# Analysis of Hydraulic Characteristics of Broad Crested Weir with Semicircle Control Section

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## ABSTRACT

This study deals with evaluation of the hydraulic characteristics such as critical depth, and discharge coefficient of a broad crested weir with semi-circle control section extend across the full width of a laboratory channel. Provided the occurrence of critical Flow at the control section, the use of solver function in Microsoft Excel replaces the traditional methods such as trial and error method and chart to solve governing equations represent the hydraulic condition at the control section. The use of solver function provides accurate solution of critical depths for different flow rates ranges, knowing these depths values make it easy for computation of theoretical discharges. Data obtained from laboratory experiments provide information on head – discharge relationship examined under free flow condition. The (HEC-RAS) software version 4.1 was developed with steady flow state yields, water surface profiles, and plot cross sections and computational of rating curve. The results achieved are compared with the observations show acceptable agreement between these two results and the flow remains critical, not supercritical along the weir crest. The study shows that theoretical discharge equation is a function of shape factor, the laboratory discharge measurement varies with the square head upstream weir crest, and the values of the discharge coefficient are not quite constant with the range of modular limit, but increases slightly with increasing discharge.

**Keywords**: control section, critical depth, HEC-RAS, rating curve, solver function, discharge coefficient.

# تحليل الخواص الهيدروليكية لجريان فوق سد غاطس عريض الحافة ذو مقطع سيطرة نصف دائري

## الخلاصة

يتناول هذا البحث التعرف على بعض الخواص الهيدروليكية لسد غاطس عريض الحافة ذو مقطع نصف دائري يمتد على عرض القناة المختبرية مثل العمق الحرج , ومعامل التصريف. يتميز هذا النوع من منشات قياس الجريان بحدوث العمق الحرج والذي تم حسابه من خلال استخدام ماكروسوفت اكسل عوضا عن الطرق التقليدية مثل طريق التجربة والخطأ وطريقة استخدام المخطط في حل معادلات الجريان الحرج في مقطع السيطرة (النصف دائري ) و تم اعتماد هذه الاعماق في حساب التصريف النظري لمثل هذا النوع من السدود الغاطسة . اظهرت النتائج المختبرية عن معادلة تجريبية تربط مابين التصريف و الشحنة المقاسة في ظروف جريان حر. تم تشغيل برنامج (HEC-RAS) ولحالة الجريان الثابت للحصول على المقاطع الطولية و العرضية للجريان ومنحنى المعايرة. اظهرت النتائج عن توافق جيد من خلال مقارنة نتائج برنامج(HEC-RAS) مع القراءات المختبرية . هناك تغير في حالة الجريان فوق السد الغاطس الى الحالة الحرجة دون الوصول الى الجريان فوق الحرج . الدراسة بينت ان معادلة التصريف النظرية هي دالة لعامل شكل مقطع الجريان .ان قيم التصريف المقاسة مختبريا تتغير مع مربع الشحنة المقاسة اعلى السد الغاطس وهناك زيادة قليلة في قيم معامل التصريف مع زيادة في مقدار التصاريف .

## INTRODUCTION

The semi-circle broad crested weir running with modular limit in which the flow occupies a segment of flow area at total angle (ϴ) related to critical depth as Shown in Figure (1).

Such cross section fits to natural shape of furrow and it may use in lined and unlined canals [1]. This type of broad crested weir discharge more water than one of any other shape[2].All types of weirs have a streamlined converging transition that lead to a Raised sill and within which critical depth flow is produced. In addition the length of the weir in the direction of flow is sufficient that the streamlines passing through the critical depth section are essentially parallel [3]. This characteristic allows establishing one dimensional hydraulic theory to be used to determine the calibration relationship between the discharge and upstream head (H) measured in the approaching channel[4] .The characteristics of transition influenced the flow at the critical section and thus this type of measuring device still relied on empirical calibration developed through laboratory testing. The computer software (HEC-RAS) makes it easy to develop ratings for the weir and permits accurate calibration of weir, and examined the accuracy of the model results by number of laboratory experiments.

**Theory:**

For abroad crested weir with semicircle control section, we may write [5]:

$$A_C = \left(\frac{1}{8}\right) d_C^2 (\Theta - \sin\Theta) \qquad \ldots(1)$$

$$B_C = \sin\tfrac{1}{2}\Theta \qquad \ldots.(2)$$

$$Y_C = \frac{d_C}{2}\left(1 - \cos\frac{1}{2}\Theta\right) \qquad \ldots(3)$$

At the critical flow the average flow velocity is:

$$V_C = \sqrt{g\,A_C/B_C} \qquad \ldots.(4)$$

Substitution of values for $A_c$ and $B_c$ into equation (4) yields:

$$\frac{V_C^2}{2g} = \frac{d_C}{16}\,\frac{\Theta - \sin\Theta}{\sin\frac{\Theta}{2}} \qquad \ldots(5)$$

And because

$$H = Y_C + \frac{V_C^2}{2g} \qquad \ldots.(6)$$

We may write equation (6) in terms of dimensionless ratio which becomes:

$$\frac{H}{d_C} = \frac{Y_C}{d_C} + \frac{V_C^2}{2gd_C} \qquad \ldots..(7)$$ and

hence

$$\frac{H}{d_C} = \sin^2\frac{\Theta}{4} + \frac{\Theta - \sin\Theta}{16 - \sin\frac{\Theta}{2}} \qquad \ldots(8)$$

All of the hydraulic parameters at the control section are related to (ϴ) which represents the angle at critical depth in radian. Since the general head- discharge Equation is:

$$Q = C_d A_c \sqrt{2g(H - Y_c)} \qquad \ldots(9)$$

Therefore the discharge is function of (ϴ) and the above equation can be reduced to:

$$Q = C_d \frac{1}{8} d_C^{2.5} \frac{(\Theta - \sin\Theta)^{1.5}}{\left(\Theta \sin\frac{\Theta}{2}\right)^{0.5}} \quad \dots (10)$$

The subscript (c) refers that all hydraulic parameters are in critical state.

**Critical depth:**

The flow depth corresponding to minimum specific energy for a given discharge in an open channel is known as critical depth which depends on the discharge and channel geometry. The general equation for computing critical depth is given as [6]:

$$\frac{Q^2}{g} = \frac{A_c^3}{B_c} \quad \dots (11)$$

Since there are only analytical equations available for direct computation of critical depth in rectangular channel, various Approximation equations have been developed for common open channel sections with various degree of estimation error [7]. In this study it has been developed a general spread sheet of Microsoft excel for direct computation of critical depth for semicircle section. After geometric parameters are computed from equations (1), (2), (3), (4) then the solver function used to determine critical depth. The accurate determination of critical depths is useful as a starting point for computing water surface profile in gradually varied flow (G.V.F) and for the computation of the theoretical discharge for different weir sections.

**Experimental work:**

The experiments were performed in a horizontal laboratory flume with (5m) length , (0.076m)width and (0.15m) depth .both bed and walls were made of fiber glass to ensure hydraulic smooth condition (n=.0085) .the flume is supplied with a constant head tank . The discharge was measured by a volume-time method; flow depth has been measured using movable point gauges. The weir dimensions are (0.076m) diameter of the cross section, (0.13m) is the weir length and (0.102m) height of the weir measured from the lower point of weir cross section. The weir placed at a distance of (3.5m) downstream outlet of the tank and fixed directly on side wall. The control section shape is selected and its elevation set to allow the desired range of flows to be measured accurately without submergence of the control section. The flow regulating valve was adjusted to give maximum possible discharge with the corresponding head up stream weir crest. The discharge reduced in seven steps and a series of readings of (Q) verses (H) where taken. All experiments done with zero slope channel bed .photograph was taken during the experiments and used to visualize the Flow, as shown in figures (2).

**Experimental results:**

One of the important advantages of the broad crested weir is that it can be accurately calibrated according to empirical relationship. The Laboratory experimental results that determine empirical discharge coefficients are most commonly used. Thus in order to establish the experimental data a, calibration equation for the weir, having the general form:

$$\mathrm{Q} = \mathrm{KH^m} \quad \dots (12)$$

Where

K and m are constants for a given weir. By using a power fit or trend line in Excel (use a spreadsheet), determination of an empirical formula describing the discharge – head relationship for this type of weir with the range of modular limit is:

$$\mathrm{Q} = 0.42\mathrm{H}^2 \quad \dots . (13)$$

The graphical representation of head – discharge equation is shown in Figure (3).

**Critical depth computation:**

The critical depth is determined by applying equation (11) and solver function in Microsoft Excel .The using of solver function requires appropriately setting up and identify component of problem; the target cell, equal to, and changing cells [8].Figure (4) shows an excel spreadsheet to compute the critical depth in semicircle cross section. A target cell contains a formula of the equation for optimization or root finding problem and must be a single cell containing formula linked with the changing cells (equations1, 2, 3 and 4). Equal to option is used to set the condition on whether the solution of equation in the target cell should be equal to a certain value (one in this problem for Froud number as a critical state) or it should be maximized or minimized (optimization problem). Changing cell are the adjustable cells that contain the solutions which are achieved iteratively by adjusting its value until the Constraints in the problem are satisfied ($\Theta \leq \pi$ in this problem). For determining the critical depth, equation (11) is selected as a target cell, and set the value to (1) for equal (option), and select cell (A5) in excel sheet as shown in Figure (4) that is the critical depth for changing cell option which requires an attention to select the initial value of($Y_c$ ).Click on solve button, solver will report whether or not find a solution for the problem.

**HEC-RAS ( model development):**

HEC-RAS is one dimensional steady flow hydraulic model designed to aid hydraulic engineer in channel and flood plain analysis [9].The primary procedure used by HEC-RAS to compute water surface profile assumes a steady, gradually varied flow scenario and is called direct step method. The basic computational procedure is based on an iterative solution of the energy equation:

$$H = Z + Y + \frac{\alpha V^2}{2g} \qquad \text{....}(14)$$

This states that the total energy (H) at any given location along the stream is the sum of potential energy (Z + Y) and kinetic energy ($\alpha V^2/2g$) the change in energy between two cross-sections is called head loss ($h_L$). The energy equation parameters are illustrated in the Figure (5). For a given flow and water surface elevation at one cross-section, the direct step method is applied to compute the water surface elevation at the adjacent cross-section. Whether the computations proceed from upstream to downstream or vice versa, depend on the flow regime. The dimensionless Froude number (Fr) is used to characterize flow regime. For a subcritical flow regime, which is very common in natural channels, direct step computations would begin at the downstream end of the reach, and progress upstream between adjacent cross-sections.

For HEC-RAS project that is a set of data files associated with a particular river Systems are categorized into three required components, the geometric data, flow data, and plan data. The geometry data consist of description of the size, shape, and connectivity of stream cross sections. The flow data contains discharge rates. Finally, plan data contain information pertinent to the run specification of the model including a description of the flow regime. The aim of using HEC-RAS is to analyze a laboratory channel reach with an inline structure of a semicircle broad crested weir located in the main channel and plotting the water surface profiles by using the energy equation for a given discharge, geometry, and resistance and compared the results with the laboratory measurements.

**Analyze HEC-RAS program output:**

With geometry and flow files established, the HEC-RAS model can be executed. Select steady flow analysis from the project window to execute the model, first ensure that the flow regime is set to subcritical and then click the compute bottom.

**Viewing the results:**

There are several methods available with which the view of HEC-RAS program output including cross – section profiles and data table. For hydraulic design it's often useful to know the calculated values of various hydraulic parameters. HEC-RAS offers numerous Options for tabular output data display. The resulting table includes a number of hydraulic parameters including water surface elevation, cross-section area, critical depth, channel width, and Froud number.

**Critical depth results and discussion:**

The work sheet can only be used to determine the critical depth under a particular set of channel parameters for one discharge at each time when the user applies solver function as shown in Figure (4). The reuse of this worksheet is required to compute critical depths for a series of discharges. The answer report which is available whenever a solution has been found provides basic information about the decision variables and constraints in the problem.

First shown are objective function and decision variables with their original values and final values. Next are the constraints with their final cell values constraints, a formula representing the constraint showing whether the constraint was binding or non-binding at the solution, and the slack value – the difference between the final and the original value. A selected report of solver function for Q=0.606l/s) shown in appendix (A).

Determining critical depth for irrigation and drainage channel cross sections is classic but also important for efficient hydraulic design .The geometric parameters of the control section are used to create Excel work sheet, and under the range of initial given values of these parameters with the use of spreadsheet solver function The Computation of critical depth achieved. A clear understanding of the hydraulic principles of the problem and utilize them to develop correct linear or non-linear equations or formulas necessary in Microsoft Excel in computation of critical depth, in addition the advantages of such depths in calculating theoretical discharge and a starting point in calculating water surface profiles .

**HEC-RAS program results and discussion:**

Profile summary tables are used to show a limit number of hydraulic variables for the main channel stations, the details of hydraulic parameter for the semicircular weir control section are shown in appendix (B).

**Calibration the HEC-RAS program:**

The ability of the HEC-RAS model to predict the flow characteristics over semicircle weir was tested by comparing the numerical simulation results against the corresponding data from laboratory experiments. The accuracy of HEC-RAS results were increased by calibrating the program. There are only three things may vary to calibrate the results with observed data which are, Manning roughness coefficient; flow range, and exact location of the critical depth. Manning roughness coefficient is the controlling parameter affecting the performance of HEC-RAS model. The value of this coefficient was adjusted to give best simulation of water surface profile comparing with the observed flow (Within a reasonable range). The water surface profiles generated by HEC-RAS are shown in Figures. (6-a) to (6-f).

**HEC-RAS program software:**

It may be seen from the flow simulation that the HEC-RAS well predicted the water surface profile upstream of the weir as well as with the main weir flow. However, it may also be observed that the model simulate the weir flow irrespective the degree of curvature of the streamlines at the brink depth and the effect of curvature is insignificant [10]. An exact value of the brink depth assigned by HEC-RAS model which is selected as a downstream boundary condition (critical depth at free over fall off horizontal weir crest) and editing H2 water surface profile [11].

**Head-discharge relationship:**

The main objective is to model HEC-RAS one dimensional flow over semicircle broad crested weir for establishing head-discharge relationship, and examine the accuracy of the model results by laboratory experiments .Figure (7) shows the predicted and simulated discharge rating curve for free flow condition and zero channel bed. Also the head exponent (n) of the equation (13) is equal to (2) which is greater than the theoretical value (1.5) [5] .essentially because of the increasing in velocity of approach with stage and because of increase of width with stage. Thus straight line rating curves for section control almost have a slope approach to (2).

**Discharge coefficient:**

The discharge coefficient ($C_d$) has been introduced in equation (9).For each value of head over weir crest (H) a matching values of ($Y_C$), ($A_c$) must be computed. Summary of calculation is shown in appendix (C).

**CONCLUSION**

1. The straight – line rating curve for semicircle section control almost have a slope approximately equal to (2).
2. The use of solver function in Microsoft excel provide more accurate solution compared with the traditional method and approximate equations.
3. The controlling parameter affecting the performance of the HEC-RAS model is the Manning roughness coefficient.
4. The flow characteristics at the control section ($V_C$, $d_C$, $A_C$, and $B_C$) are function of water depth ($Y_C$).
5. The one dimensional model is capable of treating free flow over any type of weir profile producing the profile does not have vertical face.
6. HEC-RAS could compute the water surface profile upstream of the semicircle broad crested weir fair agreement with the laboratory data.
7. HEC-RAS could compute the brink depth accurately (free over fall).
8. The discharge coefficient is not constant but varies slightly as the discharge increased.
9. The computed water surface across the weir crest follow (H2) curve.

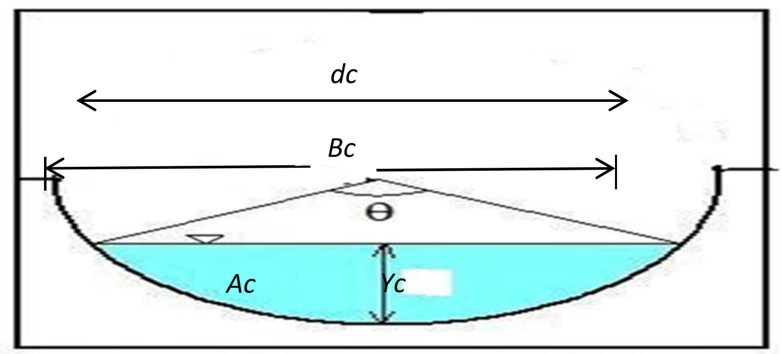


**Figure. (1) partially full weir flow (less than half)** [5] full)

**Figure (2): The experimental arrangement.**

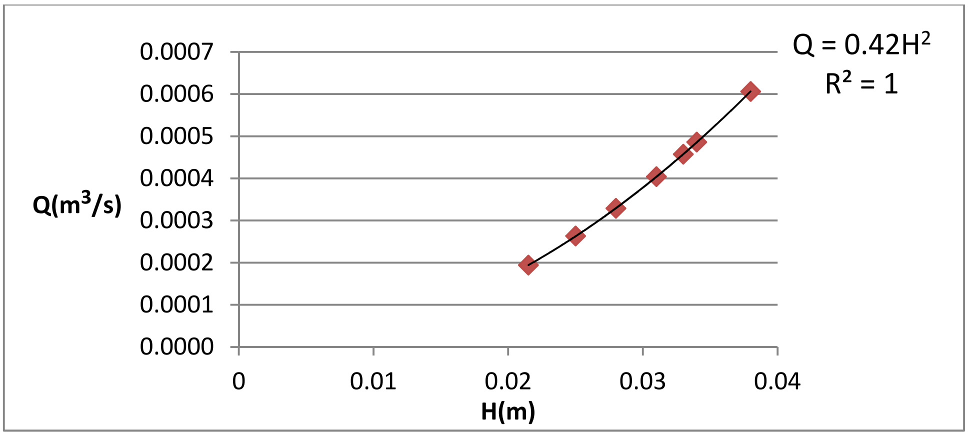


**Figure (3) the relationship between (Q) with (H)**

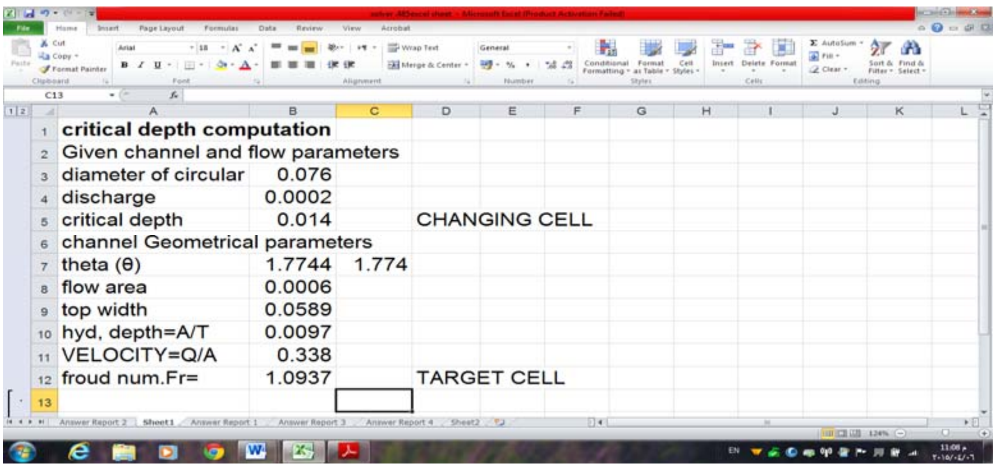


**Figure (4). Spreadsheet for computing critical depth for semicircle cross section**

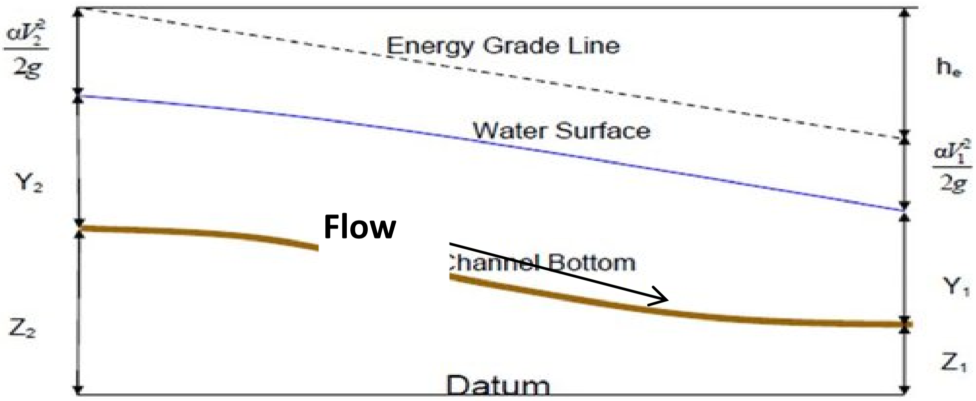


**Figure (5) Representation of terms in energy equation [9]**

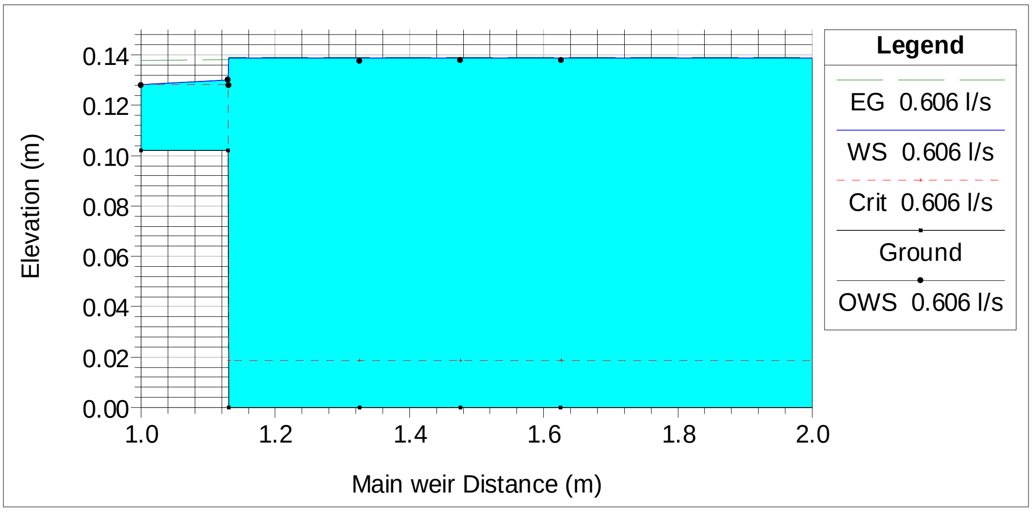


**Figure (6a).water surface profile (Q=0.606l/s)**

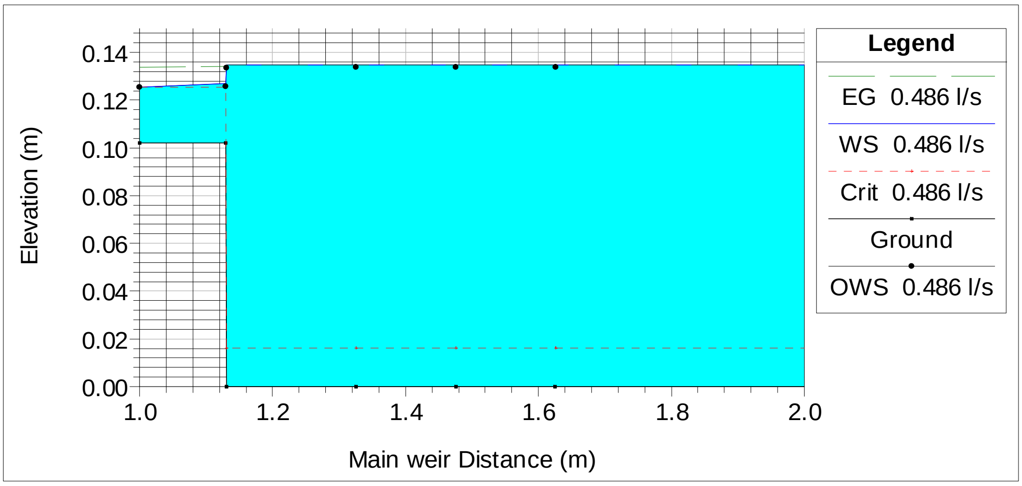


**Figure (6b).water surface profile (Q=0.486l/s)**

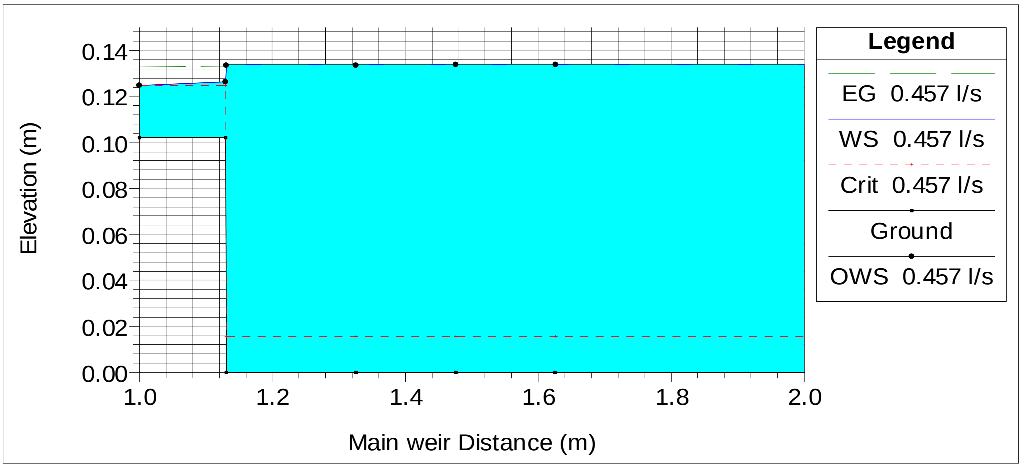


**Figure (6c).water surface profile (Q=0.457l/s)**

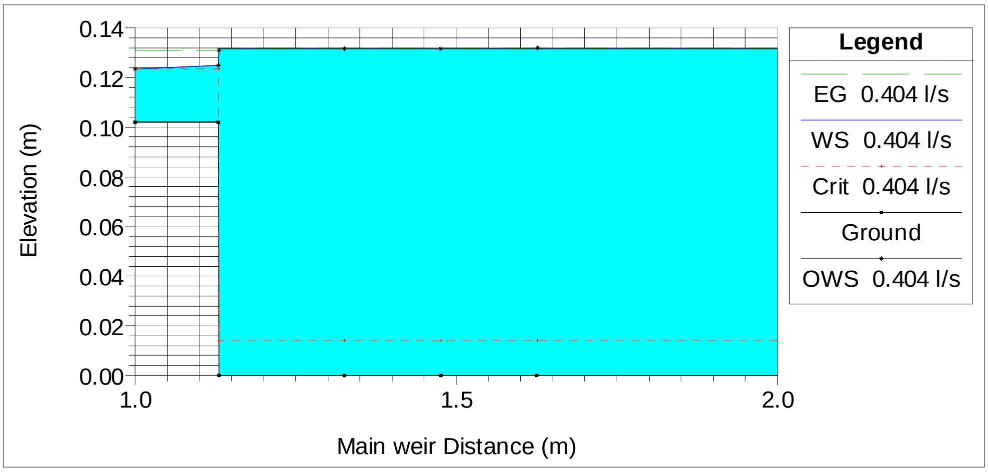


**Figure (6d).water surface profile (Q=0.404l/s)**

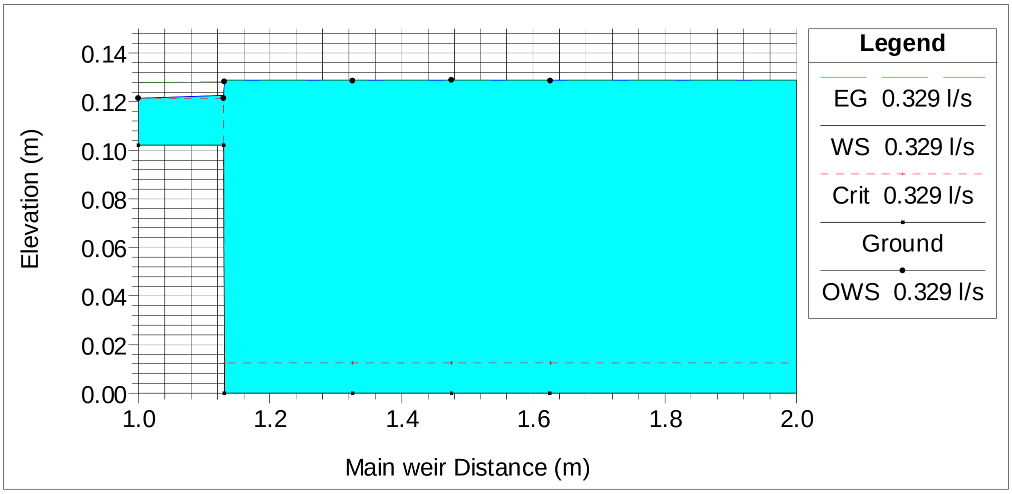


**Figure (6e).water surface profile (Q=0.329l/s)**

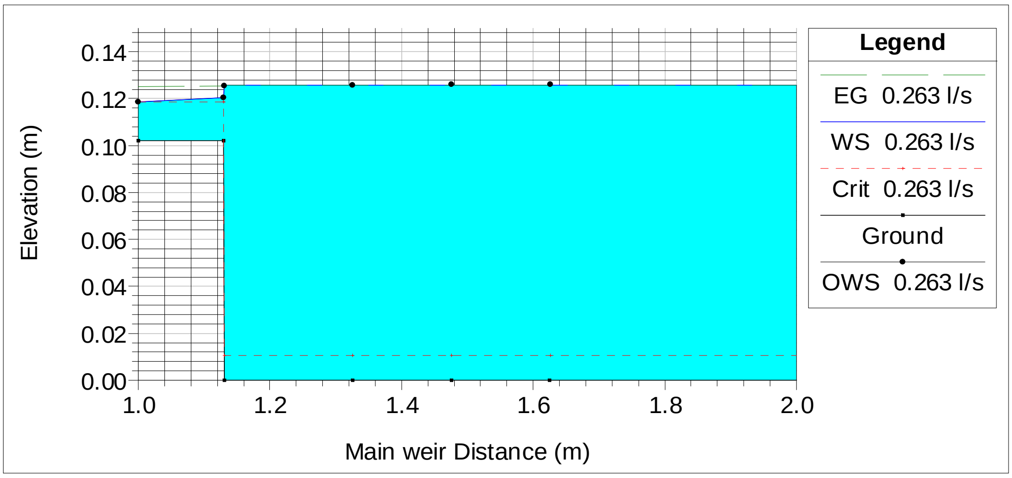


**Figure (6f).water surface profile (Q=0.263l/s)**

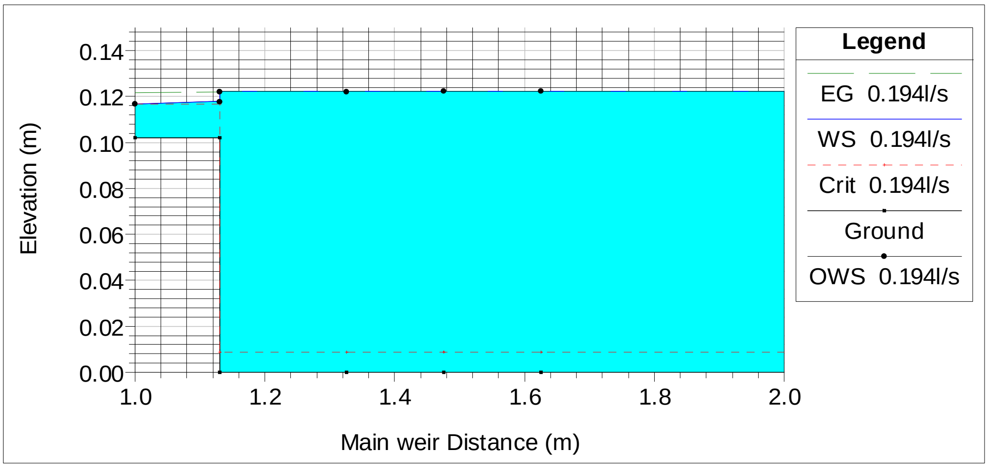


**Figure (6g).water surface profile (Q=0.194l/s)**

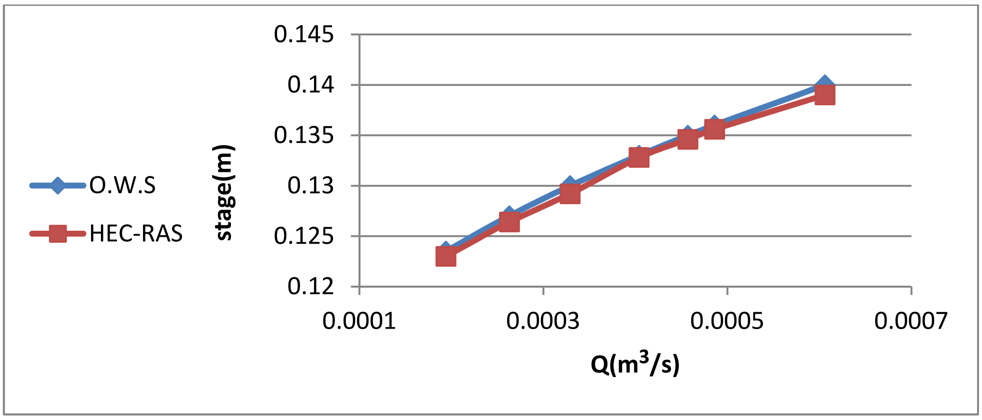


**Figure (7).measured and modelled values of head –discharge relationship**

## List of symbols

| | |
|---|---|
| A | water area |
| B | Top width |
| C | Subscript refers as critical state |
| d | Weir diameter |
| g | Gravity acceleration |
| H | Head up stream weir crest |
| K | Weir constant |
| m | Head exponent |
| Q | Discharge |
| R | Correlation coefficient |
| V | Velocity |
| y | Flow depth |
| Z | Elevation |
| α | Energy coefficient |
| ϴ | Angle at the critical depth in radian |
| EG | Energy grade line |
| OWS | Observed water surface |
| WS | Water surface |

## Appendix(A)

**Microsoft Excel 14.0 Answer Report**
**Worksheet: [Copy of solver .486excel sheet2.xlsx]Sheet1**
**Report Created: 06/02/2015 10:57:14 م**
**Result: Solver found a solution. All Constraints and optimality conditions are satisfied.**
**Solver Engine**

Engine: GRG Nonlinear
Solution Time: 0.016 Seconds.
Iterations: 2 Subproblems: 0

**Solver Options**

Max Time 100 sec, Iterations 100, Precision 0.000001
Convergence 0.0001, Population Size 100, Random Seed 0, Derivatives Forward, Require Bounds
Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 5%, Solve Without Integer Constraints

Objective Cell (Value Of)

| Cell | Name | Original Value | Final Value |
|---|---|---|---|
| $B$12 | froud num.Fr= | 1.651078008 | 0.999999241 |

Variable Cells

| Cell | Name | Original Value | Final Value | Integer |
|---|---|---|---|---|
| $B$5 | critical depth | 0.020312324 | 0.026312322 | Contin |

Constraints

| Cell | Name | Cell Value | Formula | Status | Slack |
|---|---|---|---|---|---|
| $B$7 | theta (θ) | 2.516315292 | $B$7<=3.14 | Not Binding | 0.6236847 |
| $B$12 | froud num.Fr= | 0.999999241 | $B$12=1 | Binding | 0 |

## Appendix (B)

| ReachSt. | Profile | Q Total | Min Ch El | W.S. Elev | Crit.W.S. | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ($m^3/s$) | (m) | (m) | (m) | | | | | |
| Main | 1 | 0.606 l/s | 0.000606 | 0.10211 | 0.12826 | 0.12826 | Main | 1 | 0.486 l/s | 0.000484 |
| 0.10211 | 0.12541 | 0.12541 | | | | | | | | |
| Main | 1 | 0.457 l/s | 0.000457 | 0.10211 | 0.12481 | 0.12481 | | | | |
| Main | 1 | 0.404 l/s | 0.000402 | 0.10211 | 0.12336 | 0.12336 | Main | 1 | 0.329 l/s | 0.000328 |
| 0.10211 | 0.12125 | 0.12125 | | | | | | | | |
| Main | 1 | 0.263 l/s | 0.000263 | 0.10211 | 0.11872 | 0.11872 | Main | 1 | 0.194 l/s | 0.000194 |
| 0.10211 | 0.11661 | 0.11661 | | | | | | | | |

## Appendix (B)

| | E.G. Elev | E.G. Slope | Vel. Chnl | Flow Area | Top Width | Froude |
|---|---|---|---|---|---|---|
| (m) | (m/m) | (m/s) | ($m^2$) | (m) | | |
| | 0.137980 | 0.00390 | 0.436749 | 0.00139 | 0.07231 | 1.00645 |
| | 0.133928 | 0.00387 | 0.409000 | 0.00118 | 0.07015 | 1.00494 |
| | 0.132965 | 0.00381 | 0.400052 | 0.00114 | 0.06967 | 0.99728 |
| | 0.130946 | 0.00381 | 0.385780 | 0.00104 | 0.06849 | 0.99817 |
| | 0.128033 | 0.00383 | 0.364947 | 0.00090 | 0.06598 | 0.99743 |
| | 0.125192 | 0.00430 | 0.356525 | 0.00074 | 0.06263 | 1.04906 |
| | 0.121790 | 0.00403 | 0.318969 | 0.00061 | 0.05954 | 1.00748 |

## Appendix (C)

| Upstream Water level (cm) | Water level at Control sec. ( cm) | H (cm) | Yc (cm) | H/dc | Yc/dc | dc/2-$Y_C$ (cm) | Ө (rad.) | Ө degree | Qact. ($m^3/s$) | Qth. ($m^3/s$) | $C_d$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 12.83 | 3.8 | 2.63 | 0.5 | 0.346053 | 1.17 | 1.2578 | 72.0676 | 0.0006 | 0.000672 | 0.901786 |
| 13.6 | 12.55 | 3.4 | 2.347 | 0.4474 | 0.308816 | 1.453 | 1.1784 | 67.5195 | 0.0005 | 0.000546 | 0.89011 |
| 13.5 | 12.47 | 3.3 | 2.274 | 0.4342 | 0.299211 | 1.526 | 1.1576 | 66.3231 | 0.0005 | 0.000516 | 0.885659 |
| 13.3 | 12.33 | 3.1 | 2.134 | 0.4079 | 0.280789 | 1.666 | 1.117 | 63.9968 | 0.0004 | 0.000459 | 0.880174 |
| 13 | 12.12 | 2.8 | 1.92 | 0.3684 | 0.252632 | 1.88 | 1.0533 | 60.3476 | 0.0003 | 0.000378 | 0.87037 |
| 12.7 | 11.92 | 2.5 | 1.7199 | 0.3289 | 0.226303 | 2.0801 | 0.9915 | 56.8115 | 0.0003 | 0.000304 | 0.865132 |
| 12.35 | 11.67 | 2.15 | 1.4655 | 0.2829 | 0.192829 | 2.3345 | 0.9092 | 52.0959 | 0.0002 | 0.000239 | 0.811489 |

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