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Experimental Study of Hydraulic Parameters and Shear Stress in Rectangular Open-Channel Flume

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Abstract: ***There are various experimental results developed for open channel which verified the theory of open channel flow. Study on real channel is costlier and difficult. So physical model based observation gives results which can be transferred to the prototype using model laws. The main governing factors in open flow are gravitational force, momentum change and hydrostatic force which influences to the hydraulic parameters. This study is aimed to derive the graphical relation of the hydraulic parameter with the geometrical parameter by the help of rectangular open flume of length 5m,width 0.37m and maximum depth measurement 0.3m at different slope variation from 0.001 to 0.0066. The supply of water is by the pump motor whose discharge can be measured with the help of orifice meter, V- notch and volumetric bench.From the experiments, the results obtained are much closed to the theoretical relations. The relation of hydraulic radius with depth, section factor with the slope, and the specific energy curve obtained are reliable. The non - uniform flow were observed in both gradually and rapidly varied flow. The observed and theoretical values calculated are within the range of 10% errors.The most important parameter of the channel geometry is the shear stress development in bed and side wall which is obtained by first approximation theoryequations neglecting the diffusions effects. The relation obtained with respect to the breadth /and width ratio variation are good adjustment to the relations established by[1].***

Keywords: hydraulic parameters, First approximation theory, separation of shear stress

1. Introduction

The total shear stress in an open canal is the retarding force per unit area to the flow which is given by a simple steady flow analysis in term of force acting on a fluid mass element under mass conservation. This is given by the equation as:

$$\tau = \gamma R S o \qquad (1)$$

Whereγ the specific weight of the fluid, R is is the hydraulic mean Radius given by ratio of wetted section area and wetted length (perimeter) and $S_o$the channel bed slope. The equation gives the total shear stress developed by the wetted surface area of the open channel. The computation of shear stress and its distribution varies with the section type and the boundary conditions. The rigid boundary channel resists the drag force of the high current of flow than the mobile boundary channel which depends on the critical condition and the incipient motion conditions[2]. The geometrical analysis of rigid boundary channel is simpler than mobile channel as the driving force at low velocity is enough to trigger the silt from the bed and side wall of channel. In alluvial soil the rectangular channel is not suitable and cannot be stable as the side is vertical and offer minimum shear stress to the flow resulting the high siltation even in low flow rate. To overcome the problem trapezoidal shape in suitable side slope at 45 to 60 degree slope and width(breadth) is chosen at permissible velocity less than 1 m/se. at uniform soil particles of size up to 8mm as D90 which is taken as twice of D50 or D60 particle size. For D90 the manning's roughness values is to be estimated by stickler's formula.[3]

The open channel flow in subcritical is always uneconomical as the depth of the channel is to be excavated in large depth while in supercritical flow the velocity is so high and it may cause high sediment transport to the irrigation land from bed and side wall resulting the deposition on canal reach reducing the designcarrying capacity of canal. Therefore best hydraulic section is to be chosen so that critical flow condition can be generated at which the energy required to make the maximum flow rate is minimum at safe velocity.for the design of stable channel it's all hydraulic parameters must be analyzed which depends on the geometric parameters of the channel and prominently the bed slope of the channel for a given discharge.[4]

The shear stress developed and its separation at bed and side slope is a difficult task specially in case of rectangular section and trapezoidal sections which are the most common sections used in irrigation canal[1]. In case of unsteady flow it is more complex to compute the accurate value of the shear stress due to diffusion effect and highly turbulent flow condition. In case of partially circular open flow , the shear stress distribution computation is more complex than in the rectangular and trapezoidal section and its value in bed with sediment is greater than in other sections.[5]. The effect of shear stress in friction coefficient is also important for the determination of friction coefficient of open channel as it affects to the roughness of boundary and itsmanning's value which is necessary for canal design. [6].the relation of the shear stress and roughness value of the boundary is most important factor for the economic and stable design of a canal.

In open channel for steady and uniform flow the velocity is taken as mean velocity given by chazy's or manning's equations.

The depth for a discharge is the normal depth of the flow and directly depends on the mean velocity and the corresponding depth. The total energy of the flow is measured from the bed of the canal and sum of depth and kinetic head of the flow velocity. The energy is defined as specific energy and the force is called specific force. For the minimum energy and force the Froude number goes to unit and called the critical flow and the corresponding parameters

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are called critical; parameters. The depth at which critical flow occurs has the maximum discharge. [7]

The flow may transform to non- uniform flow due to the hump and channel constriction and the chocking condition mayobtain at which no effect in upstream water level at a maximum height of hump and minimum width constriction. But after that to maintain the minimum specific energy required over the section of hump and constriction, upstream water level rises till the critical flow condition achieves over these section. The upstream energy rises due to the rise in water level. The gradually varied flow and rapidly varied flow condition and their physical phenomena are the most important for the open channel flow analysis and their applications[8].Obstruction in channel may cause the flow from super critical to critical which leads to the change in depth and velocity of flow abruptly change causing significant energy loss.[9].In case of circular section the shear stress computation is a difficult task. It depends on the Y/D values [3]. Since all are governed by the hydraulics parameter , its study in real field is very difficult so therefore simulation and modeling in physical approach are seemed very effective as the available model laws are helpful to transfer the result of model to prototype easily. That's why this study is aimed to review the all hydraulic parameter in laboratory basis in rectangular open canal flume set up having smooth side wall and enameled iron bed surface as the rectangular canal sections are mostly used for distribution of irrigation water in plain region from main canal and the most canals in hill irrigation are rectangular sections so that the study may clarify the related theories of open flow hydraulics practically bridging the gap of theories and its implementation on experimental approach.

1.1Objective of the study

1) To find out the manning roughness value of the model and its equivalent chezy's constant and its relation with the shear stress development.
2) To obtain the specific energy and the relation of hydraulic radius to depth, water conveyance factor and section factor to the depth.
3) To study the relation of shear stress development on the open channel and its separation on bed and side wall with respect to breadth and depth of open channel flow.

1.2 The governing Equations:

Several experimental analysis have been carried out on the hydraulic parameter in open channel[4]. The main objective of the study is to compute the shear stress development in smooth rectangular channel in normal steady and uniform flow condition at which the continuity equation is valid for the flow. The equation in Cartesian co –ordinate is given as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (2)$$

The flow is irrational and incompressible so the equation 1 gives the general value of the shear stress development on the boundaryfor the separation of the stress on bed and side wall of channel the theoretical analysis is given byas first approximation neglecting the secondary current and fluid shear stress[1]

$$\tau b = \frac{\gamma A b S o}{B} \qquad (3)$$

$$\tau w = \frac{\gamma A w S o}{P w} \qquad (4)$$

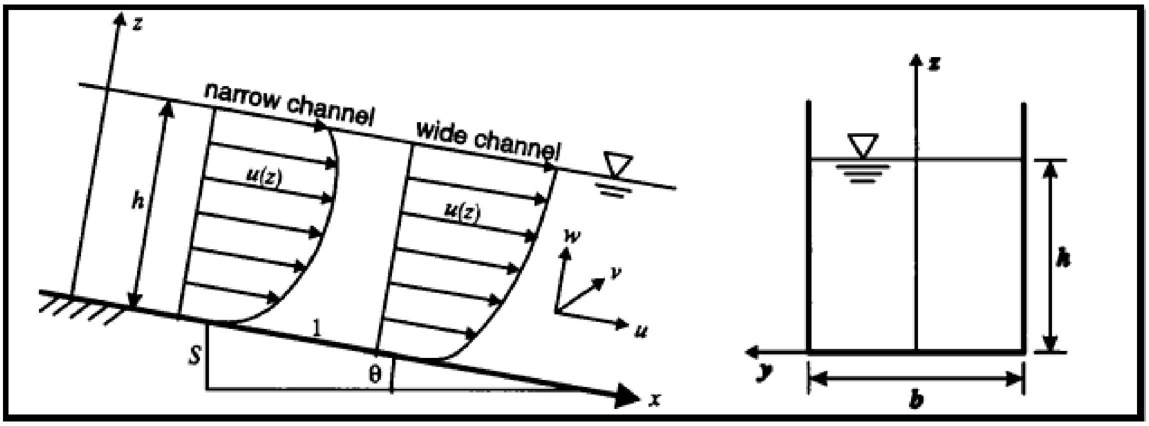

Figure 1: Longitudinal and cross section of the flow

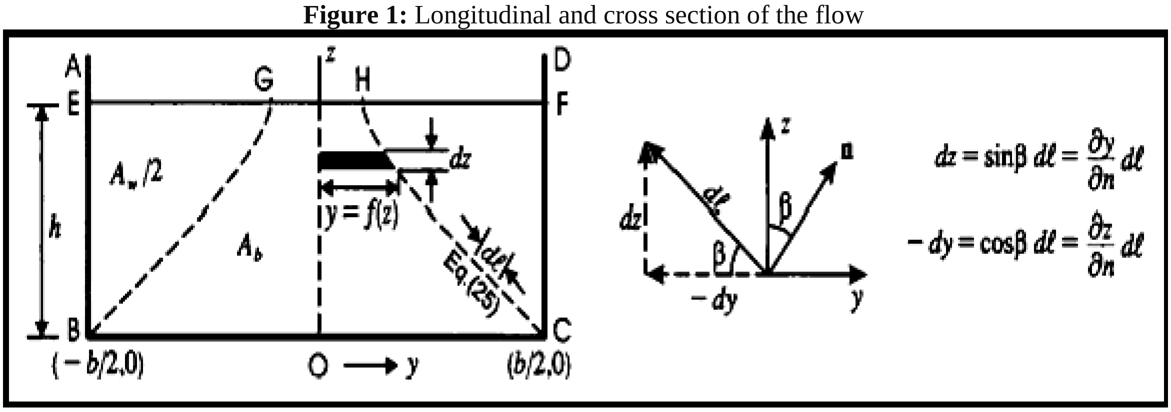

Figure 2: Partition of the shear stress on bed and side wall of the canal

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With reference to **fig 2** the area under the curve line is given by integratingdz and Y from the depth 0 to Yas:

$$Ab = \int_0^y y dz \quad (4)$$

$$Ab = \int_0^y \tan^{-1} \exp\left(-\frac{\pi z}{b}\right) dz \quad (5)$$

$$Ab = \frac{4b^2}{\pi^2} \sum_{n=1}^{\infty} (-1)^n \frac{t^{2n-1}-1}{(2n-1)^2} \quad (6)$$

In which the term t is given as:

$$t = \exp\left(-\frac{\pi y}{b}\right)$$

$$\frac{\tau w}{\gamma y S o} = \frac{b}{2y}\left(1 - \frac{\tau b}{\gamma y S o}\right) \quad (7)$$

Equation 7 gives the average wall shear stress. Also the wall shear stress can be estimated by equation 3 in which the area Aw is given $(by - Ab)$ of the cross section. These equation are the first approximation where the error are neglected.[1]

2. Material and Method of study

Laboratory experiments are carried out on a rectangular open channel flume 5m long as shown in figure 3. The open channel width is 0.37m, whereas themaximum water depth can reach about 0.3m. The transparent side walls of channelare made of acrylic glass, whereas the bottom is made of stainless steel. The flume is provided with a orifice meter flow meter, triangular notch for discharge measurement. Also, a point gauge is implemented for measuring water depth. An over-shot weir is installed at the end ofthe channel to control water depth while a sluice gate is installed in the open channel toform the hydraulic jump. The basic hydraulic bench includes a motor pump thatsupplies the flume with the required discharge controlled by a valve. The water flowsthrough a connected pipe beneath the flume where returns back to the hydraulic bench in a closed cycle flow. Several experimental runs can be performed by varying thedischarge andslopes theset up shown in **figs. 3, 4, 5** is the open canal flume product of arm field company ,U K .The study follows the following flow chart.

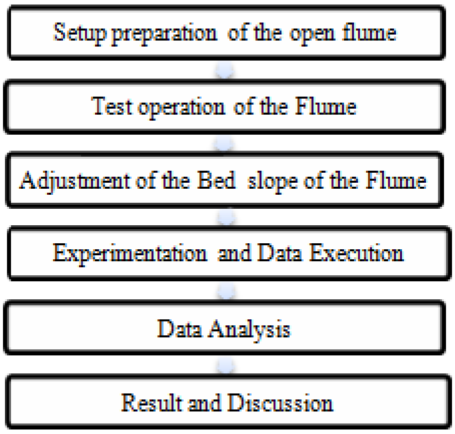

Figure 3: Rectangular open canal flume set up (Hydraulic Laboratory, Purwanchal campus , product of Arm field company, UK)

2.1 Experimental Observations

The number of experiments was conducted on the flume at a constant discharge but varying slope.The corresponding depths were measured and at constant slope with varying discharge. The discharge wasmeasured by the volumetric tank,triangular notch and orifice meter. The flow transitions were observed by humps and channel constriction. Hydraulic jump was formed with the help of vertical gate provided where gradually and rapidly varied flow was observed. The**figs 4and 5** shows the experiments conducted.The observations were carried out at different bed slope varying from 0.001 to 0.0066.

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Figure 4: Discharge through the v notch

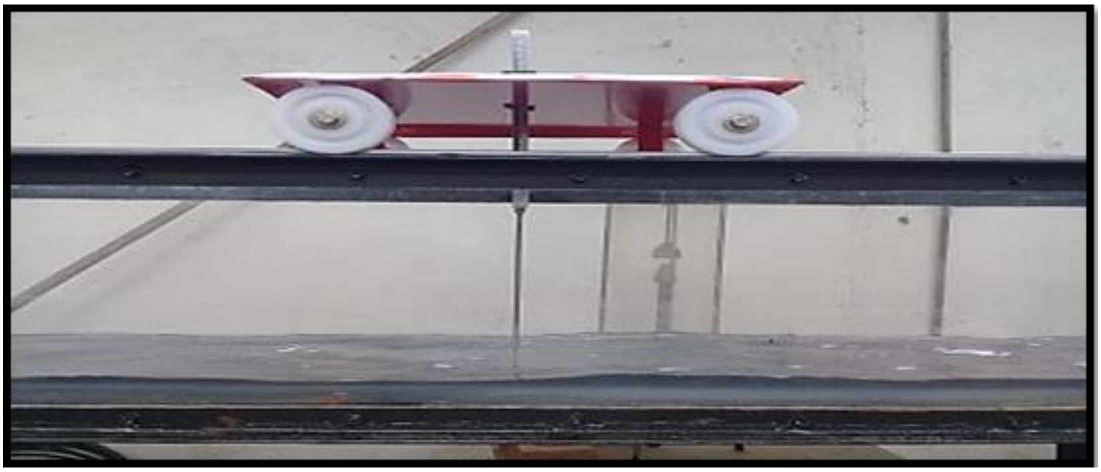

Figure 5: Flow through the flume and depth measurement

3. Results and Discussions

As the open rectangular flume has glass smooth wall and metallic iron bed , the experiments were conducted to estimate the manning's roughness value (n value) at different discharge on constant bed slope of 0.001 which shows the average roughness value of 0.018 which is a acceptable value with the standard that lies from 0,01 to 0.02 for smooth surface. Table 1 shows the estimated roughness value. The slope variations from 0.006 to 0.001 for a constant flow rate of 0.0515 cumeccaused the variation in depth which obeyed a general principle of hydraulics for a steady flow condition .For steep slope velocity increased resulting the flow area decreased. For smallslope the flow depth increased abruptly making large section area,Fig 6 shows the resultant graph relation of depth and slope variation.The corresponding hydraulic mean radius(R) , water conveyance factor (K), section factor (Z) were estimated for different slope at constant flow rate which showed a good adjustment with the theory and its application for the canal design.Fig7. Shows the resultant graph of the depth vs hydraulic mean depth and section factor curve very cl0sed with the theoretical curves at textbook.similarly, the specific energy of each depth were estimated based on the flow depth and kinetic energy head of flow at constant discharge of 0.0515 cumec but varying slope so that the depth varied. **Fig 10** shows the resultant specific energy curve which is also much closed to the theoretical curve in shape. At minimum energy the flow is critical having the minimum flow depth and below it the flow is super critical and above it the flow is subcritical. All these primary observation and results concluded the flume obeyed the fundamental principles of open flow hydraulics. The main part of the study was to determine the shear stress development in steady flow condition at which the main governing factors to flow are gravitational force ,momentum force and hydrostatic force for different slope and breadth/depth ratio, The total shear stress developed by the canal were estimated for whole section as shown in **Fig 9**. But the main factors to be considered is the turbulent velocity of flow due to which the shear stress development depends on the wall surface and bed surface independently.

Table 1: Estimation of average Manning roughness value for the flume

Q(m3/se)	So	B(m)	Y(m)	A(m2)	P(m)	R(m)	n	Avg(n)
0.001	0.001	0.37	0.060	0.022	0.490	0.0440	0.015	
0.0048	0.001	0.37	0.080	0.029	0.466	0.0620	0.017	0.018
0.00515	0.001	0.37	0.086	0.031	0.542	0.0568	0.020	
0.007	0.001	0.37	0.0956	0.035	0.560	0.0625	0.021	

3.1 Hydraulic parameters Analysis

3.1.1Depth variation

Longitudinal Bed slope is a most important geometric parameter in open channel. In alluvial soil steep slope cause high velocity of flow having high tractive force and critical

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state occurs soon causing start of siltation from the canal boundary. So the significant effect of slope variation should be considered while designing the mobile boundary canal in alluvial soil. The **fig 6** is the experimental observation of depth variation for a discharge of 0.0515 cumec of the open flume discharge at which minimum flow depth is of 0.045 m at slope 0.001 and maximum is of 0.09 m at slope 0.006.

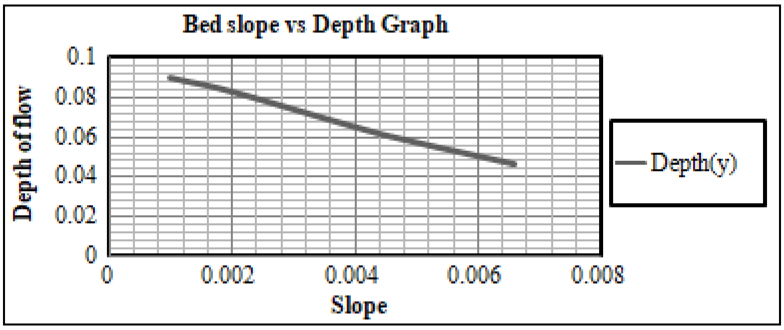

Figure 6: The variation of the Depth with the bed slope of the flume

3.1.2 Hydraulic mean radius and Section Factor variation

While designing the open canal the easy approach is to follow the depth and Section factor relationship established. It makes the work easy and fast. For a section factor the depth required for a design discharge can be considered and the computation will be fast. The relation curve in **fig 7** below shows a good adjustment to the theoretical curve obtained in the textbook. In this study the section factor is directly depended on the depth and slope of the canal. The value is of 0.09 at slope 0.006 for the flow rate of 0.0515 cumec.

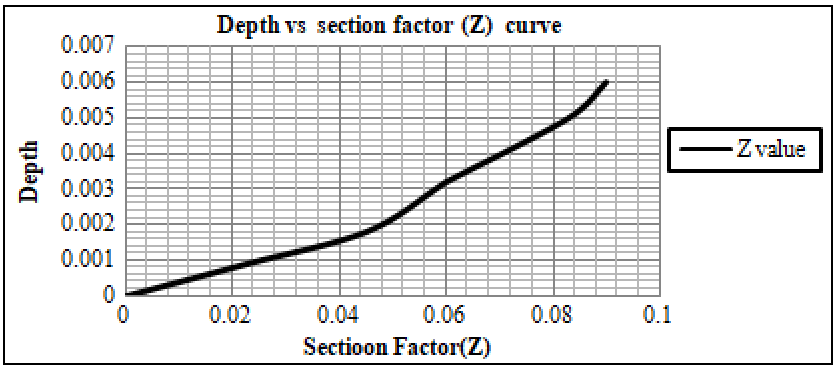

Figure 7: Variation of section factor (Z) with the flow depths

In open canal design, it is better to consider the hydraulic mean depth (Radius) which is the ratio of section area and corresponding wetted perimeter rather than the flow depth. As the flow is turbulent the velocity has diffusion error so the designed parameter may have errors. To avoid it we always use the hydraulic mean depth which minimize the error and ensure the channel stable. But the relation between depth and mean depth must be established in graphical form. The result of the study in fig 8 is the curve of hydraulic radius vs depth for a discharge 0.0515 cumec. It clearly shows the maximum value is obtained at maximum depth which is 0.096 at depth 0.09 m. The trend of the curve is very close similar to the theoretical curve.

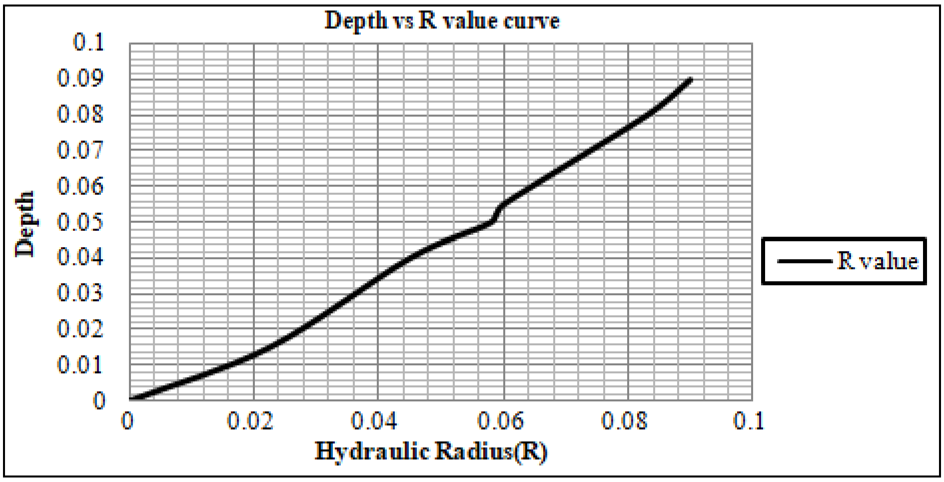

Figure 8: Variation of Hydraulic mean radius with the flow depths

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3.1.3 Specific energy and shear Stress Distribution

Shear stress development is the most important hydraulic parameter in open flow analysis. The force per unit area offered by the boundary in contact with the flow depends on the particle size and its distribution. More the contact area more will be the shear stress development by the boundary which causes the loss in energy of water. In alluvial soil the stable channel is always governed by the value of the shear stress and its distribution .for Trapezoidal section the distribution of shear stress in bed and side slope is a very important to design a stable channel. The condition at which the tractive force of water overcomes the shear stress then siltation starts from the bed and side wall of the channel. This condition is critical condition. The shear stress determines the bed deformation in alluvial soil. The greater the shear stress development more deposition of sediment in bed and aggradation occurs forming the ripples and dune in plain bed.For this reason its study is necessary .This study is focused to separate the shear stress of bed and wall of the rectangular open flume using the first approximation theory at which the eddy current of flow is neglected .from the observation and calculation the result obtained is as shown in **figs 11 and 12**.**Fig 9** shows the normal shear stress development in an open channel from the equation no 1. And its variation with the flow depth which directly depends on the longitudinal slope of the canal. As the flow depth steeper slope decreases due to increase in velocity its hydraulic radius is changed correspondingly resulting the change in shear stress which seemed flatter after a certain slope changed as in **fig.9** .With the variation of the depth the energy of flow also varies. The energy considering the depth and kinetic head is specific energy and the graph obtained as shown in **fig 10,**is specific energy curve at which the minimum energy level and its corresponding depth gives Froude number one is called critical flow condition at which is flow is maximum. The critical depth is obtained of 0.045m.since the curve obeys the shape of the theoretical curve and the corresponding Froude no. is unit the energy is minimum at this pont. To increase the energy of water there are possible alternate depths which make the flow super critical and subcritical. The graph obtained is very close to the theoretical curve.

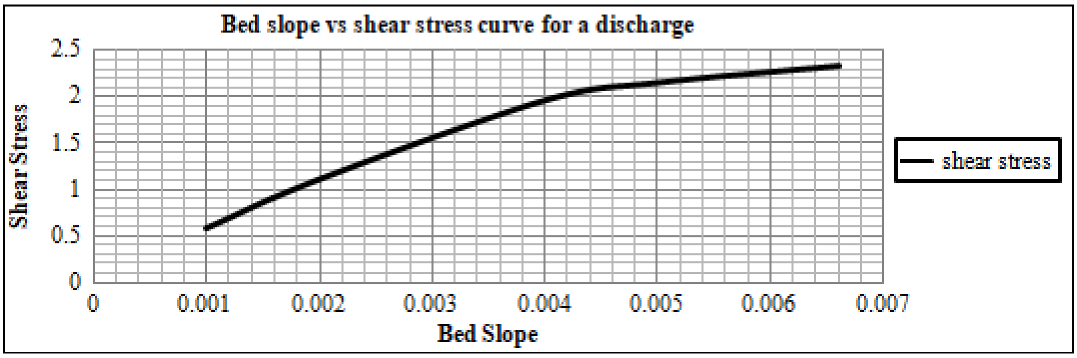

Figure 9: Variation of shear stress development with the bed slope in open flume

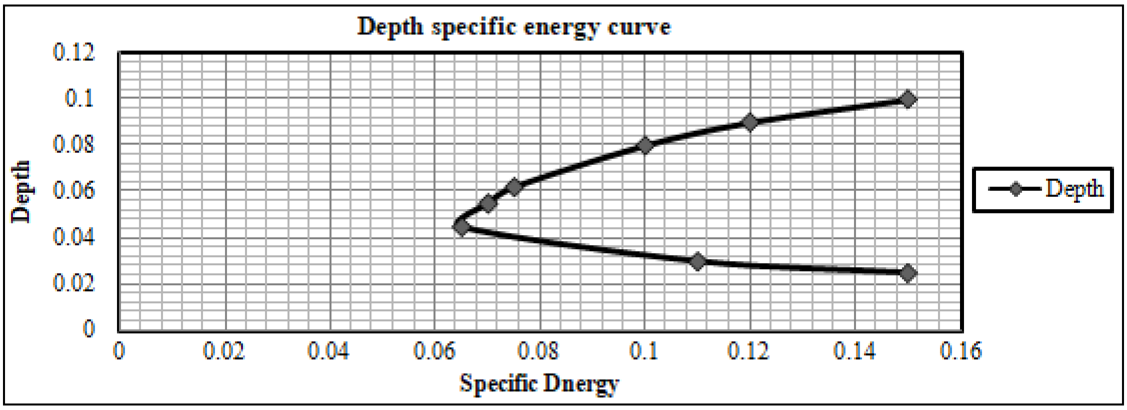

Figure 10: Specific Energy curve obtained for a Discharge at different flow depths

3.2 Non uniform flow analysis in open flume

Gradually varied flow

The experiments were carried out for a constant discharge of 0.00515 cumec measured by the volumetric bench set of the flume at a bed slope of 0.0066. The gradually varied flow was formed by the vertical gate attached on the flume end of the length so that the length of the varied flow can be observed easily. At the gate opening of 3 cm the depth from the just of the gate section to the normal depth of the flow were measured and the calculation were done for the length by direct step method. The total length computed was found 4.54 meter whereas the observed length measured was of 3.9 m. the error was of 13**%. Fig 11**shows the depth variation profile over the bed for the given discharge and slope. The flow was subcritical flow along the non -uniform flow length.

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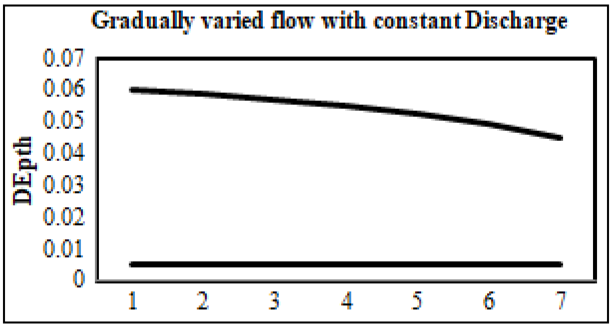

Figure 11: Gradually varied flow in open flume

Rapidly Varied flow analysis

At the downstream of the gate opening the depth variations were observed as shown in **fig.12** the initial depth was of 0.02 meter and the final maximum depth was of 0.065 m. the Froude number at the first section was of 2.6 greater than 1 and at the peak depth it was very less than one. So the standing wave formation was developed.The length calculated was of 0.31m and measured was 0.27 m which was near about equal around 10% error. So the experimental results were very close to the theoretical results computed. The depth Y2 measured was 0.06 m and calculated depth was of 0.065 m within the error 10 % and it is somehow permissible in the open flume's function. The parameters of hydraulic jump obtained experimentally are the height, length and energy dissipation. These values are justified by the theoretical calculation within acceptable range. As the setup is of short length the change in peak value was found nearly equal to the peak value and dropped down the normal depth of flow at short length which caused the graph not exactly similar to the theoretical graph.

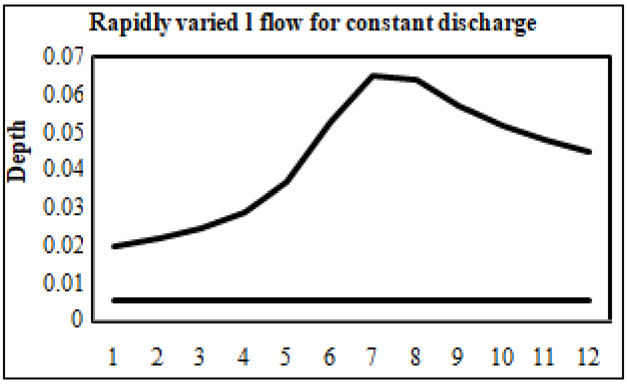

Figure 12: Rapidly flow analysis in open Flume

3.3 First Approximation results in open flume

Neglecting the diffusion and eddy current the First approximation theory was applied to separate the shear stress on bed and wall surface of the flume by the equations No .3 and 7 mentioned above. The resultant curve of shear stress and B/Y value in bed and wall were obtained as shown in figs where the graphs showed a good trend and adjustment with the result given by[1]

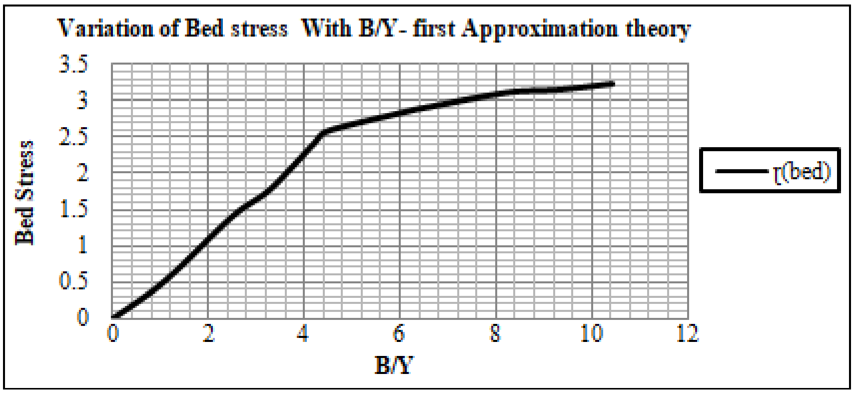

Figure 13: Variation of Bed shear stress and B/Y value in open flume

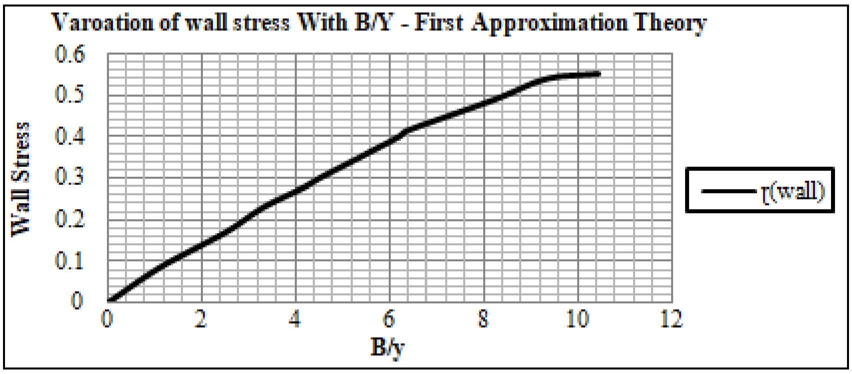

Figure 14: Variation of Wall shear stress with the B/Y in open Flume

4. Conclusion

From the Experimental observation and calculation the hydraulic parameters of the open rectangular flume obtained followed the fundamental principles of the related theory and the resultant graphs are in the well trend, similar and close to the theoretical relations. The manning's roughness value of the combined wall and bed was obtained 0.018

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which is acceptable for the smooth and rough bed of the flume.The results showed the most important role of the bed slope variation in all cases. As the geometric shape of the canal are constant with the variation of slope and discharge the relation were studied. The results obtained for the depth variation with the slope was found gradually varied types and its corresponding hydraulic radius and section factor were computed whose resultant graph were found good adjustment with the theoretical curves given. The hydraulic jump formation was observed very clearly having the depth at first section of 0.02 m as initial depth and 0.06 m of alternate depth where flow was from super critical to subcritical. Specific energy curve obtained for the discharge of 0.00515 cumec at different slopes was observed in well pattern to the theoretical specific energy curve having the critical depth of 0.045m and corresponding Froude number of unit for critical flow condition. The major part of the study is the analysis of shear stress development and its distribution.In case of the shear stress development by the boundary and its separation seemed good adjustment with the theory and governing equation of first approximation theory in which the eddy current and diffusion were neglected. The variation of Breadth width ratio prominently affected to the shear stress distribution. At high value of B/Y the both bed and wall shear stress was high value of 3.2 N per square meter in bed and 0.55N per square meter in wall of the flume.After maximum value of shear stress attained in bed and wall surface it was almost constant in wall surface but small increase in bed shear stress.

5. Acknowledgement

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