VARIATION OF ROUGHNESS COEFFICIENTS FOR UNSUBMERGED AND SUBMERGED VEGETATION

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ABSTRACT: This paper investigates the variation of the vegetative roughness coefficient with the depth of flow. A horsehair mattress is used in the experimental study to simulate the vegetation on the watercourses. Test results reveal that the roughness coefficient reduces with increasing depth under the unsubmerged condition. However, when fully submerged, the vegetative roughness coefficient tends to increase at low depths but then decrease to an asymptotic constant as the water level continues to rise. A simplified model based on force equilibrium is developed to evaluate the drag coefficient of the vegetal element; Manning's equation is then employed to convert the drag coefficient into the roughness coefficient. The data of this study are compared with those of selected previous laboratory and field tests. The results show a consistent trend of variation for the drag coefficient versus the Reynolds number. This trend can be represented by a vegetative characteristic number k . Given information such as the bed slope, the height of vegetation, and k , one can apply the proposed model to predict the roughness coefficient corresponding to different flow depths.

INTRODUCTION

Hydraulic resistance of open-channel and overland flows results from the viscous and pressure drag over the wetted perimeter. In vegetated watercourses, this drag may be conceptually divided into three components, namely, soil grain roughness, form roughness, and vegetative roughness. For most vegetated waterways, drag on the vegetal elements dominates the flow resistance (Fenzl 1962; Temple et al. 1987). Hydraulic resistance of the watercourse determines the water level and the flow distribution in the basin. Such resistance is commonly represented by parameters such as Manning's roughness coefficient (n), Chezy's resistance factor (C), or the Darcy-Weisbach friction factor (f), among which Manning's n is most frequently used in the computation of open-channel and overland flows. Reliable results of flood routing and inundation simulation rely on an accurate estimation of the resistance coefficient. Various methods for determining the vegetative roughness coefficient are found in the literature. The reader can refer to Chow (1959), the bibliography prepared by Dawson and Charlton (1988), or the summary provided by Fishenich (1994) for a comprehensive review.

The vegetative resistance varies with the flow depth or the degree of submergence. Most of the previous efforts specifically focus on the flow resistance of either the submerged or the unsubmerged vegetation in the main channels. A long-sought-after study is the variation of vegetative resistance on floodplains during overbank inundation. In a floodplain-wetland restoration study for the Kissimmee River Basin of Florida, Shen et al. (1994) pointed out the need for research on the variation of the resistance coefficient with changes of flow depth and plant growth. Recent studies have used actual vegetation to investigate flow resistance in compound channels and floodplains (Fathi-Maghadam and Kouwen 1997; Werth 1997; Rahmeyer 1998). The scope of this study is to provide an understanding of the roughness at a point in the floodplain for use in a two-dimensional model. Artificial roughness that

is not expected to behave in exactly the same manner as actual vegetation was used to investigate the variation of roughness coefficient with relative flow depth. A simplified model for evaluating the unsubmerged and submerged vegetation resistance by hydraulic and vegetative parameters is presented. The practical application of the proposed model is also provided. However, the paper is not intended to address the complexities of flow in multistage (compound) channels, nor does it investigate the biomechanical characteristics of the vegetation.

BACKGROUND

The flow resistance exerted on vegetation is usually classified by the relative flow depth to the height of vegetation (Ree 1949). For intermediate flows in which the depth of flow is greater than the height of vegetation, Ree and Palmer (1949) presented a set of graphical-format design curves for different retardance classes. Their retardance curves of n were presented as a function of VR , the product of the average velocity and the hydraulic radius. One should bear in mind that the n - VR relationship is in fact identical with the n - R relationship, due to the facts that a conventional definition of the Reynolds number is given by $R = VR/\nu$ and the viscosity (ν) of water does not vary substantially in normal conditions (Chen 1976). For most of Ree and Palmer's (1949) tests carried out with the grasses submerged, the correlation shows the n values decrease as VR increases. The decrease of n is regarded as a result of the increase of plant bending and submergence when VR increases. Kouwen and Li (1980), using the vegetation's height and stiffness as parameters, proposed an alternative method for determining the friction coefficient of the submerged roughness. Due to the empirical nature of the n - VR relationship, Kouwen et al. (1981) further claimed that the n - VR method is not valid when the slope is smaller than 5% or the vegetation is short and stiff.

For unsubmerged vegetation, Temple et al. (1987) hypothesized that an increase in flow depth less than that required to top the vegetation causes little change in the mean velocity; therefore, flow resistance tends to increase with the depth. Indeed, the increase of Manning's n with flow depth is typical for partially submerged row crops along rivers with rough and grassy banks or floodplains (Chow 1959). However, there is no evidence showing that the change of the mean flow velocity is negligible for such an unsubmerged condition. Petryk and Bosmajian (1975) presented a flow resistance model based on a postulation that the energy slope of the flow can be decomposed into the energy gradients caused by the boundary shear stress and the vegetation, respectively. Their result shows that Manning's n , representing the total resistance induced by the

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boundary friction and vegetation, can be predicted with the vegetation density, the hydraulic radius, and the boundary roughness. For heavily vegetated areas, Manning's n increases in proportion to the $2/3$ power of the hydraulic radius and the square root of the vegetation density, but it is independent of the roughness of the channel bottom. Li and Shen (1973) examined the effects of tall plants on the flow retardation by investigating the wake behind cylinders. Their experimental results indicate that the reduction of flow velocity is significantly affected by the grouping pattern of the cylinders. Chen (1976) formulated a functional relationship, with bed slope and Reynolds number as the parameters, for the friction coefficient (f) of the sheet flows over natural turf surfaces. Parallel lines showing the f - R relationship of various bed slopes can be drawn on the log-log paper with Chen's data falling in the range of laminar flow ($R < 10^4$). These lines show a decreasing trend of f with an increasing R . Meanwhile, a plot of Ree and Palmer's (1949) field data, mostly falling in the range of transition and turbulent flows, reveals that the friction coefficient tends to converge to a fixed value at higher values of R .

For large flows to which the depth of flow is much greater than the height of vegetation, the thickness of the boundary zone approaches a minimum and the portion of flow passing through the vegetation becomes negligible compared with that flowing above; hence, the resistance coefficient tends to be a constant (Temple et al. 1987). Chow (1959) claimed that vegetation has a marked effect only up to a certain stage. Therefore, to determine a flooding level that is much higher than the vegetation in the channel, one can use a constant roughness coefficient. However, for the parts of watercourses subjected to a frequent fluctuation of overbank flows, the vegetative resistance is no longer a fixed value. Use of a constant roughness coefficient in the simulation of overbank inundation will lead to significant discrepancies with the actual flood levels and flow distributions. This experimental study aims to evaluate the variation of roughness with stage for an artificial form of vegetation.

LABORATORY EXPERIMENTS

The experiments were conducted in a 1.2 m (4 ft) wide by 305 m (1,000 ft) long circulating and slope-adjustable flume, located in the hydraulic laboratory at the Richmond Field Station, California. The sidewalls and the bottom of the flume were made of glass and steel. Five series of tests (series A-E) were performed at slopes of 0.00383, 0.00533, 0.01025, 0.0273, and 0.041, respectively. A triangular weir was used to measure the flow rate. The stage measurements were made with a depth gauge mounted on a cart moving along rails. Rubberized horsehair mattress material was selected to represent the vegetative roughness on the watercourses. This kind of material is not completely rigid; it preserves a certain flexibility but is stiff enough to prevent from strong deflection/bending. Although the stiffness and density of the rubberized fibers were not measured, it is believed that these properties of the testing material are of higher magnitude than those of most natural grasses. The horsehair mattress was regarded as a suitable material to simulate the bushes/shrubs in the floodplain wetlands, because these plants have greater stiffness than row crops such as wheat and sorghum (Shen et al. 1994). A 1.2 m (4 ft) wide and 7.3 m (24 ft) long strip of this nonrigid material was installed on the bottom of the flume. A single layer of this mattress is 1.5 ± 0.3 cm (0.05 ± 0.01 ft) in thickness. For series A-C, the experiments were carried out with one to four layers of the mattress, while series D and E were only carried out with four layers of the mattress.

For each of the above 14 tests, the discharge and thus the depth of flow were incrementally altered. The testing flows covered a broad range such that the simulated vegetation ex-

perienced both the unsubmerged and submerged conditions. All the flows were subcritical, with Froude numbers ranging from 0.01 to 0.50. A previous experimental study (Wu 1994) has indicated that the roughness coefficients for subcritical and supercritical flows have opposite trends of variation. The present study only deals with subcritical flows; the effect of the Froude number on the roughness of vegetation is thus beyond the scope of this study.

For most open-channel flows, the formation of a uniform flow is accompanied by upstream and/or downstream transitions. Such transitions also occurred in the writers' flume experiments. They were especially apparent at the locations where an abrupt change of roughness appeared in the flume. However, a new equilibrium that was developed through transition would produce a uniform flow profile in part of the horsehair region. The selected length of the horsehair mattress was sufficient for the formation of a uniform flow. Measurements of the discharge and stage were made when the flow in the study reach achieved steady and uniform conditions.

THEORETICAL CONSIDERATIONS

In this study, Manning's n is used to denote the resistance coefficient. The total resistance of the testing flume is a result of the sidewall and bottom resistance, designated as n_w and n_b , respectively. Since the bed resistance is dominated by the vegetative roughness rather than the surface friction of the bottom (Fathi-Maghadam and Kouwen 1997), n_b may well be used to represent the vegetative roughness coefficient. The following sections present the procedures to calculate the vegetative roughness coefficient and the formulation for drag and roughness coefficient estimation.

Vegetative Roughness Coefficient

The cross section of the testing flume consists of different roughnesses. The computation of the composite roughness has been thoroughly reviewed by Yen (1992). The ideas and procedures suggested by Einstein (1942) are adopted herein. The cross section is conceptually divided into subareas corresponding to the sidewalls (A_w) and the bed (A_b), i.e., $A = A_w + A_b$, where A is the product of the channel width (B) and the flow depth (D) for a rectangular channel. It is assumed that the average velocity is uniformly distributed over the entire cross section. For the flow in a uniform reach, Manning's equation may be expressed by the hydraulic parameters corresponding to either the sidewalls or the bottom. For the metric system, they are

$$V = \frac{1}{n_w} R_w^{2/3} S^{1/2} \quad (1)$$

$$V = \frac{1}{n_b} R_b^{2/3} S^{1/2} \quad (2)$$

in which the average velocity $V = Q/A$, where Q is the flow-rate; S can be the friction slope, the water surface slope, or the bed slope for uniform flow; and R_w and R_b , the hydraulic radii corresponding to the walls and the bed, are equal to $A_w/2D$ and A_b/B , respectively. For the glass wall, Graf and Chhun (1976) cited the value of $n_w = 0.01$ from Chow (1959). One can use this n_w value and (1) to calculate R_w and, consequently, A_w , A_b , and R_b . The roughness coefficient of the bed is then obtained by modifying (2) as $n_b = R_b^{2/3} S^{1/2}/V$, in which n_b can be viewed as the vegetative roughness coefficient of the testing flume.

Drag Coefficient of Vegetation

Drag Coefficient for Unsubmerged Vegetation

To estimate the drag induced by the vegetal elements, the writers apply the force balance for uniform flow in the flow-

wise direction of a vegetated reach L [definition sketch shown in Fig. 1(a)]. Basically, this equilibrium can be expressed as

$$F_G = F_D + F_s \quad (3)$$

in which the gravitational force $F_G = \rho g(AL)S$, where ρ and g = mass density of water and gravity constant, respectively; F_D = drag force exerted on the vegetation; and F_s = surface friction of the sidewalls and bottom. As the sidewalls and bottom of the flume are made of smooth material, the magnitude of F_s is expected to be relatively small. Fenzl (1962), based on his study of uniform flow in a vegetated channel, also pointed out that F_s is negligible compared with F_D . In such a case, the drag of vegetation can be equated to the gravitational force, as shown in Fig. 1(a). The drag force F_D is given by

$$F_D = C_D(\lambda AL) \frac{\rho V^2}{2} \quad (4)$$

where C_D = drag coefficient; λ = vegetal area coefficient representing the area fraction per unit length of channel and the magnitude of λ is dependent upon the vegetation type, density, and configuration; and λAL = total frontal area of vegetation in the channel reach L . Equating F_G and F_D gives

$$C'_D = \frac{2gS}{V^2} \quad (5)$$

in which $C'_D = \lambda C_D$. Eq. (5) can be used to evaluate the vegetal drag coefficient C'_D , which is a coefficient of drag that accounts for the features of vegetation, as indicated above. The same result was also obtained by Kadlec (1990) for use of the average velocity and friction slope.

Drag Coefficient for Submerged Vegetation

The flow depth is greater than the vegetal height as the vegetation is submerged [definition sketch shown in Fig. 1(b)]. For uniform flow, there exists a shear force F_τ at the boundary between the vegetation and the overflow to balance the gravitational force F_{G1} , which gives $F_\tau = \rho g(BHL)S$. For the flow through the vegetation, the drag force acts to resist that shear force as well as the weight component F_{G2} . The frontal area

of the vegetation is a function of its own height; hence, the drag force becomes

$$F_D = C_D(\lambda TBL) \frac{\rho V^2}{2} \quad (6)$$

where T = height of vegetation. Herein, T is assumed to be constant, because the mattress material is stiff and thus the bending of the mattress can be ignored. Equilibrium of F_D , F_τ , and F_{G2} leads to

$$C'_D = \left(\frac{D}{T}\right) \frac{2gS}{V^2} \quad (7)$$

Although (5) and (7) are derived for uniform flow, extension of the methodology to nonuniform flow is also made possible by applying the momentum principle to solve the drag force.

Relationship between Drag Coefficient and Roughness Coefficient

For the flume used in this study, the wall effect is negligible, since the width-depth ratios are greater than 10 in most of the simulations. The main consumption of flow energy is caused by the vegetative resistance of the channel bed. According to Einstein's (1934) argument, the subarea corresponding to the glass walls will be much less than that corresponding to the bottom when the vegetative roughness on the channel bed is dominant, i.e., when the energy of flow is mainly dissipated by the vegetal elements on the bottom. Table 1 shows some typical values of A_w/A and A_b/A for various depths of flow, in which we can see that the percentages of A_b/A are far beyond those of A_w/A . Thus, for calculating R_b , the cross-sectional area A can be used as an approximation to the subarea A_b . This will lead to an immediate result of $R_b \cong D$. Using (2) as well as (5) or (7), one can convert the vegetal drag coefficient C'_D to the roughness coefficient n_b , i.e.

$$n_b = \left(\frac{D^{2/3}}{\sqrt{2g}}\right) \sqrt{C'_D}; \quad n_b = \left(\frac{D^{1/6}T^{1/2}}{\sqrt{2g}}\right) \sqrt{C'_D} \quad (8a,b)$$

Eqs. (8a) and (8b) are used for unsubmerged and submerged vegetation, respectively. One may notice that (8a) coincides with the results of Petryk and Bosmajian (1975) for the heavily vegetated situation due to the fact that C'_D contains a factor of vegetation density in the λ term.

TABLE 1. Percentages of Subareas Corresponding to Side-walls and Bottom of Channel for Various Flow Depths (Bed: $S = 0.01025$; Vegetation: $T = 1.5$ cm)

D/T (1)	A_w/A (%) (2)	A_b/A (%) (3)
0.6	0.002	99.998
0.9	0.003	99.997
1.0	0.004	99.996
1.4	0.005	99.995
1.8	0.010	99.990
2.2	0.018	99.982
2.5	0.023	99.977
2.8	0.033	99.967
3.2	0.047	99.953
4.0	0.095	99.905
5.0	0.281	99.719
5.5	0.407	99.593
6.0	0.759	99.241
6.3	0.957	99.043
6.9	1.066	98.934
7.4	1.344	98.656

FIG. 1. Definition Sketch of Force Balance: (a) Unsubmerged Vegetation; (b) Submerged Vegetation

ANALYSIS OF EXPERIMENTAL RESULTS

Variations of Roughness Coefficient and Mean Velocity with Flow Depth

Employing (2), the writers calculate the bottom roughness coefficient of vegetation, n_b , for all the trials. The results of n_b are plotted against the depth of flow. A typical graph is shown in Fig. 2(a), where four n_b - D curves for various vegetal heights under a slope of 0.01025 are illustrated. The figure reveals that the n_b - D curves have a consistent pattern of variation. With the increase of flow depth, four subregions can be distinguished for each curve, as indicated in Fig. 2(b). At low flows, where the vegetation remains unsubmerged, n_b decreases with the increase of flow depth. When the submergence of vegetation starts to occur in the second subregion, n_b tends to rise, to a certain extent, with the increasing flow (although the increase of n_b for the 1.5 cm thick vegetal material is not very explicit). This increase of n_b is followed by a substantial drop in the third subregion. As the depth of flow continues to increase, n_b curves approach asymptotic constants. It has been claimed [e.g., Chow (1959), Temple et al. (1987)] that such constants vary as a function of the height of vegetation, which is also well demonstrated in Fig. 2(a). However, due to the limitation of the experimental apparatus, the data do not allow the writers to examine the exact values of these asymptotic constants.

To investigate the variation of the vegetative roughness coefficient with flow depth, n_b and the corresponding mean flow velocity are plotted against the normalized flow depth, D/T . Fig. 3 illustrates the n_b and V curves for the same conditions

FIG. 2. (a) Variations of Roughness Coefficient with Flow Depth for Various Heights of Vegetation; (b) Four Subregions of n_b Curve

as shown in Fig. 2(a). The decrease of n_b in the unsubmerged region (i.e., for $D/T < 1$) is apparently accompanied by the increase of mean velocity. This result is a conflict with the previous hypothesis given by Temple et al. (1987), who attributed the increase of the unsubmerged vegetative roughness coefficient to the constant mean velocity. In fact, the increase of roughness coefficient with the rising flow in natural streams should not be a consequence of the unchanged mean velocity; rather, it should be attributed to the greater bulk of overbank vegetation and branches/leaves encountered with the increasing depth. For the homogeneous material (horsehair mattress) used in the present study, the effects caused by the stage-wise nonhomogeneity can be eliminated, because no branching stems and leaves exist. Alternatively, it is the relative increase of the flow depth to the inertia (i.e., velocity) that leads to a reduction in the roughness coefficient. This statement becomes apparent as one verifies the experimental data with (2). With the 6 cm thick mattress in Fig. 3, for example, a change in the flow depth from $D/T = 0.52$ to $D/T = 1.0$ and, thus, a change in the corresponding mean velocity from 0.017 to 0.029 m/s will reduce the magnitude of n_b from 0.65 to 0.57, approximately 88% of the original roughness.

FIG. 3. Variations of Roughness Coefficient and Mean Flow Velocity with Normalized Flow Depth for Various Heights of Vegetation

FIG. 4. Variations of Roughness Coefficient with Depth of Overflow for Various Heights of Vegetation

For the second subregion in which the submergence of vegetation begins, the magnitude of n_b shows a trend to increase, yet the mean velocity does not change perceptibly with the increasing flow. Fig. 1(b) shows a shear force existing at the boundary between the vegetation and the overflow. This boundary shear acts as a resistance to the free flow over vegetation. Until the flow-wise component of the weight of free overflow exceeds the magnitude of the boundary shear, no substantial increase of the velocity in the free overflow or the flow through vegetation is likely to occur. Therefore, within the boundary zone (approximately for the region of $1 < D/T < 1.5$), Manning's n tends to increase to cancel out the increased hydraulic radius (or flow depth). From the mean velocity in Fig. 3, we see that the effect of the boundary shear

FIG. 5. Variations of Roughness Coefficient and Mean Flow Velocity with Normalized Flow Depth for Various Bed Slopes

becomes insignificant as the height of vegetation reduces. To comparatively demonstrate the thickness of boundary zone, an alternative plotting of n_b versus the depth of overflow, H , is shown in Fig. 4, where we can see that the thickness of the boundary zone and the height of the vegetation are strongly correlated.

Fig. 5 is another graph showing the variations of n_b and V with D/T for a constant thickness of vegetation and various bed slopes. The overall trends of variation for the n_b and V curves are, generally speaking, identical with those shown in Fig. 3. Nonetheless, it is interesting to note the existence of a unique n_b curve in the first subregion. Such coincidence of the n_b curves in the unsubmerged region is also illustrated in Fig. 2(a), where the unsubmerged parts of n_b curves are on a unique trail of descending. Because the only difference among the four curves in Fig. 2(a) is the thickness of vegetation, it is reasonable for these curves to coincide in the unsubmerged region. Meanwhile, in Fig. 5, we also see that the mean velocity increases with the bed slope for any specific normalized depth. When $D/T = 0.5$, for example, the mean velocities are 0.009 and 0.03 m/s for the slopes of 0.00383 and 0.041, respectively. Use of Manning's equation would verify that these velocities correspond to the same value of n_b (approximately 0.67). While the vegetative roughness coefficient is independent of the bed slope in the unsubmerged region, for the drag coefficient to be discussed in the following section, the apparent effect of the bed slope is demonstrated.

Drag Coefficient of Vegetation

The vegetal drag coefficients for the unsubmerged and submerged conditions are calculated with (5) and (7), respectively. Following an approach inspired by the empirical n - VR relationship, we plot the results of C_D' versus the Reynolds number. The plot of C_D' versus R is a conventional approach to investigate the drag coefficient. Herein, R is defined as VY/ν , where Y = height of the inundated part of vegetation; $Y = D$ and T

FIG. 6. Relationship between Vegetal Drag Coefficient and Reynolds Number for Unsubmerged Condition

FIG. 7. Relationship between Vegetal Drag Coefficient and Reynolds Number for Submerged Condition

for unsubmerged and submerged vegetation, respectively; and ν = kinematic viscosity of water. The C_D' - R graphs for the unsubmerged and submerged conditions are shown in Figs. 6 and 7, respectively. Discussion of the results and their implications are presented in the subsequent sections.

Unsubmerged Vegetation

One can see, in Fig. 6, that our results of C_D' fall on five parallel lines. These lines distinctly correspond to the five different bed slopes used in this study. This shows that, under the same R , the value of C_D' is greater for the steeper bed. Regression analysis indicates that these parallel lines can be represented by the following expression, with $R^2 = 0.998$:

$$C_D' = \frac{(3.44 \times 10^6) S^{0.5}}{R^k}; \quad k = 1.0 \quad (9)$$

in which C_D' has a unit of m^{-1} . Noting that Stokes' law gives $C_D = 24/R$ for a sphere in the laminar flow with $R < 1$, one might regard as an interesting coincidence that they both follow straight lines with a slope of -1 (i.e., $k = 1$). Also, (9) provides an answer to the unique n_b curve in the unsubmerged region of Fig. 5. By substituting (9) into (8a) and using the expression of $R = D^{5/3} S^{1/2} / n_b \nu$, one can obtain

$$n_b = \left[\frac{(3.44 \times 10^6) \nu}{2g} \right] D^{-1/3} \quad (10)$$

Eq. (10) explicitly indicates that the roughness coefficient of the unsubmerged vegetation is dependent only on the depth of flow and independent of the bed slope, which is exactly illustrated in Fig. 5.

For comparison, previous experimental data gathered by Ree and Palmer (1949) and Chen (1975) are also analyzed and plotted in Fig. 6. Both of their experiments were conducted on test beds covered with natural turf surfaces. Although all of their tests involved vegetation in both the unsubmerged and

submerged conditions, only the unsubmerged data are used in this section. In Fig. 6, one can see that the trends of variation for both of their data are similar. Not only do they follow the lines of similar slopes (to the -1.4 and -1.5 power of R , respectively), they are also in a sequence such that the steeper bed has the greater value of C_D' for a given R . In other words, these lines can be expressed by a general form of $C_D' = f(S)/R^k$. The closer values of k for Ree-Palmer's and Chen's data are reasonable, because they used similar types of grass and experimental apparatus, while both their values of k are greater than ours. It is believed that the higher k values are due to the differences in vegetation characteristics. As shown in Fig. 6, our artificial roughness elements of higher stiffness and density have greater drag coefficients for most of the simulations. The consistent variation patterns of our data as well as Ree-Palmer's and Chen's data indicate that the k value of C_D' - R relationship is a characteristic of vegetation that may depend on the stiffness, density, and configuration of the plants.

Submerged Vegetation

In contrast to the unsubmerged condition, the drag coefficient for the submerged vegetation demonstrates a close correlation to the vegetal thickness T . Fig. 7 shows that our results of C_D' fall on a sequence of parallel lines following the order of bed slope and the height of vegetation. For a given R , steeper bed slopes and larger vegetal thicknesses result in greater values of C_D' . A multiple linear regression on our data leads to the following expression, with $R^2 = 0.958$:

$$C_D' = \frac{(4.50 \times 10^{10}) S^{0.89} T^{1.09}}{R^k}; \quad k = 1.7 \quad (11)$$

Eq. (11) indicates that the variation trend of the submerged drag coefficient, which is to the -1.7 power of R , is less mild than that of the unsubmerged one. Substituting (11) into (8b) and using the relation of $R = D^{2/3} S^{1/2} T / n_b \nu$ gives

$$n_b = \left[\frac{(3.23 \times 10^{35}) v^{5.67}}{(2g)^{3.33}} \right] D^{-2.67} T^{1.30} S^{0.13} \quad (12)$$

Eq. (12) reveals the fact that the roughness coefficient of the submerged vegetation is positively correlated to the thickness of vegetation, yet negatively correlated to the depth of flow. However, its correlation with the bed slope is weak. The submerged regions of Figs. 2 and 5 demonstrate such relationships well, although the lines are somewhat clustered in Fig. 5.

Again, the experimental data of Ree and Palmer (1949), Kouwen et al. (1969), and Chen (1975) are analyzed and plotted in Fig. 7. The tests of Kouwen et al. were carried out in a flume with an artificial flexible roughness (styrene sheets) glued to the bottom. To summarize, the results in Fig. 7 indicate that these data can be represented by the following expression:

$$C_D' = \frac{f(S, T)}{R^k} \quad (13)$$

The value of k is identical for the data of Ree-Palmer and Kouwen et al. (approximately to the -2 power of R), while Chen's data have a trend close to ours. Although Bermuda grass was used in both Chen's and Ree-Palmer's tests, the one used by Ree-Palmer was dormant grass that had been kept cut. The biomechanical property of the short grass used by Ree-Palmer was probably more similar to that of the artificial roughness element used by Kouwen et al.; on the other hand, the natural turf used by Chen can be modeled by our horsehair mattress under the submerged condition. Nevertheless, the data of Chen and Kouwen et al. are in an apparent sequence that follows the magnitude of bed slope.

Conversion of Vegetal Drag Coefficient into Roughness Coefficient

Using (8), one can immediately convert the vegetal drag coefficient into the roughness coefficient. Such conversion is useful because Manning's n is broadly accepted and most frequently used for hydraulic computations. As (8) is applied, the C_D' terms are evaluated with (9) and (11) for unsubmerged and submerged vegetation, respectively. Fig. 8 is a comparison of the roughness coefficients predicted with (8) and those calculated by (2). Generally speaking, the predicted n_b agrees reasonably well with the experimental n_b for both the unsubmerged and submerged conditions, which in turn confirms the

FIG. 8. Comparison of Vegetative Roughness Coefficient [Predicted by Eq. (8)] with Experimental Roughness Coefficient [Calculated by Eq. (2)]

applicability of the proposed model. However, (8) tends to overestimate n_b for the unsubmerged condition yet underestimate n_b for the submerged condition. Since the proposed model is based on the force equilibrium and Manning's equation and since (9) and (11) are results of regression, the discrepancies in Fig. 8 should originate from the error induced by either one of those approximations.

PRACTICAL APPLICATION AND LIMITATIONS

The simplified model proposed in this paper can be used to predict the vegetative roughness coefficient corresponding to various depths of flow. Basic information is required for the application, and we presume that the following conditions are given: the bed slope S , the height of vegetation T , the vegetative characteristic number k satisfying (13), and at least one set of flow depth D_1 and mean velocity V_1 from the historical overbank flow. Based on the flow depth D_1 and mean velocity V_1 , the corresponding roughness coefficient can be evaluated by $n_{b1} = D_1^{2/3} S^{1/2} / V_1$. For an arbitrary depth D_2 , we need to predict the corresponding roughness coefficient n_{b2} . Given the ratio $D_2/D_1 = m$ and assuming that n_{b2} can be determined with n_{b1} by the factor a , i.e., $n_{b2} = a \cdot n_{b1}$, then our goal is to express a as a function of m . The cases for unsubmerged and submerged conditions are described below.

Unsubmerged Vegetation

From Manning's equation and (5), one has $V_2 = (m^{2/3}/a) \cdot V_1$ and $C_{D2}' = (a^2/m^{4/3}) \cdot C_{D1}'$, where $C_{D1}' = 2gS/V_1^2$ and $C_{D2}' = 2gS/V_2^2$, respectively. Applying the above relation and (13), one can obtain

$$\frac{C_{D2}'}{C_{D1}'} = \frac{a^2}{m^{4/3}} = \left(\frac{V_1 D_1}{V_2 D_2} \right)^k = \left(\frac{a}{m^{2/3}} \right)^k \quad (14)$$

which leads to the following result:

$$a = m^\alpha; \quad \alpha = \frac{4 - 5k}{6 - 3k} \quad (15)$$

Since the vegetative roughness coefficient is decreasing with flow depth, α must be a negative number. Accordingly, the vegetative characteristic number should satisfy $(4 - 5k)(6 - 3k) < 0$, or $0.8 < k < 2$.

Submerged Vegetation

Again, from Manning's equation and (7), we have $C_{D2}' = (a^2/m^{1/3}) \cdot C_{D1}'$, where $C_{D1}' = 2gSD_1/V_1^2 T$ and $C_{D2}' = 2gSD_2/V_2^2 T$, respectively. Applying the above relation and (13), we can obtain

$$\frac{C_{D2}'}{C_{D1}'} = \frac{a^2}{m^{1/3}} = \left(\frac{V_1}{V_2} \right)^k = \left(\frac{a}{m^{2/3}} \right)^k \quad (16)$$

which leads to the following expression:

$$a = m^\beta; \quad \beta = \frac{1 - 2k}{6 - 3k} \quad (17)$$

It is only when β is a negative number that the roughness coefficient decreases with flow depth. For this to occur, the vegetative characteristic number should satisfy $0.5 < k < 2$.

To demonstrate (15) and (17), several curves for various k values are shown in Fig. 9, where the reference value n_{bT} = magnitude of n_b for the flow depth $D = T$. One can use this graph to evaluate the roughness coefficient that corresponds to different depths of flow, given the characteristic number of vegetation. Essentially, the k values of vegetal elements can be determined from the laboratory experiments or previous field tests on the plants of similar type. However, the k values

FIG. 9. Predicted Variations of Roughness Coefficient with Flow Depth for Various Vegetative Characteristic Numbers k

should be in the valid ranges of application, as indicated above. In Fig. 9, the horizontal part of the n_b/n_{bT} curve in the range between $D/T = 1$ and 1.5 is an approximation of the effect of the boundary zone. As some of the experimental results demonstrate in the rise of the roughness coefficient in the boundary zone, the horizontal line is a simplification of the boundary zone effect and thus tends to underestimate the roughness. While the magnitude of the rise of n_b in the boundary zone and the thickness of this zone are known to depend on the height of vegetation, their relationships are not well established and still need to be investigated in further detail.

CONCLUSIONS

An experimental study has been conducted using artificial roughness to investigate the variation of vegetation resistance with stage for unsubmerged and submerged conditions. A horsehair mattress has been used as a surrogate for vegetation, and it is unlikely that the matting will respond in exactly the same fashion as grasses, riparian vegetation, or other obstructions on the floodplain. Nevertheless, this paper presents a new data set and insight into the processes. The following conclusions can be drawn from this study:

1. The mean velocity increases with the flow under the unsubmerged condition, for which the corresponding roughness coefficient decreases with the increasing velocity. The vegetative roughness coefficient tends to remain constant or rise as the submergence starts to occur. The rise of n_b in this boundary zone is attributed to the unchanged mean flow velocity. This boundary zone effect is followed by a substantial decrease of n_b . The roughness coefficient appears to approach an asymptotic constant as the flow continues to increase.
2. A simplified model based on force equilibrium is proposed to evaluate the drag coefficient of vegetation. The vegetal drag coefficient can be represented by a general expression as (13) for both the unsubmerged and submerged conditions. The parameter k in (13) is a vegetative characteristic number that may depend on the biomechanical property of the plants.
3. The vegetal drag coefficient is converted into the roughness coefficient with the aid of Manning's equation. The predicted n_b agrees reasonably well with the experimental n_b for both the unsubmerged and submerged conditions, which in turn justifies the assumptions made in the simplified model.

4. The proposed model can be practically applied to evaluate the roughness coefficient corresponding to different depths of flow, given the characteristic number of vegetation and some basic information. However, the variation of n_b in the boundary zone and the thickness of this zone still need to be investigated.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A = cross-sectional area;
 A_b = subarea corresponding to bed;
 A_w = subarea corresponding to sidewalls;
 a = ratio of vegetative roughness coefficient;
 B = channel width;
 C = Chezy's resistance factor;
 C_D = drag coefficient;
 C'_D = vegetal drag coefficient = λC_D ;
 D = depth of flow;
 F_D = drag force;
 F_G = gravitational force in flow-wise direction;
 F_S = surface friction of sidewalls and bottom;
 F_τ = shear force at boundary between vegetation and overflow;
 f = Darcy-Weisbach friction factor;
 g = gravitational acceleration;
 H = depth of overflow;
 k = vegetative characteristic number in (13);

L = length of channel reach;
 m = ratio of flow depth;
 n = Manning's roughness coefficient;
 n_b = bottom roughness coefficient of vegetation;
 n_{bT} = vegetative roughness coefficient for flow depth being equal to T ;
 n_w = roughness coefficient corresponding to sidewalls;
 Q = flow discharge;
 R = hydraulic radius;
 R = Reynolds number;
 R_b = hydraulic radius corresponding to bed;
 R_w = hydraulic radius corresponding to sidewalls;
 S = slope of channel bed;
 T = thickness (or height) of vegetation;
 V = average flow velocity;
 ν = kinematic viscosity of water;
 Y = height of inundated part of vegetation;
 α, β = exponents in (15) and (17), respectively;
 λ = vegetal area coefficient = area fraction per unit length;
and
 ρ = mass density of water.