FRICTION IN HURRICANE-INDUCED SURGES

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ABSTRACT

With the increasing development of coastal areas, it is necessary to have a sound method for predicting hurricane-induced flooding in these areas, especially for studies such as the coastal construction set-back line, flood insurance rate-making and county land use planning. The objective of this study is to develop the capability of describing the friction factor in coastal areas for improved representation in numerical models of storm surges.

Five types of areas are considered: A, ocean bottom with bed forms and some vegetation; B, mangrove fringes and areas; C, forested areas and cypress swamps; D, grassy areas and saltwater marshes; and E, developed residential and commercial areas. The friction factors, which incorporate both the bottom friction coefficient and drag coefficient due to the submerged parts of obstructions were verified by conducting laboratory experiments for mangrove and developed areas, using the typical distribution found in each of these coastal areas. The formulas of the friction factor for the ocean bottom, forested areas and grassy areas are determined by adopting results from previous investigations and discussed with the results of the current study.

INTRODUCTION

Through history flood prone areas in the worlds coastal regions have had an almost magic attraction on man. Today the trend is still towards a more intense utilization of coastal areas with high risk of flooding due to hurricanes than of the safer inland areas. The result is increasing flood losses. Such losses have grown from about $60 million at the turn of the century to more than $1 billion today in the United States alone.

The accurate prediction of local elevations of the 100 year flood plain is therefore more and more important for insurance

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purposes in the coastal zone. In a rapidly developing coastal county a one foot error in the predicted flood elevation may easily result in unnecessary construction and insurance costs in the millions of dollars per year. In an otherwise correct numerical model such an error may be introduced by an erroneous representation of the influence of friction in shallow ocean and overland flows. The present paper addresses itself to this problem.

The first numerical models of storm-induced surges in the ocean did often neglect the influences of bottom friction. While such a simplifying omission of a friction term in the governing equations appears to be acceptable in the parts of the ocean where depths are substantial it does result in errors in the shallow near-cost ocean and, of course, in the even shallower overland flow.

More recently developed models are therefore including this term. For instance, the Tetra-Tech model described by Chen et al. (1977) and widely used in the National Flood Insurance Program, takes bed friction into consideration by using the Manning formula. Other models use the Darcy-Weisbach formula for the bed shear stress τ_b

$$\tau_b = f' \rho \, u_m^2 / 2 \tag{1}$$

where ρ = density of water, u_m = the spatial mean velocity in the local vertical, and f' = the friction factor.

The approach using the Manning formula for evaluation of the bed shear stress leads to the expression

$$\tau_b = \gamma \, n^2 u_m^2 / d^{\frac{1}{3}} \tag{2}$$

using S.I. Units. In Eqn. (2) γ = unit weight of water, n = Manning's n and d = local depth. Elimination of τ_b by combination of Eqns. (1) and (2) shows that the friction factor must be a function of the local depth and, of course, of n that again depends on the equivalent sand roughness of the bed. The method of using a constant value of the friction factor in the ocean, regardless of depth, does therefore not seem satisfactory, although it has given quite decent results in many cases, especially in relatively deep ocean areas.

Using the Manning formula and thereby Eqn. (2) for the bed shear stress may also lead to errors when the apparent sand roughness is not sufficiently small compared to the depth as shown by Christensen (1970). The approach using the Darcy-Weisbach equation for the bottom shear stress is therefore chosen in this paper.

MODEL EQUATIONS

Friction Factor for Surges in Unobstructed Areas

Unobstructed areas include the ocean bottom and grassy areas, the latter of which are assumed to be completely submerged in water during floods. Practically all flow in hurricane-induced surges is in the hydraulically rough flow range. A velocity profile based on a modification of Prandtl's mixing length theory proposed earlier by Christensen (1972) may therefore be applied

$$\frac{\bar{u}}{u_f} = 2.5 \ln \left(\frac{29.73z}{k} + 1\right) \tag{3}$$

where $\bar{u}$ = time-mean velocity in the direction of flow at a distance z from the bed, u_f = friction velocity, and k = Nikurades's equivalent sand roughness. This modification provides a velocity profile that satisfies the no slip condition at the bed where the classic profile yields unrealistic negative velocities approaching minus infinity.

For practical purposes, the time-mean velocity profile is transformed to a depth averaged velocity profile using the fact that the mean velocity (depth averaged), u_m, occurs theoretically at a distance z = 0.368d from the bed also for the modified logarithmic vertical velocity profile, where d/k is larger than 1. Therefore at z = 0.368d Eqn. (3) yields

$$\frac{u_m}{u_f} = 2.5 \ln \left(\frac{10.94d}{k} + 1\right) \tag{4}$$

The friction factor may in general be related to the velocity profile by introducing the Darcy-Weisbach formula into the definition of the friction velocity by

$$\frac{u_m}{u_f} = \left(\frac{2}{f'}\right)^{\frac{1}{2}} \tag{5}$$

Solving Eqn. (5) for f' and introducing Eqn. (4) gives the following expression for the friction factor

$$f' = \frac{0.32}{\left[\ln \left(\frac{10.94d}{k} + 1\right)\right]^2} \tag{6}$$

Friction Factor for Surges in Obstructed Areas

Obstructions in these areas, e.g. mangroves, woods and buildings, are defined as roughness elements with significant heights which either protrude through the water layer or consist of relatively rigid elements with height that are sufficient to cause a form drag that is much larger than surface friction on the same area. The equation presented here is based on the assumption of steady or quasi-steady flow in the rough flow range.

Consider a design flow that passes over an obstructed area where the density is M per unit area, average diameter of the obstruction in the projected plane normal to the flow is D, and average drag coefficient is C_D. The head loss per unit weight of fluid over a bed length of L, ΔH, may be written as

$$\Delta H = f'_e \frac{u_m^2}{2g} \frac{L}{R} = f' \frac{u_m^2}{2g} \frac{L}{R} (1-\varepsilon) + MC_D dD \frac{u_m^2}{2g} \frac{L}{R} \qquad (7)$$

in which R = hydraulic radius, ε = fraction of total area occupied by obstructions. An equivalent friction factor, f'_e, which includes the effects of bottom friction and form drag in the form of the Darcy-Weisbach formula is introduced. From Eqn. (7) it is seen that

$$f'_e = f' (1-\varepsilon) + MC_D dD \qquad (8)$$

where, according to Eqn. (6),

$$f'_e = \frac{0.32}{[\ln (\frac{10.94d}{k} + 1)]^2}$$

EXPERIMENTAL VERIFICATION OF FRICTION FACTOR

According to the principle of conservation of energy, the total energy head at an upstream section 1 should be equal to the total energy head at the corresponding downstream section 2 plus the head loss between the two sections, i.e.,

$$d_1 + \frac{u_{m1}^2}{2g} = d_2 + \frac{u_{m2}^2}{2g} + \Delta H \qquad (9)$$

where subscripts 1 and 2 refer to sections 1 and 2, respectively. Relating the measured results of head loss to the Darcy-Weisbach equation

$$\Delta H = f'_e \frac{u_a^2}{2g} \frac{L}{R_a} \qquad (10)$$

in which $u_a = (u_{m1}+u_{m2}) / 2$ and $R_a = (R_1 + R_2) / 2$, the equivalent friction factor f'_e can be determined for the designed roughness elements. To measure the velocities, a Novonic-Nixon type velocity meter was employed. The range of this velocity meter is from 3 to 150 cms^{-1} with an accuracy of $\pm$ 1 % of true velocity. A siphon type depth measuring device is designed to measure the water surface elevations to an accuracy of one millimeter. All the model tests were conducted in the hydraulic laboratory flume of the Civil Engineering Department at the University of Florida. The main channel of this flume is 36.6 meters long, 2.44 meters wide, and 0.81 meter deep.

Model Setup

Mangroves

Based on the average parameters obtained from eleven sampling areas in San Carlos Bay on the southwest coast of Florida, patterns of red and black mangroves were designed as shown in Figures 1 and 2. The dimensions of all stems and roots, including height and diameter of the prototype, are reduced to 1/10 for the model based on the undistorted Froude Law. The legends listed in these figures were the actual dimensions used in the model setup.

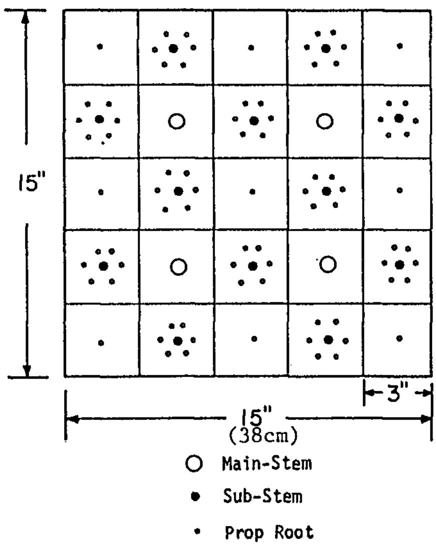

Figure 1: Model Setup for Red Mangroves

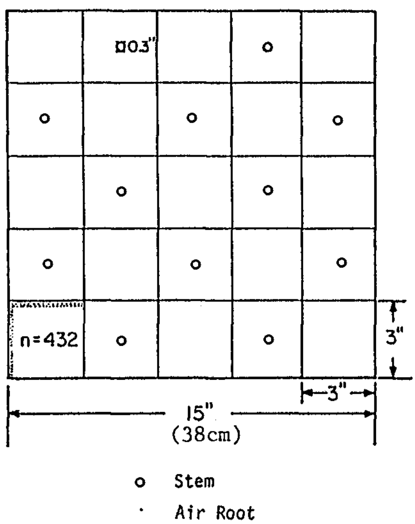

Figure 2: Model Setup for black Mangroves

The stems of red and black mangroves were simulated by dowels of the specified diameters and heights. The substems and prop roots were simulated by galvanized nails with heads removed. A manufactured nylon door mat whose strings have the same height (1.5 cm) and the same thickness (0.06 cm) as the design model dimensions of air roots was used. These dowels, nails and mats were fixed on three 2.4 meters by 1.2 meters marine plywood sheets, which covers half the flume width.

Buildings

Prototype data for the three kinds of buildings: high-rise, medium-rise and residential buildings, were taken and analyzed from aerial photographs of Broward and Dade counties, Florida. Table 1 shows a summary of the average parameters for these three categories. In this case a distorted madel with depth scale N_d and horizontal scale N_ℓ was used.

Table 1: Average parameters of Prototype and Model for Building Areas

Type of Buildings	PROTOTYPE			MODEL (N_d = 10)			
	Approximate Dimension (m)		Density	N_ℓ	Dimension (cm)		Density
	length	width	no. / 46452 m^2		length	width	no. / 2.1 m^2
High-Rise	69	33	7.19	174	39.4	19.1	10
Medium-Rise	31	15	23.62	80	39.4	19.1	7
Residential	19	9	68.87	48	39.4	19.1	7

Since the vertical dimension scale cannot follow the horizontal dimension scale in building models as the flow depth would be much too small for measurements to be made, or the viscous force would become important and cannot be neglected for the small flow depth. Therefore, a model with different vertical scale than horizontal scale is used to keep the model Reynolds numbers in the turbulent flow range. The concrete blocks with dimensions 19.1 cm x 19.1 cm x 39.4 cm were used to simulate the buildings. Figure 3 shows 21 patterns to be tested in which Nos. 1 to 13 were designed to simulate high-rise buildings, while Nos. 14 to 21 were for medium-rise buildings and residential areas. The design densities are started from low to high and cover at least the average densities obtained from the prototype. The whole width of the flume was used in this part of the experiments.

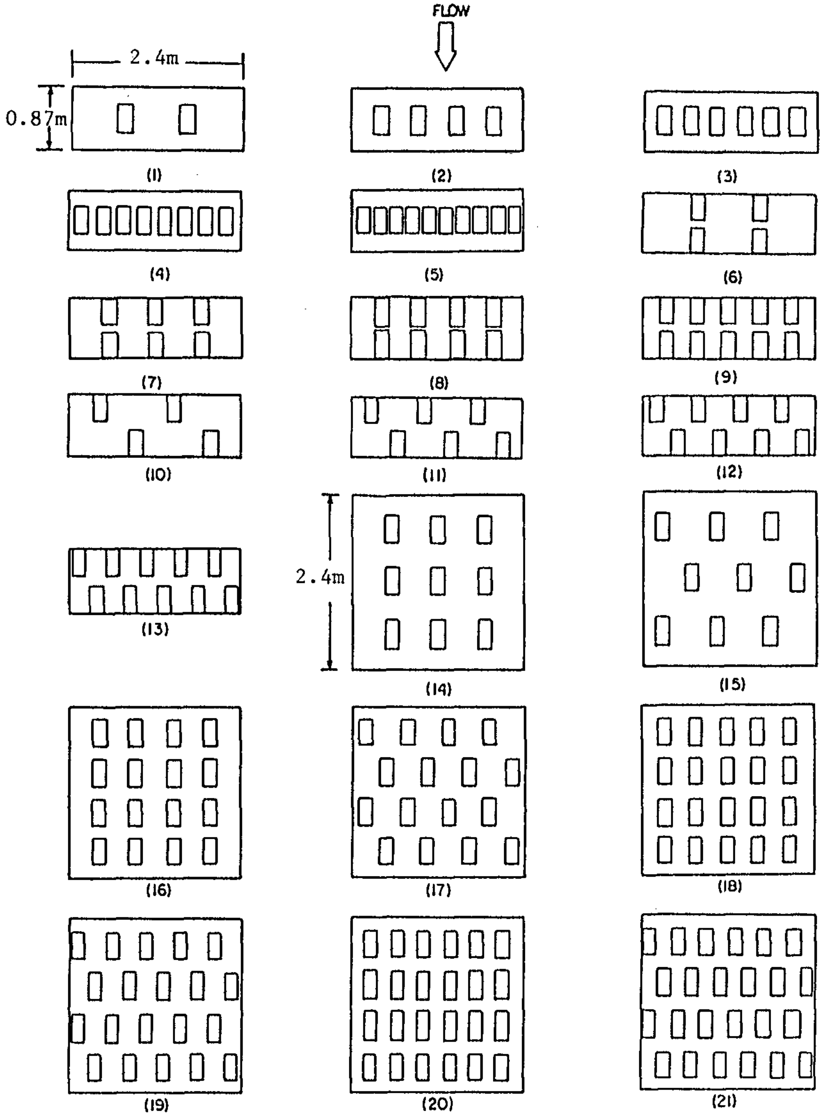

Figure 3: Building Patterns Designed for the Tests

Experimental Runs and Results

Mangrove Areas

During the first part of the experiments, 7 runs were conducted for the air roots of the black mangrove area to determine its apparent roughness height and friction factor. In the second part of the experiments, 38 runs were performed for the red mangrove area and black mangrove area by adjusting the discharge valve and changing the still water depths so that the flow Reynolds numbers covered a range from 20,000 to 55,000 while the Froude numbers varied from 0.14 to 0.44. Table 2 lists the mean values of the results and their corresponding standard deviations for the equivalent friction factors, drag coefficients and apparent roughnesses, k_a.

Table 2: Statistical Values of Experimental Results for Mangrove Areas

Mangroves	Statistical Values	f'_e	C_D	k_a (cm)	
				Model	Prototype
Red	Mean	0.129	0.732	42.69	426.9
	Standard Deviation	0.013	0.077	6.14	61.4
Black Stems	Mean	0.132	1.001	38.53	385.3
	Standard Deviation	0.020	0.090	9.72	97.2
Black Air Roots	Mean	0.028		5.26	52.6
	Standard Deviation	0.003		0.65	6.5

Building Areas

At least 10 runs were conducted for each of the 21 patterns shown in Figure 3. These runs for each pattern were controlled by adjusting the flume discharge valve and the tail gate so that they covered a range of Reynolds numbers from 20,000 to 70,000, while the Froude numbers varied from 0.1 to 0.5. The results obtained for medium-rise building areas can be converted using appropriate scaling factors to use in residential areas since these two areas are presumed to have the same relative distributions and have only dimensional differences. The statistical values of the experimental results for 21 patterns are listed in Table 3.

Table 3: Statistical Values of Experimental Results for Building Areas

Pattern No.	f'_e			C_D			Building Area
	Mean	Standard Deviation		Mean	Standard Deviation		
		value	% of mean		value	% of mean	
1	0.0013	0.0003	23	0.788	0.163	21	High-Rise
2	0.0064	0.0006	38	1.965	0.254	13	"
3	0.0180	0.0030	17	3.406	0.181	5	"
4	0.0460	0.0090	20	7.014	1.121	16	"
5	0.1580	0.0260	16	17.813	1.298	7	"
6	0.0036	0.0006	17	1.108	0.123	11	"
7	0.0046	0.0011	24	0.907	0.230	25	"
8	0.0090	0.0010	11	1.346	0.119	9	"
9	0.0130	0.0010	8	1.597	0.189	12	"
10	0.0080	0.0014	18	2.369	0.275	12	"
11	0.0154	0.0029	19	2.965	0.227	8	"
12	0.0230	0.0040	17	3.662	0.221	6	"
13	0.0350	0.0050	14	4.315	0.389	9	"
14	0.0074	0.0011	15	1.232	0.170	14	Medium-Rise
15	0.0127	0.0030	24	2.082	0.173	8	"
16	0.0117	0.0020	17	1.088	0.096	9	"
17	0.0329	0.0067	20	3.040	0.114	4	"
18	0.0158	0.0018	11	1.181	0.097	8	"
19	0.0448	0.0072	16	3.355	0.098	3	"
20	0.0265	0.0038	14	1.586	0.089	6	"
21	0.0631	0.0112	18	3.926	0.120	3	"
14	0.0123	0.0018	15	1.232	0.170	14	Residential
15	0.0211	0.0050	24	2.082	0.173	8	"
16	0.0195	0.0034	17	1.088	0.096	9	"
17	0.0548	0.0112	20	3.040	0.114	4	"
18	0.0264	0.0030	11	1.181	0.097	8	"
19	0.0747	0.0120	16	3.355	0.098	3	"
20	0.0441	0.0063	14	1.586	0.089	6	"
21	0.1052	0.0186	18	3.926	0.120	3	"

Drag Coefficient - Building Density Relations

The data obtained from pattern 1 through 13 were analyzed and plotted in Figure 4, which shows three possible relations between the drag coefficients and densities for high-rise building areas. Figure 5 shows two relations between drag coefficients and densities for the medium-rise building area and residential area, respectively.

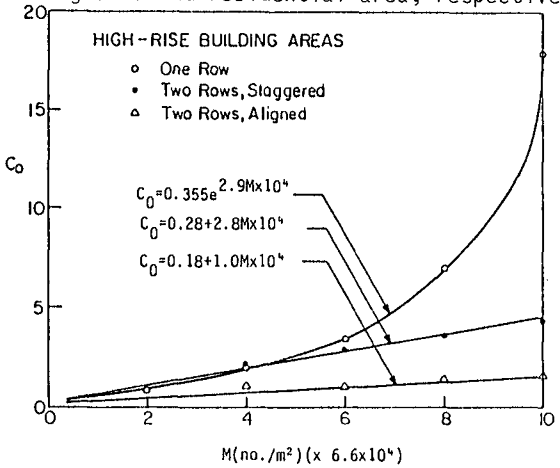

Figure 4: Relation Between C_D and Density M for High-Rise Building Areas

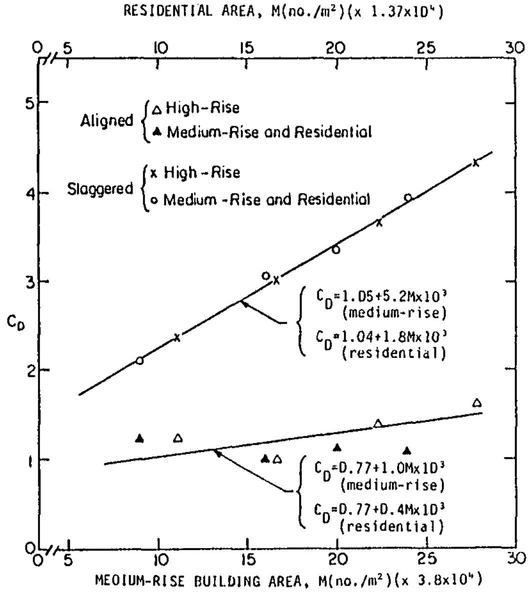

Figure 5: Relation Between C_D and Density M for Medium-Rise Building and Residential Areas

Drag Coefficient - Disposition Parameter Relations

Measuring the diagonal distance between the roughness elements in adjacent transverse rows, S_d, from building pattern 6 to 21, it is found that S_d/D and C_D show a good correlation for both aligned and staggered cases, as shown in Figure 6. This is attributed to the nature of the diagonal spacing, S_d, whose magnitude not only provides a measurement of density but also reveals a difference of disposition for the evenly distributed roughness elements. Therefore, the higher the building density, the smaller the disposition parameter, S_d/D, therefore a larger drag coefficient results. For buildings with the same dimensions and density, the disposition parameter, of the staggered pattern is smaller than that of aligned pattern, which also results in a larger drag coefficient. The same result was also substantiated by Shen (1973) who measured the mean drag coefficient of two cylinder patterns (aligned and staggered) in open channel flow.

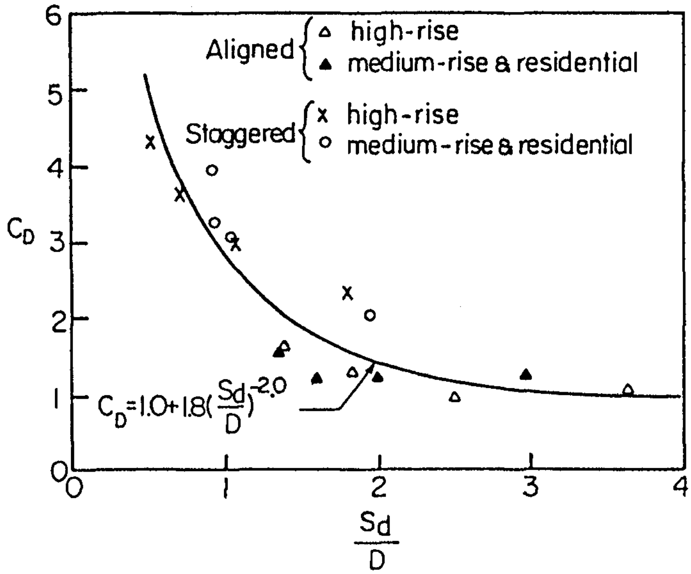

Figure 6: Relation Between C_D and S_d/D

DISCUSSIONS AND CONCLUSIONS

Ocean Bottom

The ocean bottom is mainly composed of different sizes of sands, on which vegetation and sand ripples vary with location. Hydraulic measurements in the field are the best way to determine the friction characteristics, but such measurements of velocity distributions and water depths are nearly impossible during a storm. Therefore, field measurements under normal conditions similar to a storm tide are needed. One possible instance is the flood and ebb flows through a tidal entrance in which the flow is in the fully rough range, and the effect of the temporal acceleration of the flow is generally of a lesser magnitude than the effect due to bed friction; therefore a correspondence between entrance flow and storm flood is expected. Three tidal entrances, John's Pass, Blind Pass and O'Brine's Lagoon Entrance, located on the Gulf coast of Florida were selected for hydraulic measurements to determine the bed friction characteristics (Mehta, 1978).

The values of Manning's n obtained for these three entrances are in the range from 0.020 to 0.026, which corresponds to the following bed morphologic features in open channel flows: clean, straight stream on plain (n = 0.025), gravel uniform excavated channel (n = 0.022), and uniform dredged earth channel with short grass (n = 0.022). This correspondence not only suggests that the values of n in the Manning's n table can be applied to tidal entrance, but that they can also be used for the ocean bottom during storm events. Therefore, for a rough ocean bottom, where the vegetation is significant or other roughnesses such as rocks or reefs exist, the n value is assumed to equal to 0.035, which represents an irregular, rough stream, a clean, winding stream on a plain with some weeds and stones, a dredged channel with light brush on banks, or a flood plain with scattered brush and heavy weeds in open channel flows.

As a results, the k values corresponding to the recommended n values are 0.03 m (n = 0.022) and 0.55 m (n = 0.035) for smooth and rough ocean bottoms, respectively. The friction factors for ocean bottoms can then be estimated using the equations

$$f' = \frac{0.32}{[\ln(365d + 1)]^2} \quad \text{for smooth ocean bottom} \qquad (11)$$

and

$$f' = \frac{0.32}{[\ln(20d + 1)]^2} \quad \text{for rough ocean bottom} \qquad (12)$$

Mangrove Areas

In general, the red mangroves only extend about 15 meters inland from the shoreline and it is hard to distinguish them from black mangroves on aerial photographs and conventionally used city maps. Examining the case of fine grid system for numerical models whose grid elements are usually chosen to be 1,610 meters square, the average friction for each grid element on the mangrove fringes should be represented by the sum of 1 % of the red mangrove and 99 % of the black mangrove. For engineering applications, therefore, it is not necessary to consider the small difference between red and black mangroves. The equivalent friction factor derived for black mangroves then can be used for all the mangrove areas, i.e.,

$$f'_e = \frac{0.32}{[\ln(21d + 1)]^2} + 0.07d \qquad (13)$$

Forested Areas

Forested areas may consist of many different species, like oaks, magnolia, cedar, palm, pine and cypress, where each species has different representative features. However, for a general view, some typical values of the parameters for evaluating the equivalent friction factor are suggested by Christensen and Walton (1980)

$$k = 0.5 \text{ m} \; ; \; M = 0.1 \text{ m}^{-2} \; ; \; D = 0.6 \text{ m}$$

$$\varepsilon = 0.028 \; ; \; C_D = 0.8$$

It is worthwhile to examine the drag coefficient recommended for forested areas. In Figure 6, it is seen that the drag coefficient has a tendency to become constant and equal to 1.0 when the disposition parameter S_d/D is larger then 4. This relation derived initially for the rectangular roughness elements may also be used for circular roughness elements and can be proved by comparing the measured drag coefficient (1.0) for black mangroves as seen in Table 2. For black mangroves, the disposition parameter is about 17, and the corresponding drag coefficient is 1.0 according to Figure 6, which agrees well with the measured results. Applying the same reasoning to forested areas, whose disposition parameter equals to 12, the drag coefficient can be expected to be approximately 1.0. therefore, the drag coefficient 0.8 proposed by Christensen and Walton is conservative and reasonable. Adopting these values, the equivalent friction factor can be expressed in the form

$$f'_e = \frac{0.31}{[\ln(22d + 1)]^2} + 0.048d \qquad (14)$$

Grassy Areas

Saw grasses are the dominate plant community occurring in the world's coastal zones where water stands all or part of a year. The results of studies of the flow of water over various grass covers by Palmer (1946) may provide some information to evaluate the roughness characteristics of saw grass. Palmer found that a completely submerged surface of Bermuda grass has a Manning's n of about 0.04, which corresponds to a k-value of about 1.25 m. If it is assumed that there is geometric similitude between Bermuda grass and about three times taller saw grass, Palmer's experiment with Bermuda grass may be considered as a model test of the prototype saw grass. As a results, a k-value of about 4 m for saw grass is expected. Christensen's (1980) indirect observation of the equivalent roughness of grass covered beds of estuaries on Florida's west coast have indicated a k-value ranging from 3 m to 5 m, which is in good agreement with the value derived from palmer's experiments with Bermuda grass. Introducing a k-value of 4 m in the friction factor equation, as suggested by Christensen and Walton (1980), yields

$$f' = \frac{0.32}{[\ln(2.7d + 1)]^2} \tag{15}$$

Developed Areas

The equivalent sand roughness, k, for developed areas cannot be determined by a single value, since the space between the buildings cover many different roughnesses. These roughnesses, in general, consist of pavements, grasses, light brush and trees, whose values of Manning's n are 0.013, 0.025 and 0.040, respectively. Assuming these roughnesses are evenly distributed, then an average value of n equals to 0.026 is assigned for these developed areas which gives k = 0.09 m using the Manning Strickler equation. As a result, the equivalent friction factor for developed areas may be represented as

$$f'_e = \frac{0.32}{[\ln(122d + 1]^2}(1-\varepsilon) + MC_D dD \tag{16}$$

The water depth d should be introduced in meters in all of the above expressions. The mean values of ε, M and D can be determined from the information in Table 2, or from the aerial photographs of the study areas.

The following three drag coefficient equation are suggested for friction factor calculations in developed areas:

$$C_D = 0.355\ e^{2.9M \times 10^4} \quad \text{for the one row high-rise building areas;} \tag{17}$$

$$C_D = 1.05 + 5.2M \times 10^3 \quad \text{for the staggered medium-rise building areas;} \tag{18}$$

and $C_D = 1.04 + 1.8M \times 10^3$ for the staggered residential areas; (19)

in which M is in number per meter square. The particular equation is recommended because on row high-rise buildings are the most predominate type of buildings found in highly developed coastal areas such those in Broward and Dade counties, Florida. For medium-rise buildings and residential areas, most buildings can be assumed to be staggered, since aligned buildings are scarce and the probability that floods will flow normal to the aligned building areas is very small in the field.

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