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Full Length Research Paper

Evaluating the Roughness and Hydraulic Resistance of Partly Vegetated Heterogeneous Open Channel.

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ABSTRACT

One of the key aspects of flood mitigation in open channel flow is the appropriate evaluation of flow resistance within the channel system. The flow resistance in open channel expresses the effects that the physical features have on its flow characteristics. In this work, the hydraulic resistance of an idealized partly vegetated open channel is measured and quantified. The channel bed roughness was realized with grass and gravel beds, alternately placed at the right and left side of the flume to form an elongated checkerboard. The stage-discharge curve shows a breakpoint where there is a slight change between the lower discharge and high discharge. At low discharge, the stage rises fast, causing an increase in gradient, and approximately linear at higher discharge. The overall Manning's n value is found to be 0.025 which shows an average value of Manning's roughness coefficient n selected for both grass and gravel bed for the channel. The friction factor consistently decreased with increase in discharge. The grass vegetation bed exerts more friction on the flow, and the friction for gravel bed tending towards constant value as the flow depth increases. Minimal value of f is obtained for highest flow depth and the maximum hydraulic resistance found closed to the channel bed. The stage-discharge curve provides a mean of comparison with the theoretical Manning's model to independently reveal the retarding effects of the grass and gravel roughness respectively. The work will be relevant to hydraulic engineers involved in river restoration and flood control programmes.

Key words: Open Channel, Resistance, Heterogeneous, Hydraulic, Roughness, Stage, Discharge.

INTRODUCTION

Natural rivers and open channels are characterized by hydraulic complexities, this is due to the existence of several interconnected physical features, and their mutual interaction often affects the flow characteristics of open channel systems.

Vegetation in river channels and aquatic environment has assumed a different dimension, vegetation is no longer regarded as a mere impediment to flow velocity, but rather as a means of providing river restoration, removal of nutrients and producing oxygen in water, stabilization of channels and landscapes for recreational use [2]. Vegetation plays significant roles in river restoration by providing habitat for other aquatic organisms and ecological management of channels.

A number of researchers have experimentally and numerically investigated the effects of vegetation on flow properties in open channel flow, e.g.; [3],[4], [5],[6], [7], [8]. However, the roughness characteristics and hydraulic resistance of partly vegetated channels with gravel bed has not been fully investigated.

Open Channel Flow Resistance

Flow-bed interaction is a fundamental problem when modelling rivers, the actual physical roughness and the subsequent effects of that roughness on flow termed resistance, is crucial to modelling rivers.

The physical features naturally created in rivers and channels affects flow of such channels, thereby creating resistance for the channel. Open channel flow resistance influences channel conveyance capacity and transport processes. Accurate quantification and estimation of channel flow resistance is important to predict the flow stage relation in channels to help evaluating the likelihood and prediction of channel flooding. Rouse (1965) classified flow resistance into four components: surface or skin friction, form resistance or drag, wave resistance from free surface distortion, and resistance associated with local acceleration or flow unsteadiness. He used Weisbach resistance coefficient f, to express the resistance as the following dimensionless symbolic function:

$$F = F(R, K, \eta, N, F, U) \ldots (1)$$

where R = Reynolds number; K= relative roughness, usually express as ks⁄R, where ks is the equivalent wall surface roughness and R is the hydraulic radius of the flow; ɳ is the shape of the cross sectional geometry; N is the non uniformity of the channel in both profile and plan; F is the Froude's number; U is the degree of flow unsteadiness; Frepresents a function. Relationship in Equation (1) can be applied to the Manningn or to a flow resistance slope S. The most frequent used formulas relating open channel flow velocityU, to resistance coefficient are [10]:

(Manning's) $$U = \frac{1}{n}R^{2/3}S^{1/2} \ldots (2)$$

(Darcy-Weisbach) $$U = \sqrt{\frac{8g}{f}\sqrt{RS}} \ldots (3)$$

(Chezy) $$U = C\sqrt{RS} \ldots (4)$$

in which $n, f, and C$ are Manning, Weisbach, and Chezy resistance coefficients respectively; R is the hydraulic radius, S is the slope; g is the gravitational acceleration, and R in SI units [10].

EXPERIMENTAL METHODS

Experimental work to determine the roughness characteristics of an heterogeneous channel was conducted in a straight rectangular glass wall flume 614mm in width and 22m in length at the school of Civil Engineering laboratories, University of Birmingham, UK. The flume channel is fed with water from a constant head located at the laboratory roof. A flow into the channel flume was measured by an electronic gauge installed in the feeding pipe upstream of the channel. The inlet and outlet structures of the fume were hydraulically connected to allow recirculation of stable discharges with the channel tailgate outlet being controlled by the rolling system, allowing its height to be set to achieve a normal depth flow. Water depths were measured by means of 21 pointer gauges situated at approximately 1m intervals along the channel streamwise length.

A partly vegetated channel bed was created with gravel bed. The channel was divided along the longitudinal centre line, thus the roughness configuration comprising grass vegetation and gravel, which were randomly placed in an alternated fashion to form a checkerboard configuration. The surface elevation of both grass and gravel beds were set so that the variation of the bed surface elevation will be negligible. The roughness change is at every 1.825m. The experimental channel bed configuration is illustrated in Figure 1.

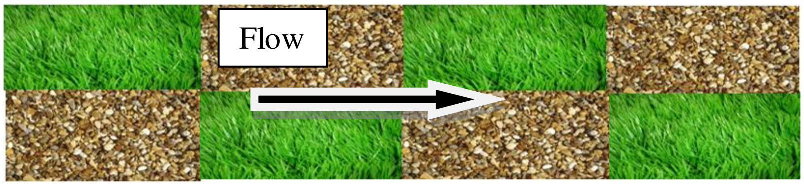

Figure 1: Bed Configuration for the Experimental Channel

The grass vegetated bed was realized by means of an Astroturf (Artificial Grass) having tiny and narrow stems with height 30.5mm. The stems were densely packed to form a carpet grass. The gravel bed was created with fine gravels having D_{70} = 10mm, and D_4 = 5mm, packed densely and fixed to the channel bed by means of waterproof adhesive.

Stage-Discharge Curve

The relationship between stage and discharge was established through a stage-discharge curve, which was achieved through the correct setting of normal depths as exemplified in Figure 2.

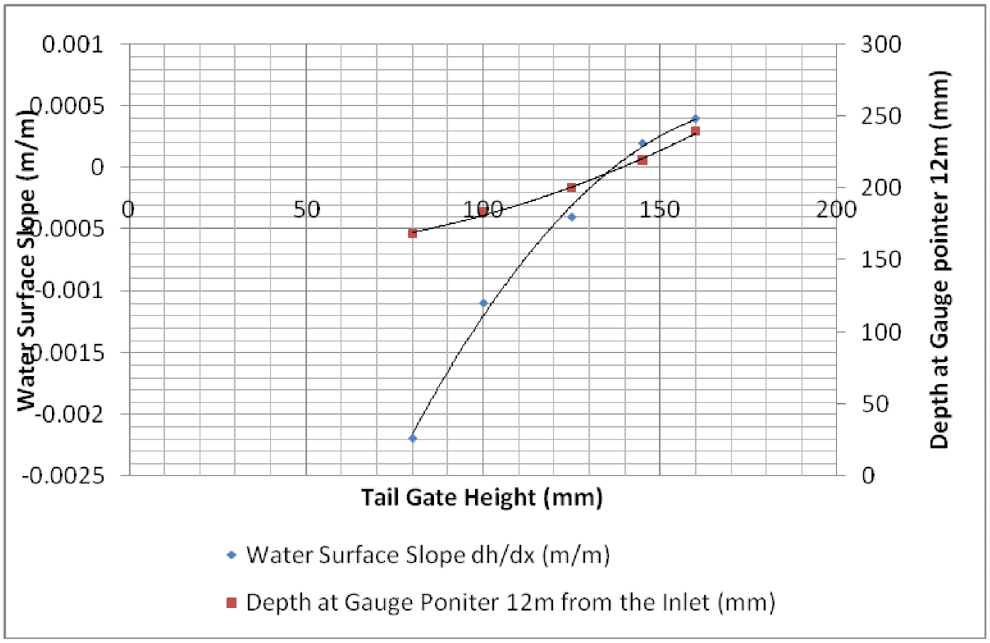

Figure 2: Example of Water Surface Slope and Depth versus Tailgate Height Graph

The stage-discharge curve for the experimental channel was constructed with a grass and gravel bed configuration and provides a mean of comparison between the theoretical stage-discharge curves constructed using the experimental data and the Manning's model. The theoretical curves were calculated from:

1. Manning's equation, using the coefficient value of 0.20 for gravel bed, $n = 0.$ [1]
2. Manning's equation, using the value for grass and weed bottomed channel, $n = 0.$ [1]

RESULTS AND DISCUSSION

Algebraic power equation of the form $Y = AX^B$ where $A and B$ are positive constants, was used to fit the stage-discharge data points.

The power curves fit the stage-discharge data with correlation coefficient R_{cc}, such that $R^2_{cc} = 0.9994$ and $R^2_{cc} = 0.9991$ for Manning's theoretical curve and experimental data respectively. This is illustrated in Figure 3.

Examining the correlation coefficient, the stage-discharge curve for the channel configured the standard form for the bed forms. The stage-discharge curve shows a "breakpoint", the point where there is a slight change between the lower discharge and high discharge. At low discharge, the stage rise fast, causing an increase in gradient, and at high discharge, the stage does not rise as fast as in low discharge, which makes it approximately linear with increase discharge.

From the stage-discharge curves, the experimental results when compared with the theoretical results shows the mutual interactions of the bed roughness and the subsequent resistance generated.

It is apparent from the curves in Figure 4, that the theoretical models under predicted the discharge for a given h for both grass $(n = 0.035)$ and gravel $(n = 0.020)$ beds respectively. The under prediction is more pronounced with the grass vegetation bed than the gravel bed.

Figure 4 shows the under and prediction, as a percentage (error) of the experimental discharge of the Manning's theoretical models for both bed roughness. The under prediction is plotted against the flow depth (h), normalized by the channel width B. The Manning's model treated the channel separately for a particular bed roughness as defined by the roughness coefficient n.

From Figure 4, considering the channel bed to be fully grassed, the results give a considerable under prediction of the discharge at all flow rates. The under prediction was found to be 29% at lowest flow rate and 52% at the highest flow rate. Treating the channel as if it were fully rough with gravel bed provides different results. At a given (h), the results gives an over prediction of discharges at lower flow rate, and predicted to be approximately of equal values with the experimental data at medium flow rates. The discharges were under predicted at higher flow rates with a difference of about 20%.

Variability of Manning's Roughness Coefficient (n) and Friction Factors (f)

The estimation of Manning's roughness coefficient n and friction factors f, depending on bed roughness are essential in describing the channel resistance and its effects on velocity and shear distributions in open channel system.

The overall value of Manning's n for the channel was calculated from the measured discharge and flow depth using Manning's Equation (2).

The friction factor f, was calculated by applying Darcy-Weisbach Equation (3) to each of $Q - h$ data from (1) and (2) using $n = 0.020\ and\ 0.035$ respectively.

The experimental results indicated Manning's n values for channel with both grass and gravel bed configuration to vary between 0.016 and 0.025, Figure 5 for the lowest and highest discharge respectively.

Figure 5 show the variation of the Manning's roughness coefficient n with the normalized flow depth $\left(\frac{h}{B}\right)$. As one may expect from the figure, the effects of bed roughness is more pronounced near bed. The hydraulic resistance of the channel is at maximum close to the channel bed. As the flow depth increases over the bed, the bed hydraulic resistance as define by n steadily decreases, with the effect of the bed roughness reducing with height above the bed, thus momentum absorbing area within the channel also reduces. The distribution of Manning's roughness coefficient n is approximately linear at higher flow depths, $0.3 \leq \frac{h}{B} \leq 0.46$, below this point, the Manning's coefficient n increases towards the channel bed reaching a value approximately 0.025, at the lowest discharge. This also provides verification for the experimental data as the average value of Manning's roughness coefficient n selected for both grass and gravel for the channel was found to be 0.027. The result further explains that the resistance coefficient varies significantly as a function of the flow depth.

Figure 6 and 7, show the variation of the friction factor (f), obtained using the Darcy-Weisbach Equation (3) with the flow depth normalized by the channel's width, $\left(\frac{h}{B}\right)$. This figure revealed a similar effect in Manning's coefficient (n). This fact is obviously observed in the curves shown in Figure 6, where the friction factor f for the experimental data and the Manning's theoretical data for grass and gravel beds falls progressively with increasing flow depth. The friction factor is also seen to consistently decrease with increase in discharge as illustrated in Figure 7.

The grass vegetation bed exerts more friction on the flow than the gravel bed. This shows the retarding effect of grass vegetation as shown in Figure 3. The friction factor for gravel bed is tending towards constant value as the flow depth increases and approximately linear at higher flow depths, $0.15 \leq \frac{h}{B} \leq 0.41$, this effect is similar to the effect observed in the friction factor for the experimental data. Generally, the minimal value of f is obtained for the highest flow rate for both the experimental data and theoretical values. In consequence, the influence of bed roughness is reduced with flow depth.

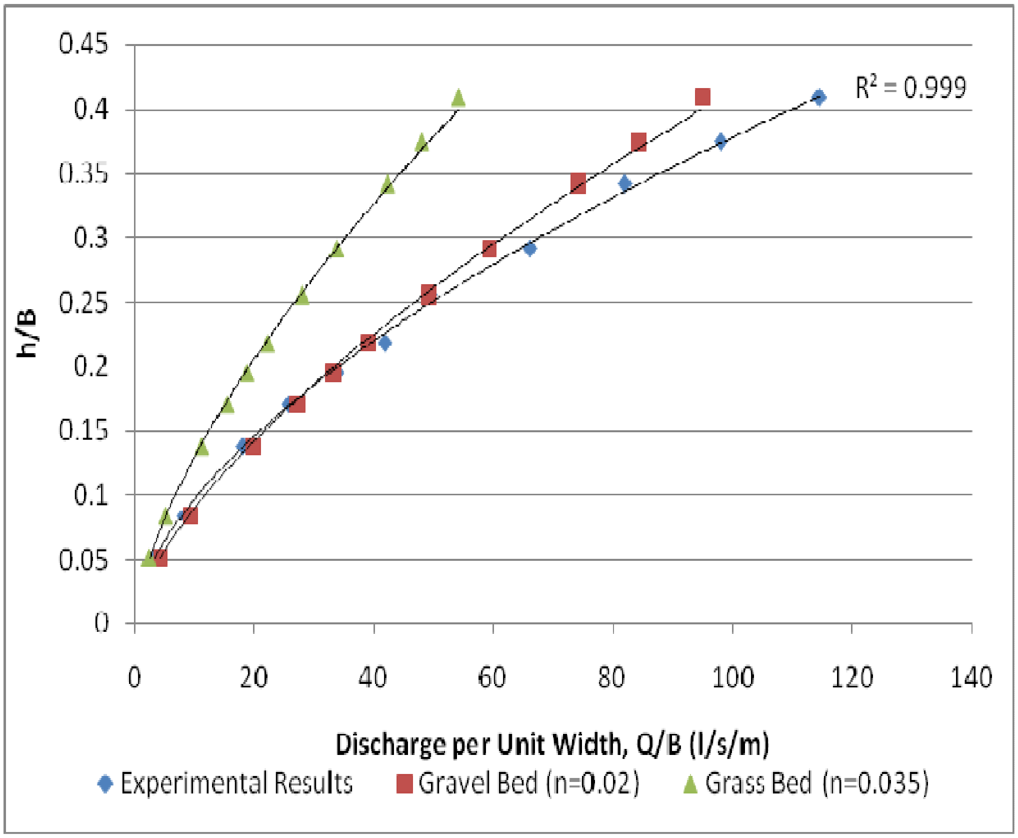

Figure 3: Stage-Discharge Curve for the Experimental Channel with Grass and Gravel Bed Roughness as Compared with Manning's Theoretical Model

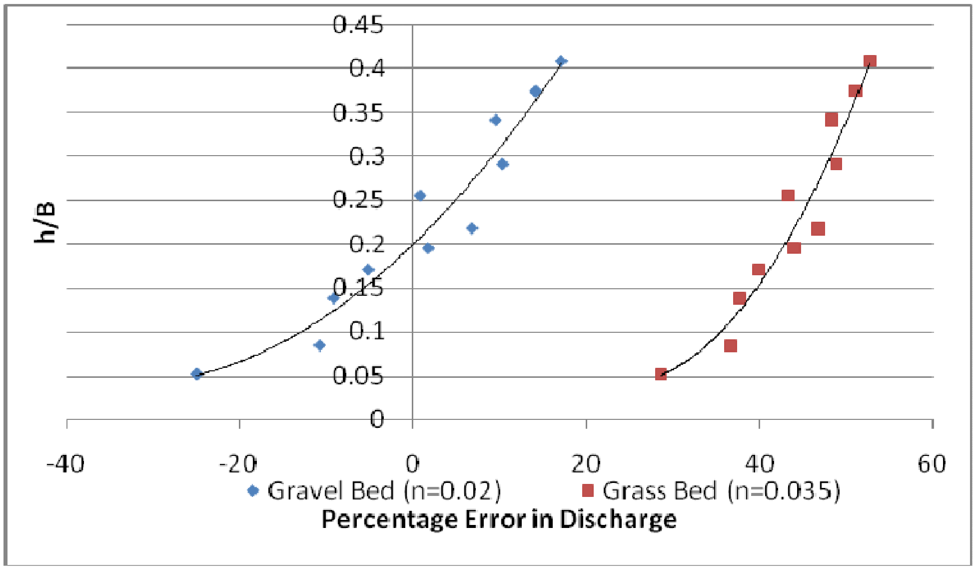

Figure 4: Percentage Error in Discharge Estimation Using the Theoretical Model

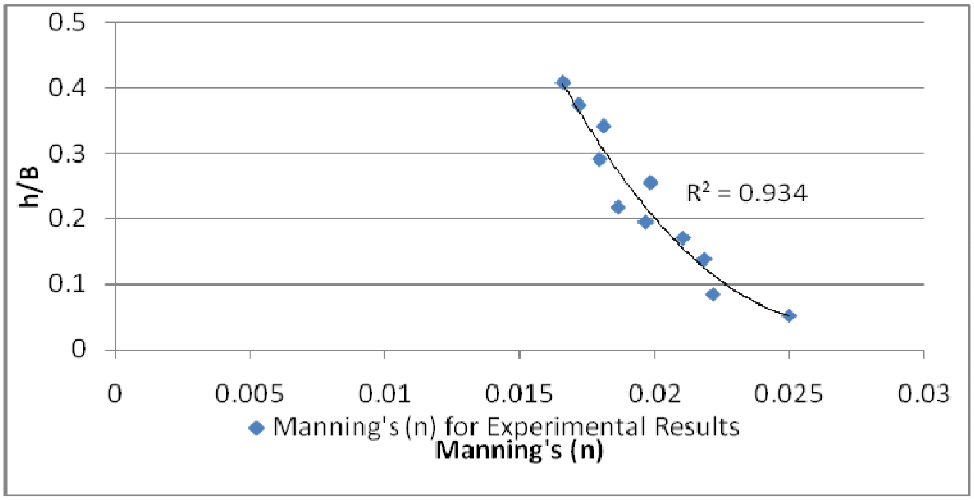

Figure 5: Variation of Manning's n with Flow Depth

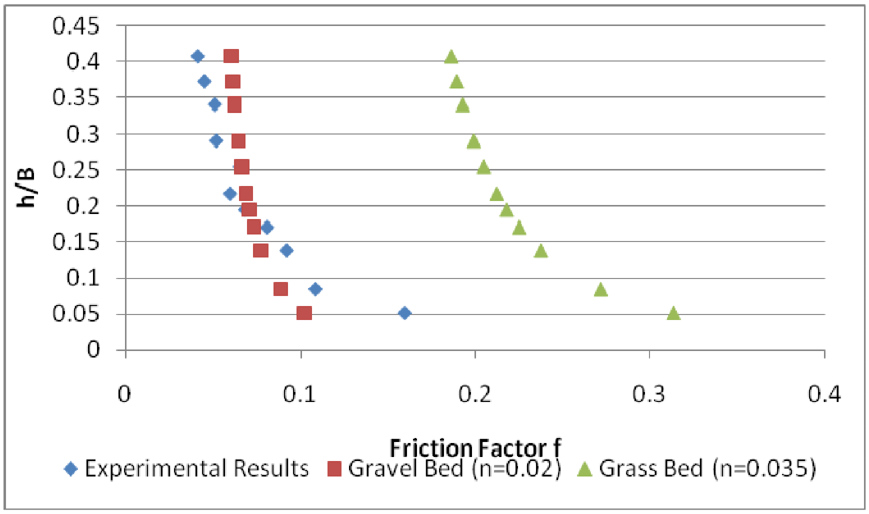

Figure 6: Variation of Friction Factor with Flow Depth for the Experimental Channel and the Theoretical Channels

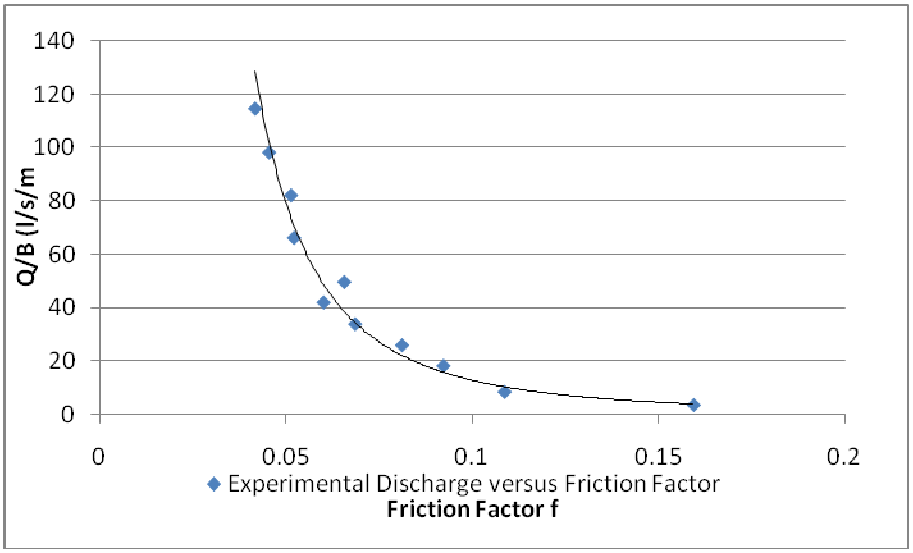

Figure 7: Variation of Friction Factor with the Experimental Discharge

CONCLUSION

This research work represents an approach for successful river restoration and flood management processes. It quantifies the roughness in heterogeneous channel to provide an accurate estimation of river and hydraulic parameters that are necessary for channel conveyance in the face of river restoration using grass vegetation. The work will also help to better understanding the physical processes and complex bed roughness interaction mechanism occurring within a partly vegetated open channel system.

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