge, m^3/s/m.

yf=depth of flow at vena-contracta for free flow condition, m.

ys=depth of flow at vena contracta for submerged flow condition, m.

yt=tail water depth, m.

yu=upstream water depth headwater, m.

ytf=tail water depth at free flow condition, m.

yts=tail water depth at submerged flow condition, m.

yuf=upstream water depth at free flow condition, m.

yus=upstream water depth at submerged flow condition, m.

APPENDIX

The equations of statistical indicators for, RMSE, MBE, NSEC, and PBIAS are as follows:-

$$\mathrm{RMSE}=\left[\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}[(\mathrm{q})_{\mathrm{o}}-(q)_{\mathrm{s}}]^2\right]^{0.5},\ \mathrm{MBE}=\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}[(\mathrm{q})_{\mathrm{o}}-(\mathrm{q})_{\mathrm{s}}],\ \mathrm{NSEC}=1-\left[\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}[(q)_{\mathrm{o}}-(\mathrm{q})_{\mathrm{s}}]^2}{\sum_{\mathrm{i}=1}^{\mathrm{n}}[(\mathrm{q})_{\mathrm{o}}-(\mathrm{q})_{\mathrm{o,av.}}]^2}\right]$$

$$\mathrm{PBIAS}=\left[100\mathrm{x}\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{q})_{\mathrm{o}}-(\mathrm{q})_{\mathrm{s}}}{\sum(\mathrm{q})_{\mathrm{o}}}\right]$$

Where $(q)_o$ and $(q)_s$ observed or measured and simulated or calculated unit discharge respectively, the $(q)_{o,av}$ is average of observed discharge and, n is a number data.

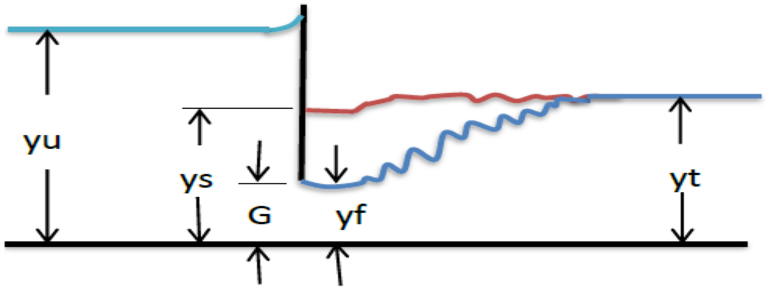

Figure 1. The schematic definition for free and submerged flow conditions.

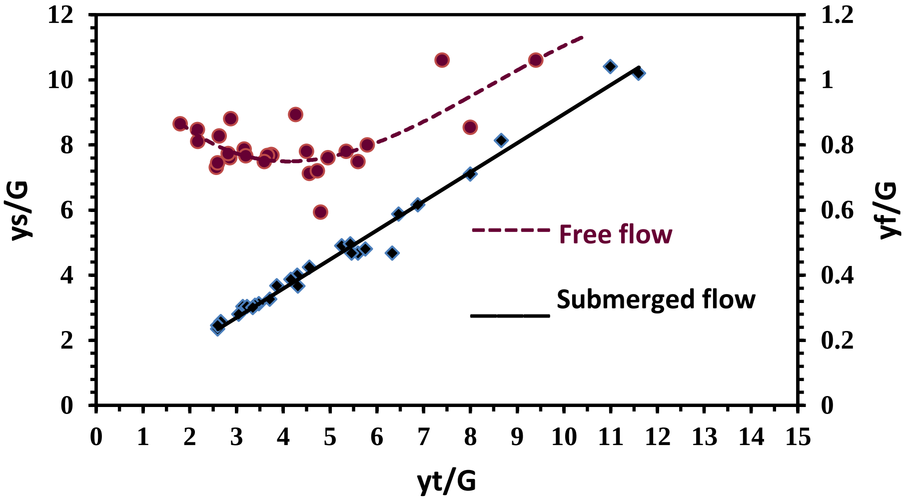

Figure 2. Design chart for depth of flow at contracted section.

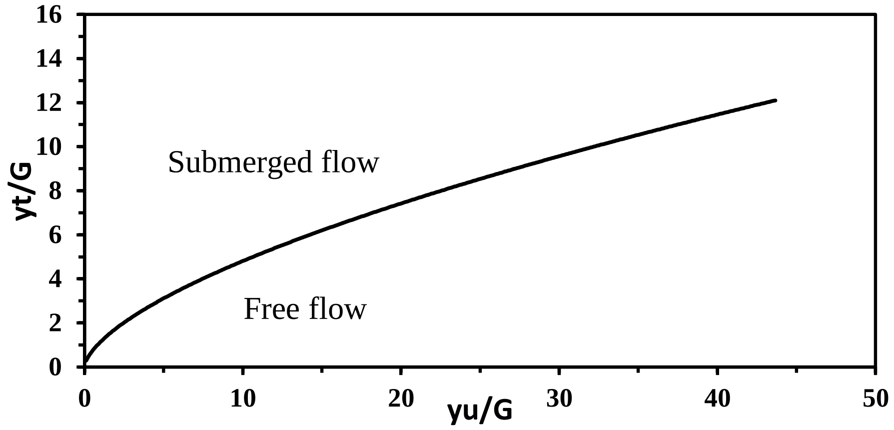

Figure 3. Distinguish curve between free and submerged flow conditions.

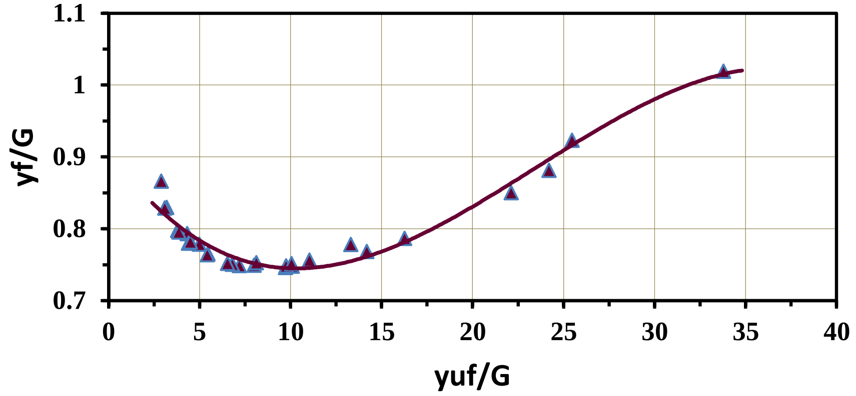

Figure4. Profile chart for depth at contracted section in free flow.

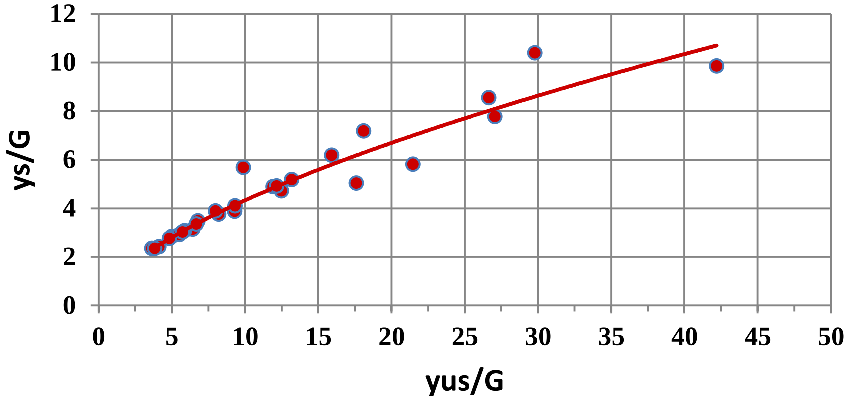

Figure 5. Profile chart for depth at contracted section in submerged flow.

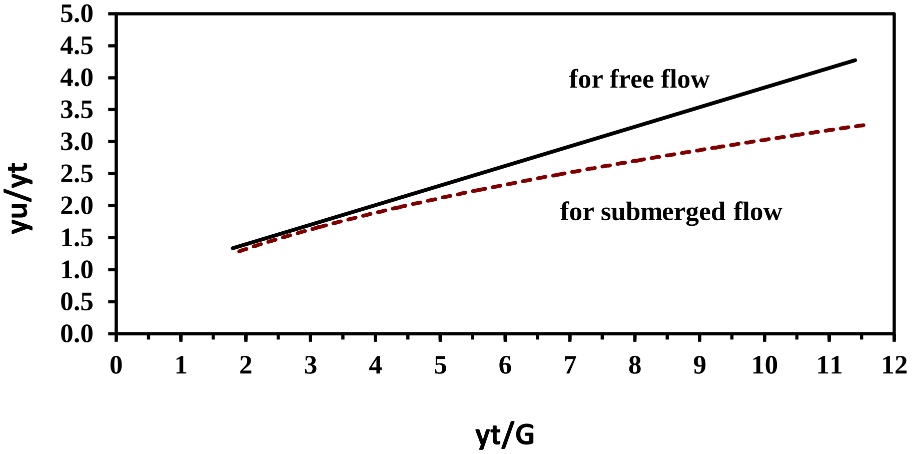

Figure 6. The ratio between upstream depth and tail water depth.

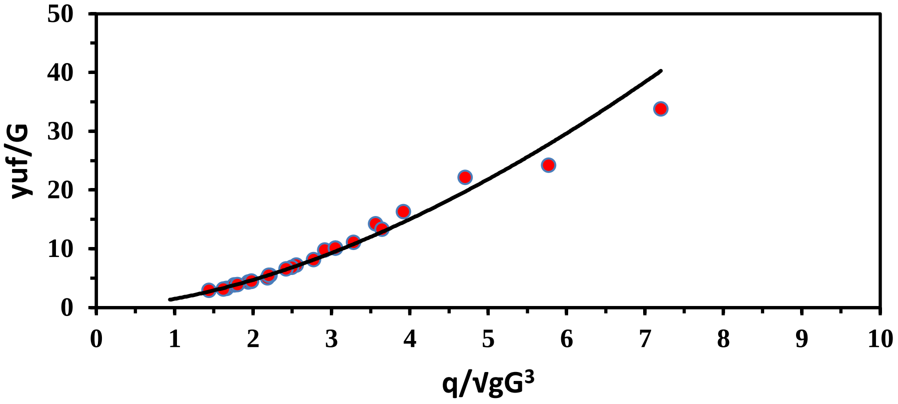

Figure 7. Deterministic chart for upstream flow depth in free flow.

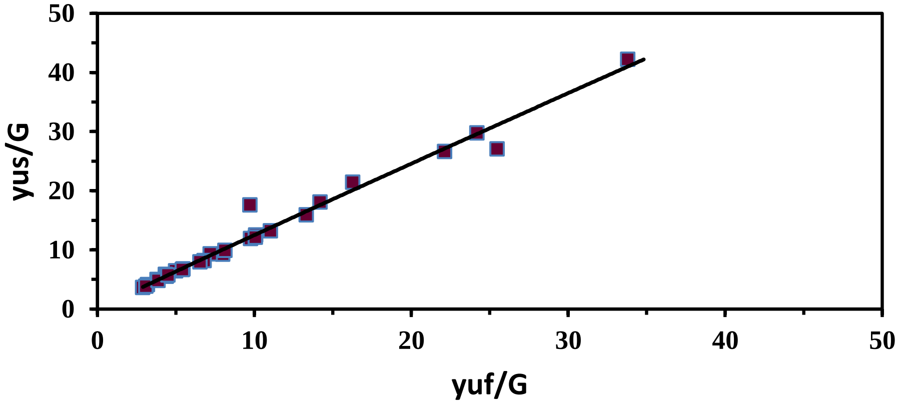

Figure 8. The upstream depths for both flow conditions at the same discharge.

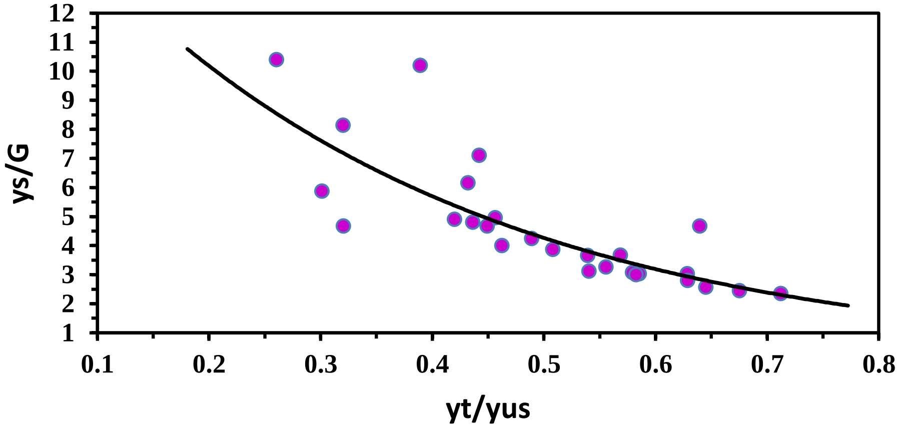

Figure 9. The upstream depth, tailwater depth, and at contracted section depth in submerged flow.

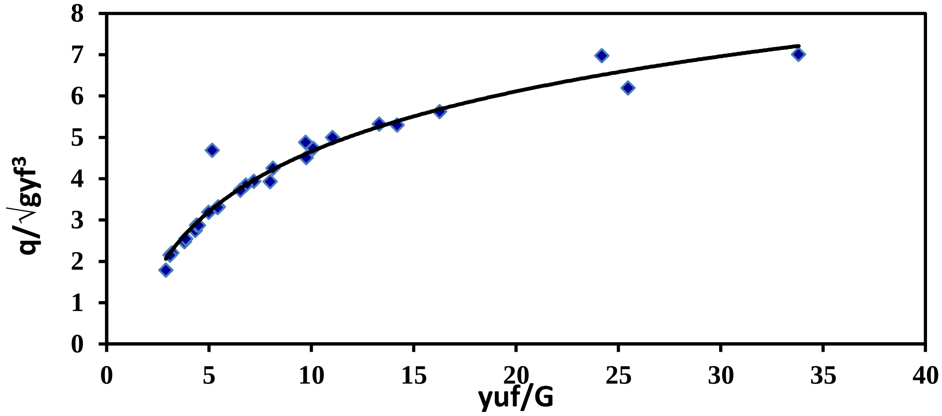

Figure 10. The relation between unit discharge and upstream depth in free flow.

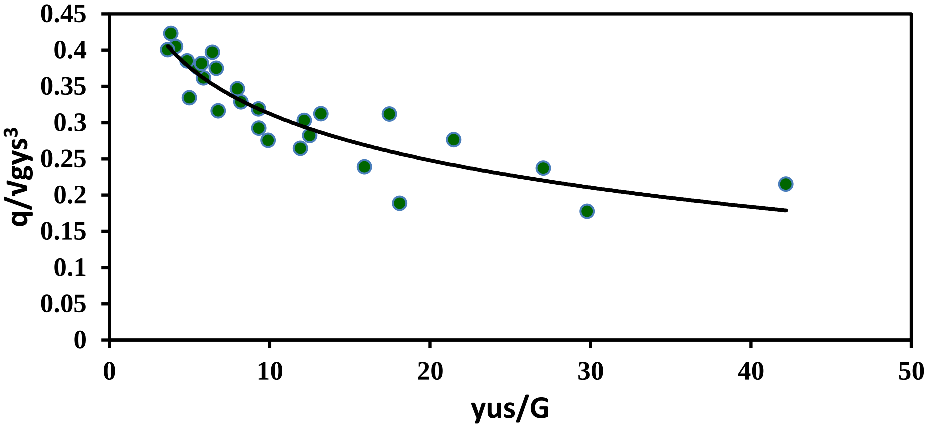

Figure 11. The relation between unit discharge and upstream depth in submerged flow.

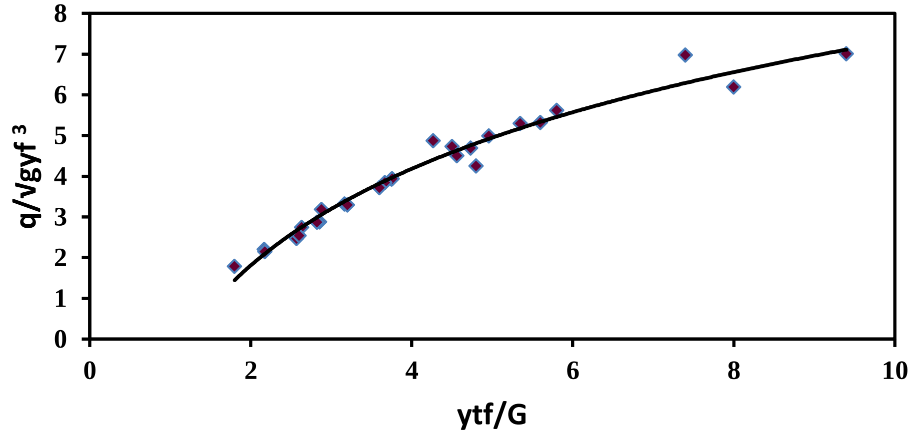

Figure 12. The relation between unit discharge and tailwater depth in free flow.

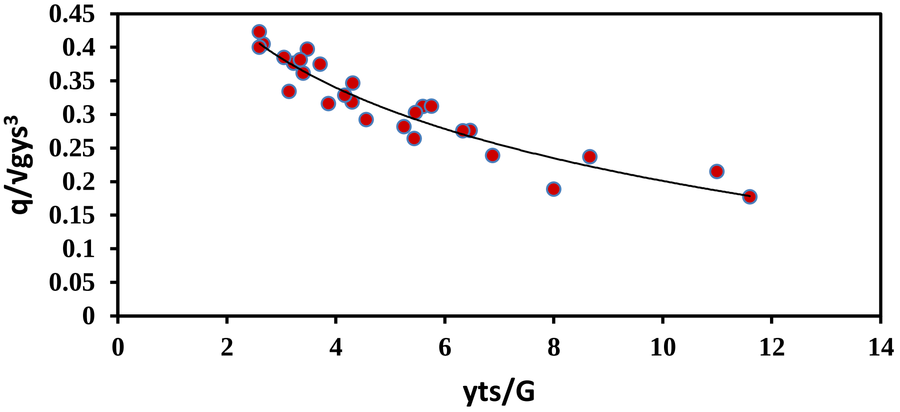

Figure 13. The relation between unit discharge and tailwater depth in submerged flow.

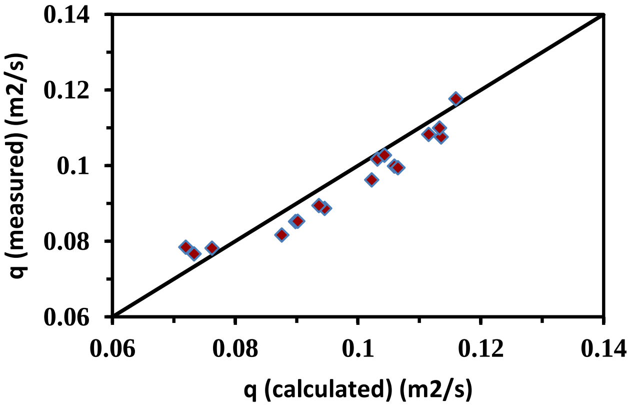

Figure 14. Comparison with Francesco Carollo et al., 2007.

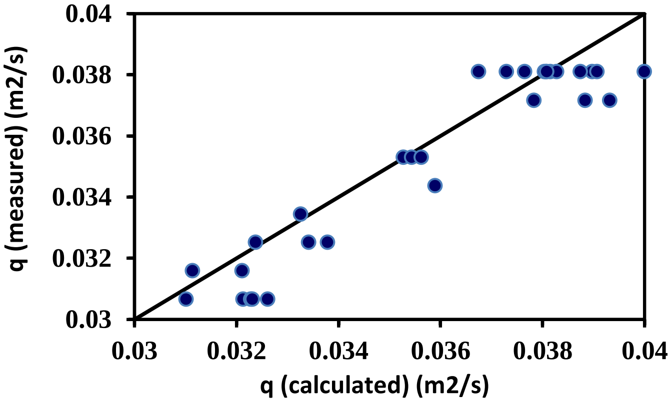

Figure 15. Comparison with Hughes, W. C., 1984.

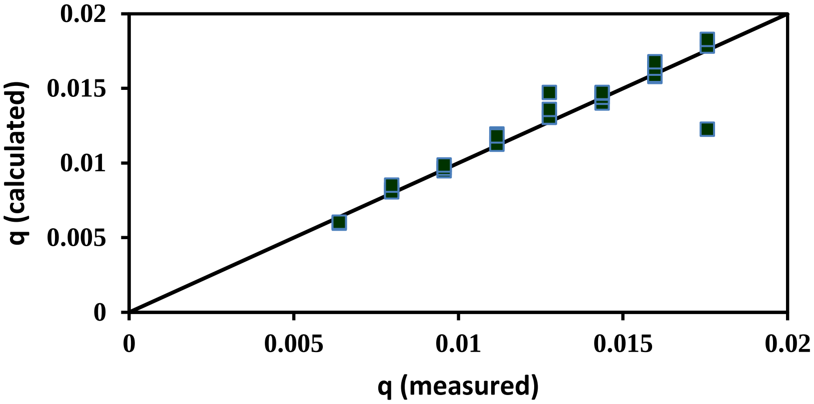

Figure 16. Verification of Eq. (15) with experimental data.

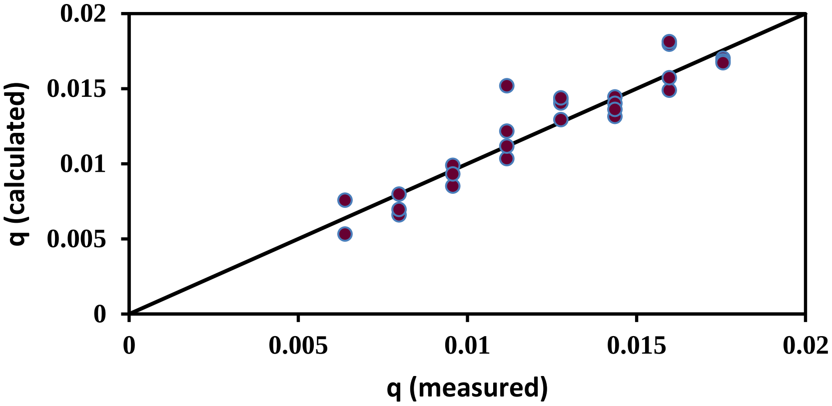

Figure 17. Verification of Eq. (16) with experimental data.

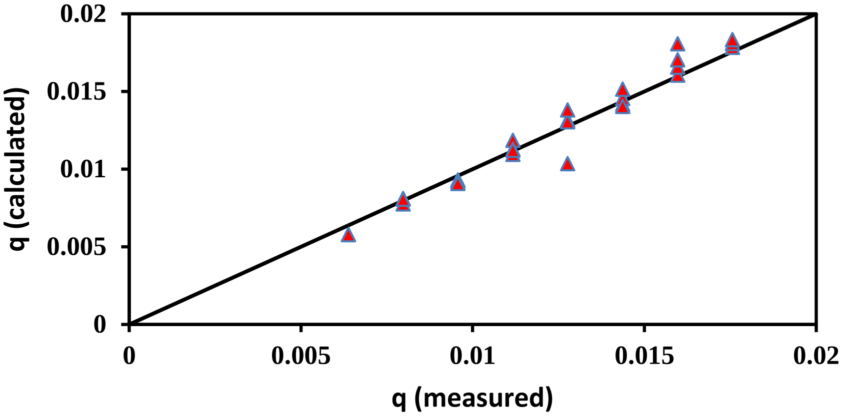

Figure 18. Verification of Eq. (17) with experimental data.

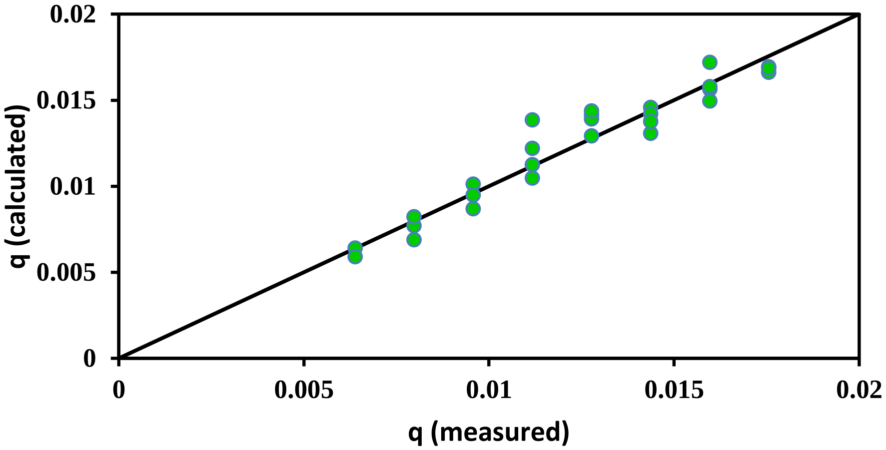

Figure 19. Verification of Eq. (18) with experimental data.

Table 1. Statistical analysis for proposed equations.

Eq.	Flow Condition	RMSE	MBE	NSEC	PBIAS	Remarks
15 16	Free Submerged	0.00116 0.00128	-.0000811 -0.000132	0.88225 0.85529	-0.65339 -1.06781	When u/s water depth and gate opening known
17 18	Free Submerged	0.00078 0.00094	-0.000107 -0.000031	0.94648 0.92253	-0.86146 -0.25317	When tail water depth and gate opening known