

EFFECT OF BED ROUGHNESS ON FLOW CHARACTERISTICS

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ABSTRACT

Resistance to flow determines several hydraulic parameters in streams and rivers that should be properly represented for estimating water discharges and sediments transport. In this research, a combination between experimental and numerical models study were carried out to investigate the influence of bed roughness of flow characteristics. Seventy two (72) runs were conducted physically and verified numerically. 6 bed materials were used (Gravel, Cement, Interlock, Grass, Formica, and Vegetations). 4 discharges and 3 tail gate water levels were tested with each bed material. Results were analyzed and were graphically presented and the percentages of errors between the obtained results from the used models were reported to define the sufficient compatibility between the used models. The Manning roughness coefficient was estimated for each bed material using the experimental and numerical models. The percentages of errors between them were reported and were under estimations. The models proved that for a given bed material, the roughness coefficient was inversely proportional to the discharge and directly proportional to the tail gate water levels.

Key words: Manning Equation, Bed roughness, Velocity Distribution, Froude number

1. INTRODUCTION

Determination of Manning's roughness coefficient (n) for natural streams remains a challenge in practices. One source for determining the n -values that has received practitioners attention to be determined from field data (measured discharge and water-surface slope) in combination to photographs and site descriptions (ancillary information). Further, improvements in the visual approach can be made in presenting site characteristics and describing site ancillary information. For deriving a general equation, many studies were done aimed to link some hydraulic coefficients each other (i.g. flow discharge or depth, bed roughness, river width and slope,) to bed and flow characteristics, Limerinos [1] and Griffiths [2].

Some studies were done for natural streams; Soong et al. [3] determined the Manning's coefficients for natural Illinois Stream using prototype measurements. The numerical models were used to estimate the bed roughness; Ding et al. [4] used numerical approach based on the memory quasi-Newton method to identify the Manning's roughness coefficient in shallow water. They dominated the used method has the advantages of higher rate of convergence, numerical stability and computational efficiency. Ding and Wang [5] used a numerical method based on optimal control theories and adjoint analysis for identifying Manning's roughness coefficients in the full nonlinear de Saint Venant equations. The bound constraints for Manning's roughness coefficients were taken into account. Wang and Dawdy [6] developed a reliable resistance formula in terms of the Darcy-Weisbach friction factor. Devkota et al. [7] studied the relation between the water depth under low flow conditions, Manning's roughness coefficient and the water depth in partially filled culverts. Vatankhah [8] derived a semi-analytical solution, based on the Manning equation, to compute the length of the GVF profile for trapezoidal channels. Also, the geological survey was involved in estimating the bed roughness; Principal and Gregory [9] used United States Geological Survey (USGS) stream flow data to calculate roughness coefficients for streams in the mountains of North Carolina. They deduced that, the bed roughness was increased during low-flow conditions, and then quickly decreased as flow increased, up to the bank full elevation. These remarks were noticed for all tested sites. Focusing on the experimental investigations for bed roughness, Wang et al. [10] used the particle image velocimetry to study the effects of roughness on the flow structure in a gravel bed channel. They established a new formula to calculate the Darcy-Weisbach friction factor for the gravel bed, expressed in terms of the Reynolds number and the surface geometric parameters. Chen and Chiew [11] and [12] studied the response of velocity and turbulence to sudden change of bed roughness in open channel flow. López and Barragán [13] determined the relation between the equivalent roughness and different grain size percentiles of the sediment in gravel bed rivers under the hypothesis that the vertical distribution of the flow velocity follows a logarithmic law. Christodoulou [14] held experiments for flow in a 16.5% sloping channel over various kinds of submerged artificial

large scale roughness elements. Sadeque et al. [15] presented the results of an experimental study of flow around cylindrical objects on a rough bed in an open channel. Cheng and Emadzadeh [16] derived a formula for the prediction of the average velocity of a solitary coarse grain moving over a rigid flat channel bed. Nikora [17] suggested several models for the vertical distribution of the double-averaged (in time and in the plane parallel to the mean bed) longitudinal velocity in the flow region between roughness troughs and roughness tops. They found that the same model for velocity distribution may be applicable to a range of flow conditions and roughness types, which share some common features.

This research was thus initiated in order to investigate influence of discharge and tail gate water level on the Manning roughness coefficient for the tested bed materials. For this reason, a combination between experimental and two dimensional finite element numerical models Molinas and Hafez [18] and Ibrahim [19] were used.

2. MODELS IN HAND

In the following subsections, the complete descriptions of the used numerical and experimental models including the methodology were presented.

2.1. The numerical model

The governing differential equations for the used numerical model were in the Cartesian XY coordinates, along and across the main flow directions. On the other hand, the Navier Stokes equations were used for motion description. The fluid was assumed to be incompressible and follows a Newtonian shear stress law, whereby, viscous force was linearly related to the rate of strain. In the model, the hydrodynamics governing relationships were the equations of conservation of mass and momentum. Conservation of mass equation takes the form of the continuity equation while Newton's equations of motion in two dimensions express the conservation of momentum. The continuity equation was given as:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (1)$$

The momentum equation in the longitudinal (X) direction is

$$U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} = -\frac{1}{\rho} \frac{\partial P}{\partial X} + \frac{\partial}{\partial X} (2\nu_e \frac{\partial U}{\partial X}) + \frac{\partial}{\partial Y} (\nu_e (\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X})) + F_x + \left(\frac{\partial}{\partial z} \left(\frac{\tau_{fx}}{\rho} \right) \right)_{z=h} \quad (2)$$

The momentum equation in the lateral (Y) direction is

$$U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} = -\frac{1}{\rho} \frac{\partial P}{\partial Y} + \frac{\partial}{\partial X} (\nu_e (\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X})) + \frac{\partial}{\partial Y} (2\nu_e \frac{\partial V}{\partial Y}) + F_y + \left(\frac{\partial}{\partial z} \left(\frac{\tau_{fy}}{\rho} \right) \right)_{z=h} \quad (3)$$

The following were the assumptions of the hydrodynamic model:

- The density is constant (incompressible fluid);
- Flow conditions are constant;
- The turbulent viscosity varies with the velocity gradient;
- Surface is analyzed in a 2D;
- Free surface is a rigid lid;
- Pressure is hydrostatic; and
- Wind stresses are neglected.

It should be denoted that the complete details concerning numerical solution of the model governing equations, the boundary conditions, and the working flow chart were presented by Ibrahim [20]

2.2. The experimental work

2.2.1. Model description

All of the experiments were conducted in a flume located at the Hydraulics Research Institute experimental hall of the National Water Research Center, Egypt.

The flume was 18m long with a rectangular cross section of 0.60m width and depth. The flume has a positive slope of 0.03, Figure 1. The flume was associated with a tail water gate to control the water level. Water was pumped into the flume from an underground reservoir tank with total capacity of 80m³ by two centrifugal pumps with a discharge capacity of 0.65m³/s. and returns to the tank at the channel end. A rectangular tank was constructed to consume the maximum volume of water conveyed to the flume. Three pipes were used for this purpose. The main pipe was used to deliver water to flume entrance. Secondary pipe was used to drain the excess water to adjust the desired discharge, also for motor protection against damage due to extra loading.

Suction pipe submerged at tank bottom to deliver water to the main one. The flume was ended by a control steel gate adjusted manually to obtain the required water depths. Six bed materials were used. Gravel, Cement, Interlock, Weeds, Formica, and Vegetations, were presented respectively in Figure 2 (a-f). Herein some descriptions for them, the Interlock blocks, (Figure 2.c) has a grooved circles of 9cm diameter and 4.5cm apart. The Grass, (Figure 2.d) was artificial of 6mm length. The Formica, (Figure 2.e) was 2mm thickness. The Vegetations, (Figure 2.f) were artificial of 16cm height and 15cm intermediate spacing.

Each bed material was tested with 4 discharges and 3 tail gate water levels. The tested discharges were 10, 20, 30, and 40 l/sec. While, the tested tail gate water levels were 0.15, 0.225, and 0.3m.

2.2.2. Model set-up and measurement techniques

Firstly, the flume bed slope was determined by using a leveling device and two point gauges. The following procedure was used for each experimental run:

1- Clean the flume bed and side walls to guarantee the results accuracy; 2-Set-up and fix the selected material in the flume bed; 3- The tail gate was completely closed, 4- The flume was then filled with water to obtain the desired depth; 4- The pump was activated and the discharge was adjusted using a control valve and ultrasonic flow-meter with an accuracy of $\pm 1\%$; 5- The tail gate was screwed gradually until the required downstream water depth was reached using the point gauge; As soon as the flow rate in the channel was stable, the running time of the test is started; 6- After 2 hours (where there is no appreciable change in flow turbulence), the velocity measurements were recorded at 8 cross sections, (Figure 3); 7- The pump was switched off, the flume was emptied from water using the tail gate.

2.2.3. Estimation of Manning roughness coefficient

Roughness coefficients represent the resistance to flood flows in channels and flood plains. The results of Manning's formula, an indirect computation of stream flow, have applications in flood-plain management, in flood insurance studies, and in the design of bridges and highways across flood plains, Limerinos [20]. For a steady state and uniform flow conditions; the mean velocity can be obtained by the following equation, Manning [21]:

$$v = \frac{1}{n} R^{2/3} S^{0.5} \quad (4)$$

The Froude number was given by:

$$F_r = \frac{v}{\sqrt{gD}} \quad (5)$$



Fig. 1. The Used Flume

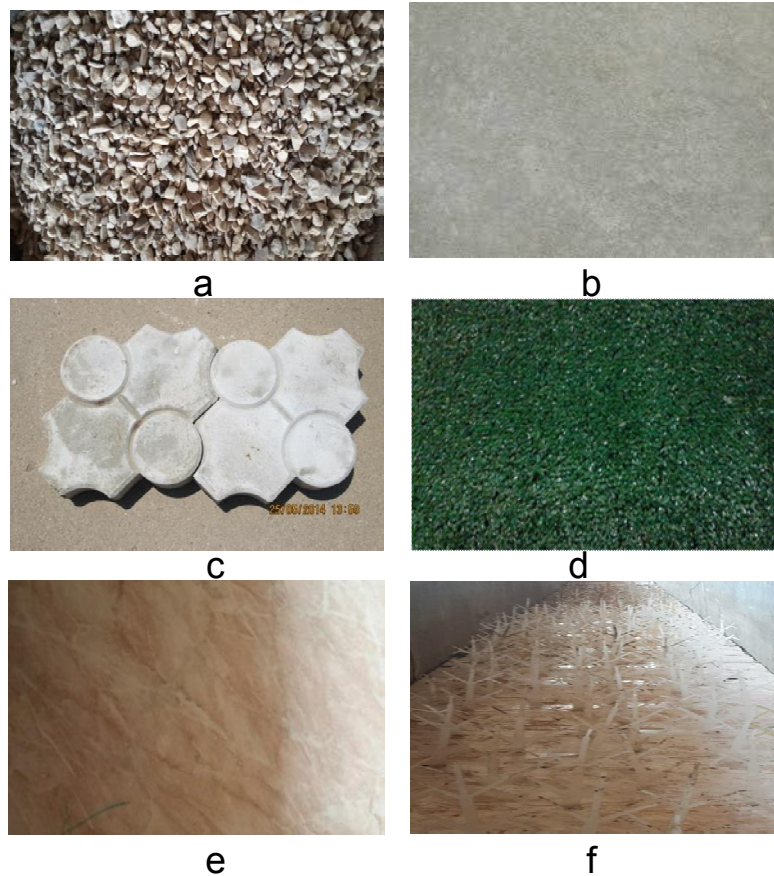


Fig. 2. The Used Bed Materials

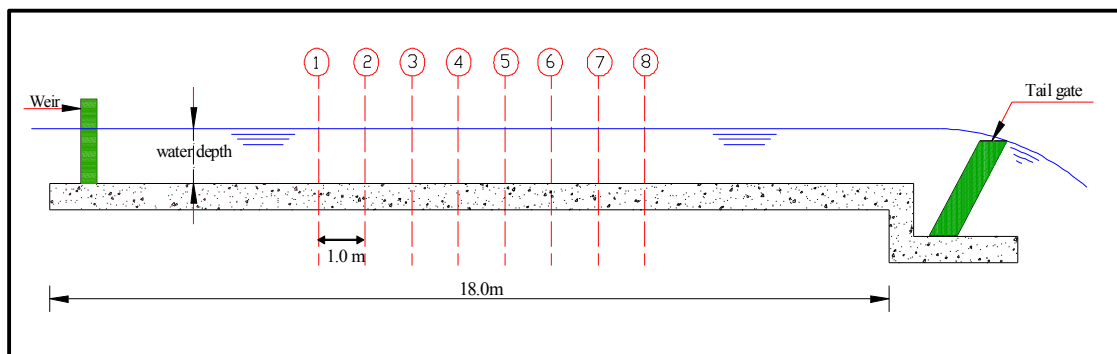


Fig. 3. The different cross section in the flume

2.3. Models calibration and verification

To assure the validity and the accuracy of the used numerical model; the model was calibrated and verified using experimental velocity measurements for 2 different bed materials one of them was natural; the Gravel and the other was artificial; the Weeds. A carefully well designed dense mesh consists of more than 8000 node were used; to increase the model sensitivity even for small changes in velocity distribution. During the calibration process, the minimum tested flow conditions from the view of discharge and tail gate water levels were used, as the tested discharge and the tail gate water level were 10 l/s and 0.15m, respectively. However, the maximum tested flow conditions (the tested discharge and the tail gate water level were 40 l/s and 0.30m, respectively) were used in model verification. The maximum and minimum flow conditions were carefully selected for more model confidence. Figures 4 and 5 defined the good correlation between the used models for the studied cases; as the percentages of errors were less that 10%.

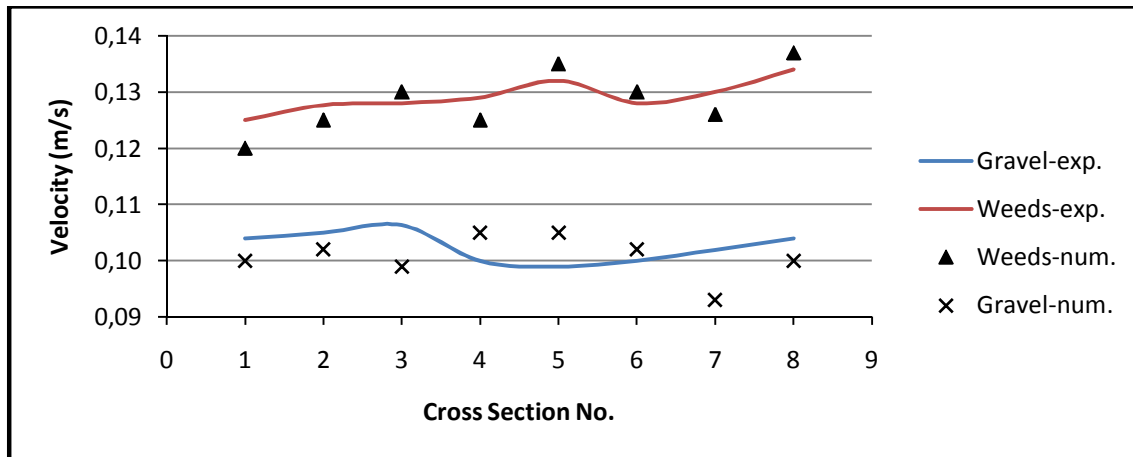


Fig. 4. Model Calibration

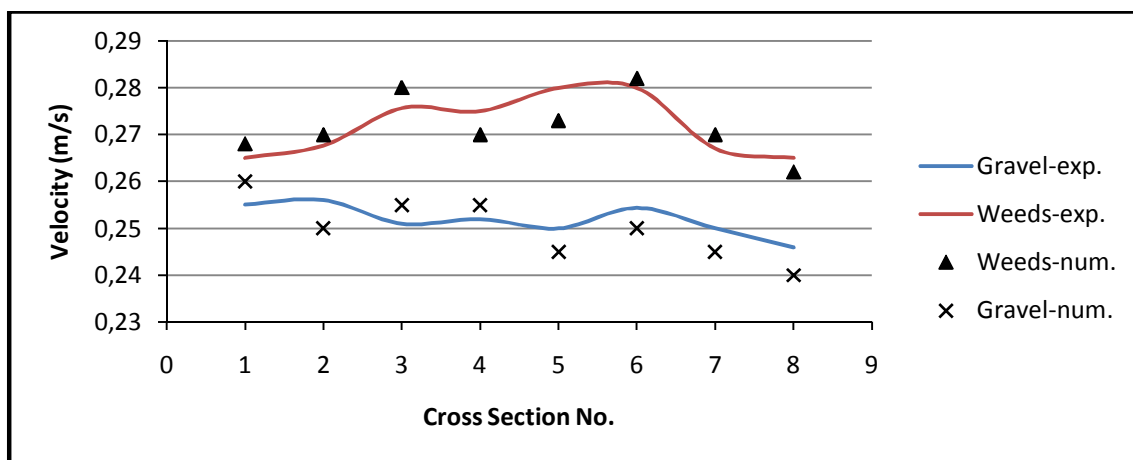


Fig. 5. Model Verification

3. RESULTS AND ANALYSIS

The analysis procedure was categorized to investigate the influence of discharge, tail gate water level, and hydraulic radius on Manning roughness coefficient. The effect of bed materials on the velocity distribution at different cross sections along channel was also presented. Finally, a comparison between the Manning roughness coefficients for the tested bed materials obtained experimentally and numerically was held. The percentages of errors were presented.

3.1. The discharge and the Manning roughness coefficient

Figure 6 showed the relation between the discharge and the Manning roughness coefficient for the tested bed materials under fixed tail gate water level of 0.15m. The preliminary figures inspections, similar curves trend was highlighted. Also, it's noticed that the maximum and minimum Manning coefficients were found in case of Formica and artificial vegetation bed materials, respectively. Moreover, fixing the bed material, the maximum and minimum Manning coefficients were located at the discharges of 10 and 40 l/s, respectively. Consequently, it's concluded that the Manning roughness coefficient was inversely proportional to the discharge for fixed bed material.

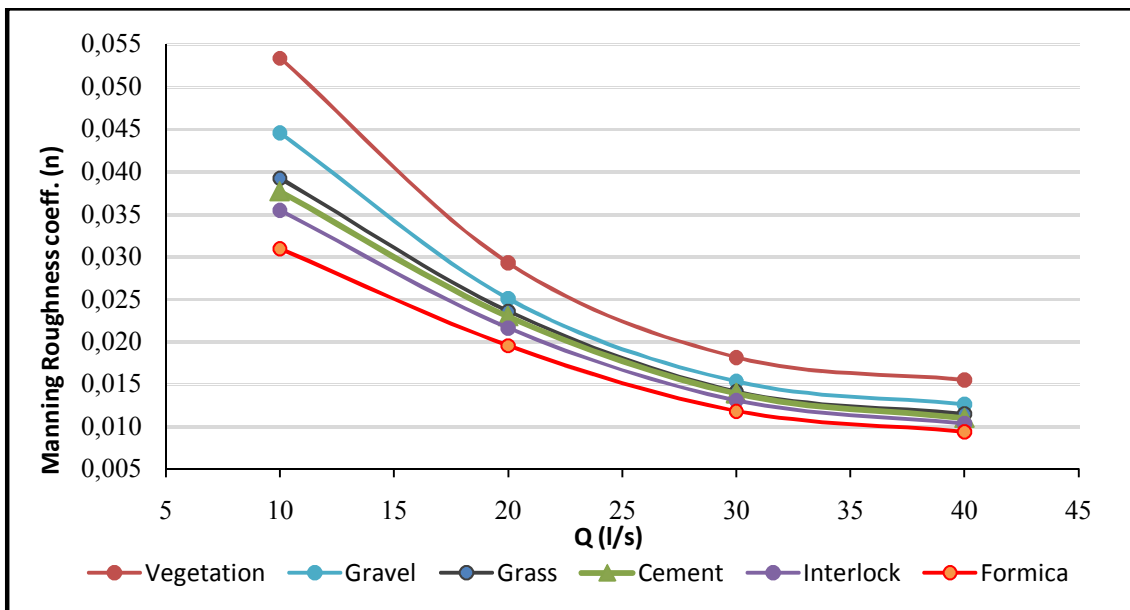


Fig. 6. Effect of Discharge on Manning Roughness Coefficient

3.2. The tail gate water level and the Manning roughness coefficient

To investigate the relationship between the tail gate water level and the Manning roughness coefficient; figure 7 was plotted under fixed discharge of 10 l/s. Similar curves trend was noticed. Also, it's illustrated that artificial vegetations bed material gave the peak Manning coefficient. However, the Formica presented the lowest values. The figure indicated that for fixed bed material, the maximum and minimum Manning coefficients were located at tail gate water levels of 0.30 and 0.15 m, respectively. Consequently, it's demonstrated that fixing the bed material, the Manning roughness coefficient was directly proportional to the tail gate water level.

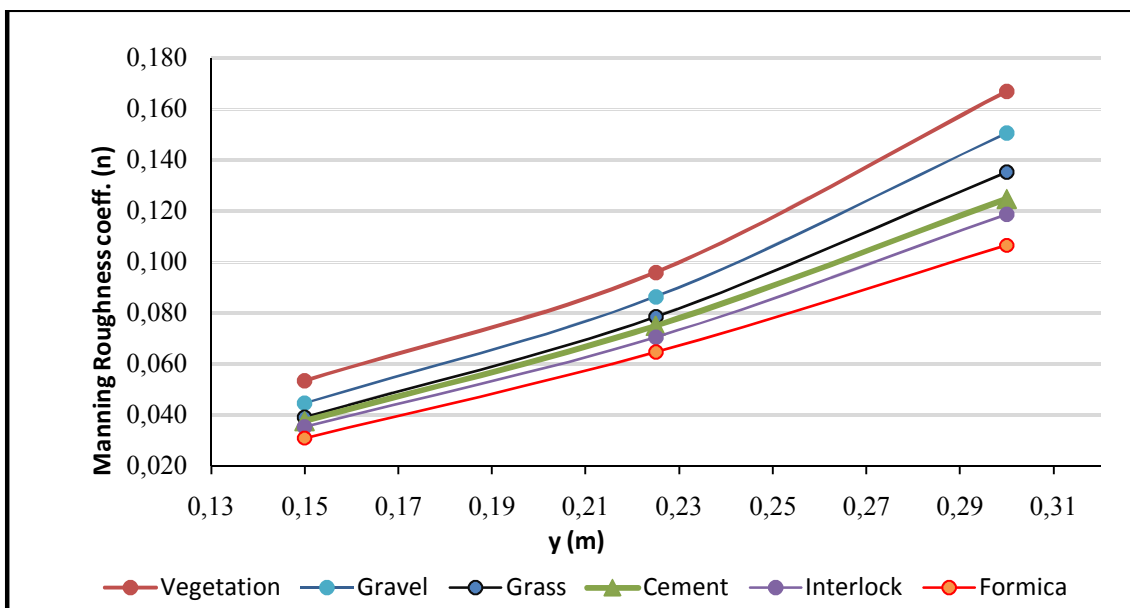


Fig. 7. Effect of Tail Gate Water Level on Manning Roughness Coefficient

3.3. The hydraulic radius and the Manning roughness coefficient

Figure 8 was plotted for the Interlock bed material to define the effect of the hydraulic radius on Manning roughness coefficient at different discharges. It should be denoted that the same figure was plotted for the tested bed materials and the same trend was found. Investigating the figure, it's noticed that for the same discharge, the minimum and maximum Manning roughness coefficients were located at the hydraulic radius of 0.10 and 0.15, respectively. Consequently, it's deduced that the Manning roughness coefficient was directly proportional to the hydraulic radius.

For a constant hydraulic radius, the figure showed that the minimum and maximum Manning roughness coefficients were found at discharges of 40 and 10 l/s, respectively. That agreed and emphasized the findings reported in sub-section 3.1, that the Manning roughness coefficient was inversely proportional to the discharge.

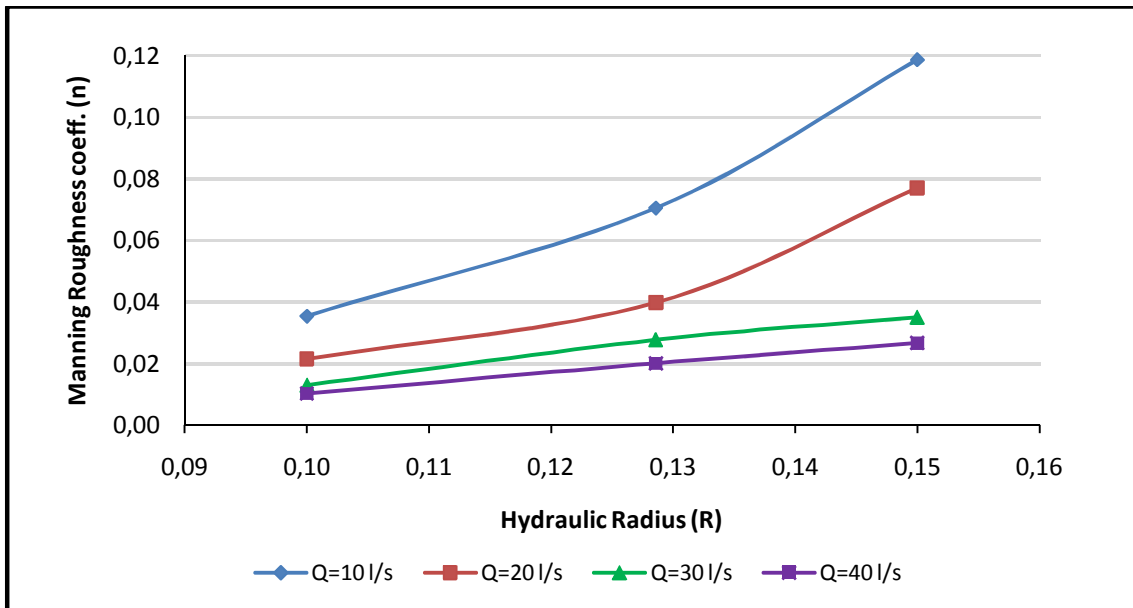


Fig. 8. Effect of Hydraulic Radius on Manning Roughness Coefficient

3.4. The Velocity distribution along channel

To define the influence of bed material on the longitudinal velocity distribution at the mid channel; figure 9 was plotted under fixed discharge of 10 l/s, and tail gate water level of 15cm. The figure showed that for velocity fluctuations at the different cross sections for the considered bed materials except the Vegetation were small. Focusing on the Vegetations, the velocity distribution has multi-peak higher and lower values. That owned to during fixing the Vegetations process, the intermediate distance between the one stick and another was 15cm; also the Vegetations were 16cm length (figure 2.f). Conversely, the other bed materials have not any intermediate spacing. The figure also presented that the Formica gave the peak velocities that were much closer to the corresponding in the case of the Interlock. On the other side and excluding the Vegetations, the minimum velocity values were noticed in case of Gravel.

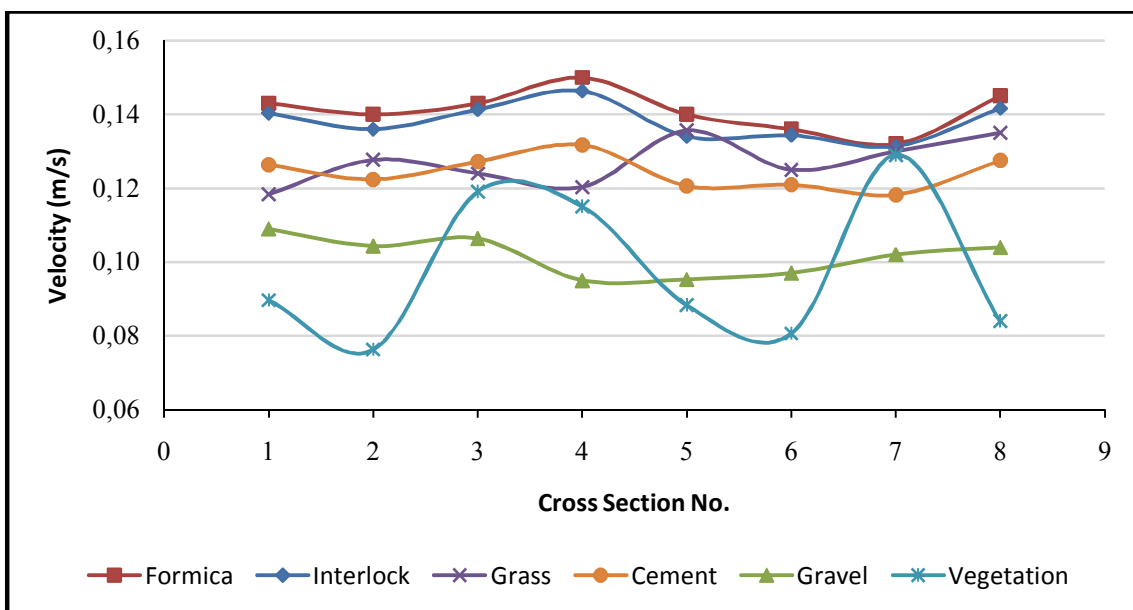


Fig. 9. Effect of Bed Material on Velocity Distribution

3.5. Effect of Froude and Reynolds numbers on the Manning roughness coefficient

Figures 10 and 11 were plotted to define the relationship between the Froude and Reynolds numbers on the Manning roughness coefficient, respectively. The results of the 72 runs were scatter presented. Multiple regression power equations were developed. The figures demonstrated that both Froude and Reynolds numbers were inversely proportional to the Manning roughness coefficient. Also, the correlation between the Manning roughness coefficient and the Froude No. was higher than the Reynolds No.

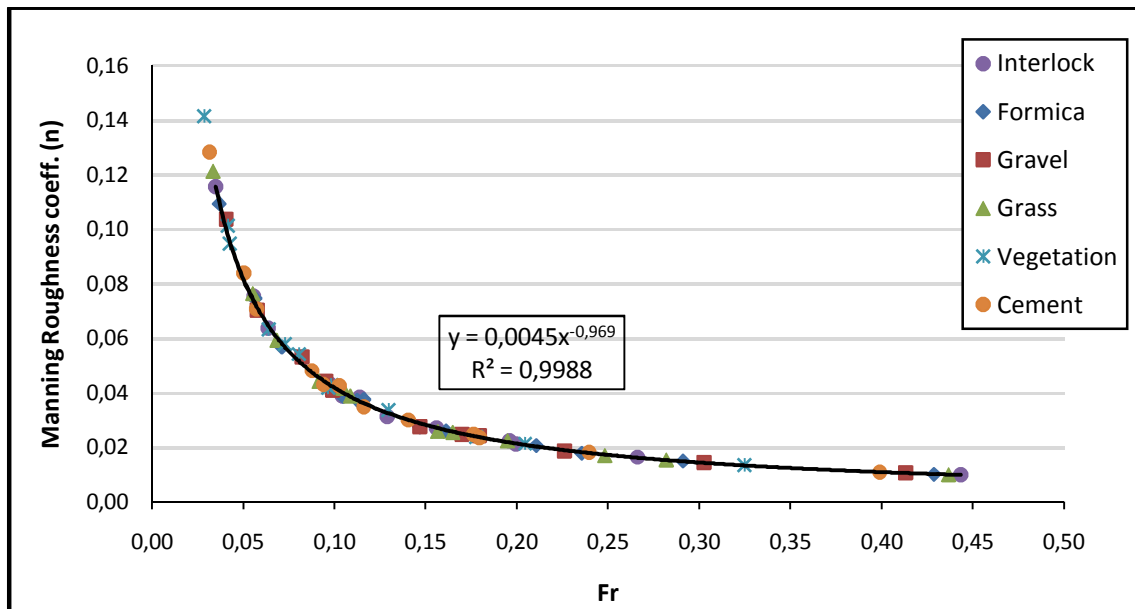


Fig. 10. Effect of Froude No. on Manning Roughness Coefficient

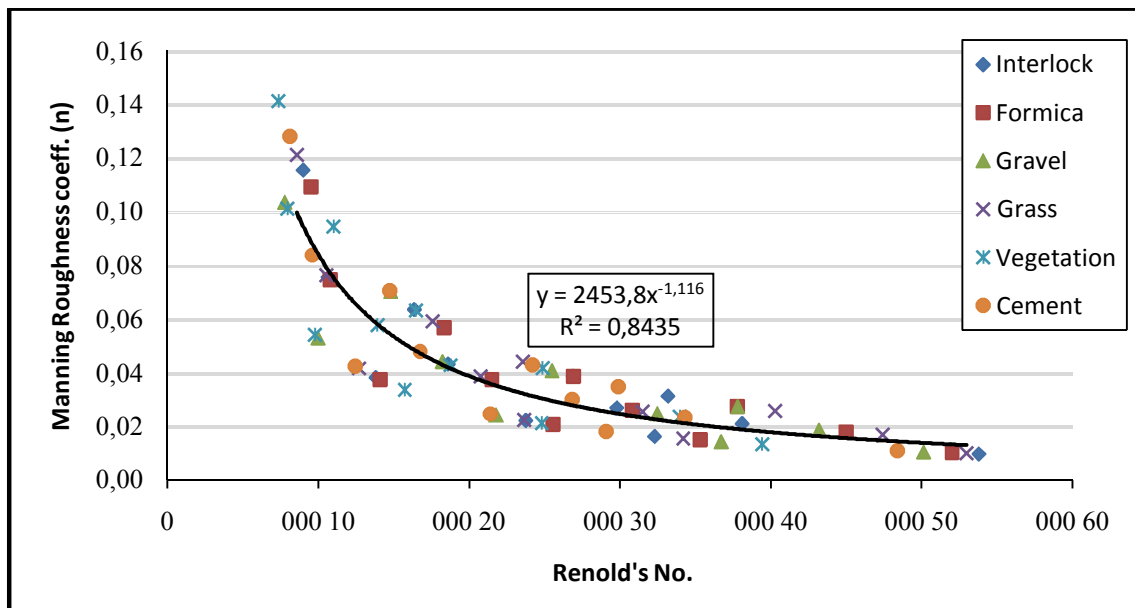


Fig. 11. Effect of Reynolds No. on Manning Roughness Coefficient

3.6. Estimation of the Manning roughness coefficient

After 12 experimental and 12 numerical runs were done for the 6 bed materials considered in the present study, the average Manning roughness coefficient was determined for each bed material. The bed materials were presented in the table in an ascending form according to the Manning roughness coefficient. Table 1 illustrated the comparison between the Manning roughness coefficient observed from the experimental model measurements and the predicted from the numerical model. The percentages of errors between the two models were also presented and were under estimations that emphasized the good correlation between them. The table indicated that the Formica and the Vegetations bed materials gave the minimum and maximum Manning roughness coefficient, respectively. That explained and agreed the findings reported in sub-section 3.4 as the Formica gave the peak velocity values at all cross sections. Consequently, combining table 1 and figure 9 it's

concluded that the velocity increased as the Manning roughness coefficient decreased, that agreed with the obtained by Manning [21].

Table 1. Observed and predicted Manning roughness coefficient

Bed Material	Manning Roughness coefficient		
	Observed	Predicted	%Error
Formica	0.039	0.042	7.692
Interlock	0.041	0.039	-4.878
Grass	0.043	0.042	-2.325
Cement	0.047	0.046	-2.127
Gravel	0.051	0.049	-3.921
Vegetations	0.057	0.060	5.263

4. CONCLUSIONS

The experimental and numerical study of the effect of bed material roughness presented in Manning coefficient on flow including the discharge and the tail gate water levels led to the following conclusions:

- For fixed bed material, the Manning roughness coefficient was inversely proportional to the discharge, and directly proportional to the tail gate water levels.
- For fixed discharge, the Manning roughness coefficient was directly proportional to the hydraulic radius.
- For fixed hydraulic radius, the Manning roughness coefficient was directly proportional to the discharge.
- The Froude and Reynolds numbers were inversely proportional to the Manning roughness coefficient.
- The velocity distribution was inversely proportional to the Manning roughness coefficient.

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NOTATIONS

U = Longitudinal surface velocity	[m/s]
V = Transverse surface velocity	[m/s]
P = Mean pressure	[kg/m ²]
F _x = Body force in X direction	[kg.m/s ²]
F _y = Body force in Y direction	[kg.m/s ²]
g = Gravity acceleration	[m/s ²]
Q = Discharge	[m ³ /s]
y = Tail gate water level	[m]
R = Hydraulic radius	[m]
n = Manning roughness coefficient	[s/m ^{1/3}]
Fr = Froude number	

GREEK SYMBOLS

ν_e = Kinematics eddy viscosity	[kg/m.s]
ρ = Fluid density	[kg/m ³]
τ_{fx} = Turbulent frictional stresses in X-direction	[kg/m ²]
τ_{fy} = Turbulent frictional stresses in Y-direction	[kg/m ²]

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