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EFFECT OF PARTIALLY OR FULLY SUBMERGED VEGETATION ON ROUGHNESS COEFFICIENTS IN RECTANGULAR OPEN CHANNELS

Abdelazim M. Negm
Professor of hydraulics, Water. & W. Str., Engineering Dept.,
Faculty of Eng., Zagazig University, Zagazig, Egypt
e-mail: amnegm85@yahoo.om

ABSTRACT

This paper presents the results of an experimental investigation on the effect of both partially and fully submerged non-vertical non-rigid cylindrical vegetation on the roughness indices in open channels. The considered roughness indices are the friction factor f, the Chezy's roughness coefficient C, and the Manning's roughness coefficient n. Six models were tested using three different channel bottom slopes. The vegetation (roughness) elements were distributed in staggered way in four of them and in parallel way in the other two for fully submerged vegetation. While, for partially submerged vegetation, only staggered distribution was considered. It was found that the trend of variation of the roughness indices with the Froude number are similar regardless of the distribution pattern. The values of the roughness indices were found to be a function of Froude number F_n, the channel bottom slope S, and the roughness density I. Statistical prediction models were developed to estimate the roughness indices in terms F_n, S and I using the multiple linear regression analysis. Good agreement were obtained between predictions of the developed models and the measured values.

KEYWORDS:

Open channels, Hydraulics, vegetation, roughness indices, friction factor, Manning roughness coefficient, Chezy resistance.

INTRODUCTION

Management of rivers and canals flows necessitates sufficient information on the type of vegetation, its density, degree of submergence and degree of resistance to the flow. Such information may be obtained through different kinds of studies either by various methods of simulation and modeling techniques like those done by Shimizu et al. [1,2]˙ Shimizu & Tsujimoto [3], Kutija & Hong [4], Nezu & Onitsuka [5], Choi [6] and Fischer-Antze et al. [7], or through field measurements such that those carried out by Bakry et al. [8] and Dolgopolova [9], or achieved by experimental tests of roughness elements simulating the vegetation either in rigid state, such as those accomplished by Shimizu et al. [10] and Tsujimoto et al. [11], or for flexible case, such as that done by Kouwen and Unny [12], Christensen [13], EL-Hakim & Salama [14] and El-Samman & Attia [15] or for non-flexible no-rigid state which was covered by Fahti-Maghadam and Kouwen [16] and Wu et al. [17].

The resistance of vegetation to the flow may be measured by one of the roughness indices as the friction factor (f), the Chezy's roughness coefficient (C), Manning's roughness coefficient (n) or the so-called retardance coefficient (N). This paper presents the analysis and discussion of the results of an experimental investigation on the effect of using non-rigid cylindrical roughness simulating partially and completely submerged vegetation under different flow conditions using various bottom slopes and various roughness densities arranged in either staggered or parallel patterns.

THEORETICAL BACKGROUND

Using the dimensional analysis, the roughness indices could be proved to be function of the relative roughness height K/R (K is the height of roughness and R is the hydraulic radius), the Froude number, F_n, the bottom slope, S, the roughness intensity, I, and the method of distribution of vegetation, ϕ (staggered or parallel) as follow:

$$\mathrm{f\ or\ C\ or\ n} = \phi_1\left(\frac{K}{R}, F_n, S, I, \phi\right) \qquad (1)$$

in which F_n ($F_n = V/(gy)^{0.5}$, V is the average velocity, y is the average depth of flow, g as the gravitational acceleration. Normally it is difficult to obtain precise values of K/R in open channels and hence it will be dropped from Eq.(1). Thus Eq.(2) becomes:

$$\mathrm{f\ or\ C\ or\ n} = \phi_2\left(\mathrm{F_n, S, I, \phi}\right) \qquad (2)$$

Also, ϕ is neglected because a limited number of distribution pattern is used. The function ϕ_2 is an arbitrary function to be determined by using the multiple regression analysis based on the experimental data.

EXPERIMENTAL WORK

The experiments of the present study were conducted on a glass sided tilting flume of 9 m long working section. The flume is 30.5 cm wide and 30 cm deep. The water depths were measured by means of point gauges (of ±0.1 mm accuracy) mounted on instrument carriages. The discharge was measured by a pre-calibrated V-notch installed in a measuring tank. The measuring tank is located below the outlet of the flume at its downstream end and is connected directly to underground sump tank. The flume is equipped with a tailgate to control the tailwater depth. A centrifugal pump lifts the water from the underground sump to the flume inlet. The water runs through the flume working section then returns back to the sump tank via the measuring tank [18,19].

Plastic cylinders tubes of diameter equals 7.35 mm and height of 50 mm was used to simulate the vegetation in the channel bed. The plastic tube is normally flexible when its length and the affecting force are sufficient. However, a length of 50 mm from such tubes is being non-vertical but the flow forces are not capable to move any portion of the fixed cylinders and therefore they are termed non-vertical rigid vegetation. The elements were fixed in the flume bed through holes of equal diameters in a wooden plate 354.735 cm long. The model was fixed at 300.05 cm from the flume entry. Each tested model consisted of many elements arranged either in staggered or parallel to form one of the tested models. Three models were tested under partial submergence conditions. The intensities of the roughness were 0.6%, 1.2% and 2.1% for the three tested models [18]. For fully submerged roughness elements, a total of six models were tested under submerged flow conditions. Out of the six tested models [19], the elements in 4 models were arranged in staggered way with intensities of 0.6%, 2.1%, 2.327% and 8.8%. The elements of the other two models were arranged in parallel way with intensities of 1.2% and 4.654%. The roughness intensity was calculated by multiplying the cross section of one element by the number of element in the model divided by the product of the roughened length and the width of the flume. A typical staggered model with intensity of 0.6% consisted of 148 cylinders with 59 rows having transverse spacing of 6 cm and longitudinal spacing between roughness elements of 10 cm. The tests were conducted under uniform flow conditions when no roughness elements were used but with roughness elements the flow through the test section varies due to the increasing head loss from upstream to downstream side of the model. The bottom slope was varied three times for each tested model as 0.3765%, 0.7538% and 1.1307%. The depths of flow were measured at four locations. The first depth measurement was taken at 5 cm upstream the model. The other three depth measurements were taken at equal spacing from the first one, each one is 100 cm apart from the other one, such that the fourth reading is at 65 cm away from the end of the model.

RESULTS AND DISCUSSIONS

PARTIALLY SUBMERGED VEGETATION

The friction factor is computed from the measured quantities using equation $f = \frac{8gRS}{V^2}$ in which V is the average values of the velocity at the three locations over the length covered by vegetation, R is the average hydraulic radius, S is the bottom slope and g is the acceleration due to gravity. The computed values of f are used in Coolebroke resistance equation, to compute the relative roughness height K/R by trials and error procedure. The values of friction factors for non-vegetated channel, f_s, is calculated using Blasius equation, $f_s = 0.223 R_n^{-0.25}$, in which R_n is the Reynolds number. The friction factor for the vegetated bed is obtained by subtracting f_s from f. The Chezy roughness coefficient is computed using $C = \sqrt{\frac{8g}{f}}$ while Manning n is computed using $n = \frac{R^{1/6}}{C}$.

The variations of total friction factor f with F_n for different tested vegetation intensities, I, different patterns, and channel bottom slope, S are given in Figure 1. It is observed that the friction factor is very small for non-vegetated channel compared to vegetated one. The trend of variation of f with F_n is nonlinear with higher values at lower Froude number and vice versa. Steeper bottom slopes produces higher values of the friction factor which match with the fact that the friction increases with the increase of the energy slope as more energy is dissipated when the resistance to the flow is large. The friction factors for larger vegetation density is greater than for those for smaller vegetation density. Larger vegetation densities produce higher friction factors at smaller Froude number because the velocity is reduced when the flow suffers from high vegetation or roughness resistance. It should be mentioned that the friction factor due to vegetation only, f_r, (Figure 2) follows the same trend of variation as the total friction factor which the sum of the friction factor due to non-vegetated and vegetated channel.

The variation of Manning Roughness n with F_n shown in Figure 3 shows similar trend as f with F_n because n is inversely proportional with the velocity and directly proportional with the slope. Also, at low values of F_n and larger values of I, the friction factor is higher. Manning's n decreases with the increase of F_n at constant slope since small values of n means little resistance to the flow and hence high velocity values that yield larger F_n. Low density of vegetation offer relatively smaller resistance to the flow and hence it produces smaller values of n.

Inversely to f and n, the variations of C with F_n as shown in Figure 4 follow a linear increasing trend assuming constant slope with smaller values of C at low F_n and high I. The values of C is higher for larger slopes. The values of C for non-vegetated bed is very high compared to those of vegetated channels. Vegetation with higher densities offers more resistance to the flow and hence the coefficient C will be smaller yielding smaller velocity value at constant slope.

It is interestingly to observe that the plot of the equivalent roughness height, K/R with F_n indicated in Figure 5 follow similar trend to those of f with F_n and n with F_n because larger values of K/R normally produce higher roughness indices f and n at lower values of F_n.

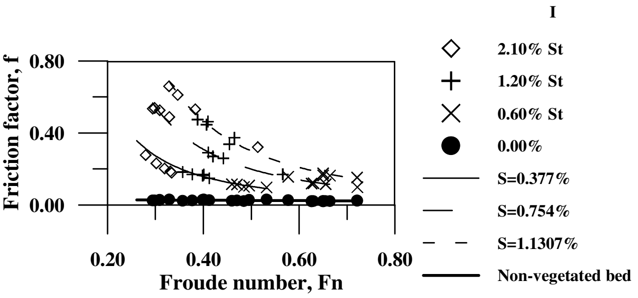


Figure 1 Relationship between friction factor, f and Froude number, F_n

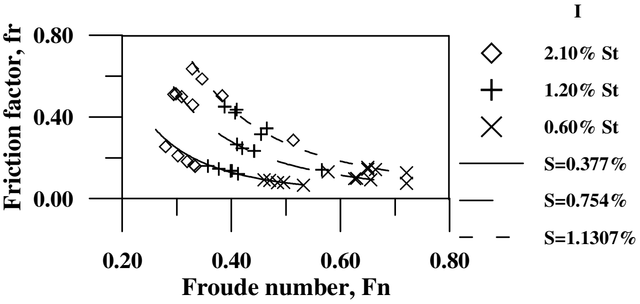


Figure 2 Relationship between friction factor, fr and Froude number, F_n

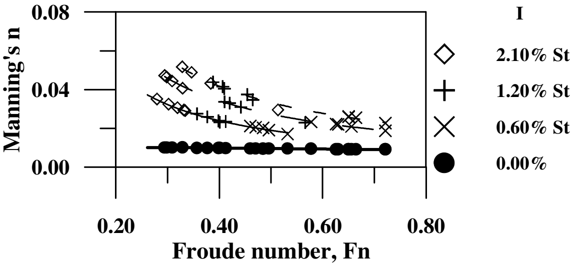


Figure 3 Relationship between Manning roughness coefficient, n and Froude number, F_n

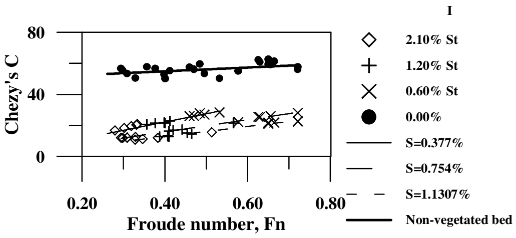


Figure 4 Relationship between Chezy roughness coefficient, C and Froude number, F_n

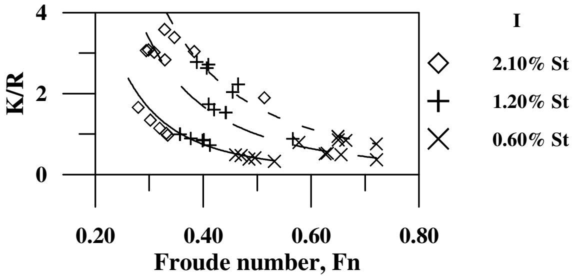


Figure 5 Relationship between relative roughness height K/R, and Froude number, F_n

FULLY SUBMERGED VEGETATION

The variations of total friction factor f with F_n for different tested vegetation intensities, I, different patterns, and channel bottom slope, S are given in Figure 6. It is observed that the friction factor is very small for non-vegetated channel compared to vegetated one. The trend of variation of f with F_n is nonlinear with higher values at lower Froude number and vice versa. Steeper bottom slopes produce higher values of the friction factor which match with the fact that the friction increases with the increase of the energy slope as more energy is dissipated when the resistance to the flow is large. The friction factors for larger vegetation density is greater than for those having smaller vegetation density. Larger vegetation densities produce higher friction factors at smaller Froude number because the velocity is reduced when the flow suffers from high vegetation or roughness resistance. It should be mentioned that the friction factor due to vegetation only, f_r, (Fig. 7) follows the same trend of variation because the total friction factor is the sum of the friction factor due to non-vegetated and vegetated channel beds.

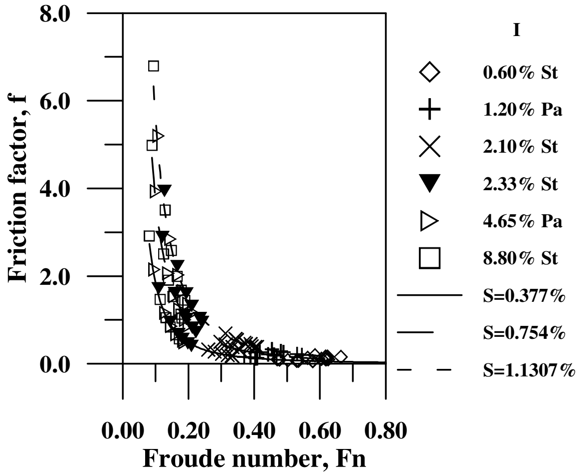


Figure 6. Relationship between f and F_n for different vegetation intensities and slopes

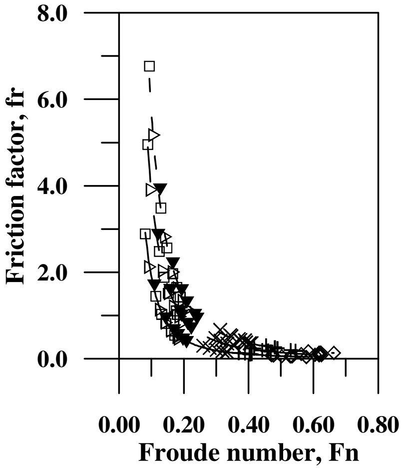


Figure 7. Relationship between f_r and F_n for different vegetation intensities and slopes

The variation of Manning Roughness n with F_n shown in Figure 8 shows similar trend as f with F_n because n is inversely proportional with the velocity and directly proportional with the slope. Also, at low values of F_n and larger values of I, the friction factor is higher. Manning's n decreases with the increase of F_n at constant slope since small values of n means little resistance to the flow and hence high velocity values that yield larger F_n. Low density of vegetation offer relatively smaller resistance to the flow and hence it produces smaller values of n.

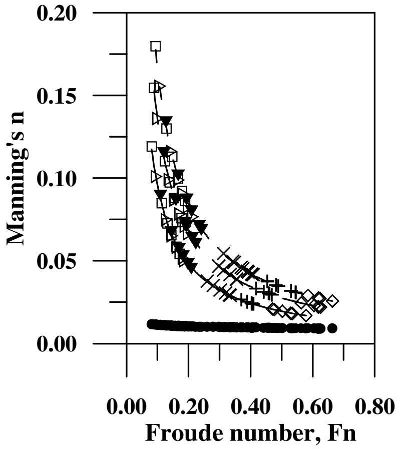


Figure 8. Relationship between n and F_n for different vegetation intensities and slopes

Inversely to f and n, the variations of C with F_n as shown in Figure 9 follows a linear increasing trend assuming constant slope with smaller values of C at low F_n and high I. The values of C is higher for larger slopes. The values of C for non-vegetated bed is very high compared to those of vegetated channels. Vegetation with higher densities offers more resistance to the flow and hence the coefficient C will be smaller yielding smaller velocity value at constant slope.

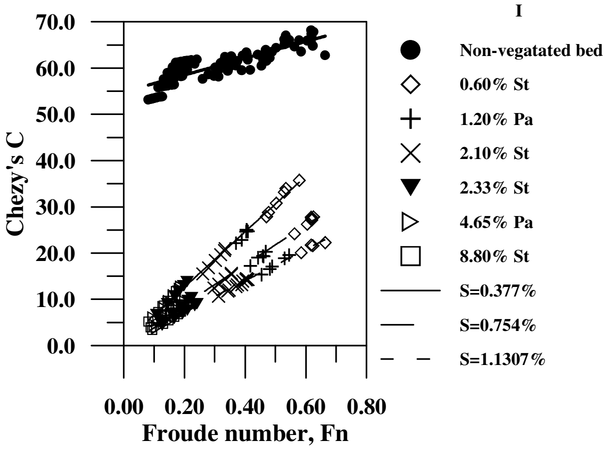


Figure 9. Relationship between C and F_n for different vegetation intensities and slopes

It is interestingly to observe that the plot of the equivalent roughness height, K/R with F_n indicated in Figure 10 follow similar trend to those of f with F_n and n with F_n because larger values of K/R normally produce higher roughness indices f and n at lower values of F_n.

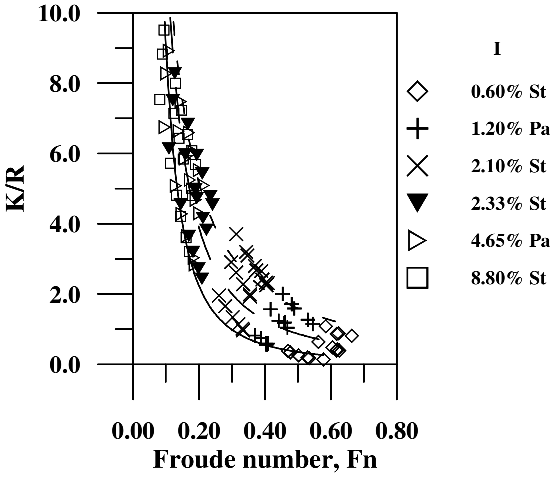


Figure 10. Relationship between K/R and F_n for different vegetation intensities and slopes

PREDICTION OF ROUGHNESS COEFFICIENTS

PARTIALLY SUBMERGED VEGETATED

Using the collected data for the three roughness patterns and the three bottom slopes, the multiple linear and non-linear regression is used to test numerous proposed model to correlate the parameters of eq. 2. The following set of equations are found to be well representative for the data.

$$f_r = 8.373(F_n)^{-1.936}(S)^{1.067}(I)^{0.148} \qquad (3)$$

hence,

$$f = 0.223R_n^{-0.25} + 8.373(F_n)^{-1.936}(S)^{1.067}(I)^{0.148} \qquad (4a)$$

or alternatively,

$$f = 5.836(F_n)^{-1.704}(S)^{0.929}(I)^{0.147} \qquad (4b)$$

Also,

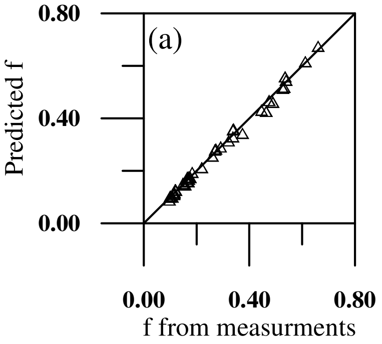
$$C = 3.667(F_n)^{0.852}(S)^{-0.464}(I)^{-0.074} \qquad (5)$$

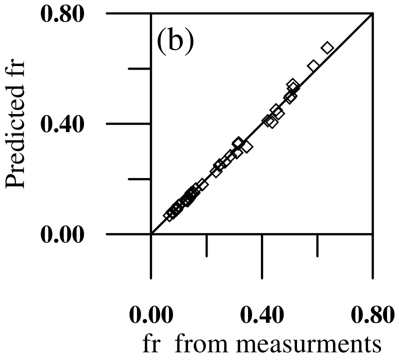
and

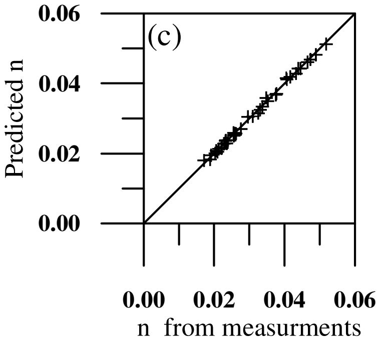
$$n = 0.166(F_n)^{-1.1626}(S)^{0.537}(I)^{-0.083} \qquad (6)$$

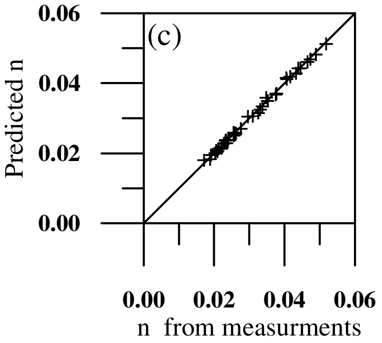
The coefficients of determination of the eqs. 3, 4b, 5 and 6 are 0.997, 0.994, 0.994 and 0.996 respectively while the standard error of estimate for the same equations are 0.017, 0.02, 0.01 and 0.009 respectively.

Figures 11a,b,c,d show the comparison of the measured values of the roughness indices and the predicted values using eqs. 3 to 6. Clearly, good agreement between predicted values of the roughness indices and the measured values is obtained









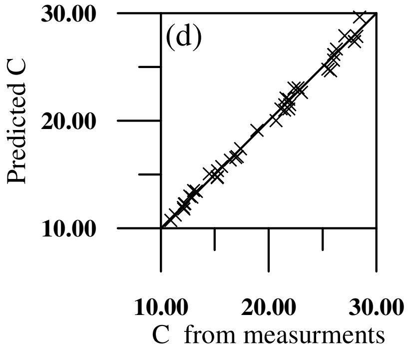


Figure 11. Measured values for roughness indices versus predicted ones (a) f using eq.(3), (b) f_r using eq. 4b, (c) n using eq. 5, and (d) C using eq. 6.

FULLY SUBMERGED VEGETATED

Similarly, the following set of equations were found to be well representative for the data of fully submerged vegetation.

$$f_r = 7.526(F_n)^{-2.088}(S)^{1.100}(I)^{-0.048} \tag{7}$$

hence

$$f = 0.223R_n^{-0.25} + 7.526(F_n)^{-2.088}(S)^{1.100}(I)^{-0.048} \tag{8a}$$

or alternatively,

$$f = 6.549(F_n)^{-2.022}(S)^{1.035}(I)^{-0.076} \tag{8b}$$

Also,

$$C = 3.462(F_n)^{1.011}(S)^{-0.518}(I)^{0.038} \tag{9}$$

and

$$n = 0.164(F_n)^{-1.009}(S)^{0.507}(I)^{-0.016} \tag{10}$$

The coefficients of determination of the equations 7, 8b, 9 and 10 are 0.997, 0.997, 0.994 and 0.999 respectively while the standard error of estimate for the same equations are 0.025, 0.031, 0.013 and 0.004 respectively.

Figures 12a,b,c,d show the comparison of the measured values of the roughness indices and the predicted values using Eqs.(7), (8b), (9) and (10). It is observed that good agreement was achieved between measured values and predicted ones using the developed equations.

Combining the data of the partially submerged vegetations with the data for fully submerged vegetations, the following equations were obtained.

$$f_r = 7.898(F_{nr})^{-2.014}(S)^{1.086}(I)^{-0.028} \tag{11}$$

hence,

$$f = 0.223R_n^{-0.25} + 7.898(F_n)^{-2.014}(S)^{1.086}(I)^{-0.028} \tag{12a}$$

or alternatively,

$$f = 6.561(F_n)^{-1.944}(S)^{1.009}(I)^{-0.061} \tag{12b}$$

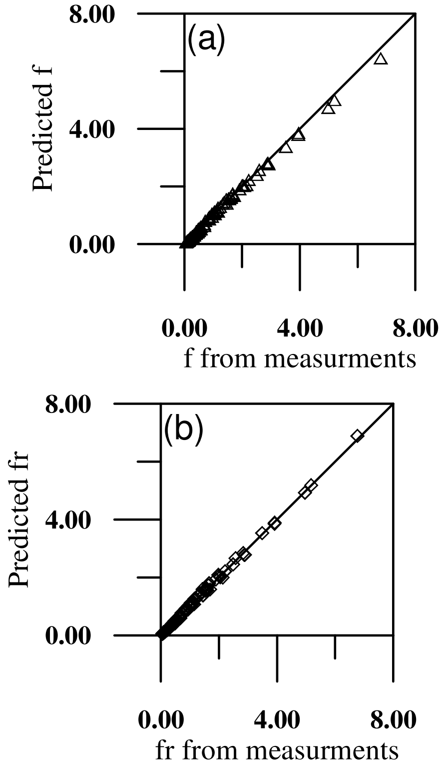
Also,

$$C = 3.459(F_n)^{0.972}(S)^{-0.505}(I)^{0.030} \tag{13}$$

and,

$$n = 0.163(F_n)^{-1.021}(S)^{0.509}(I)^{-0.02} \tag{14}$$

The coefficients of determination of the equations 11, 12b, 13 and 14 are 0.992, 0.993, 0.992 and 0.999 respectively while the standard error of estimate for the same equations are 0.042, 0.044, 0.021 and 0.007 respectively.



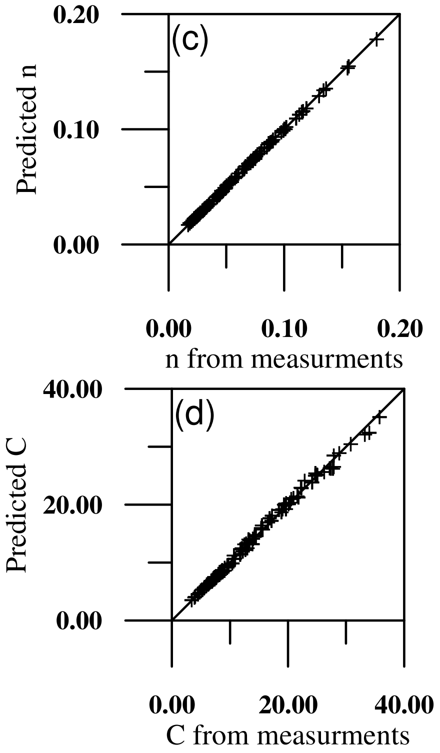


Figure 12. Measured values for roughness indices versus predicted ones, (c) n using eq.(9), and (d) C using eq. (10).

CONCLUSIONS

The results of an experimental investigation on the effect of Froude number, F_n, channel bottom slope, S, and vegetation intensity, I on the roughness indices of partially and fully submerged cylindrical non-rigid non-vertical vegetation were presented. The total friction factor, f, the friction factor due to vegetation only, f_r, the Manning roughness coefficient, n, and the Chezy roughness coefficient, C, were all used in the analysis. For partially submerged vegetation, the trend of variation of f, f_r and n with F_n were all similar and having decreasing trend with the increase of F_n while C is increasing with the increase of F_n. The values of the roughness indices are higher for steeper slopes and for larger vegetation intensity. Prediction models were developed to predict the roughness indices. Prediction equations from (3) to (6) were developed in terms of the parameters of equations (1) and (2).

On the other hand, for fully submerged vegetation, the trend of variation of f, f_r and n with F_n were all similar and having decreasing trend with the increase of F_n while C is increasing with the increase of F_n. The values of the roughness indices are higher for steeper slopes and for larger vegetation intensity. Prediction models (Eqs. 7, 8, 9 and 10) were developed using the statistical methods to predict the roughness indices. Comparison of predicted values with those obtained from measurements indicated good agreement. Also, general models (Eqs. 11, 12, 13 and 14) for both partially and fully submerged vegetations were developed by combining all data together. Good agreement was achieved between measred and predicted values of roughness coefficients within less than 5% accuracy.

NOMENCLATURE

C	Chezy's roughness coefficient;
f	friction factor;
F_n	Froude number;
g	gravitational acceleration;.
K	roughness height;
I	roughness intensity;
n	Manning roughness coefficient;
R	hydraulic radius;
R_n	Reynolds number;
S	channel bottom slope;
V	average velocity of flow; and
ϕ	rouhgness arrangement pattern.
St	staggered
Pa	parallel

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