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Experimental Setting of Normal Depths for Achieving a Uniform Flow in Open Channel System

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Abstract
Achieving a good flow distribution is a key parameter in open channel hydraulics, due to the nature of open channel system, the need to achieve uniform flow leads to the elimination of irregular flow properties, for example velocity been localized to cause uneven flow property distribution that can lead to inaccurate estimation of flow quantities along the channel section. The parallel nature of the energy grade line, water surface and channel bottom slopes are the main results when an open channel operates under a uniform condition. To achieve and maintain uniform flow under a wide range of flow conditions in laboratory open channels, experiments have been performed, this paper presents the study which shows the correct setting of the normal depths through flow profiles for selected discharges. The channel tailgate was adjusted periodically to provide corresponding surface flow profiles for normal depths estimation.

Keywords: *Open channel, gauge, environment etc.*

Introduction
Uniform flow balances gravitational forces against shear forces along the channel boundary

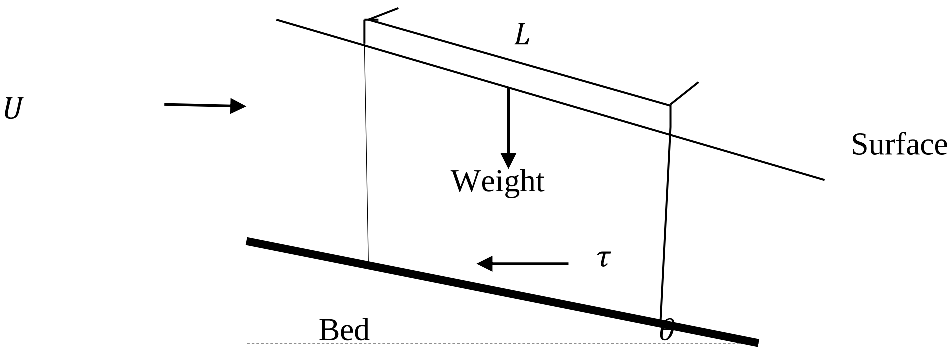

Fig 1: *Gravity force in the direction of flow*

From Figure 1, the resolution of gravity force in the direction of flow becomes (Rouse, 1965):

$$Gravityforce = \rho gALsin\theta \quad (1)$$

The boundary shear force resolved in the direction of flow is:

$$Shearforce = \tau PL \quad (2)$$

The balance between equation (1) and (2) gives the uniform flow:

$$\tau PL = \rho gALsin\theta \qquad (3)$$

Considering a channel of small slope for uniform flow:

$$Sin\theta \approx tan\theta = S_0 \qquad (4)$$

Express equation (4) in (3):

$$\tau = \frac{\rho gAS_0}{P} = \rho gRS_0 \qquad (5)$$

where $R = \frac{A}{P}$ the hydraulic radius, A = cross sectional area, P = wetted perimeter. Equation (5) represents the mean bed shear stress in a uniform flow.

Experimental Methods

The experiments were conducted in 22mm long rectangular re-circulating flume of width $B = 614mm$ at the University of Birmingham. The channel is supplied from a constant head tank with a capacity of $45{,}500l$ in the laboratory roof. Twelve flow discharges (Q) were investigated with corresponding flow depths and water surface profiles to achieve a uniform flow condition for two different experimental conditions. In what follows these experimental conditions are referred to as EXPT1 and EXPT2 respectively.

Results and Discussion

Bed Slope

The bed slope of the channel was measured by setting a horizontal water surface which was used as a datum. The water depth was measured longitudinally using the 21 Vernier gauges stationed along the channel and the channel bed slope calculated from the water depth measurements. The uncertainty in the depth measurement is estimated as$\pm 0.5mm$. Two methods were used to calculate the bed slope, S_o. The first method is the least square regression method of the form $y = ax + b$, where a and b define the slope and the intercept respectively. Figure 2 illustrates the channel bed slope using the least square regression method with two different quantities of water for both EXPT1 and EXPT2. The slopes are consistent for the two quantity of water measured.

The second method was used to verify the consistency of the linear regression method. Defining H_i and Δx_i as the depth at the i^{th} guage and the distance of the i^{th}gauge from the $(i-1)^{th}$ gauge respectively, for$N$ gauges the first to last mean was calculated (Jesson, 2011) as:

$$S_o = \frac{H_N - H_1}{\sum \Delta x_i} \qquad (6)$$

The calculated bed slopes using both methods are given in Table 1.

Table 1: *Calculated Bed/Water Surface Slope Results*

Experiment	Quantity of Water	Regression Method	First-to-Last Method
EXPT1	Depth 1	0.0008±0.0001	0.0008±0.0001
EXPT1	Depth 2	0.0008±0.0001	0.0008±0.0001
EXPT2	Depth 1	0.0011±0.0001	0.0011±0.0001
EXPT2	Depth 2	0.0011±0.0001	0.0011±0.0001

Given the constraints of constructing the experimental channel, the channel bed slopes are slightly different due to the different roughness distribution.

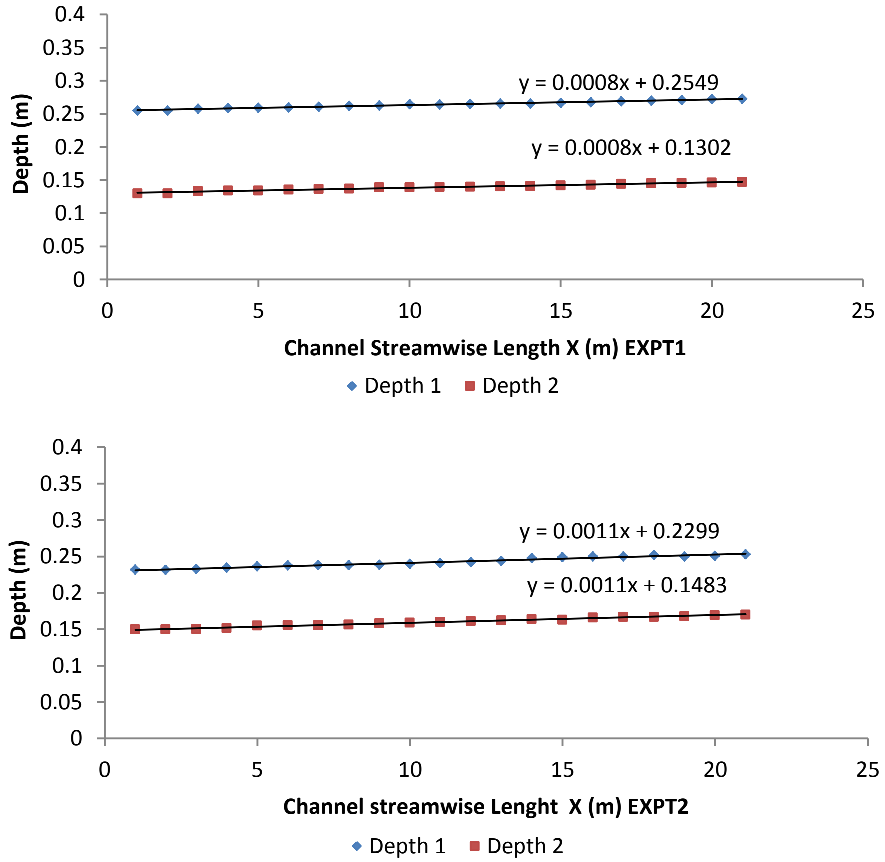

Fig 2: *Bed Slope for (a) EXPT1 and (b) EXPT2*

To achieve a uniform flow, it will be more instructive to provide some insight into the flow behaviour through water surface profiles. Water surface profile within a channel exhibits hydraulic curves which can be used to describe the shape of the flow based on the bed slope and flow depth as adjusted by the channel tailgate. Figure 3 and Figure 4 illustrate the water surface profiles for the experimental channel for EXPT1 and EXPT2. It can be seen from the figures that the near zero profile do not exhibit any slope distortion or changes, furthermore, it can be seen that each of the profiles takes standard curve for gradually varied flow as it relates and do not show any obstruction or change to the flow in both positive (M1) and negative (M2) profiles for both EXPT1 and EXPT2. This is an indication of the good quality of the channel bed for the experimental work.

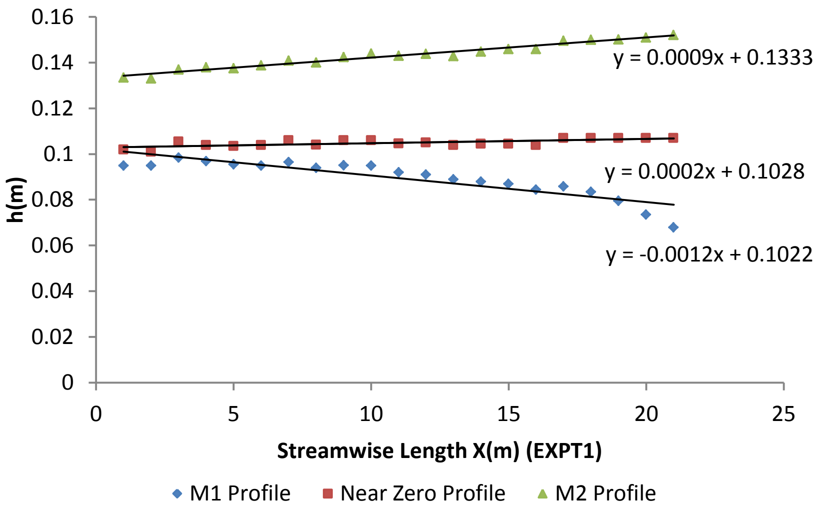

Fig 3: *Water Surface Profile (EXPT1)*

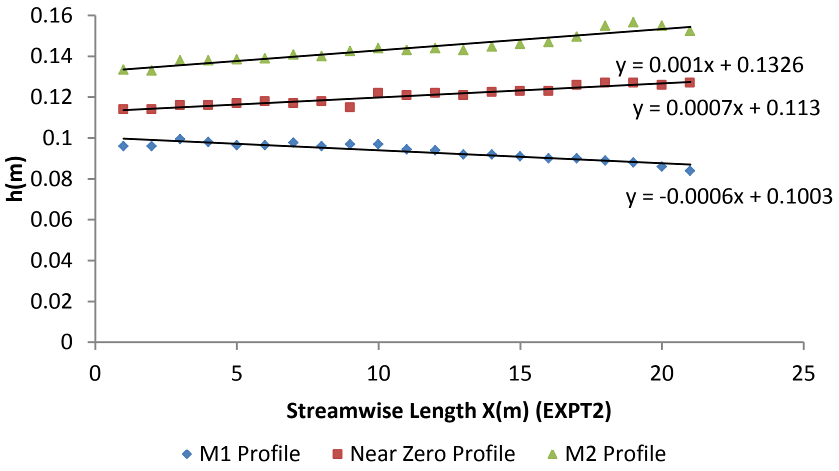

Fig 4: *Water Surface Profile (EXPT2)*

To examine the lateral variation in water levels, three series of measurement were undertaken in the transverse direction at the measured cross-sections over a distance of 0.6 meters. The measurements were taken with respect to a movable transverse carriage on which a Vernier gauge was attached. Figure 5 illustrate the lateral water surface profiles of at the measured cross-sections (CRS1, CRS2 and CRS3). The figures show approximately a $\pm 0.1mm$ variation in water surface level for all the three cross sections measured and is within the measurement accuracy of $\pm 0.5mm$.

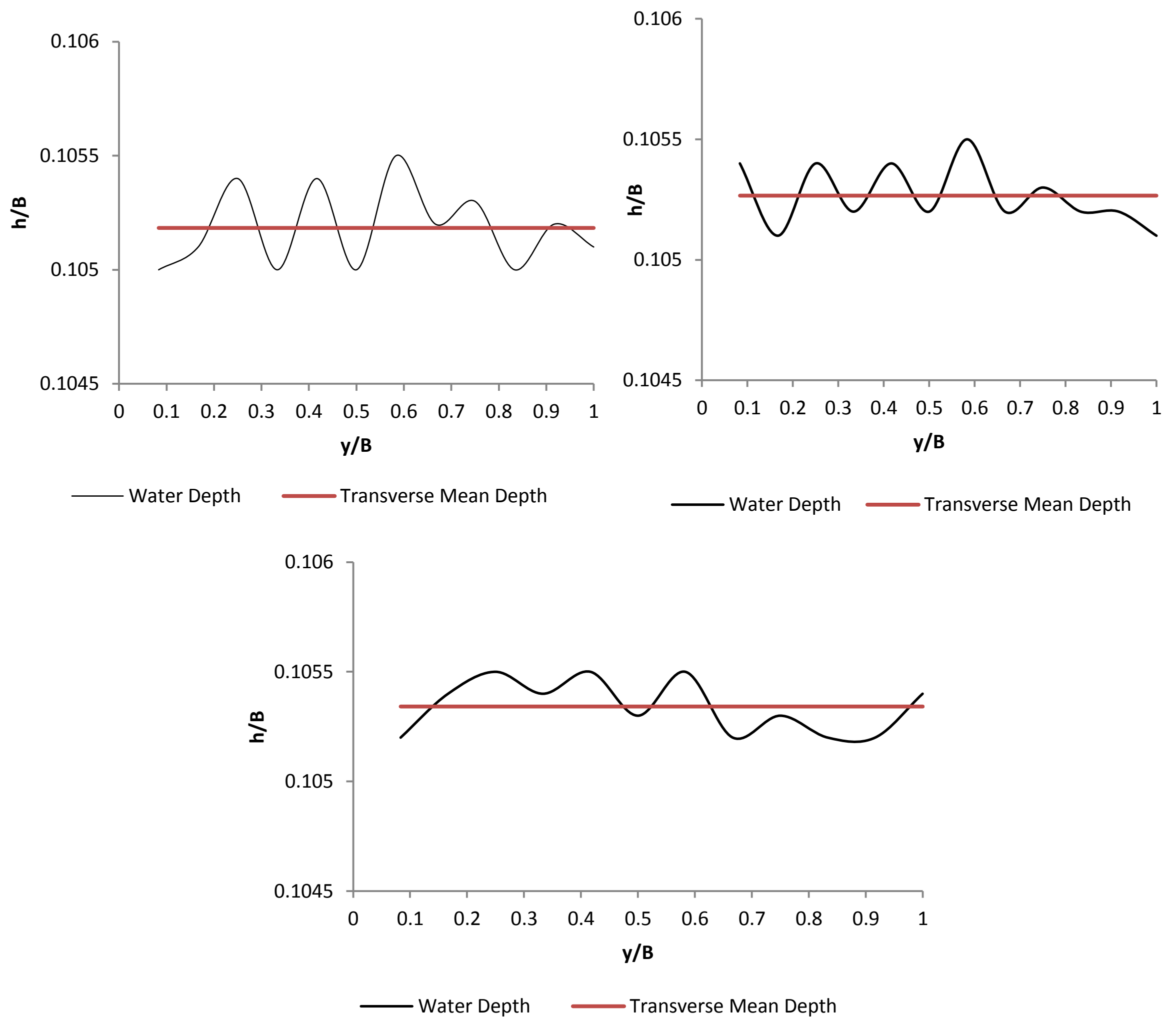

***Fig 5:** Lateral Variation of Water Surface Profile CRS1, CRS2 and CRS3*

Normal depth for uniform flow

In order to obtain uniform flow for the experimental channel, it is necessary to find the normal depths at a number of different discharges. For each selected discharge, the tailgate was adjusted and the water depths measured using the Vernier gauges along the channel. The water surface slopes were calculated from these measurements. This process was repeated five times, with the adjustment of tailgate to give two positive water surface slopes (M1 profiles), two negative (M2 profiles) and a near zero water slope (Figure 3&4). The water depth was measured at 17.5m downstream for all the adjusted tailgate heights. Plotting the water surface slope and the corresponding depth as shown in Figure 6, normal depth was evaluated graphically. From the figure, water surface slope is zero for a tailgate height of 135mm with the corresponding depth of 222mm, which gives the normal depth for this flow discharge.

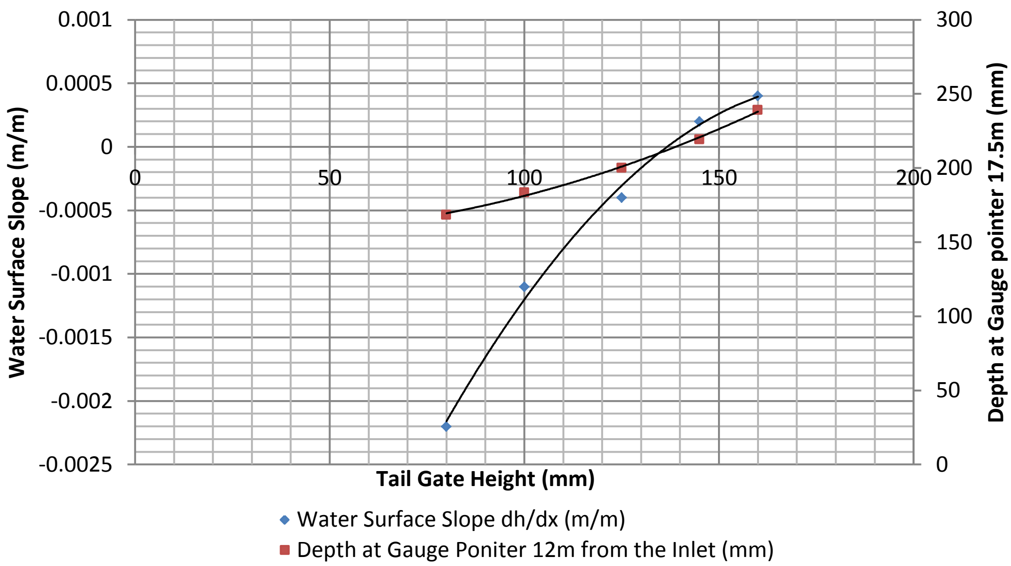

***Fig 6:** Example of Water Surface Slope and Depth versus Tailgate Height Graph*

This process was repeated for a total of twelve discharges over a range of flow rates$(0.004 - 0.085 m^3 s^{-1})$. The normal depth criterion is necessary to obtain a true uniform flow which will allow the mean flow properties to remain unchanged for a reach of the channel sections. Due to minor variation in water surface, the water depth was measured to an accuracy of $\pm 0.5mm$ and the discharge measured to an accuracy of $0.2ls^{-1}$ due to fluctuations in discharge readings.

To verify the consistency of normal depths obtained, Figure 7 illustrates the stage-discharge curves for EXPT1 and EXPT2. The power curves fit with correlation coefficient,R_{cc}, such that $R_{cc}^2 = 0.9991$ and $R_{cc}^2 = 0.9989$ for EXPT1 and EXPT2 respectively. From the correlation coefficients, it can be seen that the stage-discharge curves for the experimental channel follows the standard form for open channel flow for both roughness configurations. Moreover, the results show some similarities in the stage-discharge relationship with increasing gradients at low flow rates (Figure 7) relative to higher flow rates.

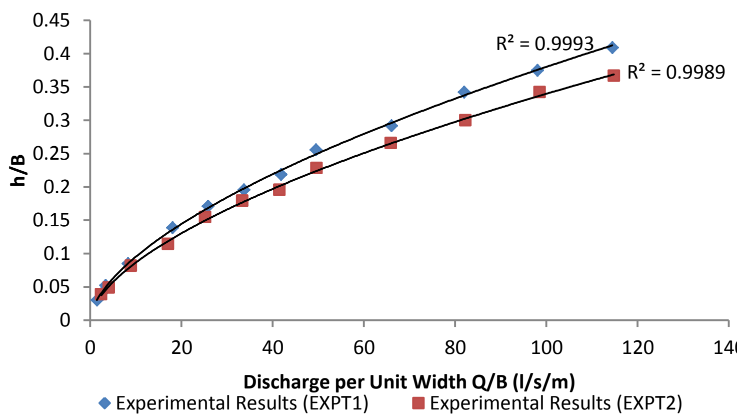

***Fig 7:** Stage-Discharge Curve for EXPT1 and EXPT2 Showing Increase in Stage in EXPT1 for A Given Discharge*

The bulk mean velocity U_b in Figure 8 was calculated from $\left(U_b = \frac{Q_s}{A}\right)$ where Q_s is the actual selected discharge and A is the channel cross-section area(Bh), B is the channel width and h is the normal depth.

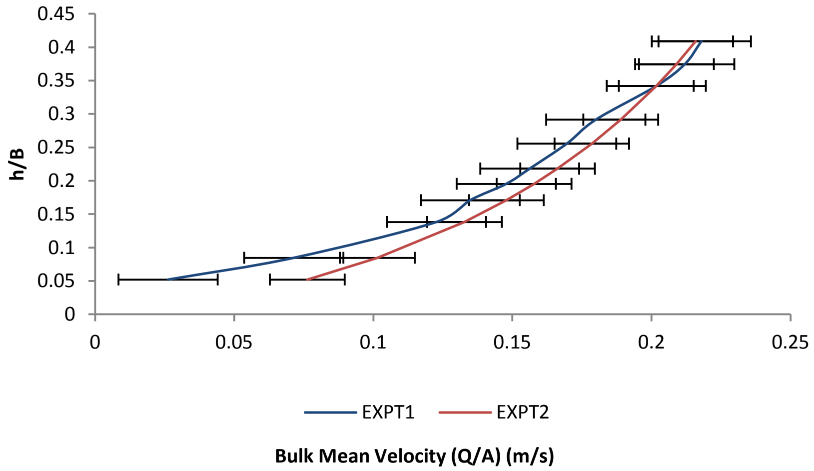

Fig 8: *Channel Mean Velocity (Q/A) for EXPT1 and EXPT2*

In order to verify uniform flow and flow development in the adjusted experimental channel, the vertical velocity profile was measured at cross-sections (CRS1, CRS2 and CRS3) 6m apart. Figure 9 show the vertical velocity profile of the measured cross-sections undertaken at the center region (y/B= 0.5) of the channel. From Figure 9, it can be seen that, the vertical profiles at the measured cross-sections are identical (within the uncertainty limits) for both EXPT1 and EXPT2. The results demonstrate that the flow is uniform at the measured cross-sections.

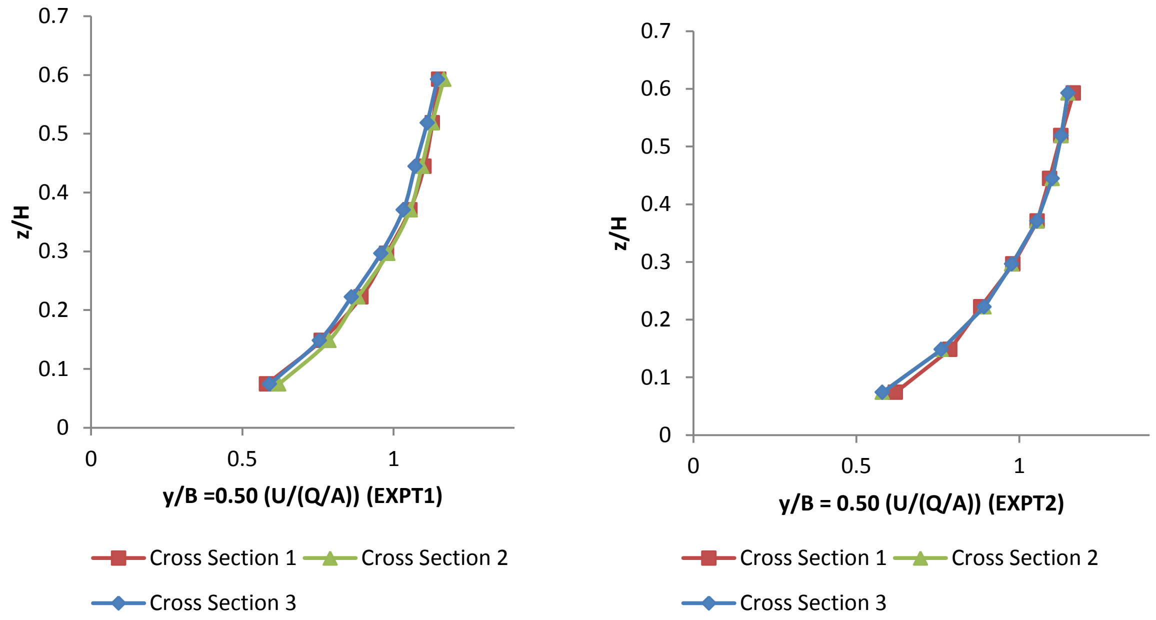

Fig9: *Vertical Distribution of Mean Velocity **U** at the three Cross-Sections Measured; (a) EXPT1; (b) EXPT2*

CONCLUSION

Uniform open channel flow in which the channel slope, velocity, depth of flow and cross-sections remain constants is relevant to civil engineers, hydrologist, hydraulic engineers and environmental engineers. Open channel flow properties are related using uniform open channel equations such as Manning's. A typical importance of uniform flow is in the design of open channels to obtain cross-sections for maximum discharge. This paper demonstrates the establishment of uniform flow conditions in laboratory flume through depth of flow and discharge measurements for constant slope value.

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