Experimental Verification of Gradually Varied Flow Profile Computation

Conference Paper · September 2009

DOI: 10.13140/RG.2.1.3129.3928

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EXPERIMENTAL VERIFICATION OF GRADUALLY VARIED FLOW PROFILE COMPUTATION

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Abstract

The study aims at verifying computational methods used to determine Gradually Varied Flow (GVF) profiles; namely a dimensionless form developed by Chen and Wang (1969) and the well-known standard step method with experimental work.

GVF profile is measured in a laboratory flume 5.31-m long, 7.6-cm wide and 25-cm deep. The results are compared with the above-mentioned equations. Laboratory validation is limited to mild slopes.

The study includes determination of GVF water surface profile for different bed slopes using regulators and free over-fall

1. Introduction

The water surface profile of the gradually varied flow is depending on the channel slope and other conditions. The channel may have one of the following five slopes: Mild, Critical, Steep, Adverse, and Horizontal slopes. The GVF is created at and around sudden transition, sluice gate, weir, hydraulic jump, end of channel (over fall) and at the change of channel slope (Rashwan 2004)

Water surface profile computation is used to determine pairs of Y and X, where X is the distance measured from an arbitrary reference and Y is the water depth. Most of the computational methods consider each profile separately, but the profiles computed by the dimensionless forms are applicable for all flows that have the same Froude number. Thus, the dimensionless methods greatly reduce the computational effort.

In 1769 the French engineer Antoinue Chezy developed probably the first uniform- flow equation (Chaw, 1956), stating

$$V = C\sqrt{RS} \tag{1}$$

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where V is the mean velocity (L/T), R is the hydraulic radius (L), S is the slope of the energy line ($M^0L^0T^0$), and C is a constant called Chezy's coefficient ($L^{1/2}T^{-1}$). Chezy's coefficient is a function of the mean velocity, hydraulic radius, channel roughness, viscosity, and many other factors.

In general, the flow in a long constant slope channel will tend to be uniform. Non-uniform flow may be either gradually varied in which the change in conditions extends over a long distance, or local non-uniform flow known as 'rapidly varied flow' in which changes take place suddenly as in hydraulic jump.

In many practical problems of hydraulic engineering applications concerning open channels, a correct evaluation of the water elevation in various sections is required. The objective, achieved by sketching the gradually-varied-flow profile, requires integration of the governing equations (Venutelli, 2004).

The standard step method can be applied to non-prismatic channels and therefore to natural streams. In the method, the station positions are predetermined and the water depths are calculated at the station by trail and error.

Many advantages can be obtained by using dimensionless equation for example graphical representation of the solution in a normalized form, with the normal-flow Froude number as computation parameter (Chen and Wang, 1969).

The current study is an experimental verification of The standard step method and the dimensionless equation developed by Bresse (1860) and reported by Chen and Wang (1969). Both methods are used to calculate GVF profile. The experiment is conducted on an educational laboratory flume. The flume cross-section is rectangular, 76-mm wide, 250-mm high and 5.31-m long. The computational results are compared with the laboratory measurements. The results of the dimensionless equation are converted into dimensional form so that both experimental and numerical results become comparable.

The study is conducted to fulfill the following objectives. Firstly, verifying experimentally theoretical and analytical solutions namely, dimensionless and standard step method equations. Secondly, estimating Chezy's coefficient for the laboratory flume. Finally, conducting sensitivity analysis for two parameters. the first is effect of Chezy's coefficient on GVF profile computation; the second is the dependency between X and Y values in dimensionless equation.

2. Setup

The experimental work was conducted on an education open channel. The education open channel has a section of 76-mm width, 250-mm height and 6-m length.

The main channel support is a 76×76 mm square pipe at both ends to support head tank and flume. The under frame has two floor supports, one with height adjustment for tilting.

The channel bed is 3-mm stainless steel. Side support can be adjusted such that the wall is straight and vertical and the channel width is 76 mm throughout. Holes are provided at mid section of the channel bed to hold models to the bed. Side walls are 8mm thick acrylic with side supports. The supports can be adjusted such that all supports are vertical and in line. The support adjustment is made at the factory. Scales are provided between each pairs supports of one side to indicate water level in the channel.

The head tank is made of stainless steel. Its purpose is to act as a temporary reservoir of water from the pump before discharge more uniformly to the channel through perforated plates.

The end tank is made of stainless steel. Its purpose is to act as a temporary reservoir of water from the channel before re-discharging to the storage tank or a measuring tank.

The storage tank is made of PVC. The tank is separated into 2 parts. One part takes up water from the channel and the other provides water for the pump.

The pump is a 0.55kW; 220V; 1Ph; 50Hz; 2900rpm with 2feet suction and discharge pipe. Its maximum delivery is about 150 *l*/min.

Adjustment of the channel slope is by manual screw. Slope adjustment ranges from -2% to +5%. The slope is set using water level and scales at the side of the channel. The following steps are taken to set or check the slope. First, close the downstream sluice gate and pump water into the channel, then turn off the pump and close the channel inlet valve. Now, adjust the slope until water level at the upstream end equals to the downstream end. The slope of the channel is now “0”. Move the slope scale by adjusting its vertical position.

Flow is controlled by a valve on the delivery pipe after the pump. Flow rate is obtained by timing the water meter.

Accessories
One model (short sluice gate) and free over fall are used to create different water profiles. The short sluice gate is provided with attachment to the top angle of the channel. The gate can be slid up and down by hand and fixed onto position by a screw. The measurement devices include a stop watch, and Vernier hook and point gauge which is made of stainless steel with 250 mm range and 0.05mm reading. The hook is held by an .attachment gear to the channel

3. Experimental Work

The bed slope is measured using surveying instruments. A level is used to determine the relative level of four pre-defined stations along the flume. The slope is determined as the level difference divided by the distance between the stations. It is noticed that the flume is divided into two reaches, connected by a junction. The slope of the upstream reach is milder than the slope of the downstream one. The experimental readings are limited to the downstream reach.

The discharge is measured by recording the volume of water flowing through the flow-meter and the period of flow by a stopwatch. The discharge is computed by dividing the volume of flowing water by the time.

Normal water depth (y_n), and Chezy's coefficient (C) are determined for the pre-defined bed slope (S_0) and different discharges (Q) as follows. First step is to measure bed slope (S_0). Second step is to measure discharge (Q). Finally, a uniform flow is created as follows. The gate is positioned at the DownStream (DS) end of the flume. The gate is gradually opened.

Basically, the water piles UpStream (US) the gate forming M1 profile. If the reach is long enough, the depth far US the gate will be normal depth (y_n). Because the experimental reach is too small to permit full development of M1 profile, it is not possible to create y_n at the US end of the reach. Moving the gate slowly upwards increases the DS discharge and reduces the length of M1 profile. Eventually, the gate opening allows uniform discharge to pass to the DS end and the M1 profile at the US of the gate vanishes. When the depths at four station along the DS reach of the flume are identical (with a tolerance of $\pm$0.5mm), it is assumed that M1-profile vanishes and the flow depth is the normal depth (y_n).

Having measured the discharge (Q), the bed slope (S_0) which is identical to the energy line slope for uniform flow, and the normal depth (y_n) and substituting in Chezy's formula (Eq. 1), one gets Chezy's coefficient (C).

Measuring of GVF profile

The DS reach of the flume is divided into equally spaced stations. The distance between the stations is 20 cm for M1 and M2 curves and 10 cm for M3 curves.

The depth at every station is measured by the hook with the channel bottom at each station as a reference.

Measurement corrections

The water surface does not have the same trend (dy/dx) because of inaccuracy in measuring water depth. The inaccuracy in measuring water depth which is measured by a hook is due to:

1. The waves which are generated at entrance and propagate along the flume.
2. Effect of the flume boundaries on the flow
3. Effect of friction between the bed and the water

There are many methods for correction of measurements. The Lagrange method is used. It is formulated as follows (Burden and Faires, 1989)

$$P_N(x) = \sum_{j=0}^{n} f(x_j) L_j(x) \tag{2}$$

where

$$L_j(x) = \prod_{\substack{i=0 \\ i \neq j}}^{N} \frac{(x - x_i)}{(x_j - x_i)} \tag{3}$$

The method is applied as follows

1. Free-hand sketch of smooth curve approximating water surface and passing through points of measurement.
2. From among the measurement points, choosing the points which best fit the sketched curve. The chosen points are pairs of (x_j, y_j). They can be used for substitution in Eqs. 2 and 3.

For Froude Number (Fn) of 0.39422, the smoothing process for M-family curves is shown in Figs 1 to 3.

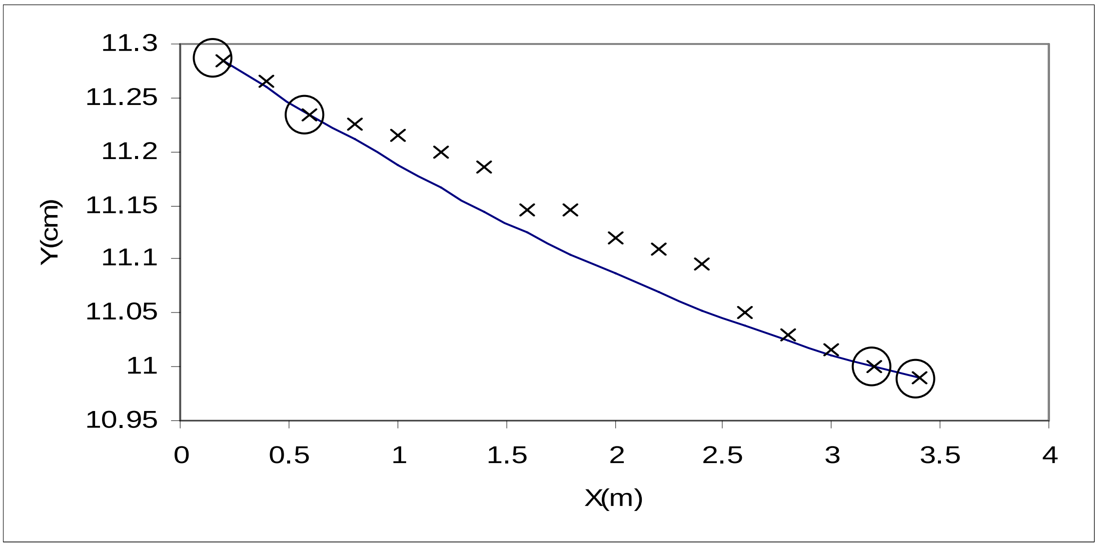

Fig (1) measurements (×) and smoothing curve (continuous line) for M1 curve with Fn = 0.39. Best fit points (circled) N = 4. Zero of measurements is at the DS end of the curve

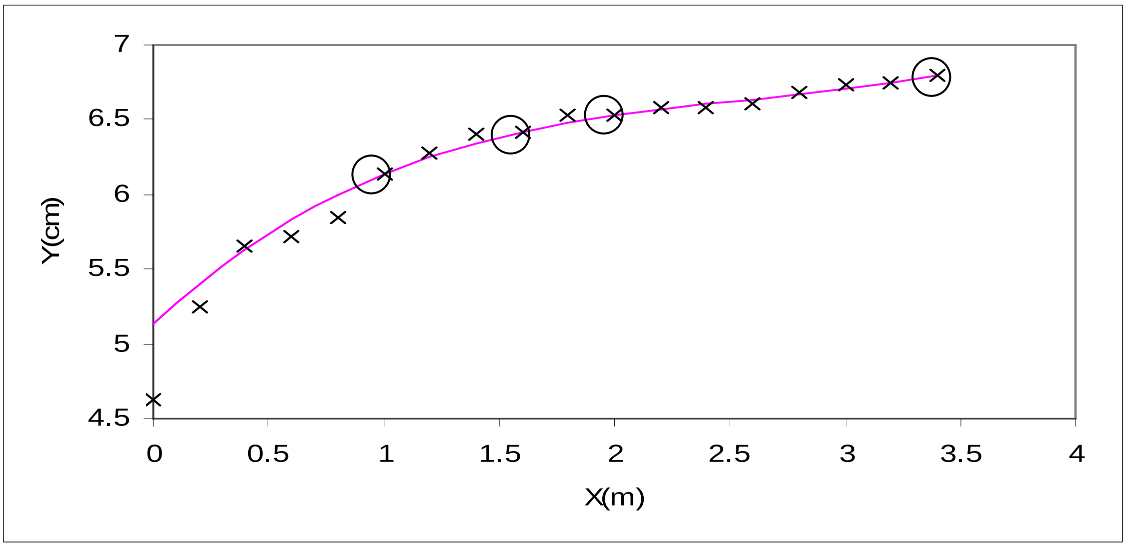

Fig (2) measurements (×) and smoothing curve (continuous line) for M2 curve with Fn = 0.39. Best fit points (Circled) N = 4. Zero of measurements is at the DS end of the curve

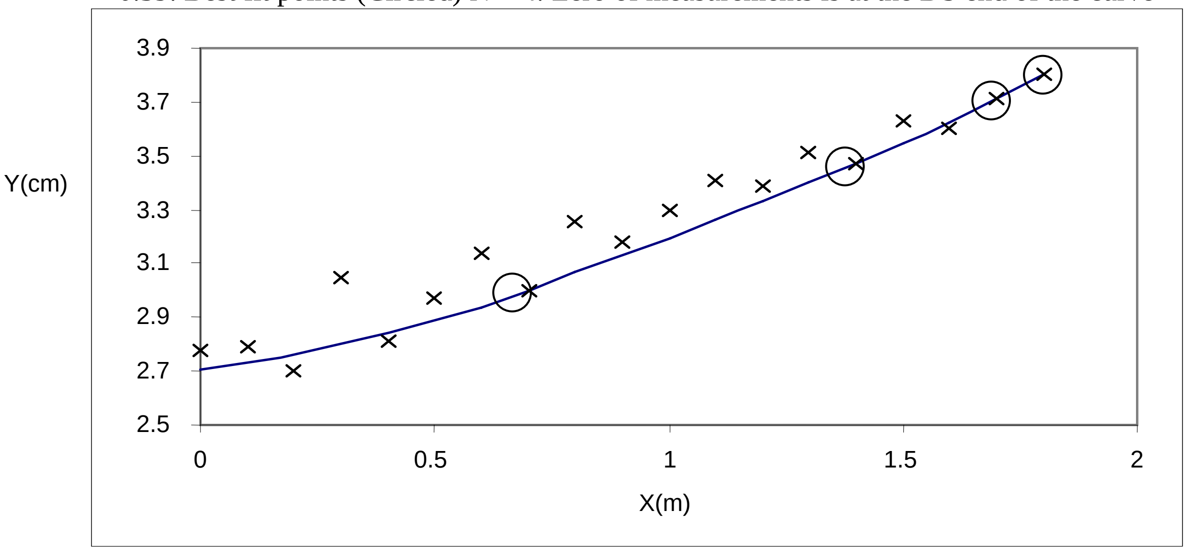

Fig (3) measurements (×) and smoothing curve (continuous line) for M3 curve with Fn = 0.39. Best fit points (Circled) N = 4. Zero of measurements is at the US end of the curve

4. Gradually varied flow computation

a) Gradually varied flow computation by dimensionless equation
Chen and Wang (1969) equation is used in the current study. The equation is:

$$\frac{xs_c}{y_c} = F_n^{\,2}\left(\frac{y}{y_c}\right) - F_n^{\,2/3}\left(F_n^{\,-2} - 1\right)\varphi\left(y/y_c, F_n\right) + \text{constant} \tag{4}$$

where:

$$\varphi\left(y/y_c, F_n\right) = \frac{1}{6} Ln \frac{F_n^{\,2/3}\left(\frac{y}{y_c}\right) + F_n^{\,2/3}\left(\frac{y}{y_c}\right) + 1}{\left(F_n^{\,2/3}\left(\frac{y}{y_c}\right) - 1\right)^2} + \frac{1}{\sqrt{3}} \tan^{-1} \frac{F_n^{\,2/3}\left(\frac{y}{y_c}\right) + 1}{\sqrt{3}} \tag{5}$$

EXCEL Spread sheet is used to perform the computations

b) Gradually varied flow computation by standard step method

The GVF profiles are calculated from the standard step method equation using Excel spreadsheet for different Froude numbers.

The water depths are determined at the stations by trail and error. In other words, the water depth (y) is the dependent variable and the distance along the flume from an arbitrary origin (x) is the independent variable

5. Sensitivity Analysis

a) The dependency between X and Y values in dimensionless equation

This sensitivity analysis is conducted to estimate the effect of the change in water depth (y values) on the incremental distance (x values)

The following case is used.
Type of curve is M2
Discharge (Q) = 0.0022 m^3/s
Critical depth (y_c) = 0.044 m
Normal depth (y_n) = 0.088 m
Froude number (Fn) = 0.3576
Critical bed slope (S_c) = 0.010128

On an EXCELL spreadsheet, the values of X corresponding to Y-values ranging from y_c to y_n are determined using the dimensionless equation (Eqs. 4 and 5).

It is noticed that the increment in Y values is constant (0.1 m), but increment in X values is relatively small (1458 m) near critical depth, while it is relatively large (9296 m) near normal depth as shown in figure (4)

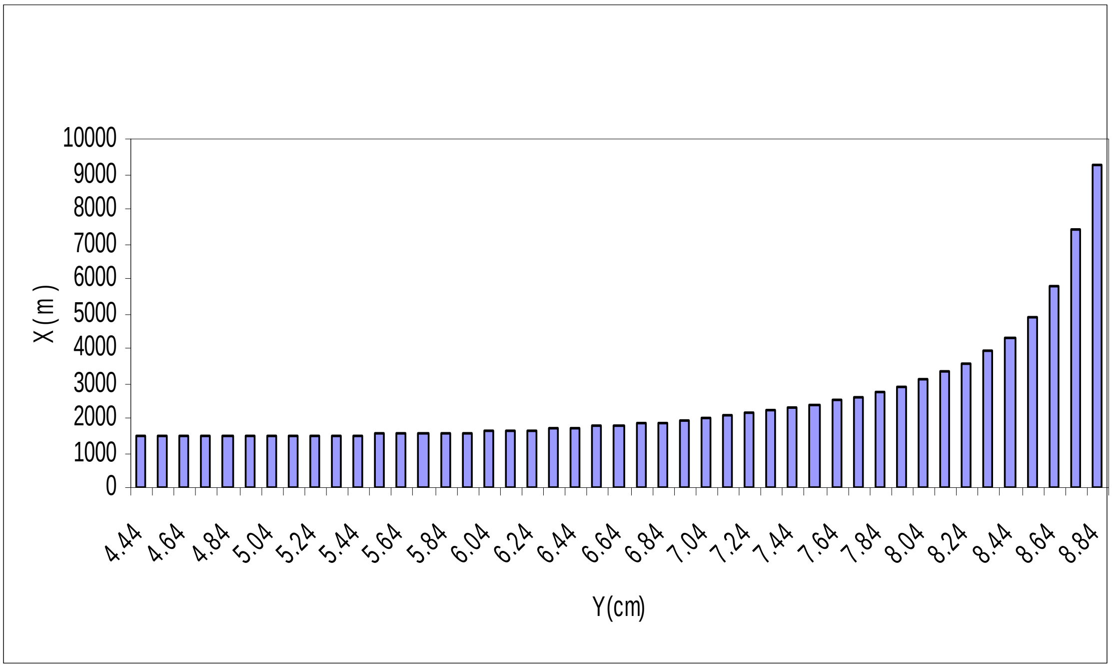

Fig (4) sensitivity of X to changes in Y

b) Effect of Chezy's coefficient on GVF profile computation

This analysis is conducted to see how far the change in estimation of Chezy's coefficient, which indicates friction would change water surface profile prediction. For the same discharge and bed slope, water surface profiles are determined using Chezy's coefficient (C) values ranging from 30 to 100 with a step of 10 and applying in the dimensionless equation

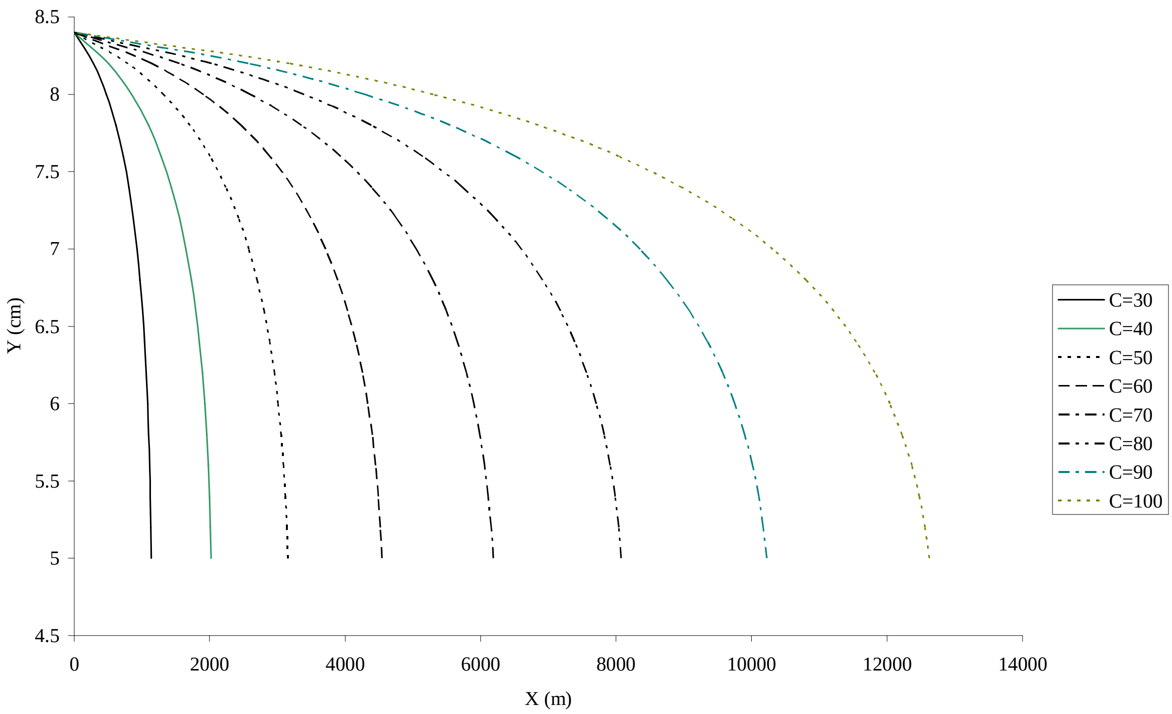

Fig (5) sensitivity of GVF profiles to C-values

(Eqs 4 and 5).

The following case is used.
Type of curve is M2
Discharge (Q) =0.0022 m^3/s
Critical depth (y_c) = 4.4 cm

Computation results are presented in Fig. 5. It is clear that as C-value increases, the change in C-value causes significant change in water surface profile. To minimize the effect of Chezy's coefficient on the computation and comparison, Chezy's coefficient is not assumed constant for the flume; rather, it is estimated for each discharge, as explained on Section 3.

6. Comparison

The results obtained from the laboratory are compared after correction with the results obtained from the dimensionless equation and the standard step method.

The comparison is performed for three subcritical discharges corresponding to Froude numbers of 0.35, 0.39, and 0.47. The results are similar. The results for flow with Froude number (Fn) of 0.39 are presented here. The comparison is shown in Figs 6 to 8. In general, both the standard step method and the dimensionless equation provide similar prediction with the standard step method results closer to the observations than the dimensionless equation results. It should be noted that the dimensionless equation is derived for wide rectangular channel; an assumption which is not valid in the current experimental work. They are identical for M2 curve. Both methods deviate from the laboratory observation. It is expected that the deviation is due to estimation of C-value, which is a function of many parameters including water velocity.

7. Conclusion

The gradually varied flow profile is measured in laboratory for mild slope using different Froude numbers for rectangular open channels. There are small errors due to accuracy of the hook and small waves generated from both entrance and friction. The measurements are corrected using Lagrange method (Eqs. 2 and 3). C-values are experimentally estimated by controlling the DS section so that the flow depth within the flume is normal and applying Chezy's equation (Eq. 1) to the flow.

The M-family (M1, M2, and M3) curves are predicted using dimensionless (Eqs. 4 and 5) and standard step equations for the flows measured in the laboratory.

The comparison between laboratory results, dimensionless equation and the standard step method shows similarity between both numerical methods with minor superiority of the standard step method. Both methods have difference with the laboratory measurements. The difference is attributed to the estimation of Chezy's coefficient. Moreover, the dimensionless equation was derived for wide rectangular section, which is not the case of the laboratory flume.

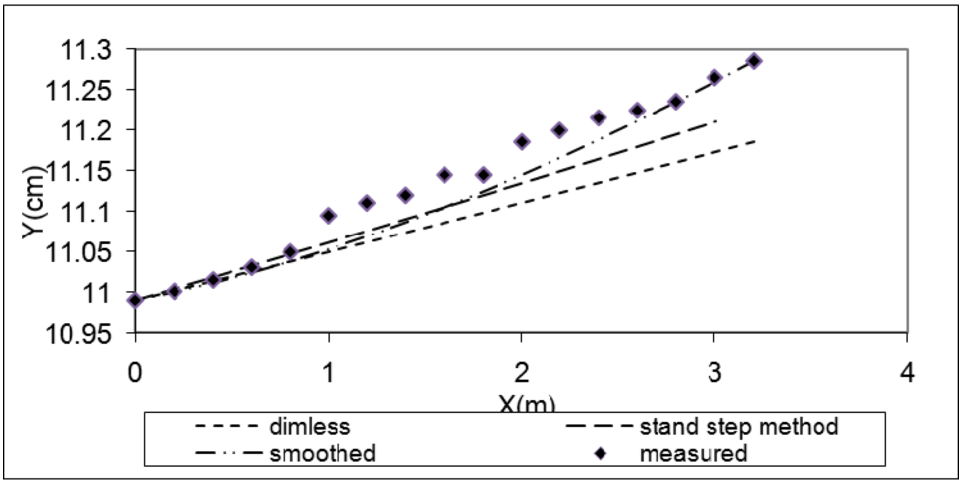

Fig (6) comparing laboratory M1 profiles with computations

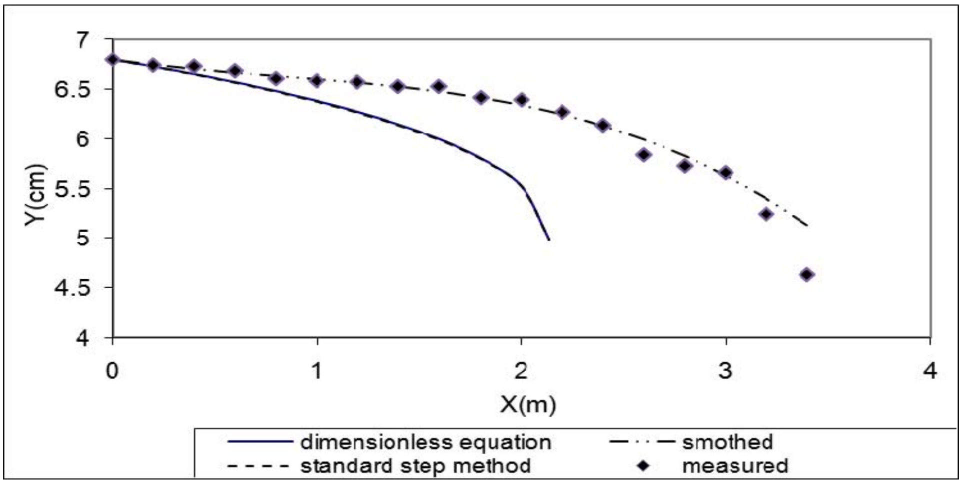

Fig (7) comparing laboratory M2 profiles with computations

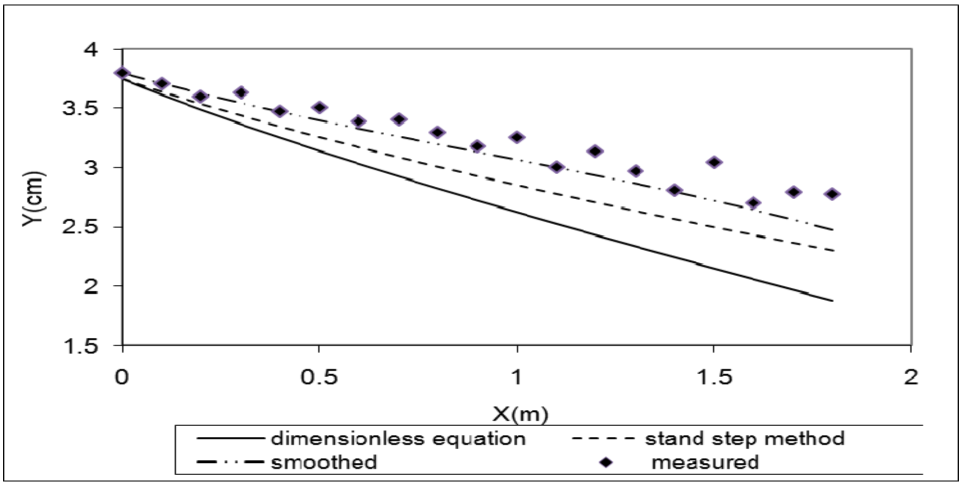

Fig (8) comparing laboratory M3 profiles with computations

The sensitivity analysis is conducted for two parameters. First, dependency between X- and Y-values in dimensionless equation is investigated. It is clear that closer to the normal depth where the water surface approaches the uniform flow surface asymptotically, a small change of Y-values corresponds to large change in X-values. Second, effect of Chezy's coefficient on GVF profile prediction is made. It is concluded that errors in estimating C-values are more significant at larger values of C. In other words, for smoother surface (small C-values) the effect of C on the GVF profile is smaller compared with the effect in case of rough surfaces (large C-values).

Here are some recommendations

Errors in measuring discharge can be minimized by using Pitot tube or any other accurate instrument instead of water meter. The current work is conducted for one bed slope. Further work can be conducted for different bed slopes. The slope adjustment mechanism can be used instead of the surveying instruments to control the bed slope provided that the flume is properly installed to insure good leveling of the flume trestle. The sides of the flume are not perfectly vertical. It is proposed to provide lateral ties to keep them vertically.

8. Acknowledgement

This paper concludes the work of the first three authors on their graduation project of final year civil engineering under the supervision of the other two authors.

References

Chow , V.T. (1973) “Open Channel Hydraulics”, M c Graw-Hill Book Company , , Japan, 680 pp.

Chen, C. and C. Wang (1969) “Non-dimensional Gradually Varied Flow Profiles”, ASCE Journal of the Hydraulics Division, 95 (HY5), pp 1671-1686.

LMNO Engineering, Research, and Software, Ltd., http://www.LMNOeng.com

Ali, N.A., and G. A. Abdel-Rahem (2004) “Open Channel Hydraulics and Hydraulic Machines, theory and problems”, Civil Engineering Department, Assuit University, 220 pp.

Rashwan, I (2004) “Generalized Gradually Varied Flow Profiles through Triangular Open Channels”, Engineering Research Journal, Faculty of Engineering, Minoufiya University, 27 (3), pp 257-264.

Vallentine, H. R.(1967) "The Non Dimensional Representation of Profiles of Gradually Varied Flow", ASCE Journal of the Hydraulics Division 93(HY2),pp 17-24.

Burden, R. L., and J. D. Faires (1989) “Numerical Analysis”, PWS-KENT Publishing Company, USA, 729 pp.