TP 77-12

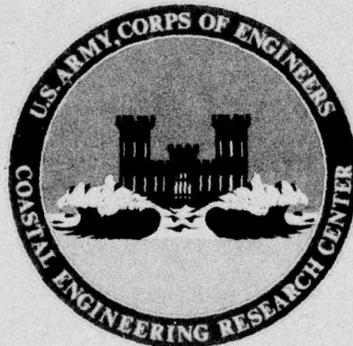# Wind-Wave Propagation Over Flooded, Vegetated Land

by

Frederick E. Camfield

TECHNICAL PAPER NO. 77-12
OCTOBER 1977

U.S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING RESEARCH CENTER

Kingman Building
Fort Belvoir, Va. 22060

Reprint or republication of any of this material shall give appropriate credit to the U.S. Army Coastal Engineering Research Center.

Limited free distribution within the United States of single copies of this publication has been made by this Center. Additional copies are available from:

National Technical Information Service
ATTN: Operations Division
5285 Port Royal Road
Springfield, Virginia 22151

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CERC -TP-77-12	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* WIND-WAVE PROPAGATION OVER FLOODED, VEGETATED LAND.		5. TYPE OF REPORT & PERIOD COVERED Technical Paper
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Frederick E. Camfield		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CEREN-CD) Kingman Building, Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS F31234
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center Kingman Building, Fort Belvoir, Virginia 22060		12. REPORT DATE October 1977
		13. NUMBER OF PAGES 42 45 p.
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Shallow water   Wave generation   Wind waves

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report presents an approximate method for estimating wind-wave growth and decay over flooded areas where there is a major effect from bottom friction because of dense vegetation.

DD ₁ FORM JAN 73 1473   EDITION OF 1 NOV 65 IS OBSOLETE   UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*
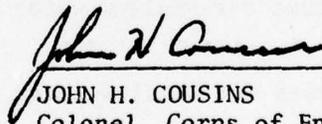
037 050

PREFACE

This report describes a method for estimating wind-wave growth and decay over flooded areas where there is a major friction effect because of dense vegetation. The report was initiated in response to a request from the U.S. Army Engineer Division, Lower Mississippi Valley, New Orleans District at the Division's 14 September 1976 Research and Development Workshop, indicating a need for technical guidelines for predicting wind-wave generation over flooded coastal areas. The work was carried out under the coastal construction program of the U.S. Army Coastal Engineering Research Center (CERC).

These technical guidelines are an extension of the procedures given in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975). The design curves in the SPM are limited to waves passing over a sandy bottom. A condensed description of the method is presented in CERC Coastal Engineering Technical Aid No. 77-6 (Camfield, 1977).

This report was prepared by Dr. Frederick E. Camfield, Hydraulic Engineer, under the general supervision of R.A. Jachowski, Chief, Coastal Design Criteria Branch.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 70th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

CONTENTS

FIGURES

4

CONTENTS

FIGURES--Continued

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

d	water depth
d_i	water depth at seaward or beginning edge of segment
F	fetch length
F_a	adjusted fetch length for distance across a segment in the direction of wave motion
F_e	equivalent fetch length for the initial wave at seaward or beginning edge of segment
f_f	bottom-friction factor (Darcy-Weisbach friction factor)
f_{fi}	bottom-friction factor at seaward or beginning edge of segment
G_i	fractional growth factor of equivalent initial wave
g	gravitational acceleration
H	wave height
H_D	decayed wave height at end of fetch
H_e	equivalent wave height at end of fetch
H_f	wave height at end of fetch
H_i	wave height at seaward or beginning edge of segment
H_{ie}	equivalent initial wave height
H_m	maximum stable wave height
H_{sm}	maximum significant wave height which would be generated for given windspeed and water depth
K_f	decay factor
$K_{f.01}$	decay factor when the bottom-friction factor, $f_f = 0.01$
K_{fa}	decay factor when the bottom-friction factor, f_f, has a value different than 0.01
K_s	shoaling coefficient
L	wavelength
L_o	deepwater wavelength for a wave with period, T

7

SYMBOLS AND DEFINITIONS--Continued

n   Manning's roughness coefficient

p   incremental multiple of wave height

R_i fractional reduction of initial wave at seaward edge of segment, as compared to the maximum stable wave height

T   wave period

U   windspeed

x   distance in the direction of wave motion

α   factor for reducing fetch length to the adjusted length

$α_r$ factor for increasing fetch length to the adjusted length = 1/α

Δ   incremental change

Δx   actual distance across a segment in the direction of wave travel

8

WIND-WAVE PROPAGATION OVER FLOODED, VEGETATED LAND

by
Frederick E. Camfield

I. INTRODUCTION

An important factor in the planning and design of works to protect
upland property during periods of storm surge is the prediction of the
wave height and period that will prevail at and seaward of the protec-
tive works (i.e., levee, dike, seawall) for a selected design storm.
Although improvements are needed, guidelines are available for predic-
tion of the water levels in upland areas resulting from storm surge;
however, no guidelines are presently available for computing the wave
attenuation for conditions when storm-generated waves travel a distance
across shallow flooded areas where the bottom characteristics include
vegetation which causes a moderate to high frictional stress. Therefore,
it is necessary to estimate the heights and periods of these storm-
generated waves.

Theoretical methods and field measurements are currently unavailable
to provide an estimation procedure. This report presents a *preliminary*
(approximate) method for estimating the growth or decay of waves travel-
ing through shallow water over areas with a high frictional resistance
from vegetation. The method is based on previously developed equations
(U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975)
for wave growth over areas with low bottom friction, and an equation for
the decay of gravity waves over areas with a constant water depth and
high bottom friction. This method uses existing shallow-water wave fore-
casting curves by adjusting fetch lengths to account for higher bottom
friction. Simplifying assumptions are used. The water depth is assumed
to have only gradual variations, and the frictional resistance is treated
as bottom friction. The procedure discussed in this report has not been
verified in the field and may not be applicable to other problems relat-
ing frictional resistance to wave development.

Only limited data are available on the effects of high values of
bottom friction on wind waves. Friction factors are estimated by compar-
ing vegetation to similar conditions in river channels and on flood plains.
The effect of the vegetation on wind stress and the possible effects of
motion of the vegetation are not considered. Dense vegetation effects
near the water surface which will dampen short-period waves much faster
than long-period waves are also not considered. The results obtained
are considered to be conservative; i.e., the predicted wave heights are
expected to be slightly higher than the wave heights which actually occur.

II. WAVE FORECASTING CURVES

The Shore Protection Manual (SPM)(U.S. Army, Coastal Engineering
Research Center, 1975) discusses a procedure for predicting the growth
of waves over shallow water, which is a modification of a method

9

developed by Bretschneider (1952, 1958, 1970) and incorporates the results of Ijima and Tang (1966). The SPM method assumes that bottom friction $f_f = 0.01$. The significant wave height and wave period are obtained from empirical equations given as

$$\frac{gH}{U^2} = 0.283 \tanh\left[0.530\left(\frac{gd}{U^2}\right)^{0.75}\right] \tanh\left\{\frac{0.0125\left(\frac{gF}{U^2}\right)^{0.42}}{\tanh 0.530\left(\frac{gd}{U^2}\right)^{0.75}}\right\} \quad (1)$$

and

$$\frac{gT}{2\pi U} = 1.20 \tanh\left[0.833\left(\frac{gd}{U^2}\right)^{0.375}\right] \tanh\left\{\frac{0.077\left(\frac{gF}{U^2}\right)^{0.25}}{\tanh\left[0.833\left(\frac{gd}{U^2}\right)^{0.375}\right]}\right\} \quad (2)$$

where

  H = significant wave height

  T = significant wave period

  d = water depth

  U = windspeed

  F = fetch length

  g = gravitational acceleration.

Since the terms are evaluated in dimensionless form, any consistent system of measurements may be used. Equations (1) and (2) are plotted as curves in Figures 1 and 2, respectively, for constant values of water depth. Design curves for predicting the growth of waves in shallow water for specified constant water depths are shown in Figures 3 to 12 (after SPM, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975).

III. CALCULATION OF ADJUSTED FETCH

The long dashline in Figure 1 indicates the maximum significant wave height, H_{sm}, which will occur for any given water depth and windspeed
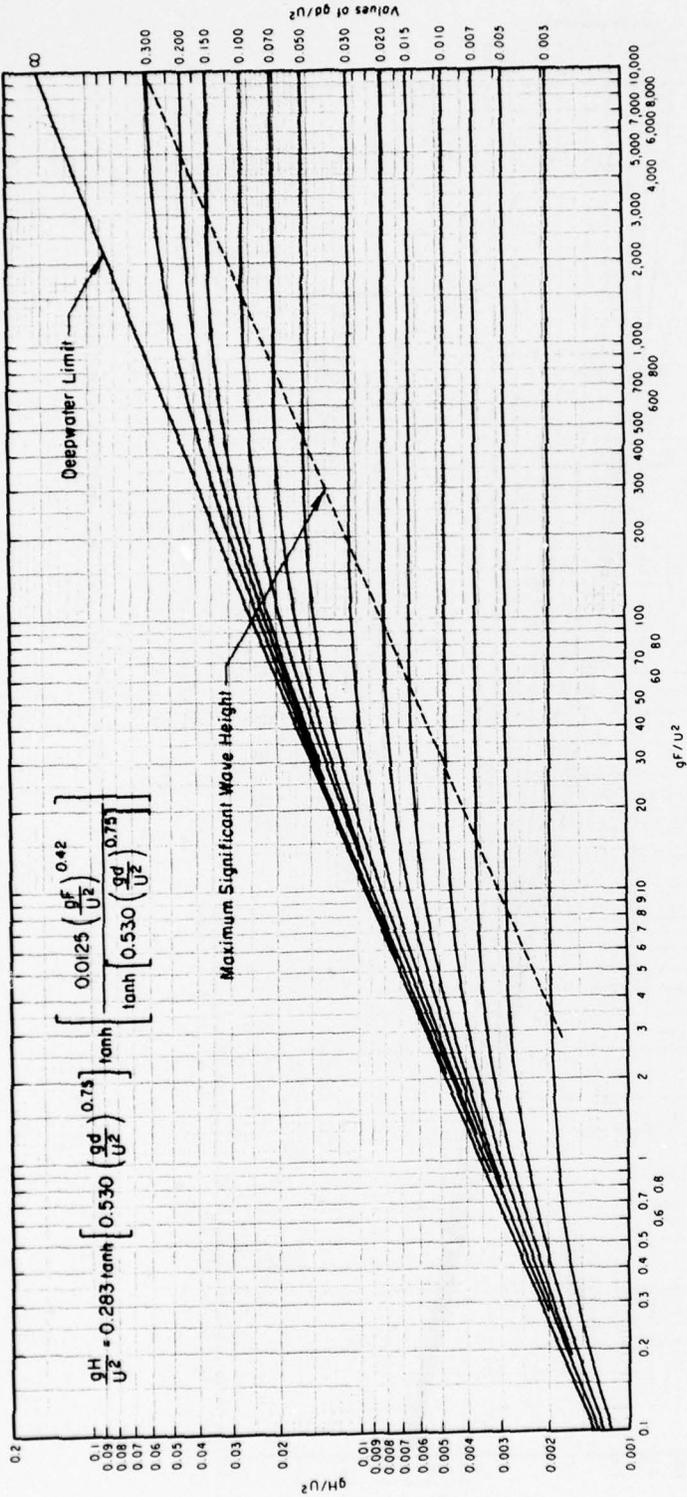
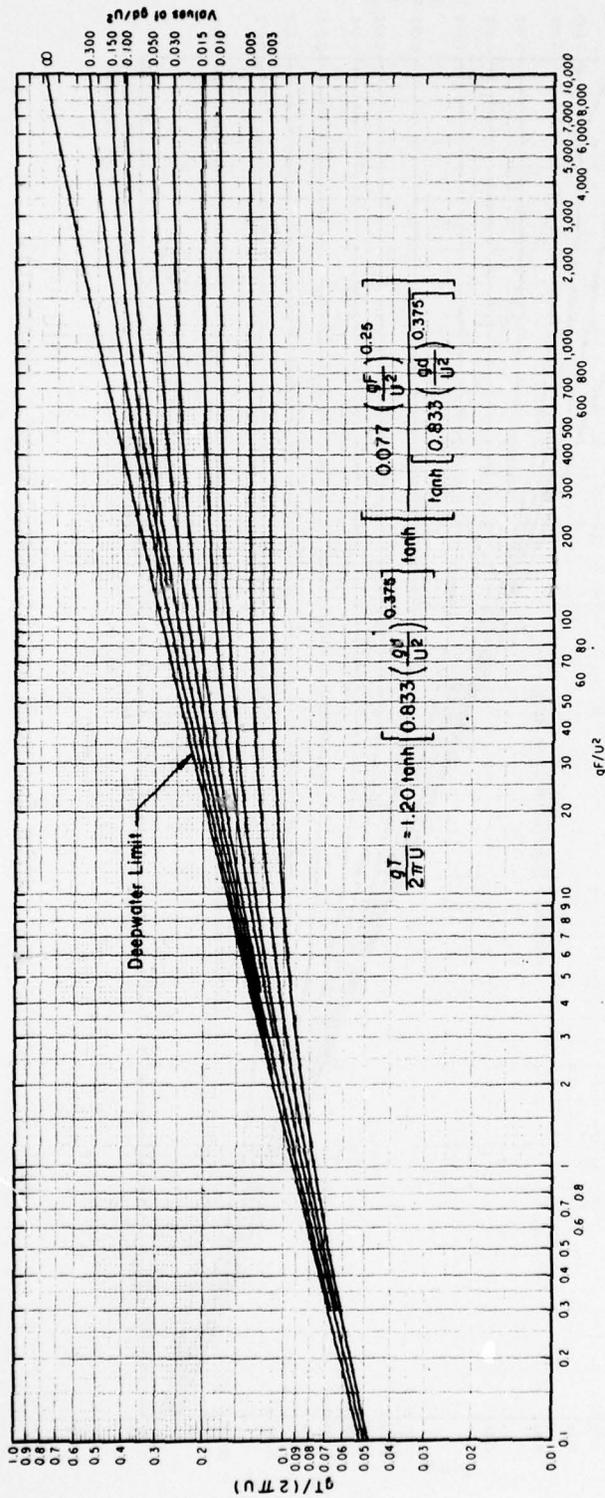Figure 1. Forcasting curves for wave height (water depths constant).

11

Figure 2. Forecasting curves for wave period (water depths constant).
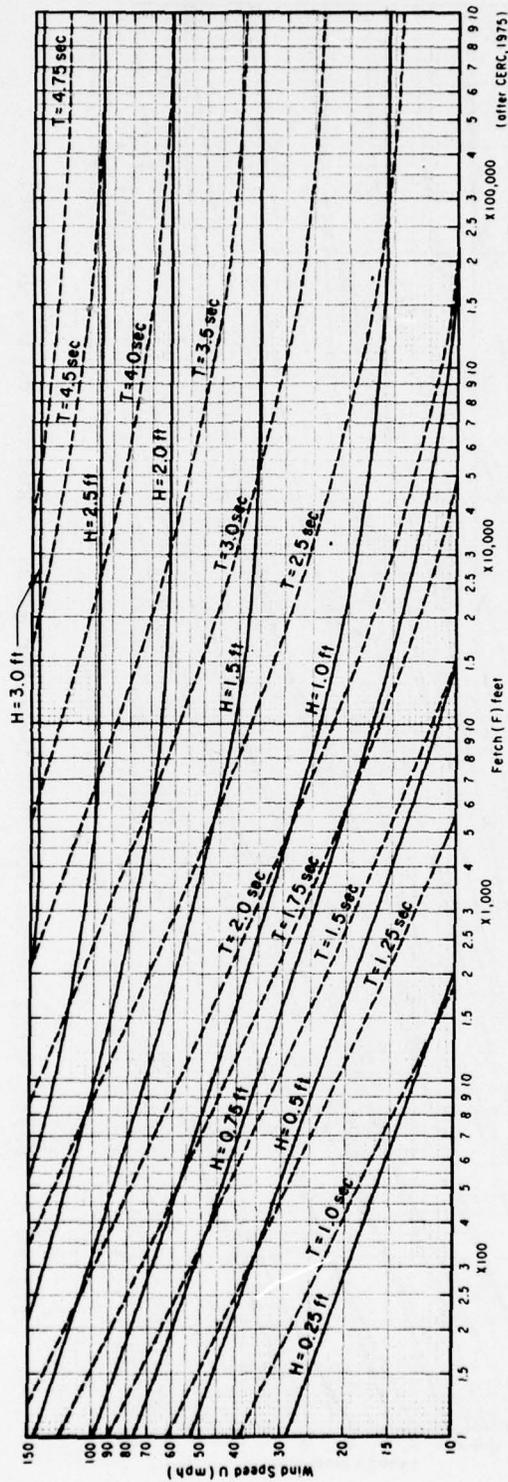
12

Figure 3. Forecasting curves for shallow-water waves (constant depth, 5 feet).
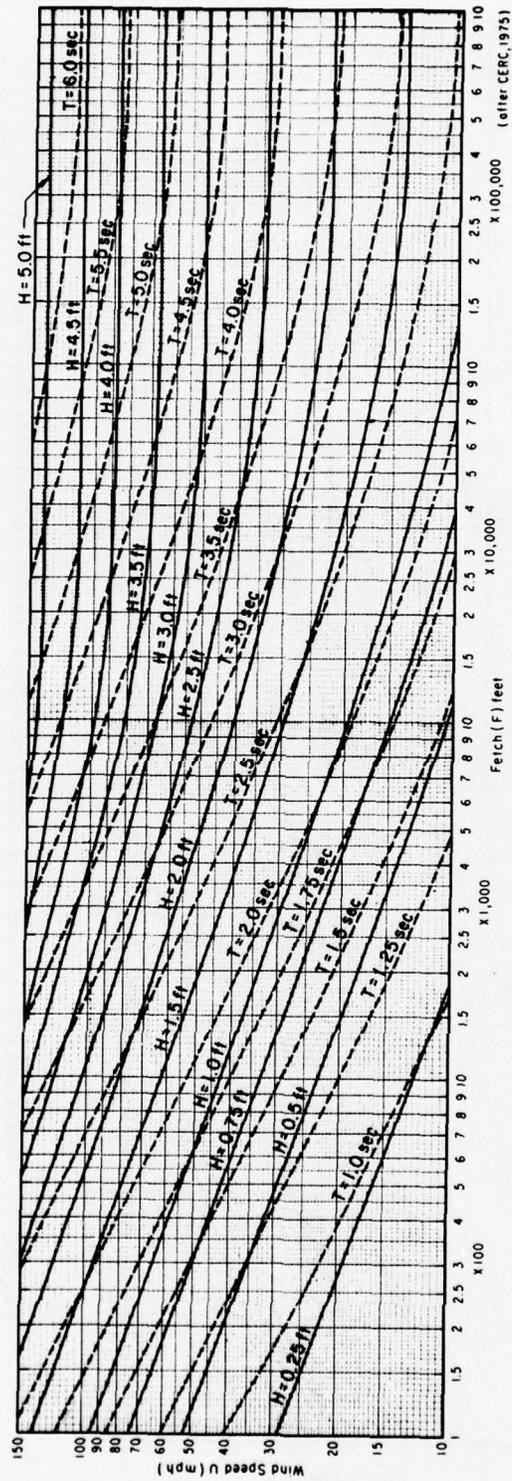
13

Figure 4. Forecasting curves for shallow-water waves (constant depth, 10 feet).

14

Figure 5. Forecasting curves for shallow-water waves (constant depth, 15 feet).

15

Figure 6. Forecasting curves for shallow-water waves (constant depth, 20 feet).

16

Figure 7. Forecasting curves for shallow-water waves (constant depth, 25 feet).
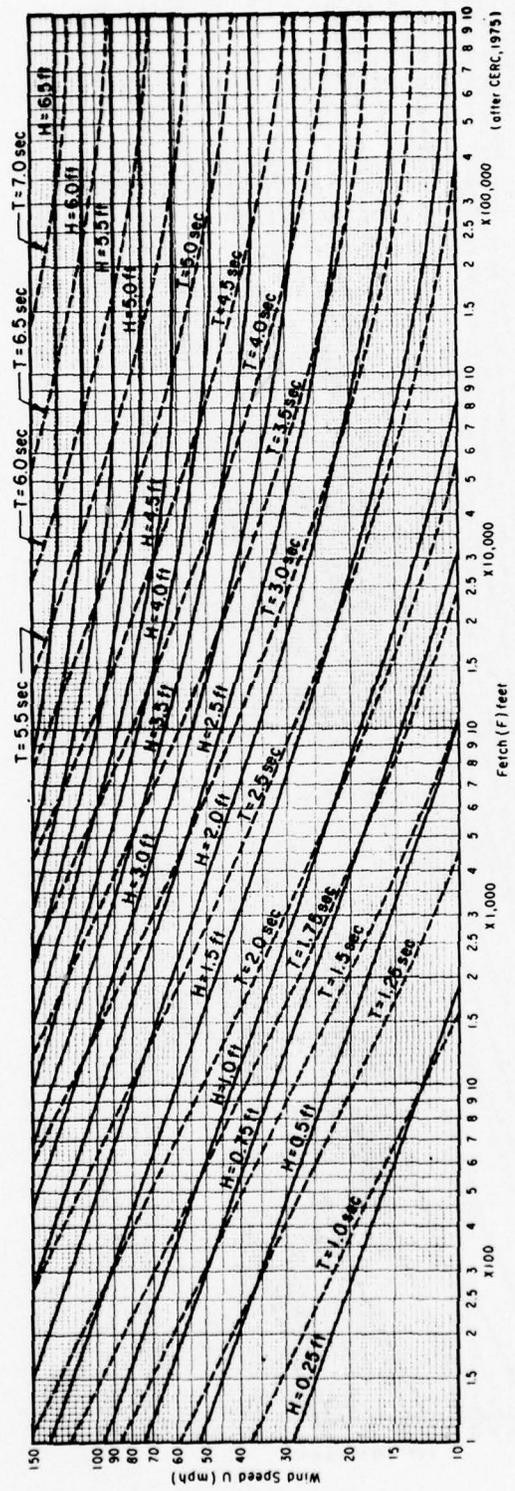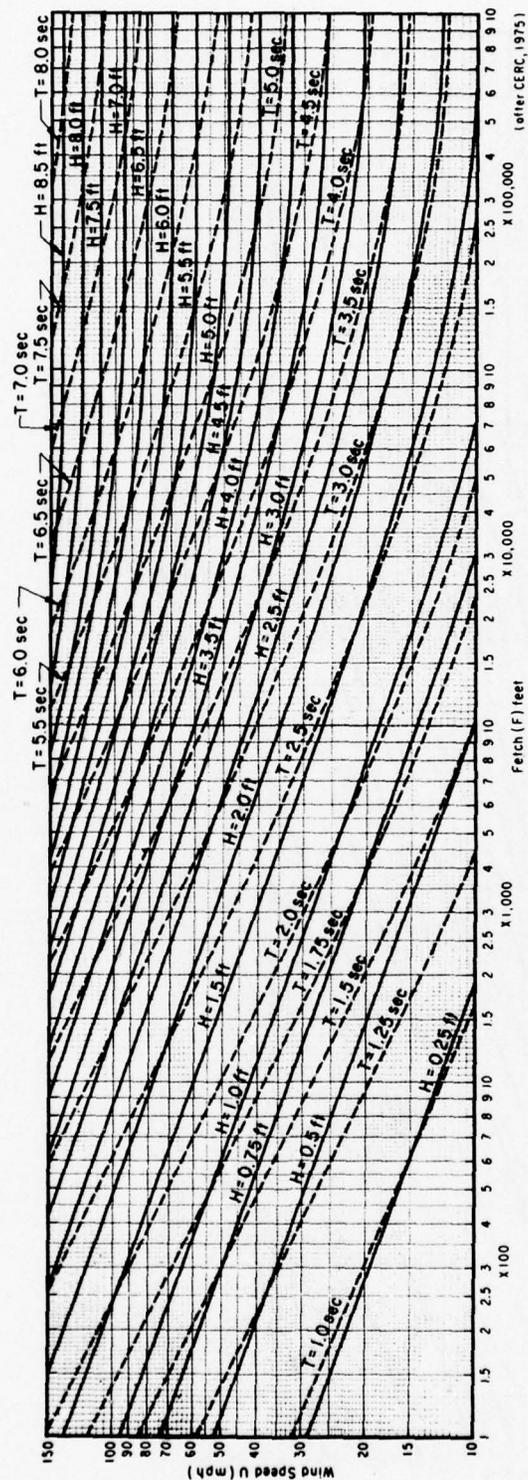
17

Figure 8. Forecasting curves for shallow-water waves (constant depth, 30 feet).

Figure 9. Forecasting curves for shallow-water waves (constant depth, 35 feet).

19

Figure 10. Forecasting curves for shallow-water waves (constant depth, 40 feet).

20

Figure 11. Forecasting curves for shallow-water waves (constant depth, 45 feet).

21

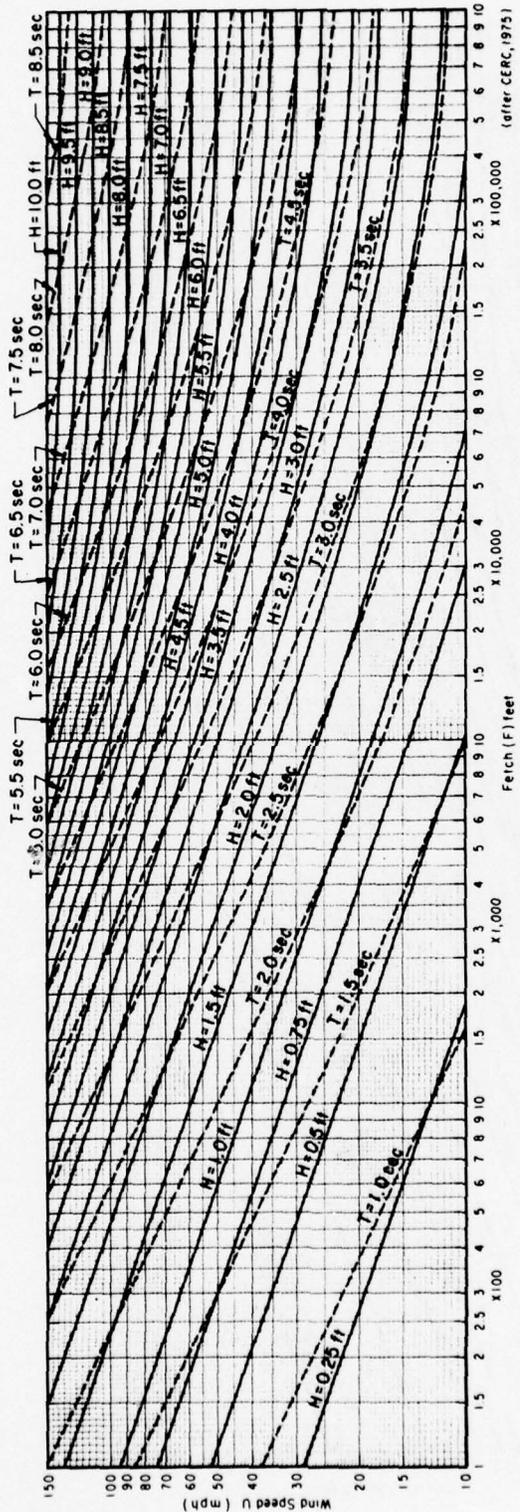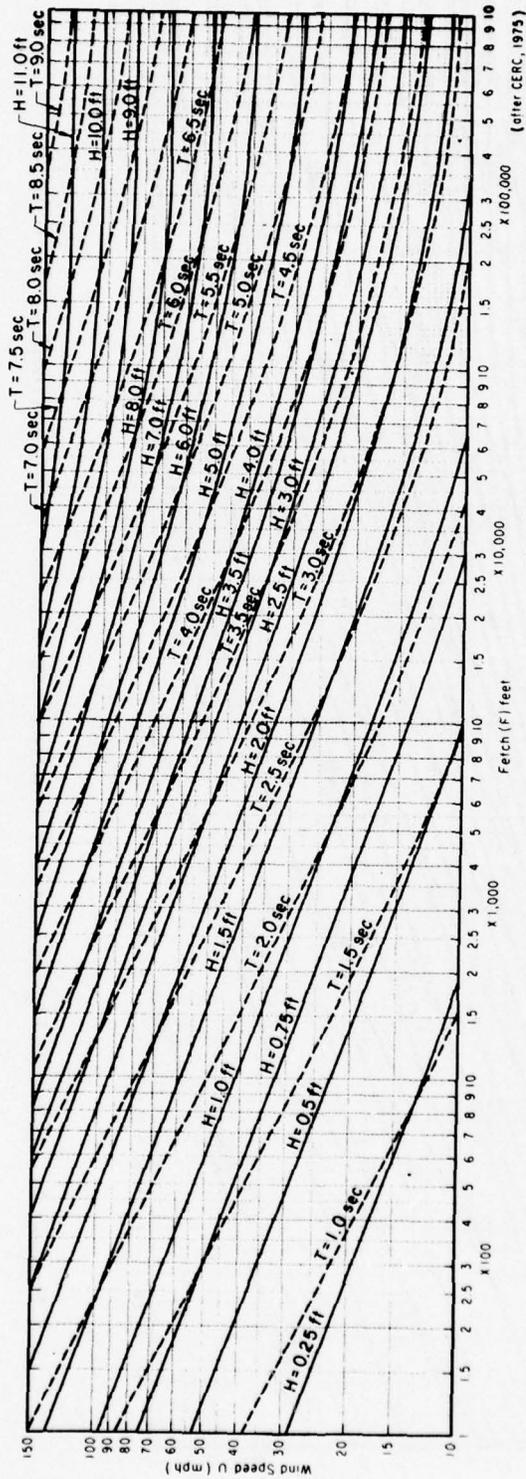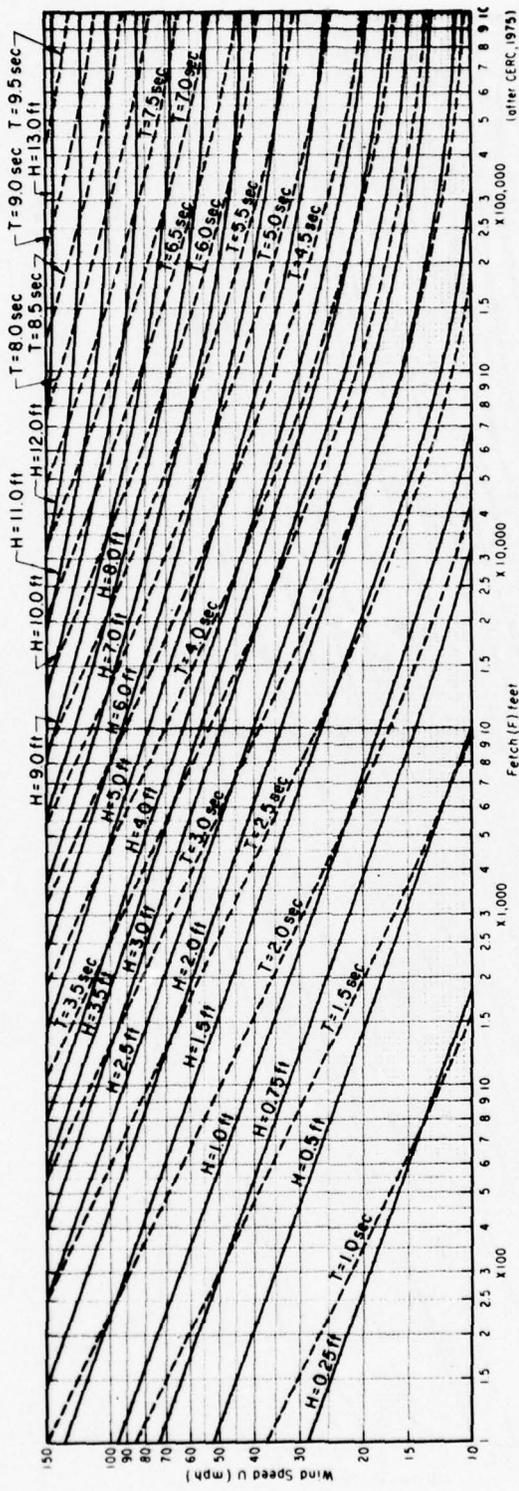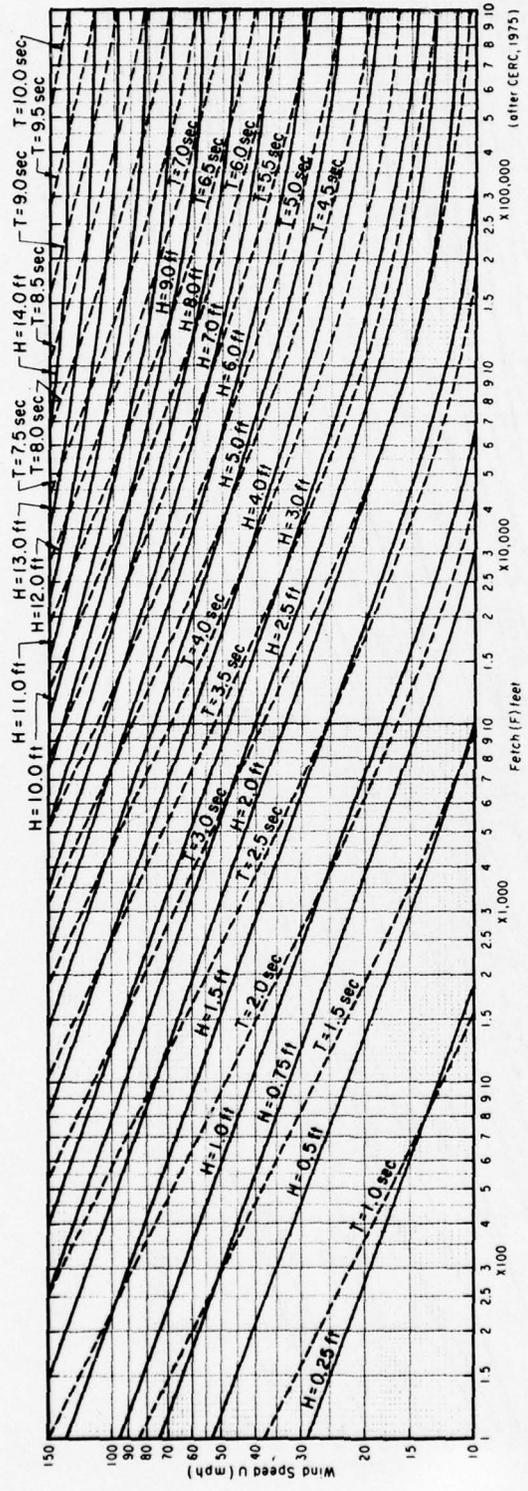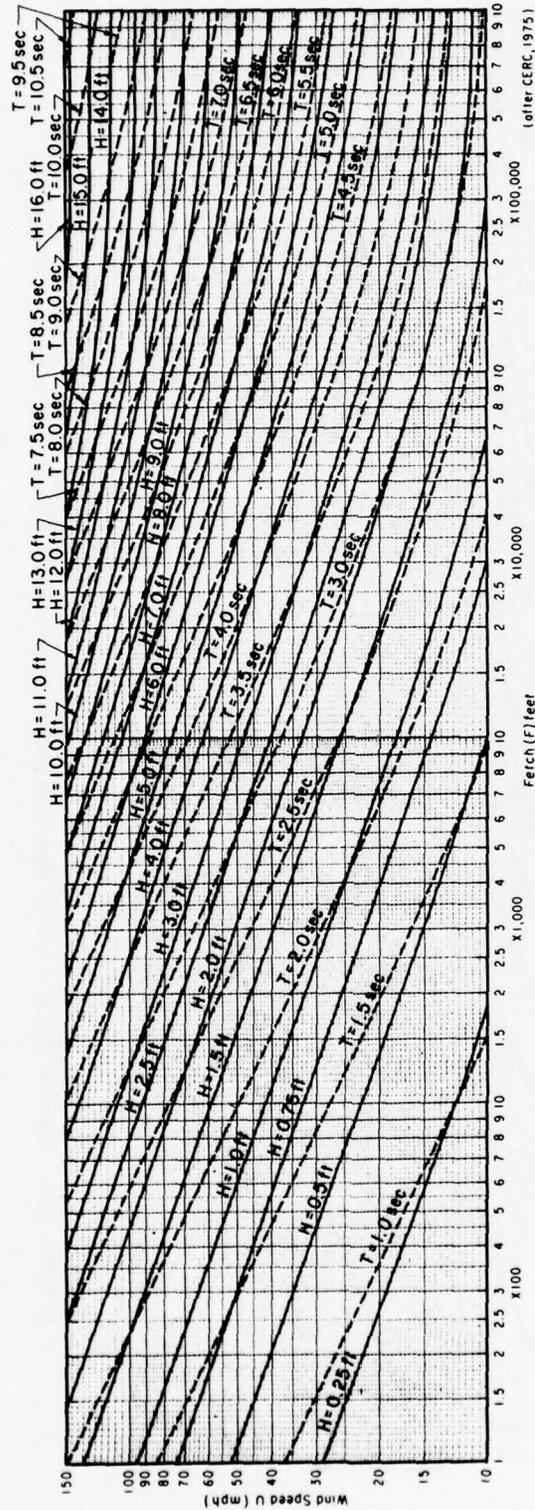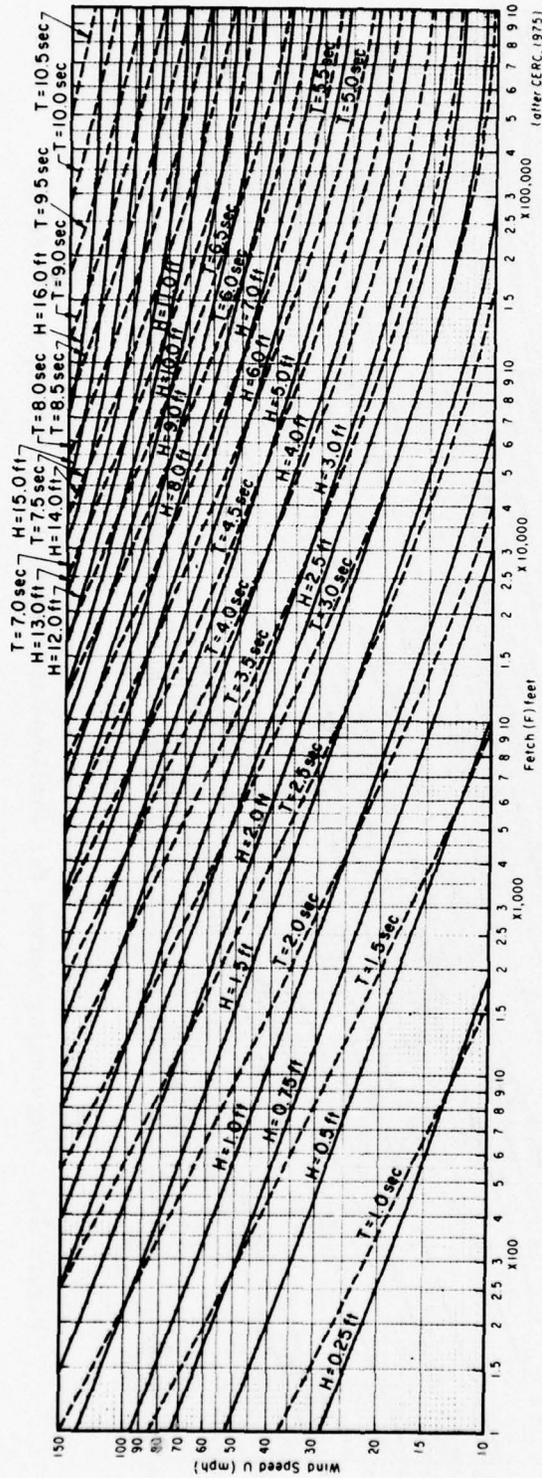Figure 12. Forecasting curves for shallow-water waves (constant depth, 50 feet).

22

when the fetch is sufficiently long. From Figure 1, the relationship
between the wave height, H_{sm}, and the water depth, d, is given by

$$\frac{g\,H_{sm}}{U^2} = 0.146\left[\frac{gd}{U^2}\right]^{0.75} \qquad (3)$$

Where the bottom-friction factor $f_f = 0.01$, and for a given water depth
and windspeed, when the initial wave height, H_i, at the beginning of
the fetch is less than H_{sm}, the wave will continue to grow in height as
it travels across the fetch, with the height approaching the maximum sig-
nificant wave height, H_{sm}. When H_i is greater than H_{sm}, it is as-
sumed that the wave height will decay as the wave travels across the
fetch, with the wave height again approaching the maximum significant
wave height, H_{sm}.

Where the bottom-friction factor $f_f > 0.01$, i.e., vegetation in-
creases the frictional resistance, and the initial wave height $H_i < H_{sm}$,
it is assumed that the wave will grow to a final height less than or
equal to H_{sm}, but that the growth will occur at a slower rate than
where $f_f = 0.01$ (Fig. 13). Although the higher frictional resistance
may limit the wave growth in this case to a height less than H_{sm}, no
data are available on this effect. Therefore, as a conservative estimate,
it is assumed that the maximum significant wave height will have the same
value, H_{sm}, as where $f_f = 0.01$.

Where the bottom-friction factor $f_f > 0.01$, and the initial wave
height $H_i > H_{sm}$, it is assumed that the wave will decay to a final
height less than or equal to H_{sm}, but that the decay will occur at a
greater rate than where $f_f = 0.01$ (Fig. 14). Although the higher fric-
tional resistance may cause the wave to decay to a height less than H_{sm},
no data are presently available. Therefore, the maximum significant wave
height is assumed equal to the value of H_{sm} where $f_f = 0.01$ as before.

Where the bottom-friction factor $f_f > 0.01$, the fetch length is ad-
justed to an equivalent fetch, F_a, which has a bottom friction $f_f = 0.01$, and which will give the same growth or decay as the actual fetch
with the actual bottom friction. The relationship between the adjusted
fetch, F_a, and the actual fetch distance, Δx, is shown in Figures 13
and 14. After the adjusted fetch, F_a, has been determined, Figures 1 to
12 are used to predict wave growth or decay (see Secs. IV and V).

1. Determination of Friction Factor.

Limited data are available to define friction factors for water wave
motion through dense stands of marsh grass, brush, or trees. Saville
(1952) presented marsh correction factors for correcting values of wave
setup over flooded marsh areas. However, this was not extended to pro-
vide corrections for wave heights. Whitaker, et al. (1975) developed
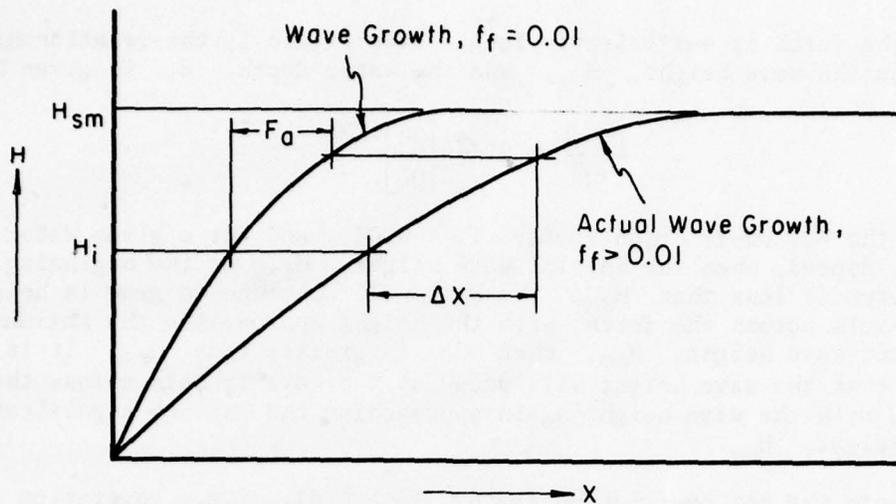numerical simulations of water level changes which considered the effects
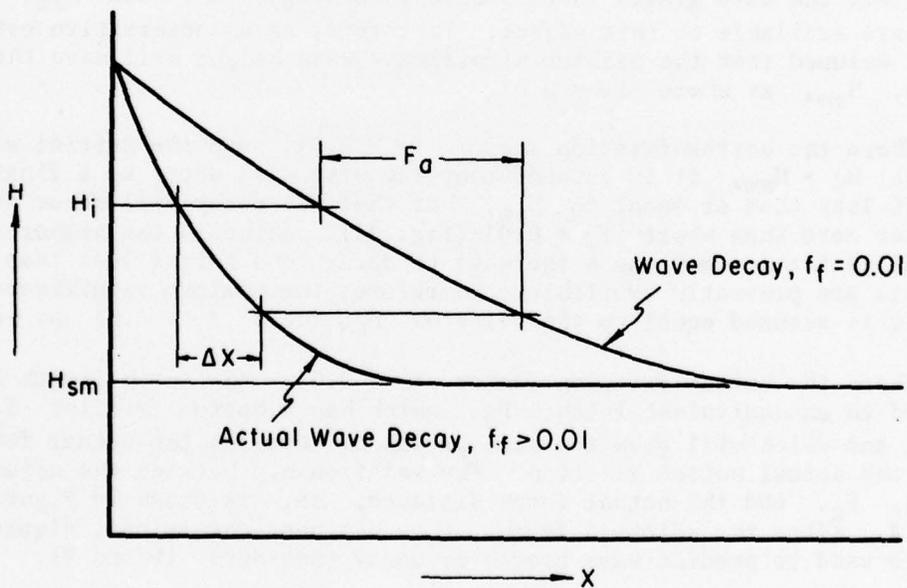
23

Figure 13. Wave growth.

Figure 14. Wave decay.

24

of vegetation in terms of drag coefficients, but effects on wave heights were not considered. Wayne (1975) investigated the decay of very low amplitude waves, from 0.126 to 0.744 foot high (0.038 to 0.227 meter), traveling short distances over grass. However, he did not establish the dependence of wave period, initial wave height, and water depth, or consider the combination of wind stress with bottom friction.

To obtain values of bottom-friction factors, estimates of Manning's roughness coefficient, n, have been made using values shown in Chow (1959) for flow over flood plains. These estimated roughness coefficients are conservative; i.e., they are expected to give predicted wave heights somewhat greater than the wave heights which actually occur. The reduction in wind stress due to vegetation extending above the water surface is not considered. The roughness coefficient, n, can be related to the friction factor, f_f, for flow over ground by combining the Darcy-Weisbach and Manning equations for energy losses due to friction. However, the Manning equation contains a dimensional coefficient which varies depending on the dimensional units in the equation. Using a foot-pound-second system of units,

$$f_f = \frac{3.60 \ g \ n^2}{d^{1/3}} \ , \tag{4}$$

where d is in feet and g is in feet per second squared. (In a meter-kilogram-second system of units, the coefficient 3.60 in equation (4) becomes 8.0.)

The roughness coefficient, n, will vary as a function of depth due to the height of the vegetation in relation to the depth of the water. In addition, the friction factor, f_f, has an inverse relationship to the water depth, d, as shown by equation (4). Values of f_f used for various kinds of ground cover are shown as curves A to D in Figure 15. Curve A is for a sandy bottom (Bretschneider, 1952, 1958, 1970), where f_f is assumed constant. This curve was used for developing the curves in Figures 1 to 12. Curve B is for coastal areas with thick stands of grass. The grass will create a high resistance at low water levels where the depth of water and the height of the grass are nearly equal, but the resistance will rapidly diminish as the water depth becomes greater than the grass height; i.e., the water particle motion under the wave is influenced less by the vegetation. Curve C is for higher levels of vegetation, such as brush or low bushy trees which extend above the height of the grass. The friction effects will be higher for curve C than for curve B because the higher vegetation will have more influence on the water particle motion for any given water depth. Curve D is for tall trees which will always be higher than the depth of water. The frictional resistance will be high at all water levels, and somewhat higher at low water levels because of the added resistance from the ground. Curve D is for a relatively close spacing of trees; e.g., a second-growth pine forest which will give the highest frictional resistance. A more scattered spacing of trees would give a lower value of f_f for a given
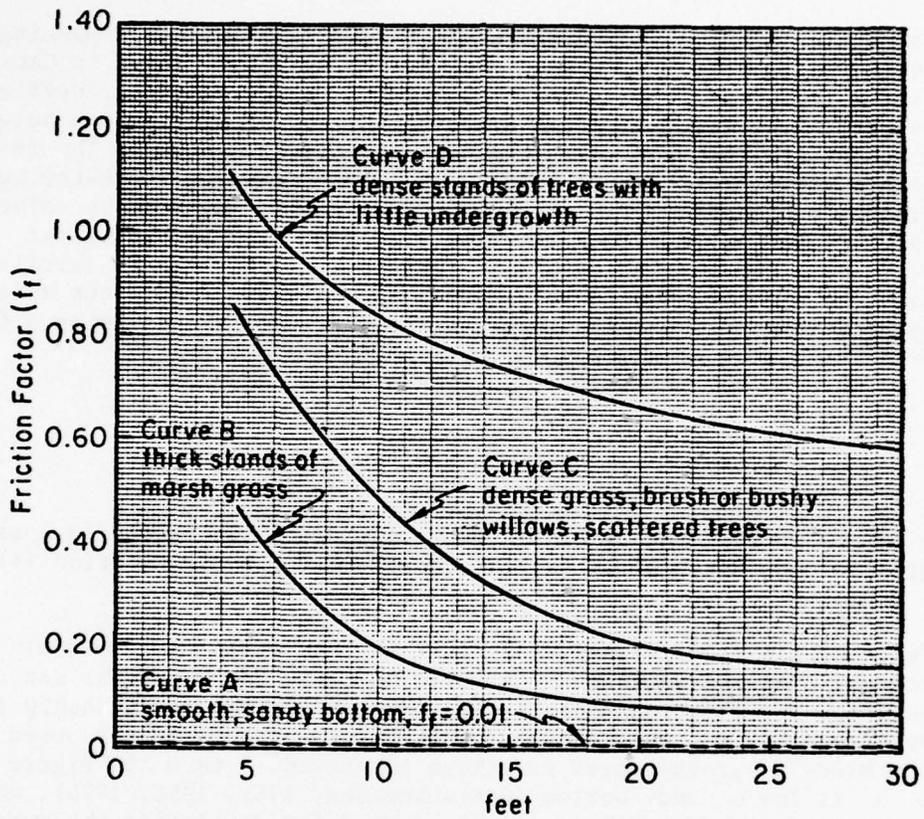
25

Figure 15.   Bottom friction factors.

water depth. Chow (1959) provides values of n for a wider range of conditions.

2. Selection of Fetch Segment.

The growth or decay of a wave at any point is dependent on the water depth, the wave height and period at that point, the bottom friction, and the windspeed. For the method used here, the windspeed is assumed to be constant across a fetch. To accurately predict the growth or decay of waves traversing a particular fetch, it is necessary to divide the fetch into segments according to water depth and bottom friction. The bottom friction may vary substantially as a function of water depth for a particular type of vegetation (Fig. 15).

Figures 1 to 12 were derived for a constant depth; any variation in depth is assumed to be very gradual, and these figures are applied to an average depth across a fetch segment. Therefore, the total variation in depth across a fetch must be considered. The type of vegetation may also vary, with sections of marsh grass, brush, trees, or shallow lagoons. Wave heights will normally vary across a fetch and, as the decay factors will depend on the wave height, new decay factors must be calculated if the wave height varies excessively. A fetch segment is also considered to be much longer than a single wavelength.

Dividing the fetch into segments, the segment distance (length in the direction of wave travel) is determined so that, first,

$$\Delta d < 0.25 \ d_i \quad , \qquad (5)$$

where Δd is the change in depth over the segment distance and d_i is the depth at the seaward or beginning edge of the segment; second,

$$\Delta f_f < 0.25 \ f_{fi} \quad , \qquad (6)$$

where Δf_f is the change in the bottom-friction factor over the segment distance and f_{fi} is the friction factor at the seaward or beginning edge of the segment; and third, after the change in wave height across the segment, ΔH, has been determined,

$$\Delta H < 0.5 \ H_i \quad , \qquad (7)$$

where H_i is the initial wave height at the seaward edge of the segment. Wave decay is also assumed to be small (less than $0.1 \ H_i$) over a single wavelength. The segment distance may require adjustment; i.e., a shorter segment may be necessary if the computed value of ΔH is unacceptable. The numerical coefficients used on the right-hand side of equations (5), (6), and (7) are arbitrarily chosen. Smaller coefficients would be expected to increase the calculations required for a solution; larger coefficients would be expected to produce a greater error in the estimated wave height obtained.

Because of the storm conditions producing the surge, it is assumed that waves will always exist at the seaward edge of the initial segment (i.e., $H_i \gg 0$), and values of wind velocity, U, greater than, e.g., 50 miles per hour (73 feet or 22.4 meters per second) will be expected. In case where $H_i = 0$, the methods presented here do not apply. Initial wave growth would consist of very low amplitude waves with very short periods. These initial waves will only be influenced by vegetation if the vegetation extends above the wave surface. That case has not been investigated, and cannot be treated by the method discussed in this report.

3. Adjustment of Fetch Length.

The adjusted fetch length of the segment is determined by comparing the decay factor, K_f, for the actual bottom friction of the segment (from Fig. 15) with the decay factor obtained for the friction factor $f_f = 0.01$ which was used for the wave predictions in Figures 1 to 12. Using the method of Bretschneider (1954) (Fig. 16), the decay factor, K_f, is obtained by using the two factors $f_f H_i \Delta x/d^2$ and $2\pi d/(gT^2)$, where Δx is the *actual* segment distance in feet in the direction of wave motion.

The decay factor, K_f, was defined by Bretschneider as

$$K_f = \frac{1}{\dfrac{f_f H_i \Delta x}{d^2} \left(\dfrac{2\pi d}{gT^2}\right)^2 \dfrac{16\pi K_s^2}{3\left(\sinh \dfrac{2\pi d}{L}\right)^3} + 1} \quad , \tag{8}$$

where K_s is the shoaling coefficient defined as H/H_o' in Table C-1 of the SPM. By noting that

$$\frac{d}{L_o} = \frac{2\pi d}{gT^2} \quad , \tag{9}$$

where L_o is the deepwater wavelength, and K_s and sinh $(2\pi d/L)$ are functions of d/L_o and therefore of $2\pi d/(gT^2)$, it can be shown that when $2\pi d/(gT^2)$ *is held constant* that the right-hand side of equation (8) is then a function of $f_f H_i \Delta x/d^2$ only.

Bretschneider (1954) used the work of Putnam and Johnson (1949) to define a friction factor for an impermeable sandy bottom as $f_f = 0.01$. The curves in Figures 1 to 12 were developed for that friction factor. The wave decay is proportional to $(1 - K_f)$. To compare wave decay over a fetch segment with high bottom friction to wave decay over a fetch segment where the bottom friction $f_f = 0.01$ (H_i, d, and U being the same), a proportionality factor, α, is defined by
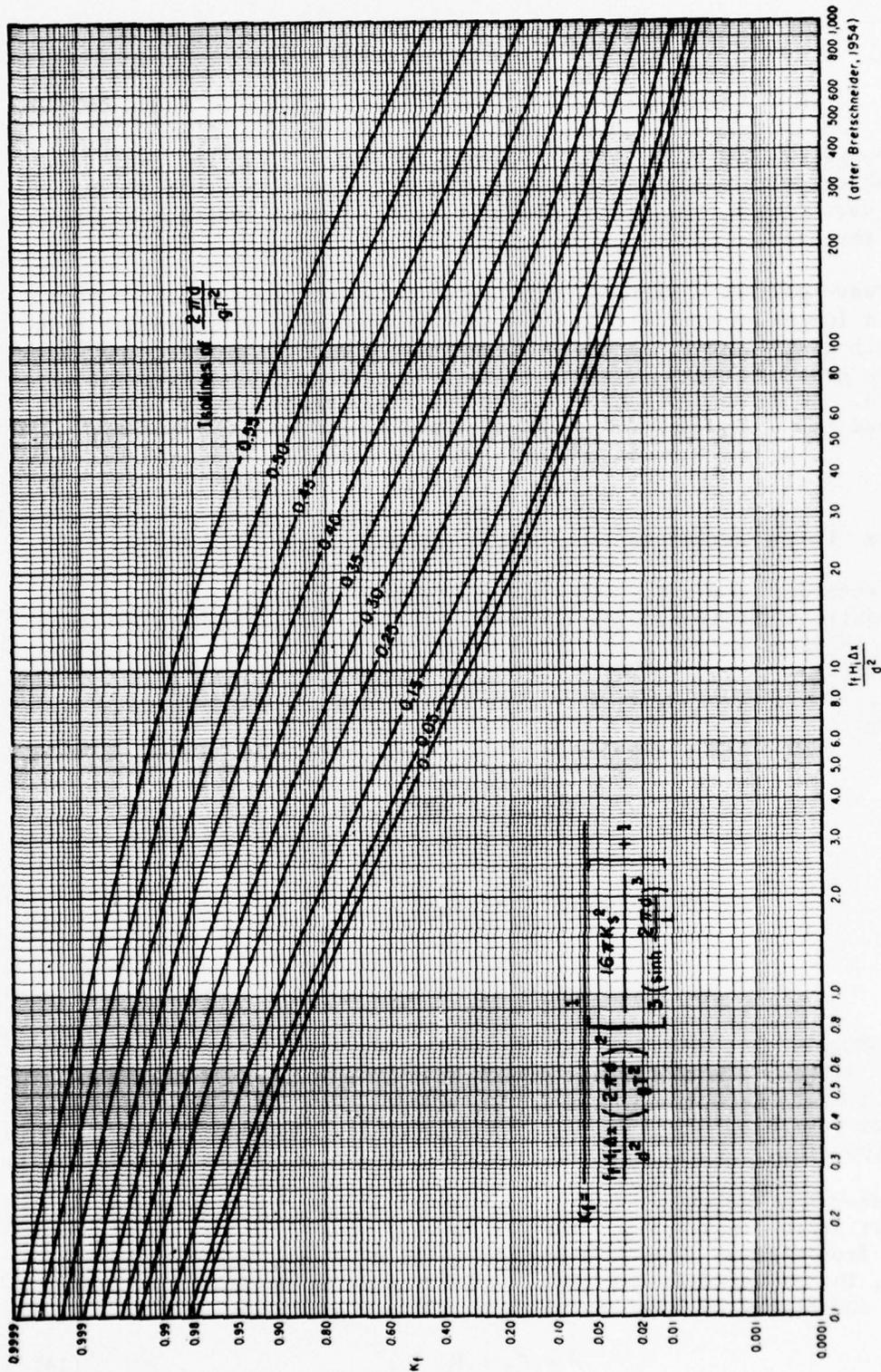
28

Figure 16. Decay factors.

29

$$\alpha = \frac{(1 - K_{f.01})}{(1 - K_{fa})} \quad , \tag{10}$$

where $K_{f.01}$ is the decay factor defined for $f_f = 0.01$ and K_{fa} is the decay factor defined for the actual bottom friction with water depth, d, initial wave height, H_i, windspeed, U, and segment length, Δx, remaining the same.

For wave growth, a segment with bottom friction $f_f > 0.01$ would require a longer segment length for waves to grow to a given height than the length that would be required where $f_f = 0.01$. Therefore, the segment with greater bottom friction is equivalent to a shorter segment with $f_f = 0.01$. As an approximation, the shorter adjusted segment length, F_a, is defined as

$$F_a = \alpha \, \Delta x \quad , \tag{11}$$

where Δx is the actual segment length (see Fig. 13).

For wave decay, a fetch segment with bottom friction $f_f > 0.01$ would require a shorter length for waves to decay to a given height than would be required where $f_f = 0.01$. Therefore, the segment with higher bottom friction is equivalent to a longer segment with $f_f = 0.01$ (see Fig. 14). The *longer* adjusted segment length, F_a, in this case is defined as

$$F_a = \alpha_r \, \Delta x \quad , \tag{12}$$

where

$$\alpha_r = \frac{1}{\alpha} = \frac{(1 - K_{fa})}{(1 - K_{f.01})} \quad . \tag{13}$$

IV.   WAVE GROWTH IN SHALLOW WATER

From Figure 1 or equation (3), for any given water depth, windspeed, and fetch length, a maximum significant wave height, H_{sm}, which would be generated can be defined. If the initial wave height, H_i, at the seaward or beginning edge of the fetch segment is less than H_{sm}, it is assumed that the wave will grow to a higher height as discussed previously.

To determine the wave growth, it is necessary to first determine an equivalent fetch length, F_e, for the initial wave. This is obtained directly from Figures 1 to 12 using the given windspeed and water depth. Secondly, the adjusted fetch, F_a, is determined using equations (10) and (11) and Figure 16. The total fetch is then given as

$$F = F_e + F_a \quad . \tag{14}$$

30

Re-entering Figures 1 to 12 with the fetch length, F, the windspeed, U, and water depth, d, the final wave height at the end of the fetch segment, H_f, is determined. This is shown schematically in Figure 17 and in the following example problem.

* * * * * * * * * * * * * * EXAMPLE PROBLEM 1 * * * * * * * * * * * * *

GIVEN: A wave passes into shallow water over a flooded coastal area. The water depth, d_i, at the seaward edge of the area is 23 feet (7 meters), and at the landward edge of the area the depth is 13 feet (4 meters). The distance across the area in the direction of wave motion is 10,000 feet (3,050 meters). The wave height, H_i, at the seaward edge of the area is limited by large sandbars seaward of the area being considered and is 3 feet (0.91 meter); the wave period is 3.2 seconds. The windspeed is 70 miles per hour (102.7 feet or 31.3 meters per second). The flooded area is covered with thick stands of tall grass.

FIND: The height and period of the significant wave at the landward edge of the segment.

SOLUTION:
$$0.25 \, d_i = 0.25 \, (23) = 5.75 \text{ feet}$$

$$\Delta d = 23 - 13 = 10 \text{ feet} > 0.25 \, d_i \, .$$

Since this does not meet the condition of equation (5), the area should be divided into two fetch segments. Assuming a uniform variation in depth, take the first segment as a distance $\Delta x = 5,000$ feet with a depth variation from 23 to 18 feet. Then

$$\Delta d = 23 - 18 = 5 \text{ feet} < 0.25 \, d_i \, .$$

At the 23-foot depth (from Fig. 15, curve B),

$$f_f = 0.080$$

and at the 18-foot depth (curve B),

$$f_f = 0.095$$

$$\Delta f_f = 0.095 - 0.080 = 0.015$$

$$0.25 \, f_{fi} = 0.25 \, (0.080) = 0.020$$

$$\Delta f_f = 0.25 \, f_{fi} \, .$$

Equations (5) and (6) are satisfied, so the fetch segment chosen is used. For a uniformly varying depth, the average depth can be taken as the average of the depths at the beginning and the end of the segment; i.e.,
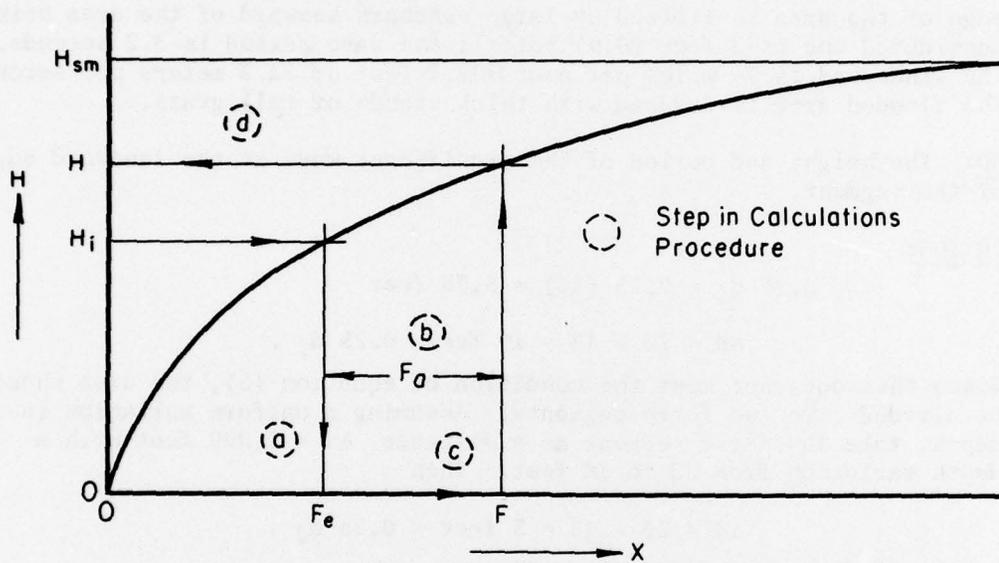
31

Figure 17. Schematic of wave growth calculation.

$$d = \frac{23 + 18}{2} = 20.5 \text{ feet} .$$

For a uniform type of vegetation, the friction factor will vary as a function of water depth (Fig. 15). As an approximation, the average friction factor can be taken as the average of the friction factors at the beginning and the end of the segment, i.e.,

$$f_f = \frac{0.080 + 0.095}{2} = 0.088 .$$

For d = 20.5 feet, H_i = 3 feet, and U = 70 miles per hour from Figures 1 or 6

$$\frac{gd}{U^2} = \frac{32.2 \times 20.5}{(102.7)^2} = 0.0626$$

$$\frac{gH_1}{U^2} = \frac{32.2 \times 3}{(102.7)^2} = 0.00916$$

and from Figure 1

$$\frac{gF}{U^2} = 12.2$$

$$F_e = 12.2 \frac{U^2}{g} = 12.2 \frac{(102.7)^2}{32.2} = 4,000 \text{ feet} .$$

For f_f = 0.01,

$$\frac{f_f H_i \Delta x}{d^2} = \frac{0.01 \times 3 \times 5,000}{20.5^2} = 0.357 ;$$

for f_f = 0.088,

$$\frac{f_f H_i \Delta x}{d^2} = \frac{0.088 \times 3 \times 5,000}{20.5^2} = 3.14 .$$

For the period, t = 3.2 seconds, and d = 20.5 feet,

$$\frac{2\pi d}{gT^2} = \frac{2\pi (20.5)}{32.2 (3.2)^2} = 0.391 .$$

For $2\pi d/(gT^2)$ = 0.391 (from Fig. 16)

$$K_{f.01} = 0.996 \text{ for } f_f = 0.01 \text{ and } f_f H_i \, \Delta x/d^2 = 0.357$$

$$K_{fa} = 0.965 \text{ for } f_f = 0.088 \text{ and } f_f H_i \, \Delta x/d^2 = 3.14 \ .$$

From equation (10),

$$\alpha = \frac{1 - K_{f.01}}{1 - K_{fa}} = \frac{1 - 0.996}{1 - 0.965} = \frac{0.004}{0.035} = 0.114 \ ;$$

from equation (11),

$$F_a = \alpha \, \Delta x = 0.114 \, (5{,}000) = 570 \text{ feet; and}$$

from equation (14),

$$F = F_e + F_a = 4{,}000 + 570 = 4{,}570 \text{ feet} \ .$$

For $d = 20.5$ feet, $U = 70$ miles per hour, and $F = 4{,}570$ feet (from Figs. 1 and 2, or 6)

$$H_f = 3.17 \text{ feet and } T = 3.31 \text{ seconds}$$

$$\Delta H = 3.17 - 3 = 0.17 \text{ feet} < 0.50 \, H_i \ .$$

This satisfies the requirements of equation (7), and the solution may proceed to the next segment which is the remaining 5,000 feet of the area, with the water depth varying from 18 to 13 feet, so

$$0.25 \, d_i = 0.25 \, (18) = 4.50 \text{ feet} \ .$$

Since $\Delta d = 18 - 13 = 5$ feet $> 0.25 \, d_i$, which does not satisfy equation (5), a shorter segment is required. For a 3,000-foot segment, assuming a uniform depth variation, the depth will vary from 18 to 15 feet. For the 15-foot depth (using curve B in Fig. 15)

$$f_f = 0.120$$

$f_{fi} = 0.095$ at the 18-foot depth as previously shown.

$$\Delta f_f = 0.120 - 0.095 = 0.025 \simeq 0.25 \, f_{fi} \ .$$

This satisfies equation (6) and the solution may proceed. The average depth, $d = 16.5$ feet, and the average friction factor, $f_f = 0.108$. For $d = 16.5$ feet and $H = 3.17$ feet (from Fig. 1)

$$F_e = 5{,}400 \text{ feet} \ ;$$

34

for d = 16.5 feet, H_i = 3.17 feet, f_f = 0.108, Δx = 3,000 feet, and T = 3.31 seconds (from Fig. 16)

$$\frac{2\pi d}{gT^2} = 0.294$$

$K_{f.01}$ = 0.988 for f_f = 0.01 and f_f H_i $\Delta x/d^2$ = 0.349

K_{fa} = 0.88 for f_f = 0.108 and f_f H_i $\Delta x/d^2$ = 3.77 ..

Using equation (10), α = 0.1 and

$$F_a = \alpha \Delta x = 0.1 \ (3,000) = 300 \text{ feet}$$

$$F = F_e + F_a = 5,400 + 300 = 5,700 \text{ feet} .$$

For d = 16.5 feet (from Figs. 1 and 2)

$$H_f = 3.27 \text{ feet and } T = 3.41 \text{ seconds} .$$

The remaining 2,000 feet of the fetch can then be treated as a third segment. The average depth, d = 14 feet, and the average friction factor, f_f = 0.13.

For d = 14 feet and H_i = 3.27 feet (from Fig. 1),

$$F_e = 7,200 \text{ feet; ;}$$

for d = 14 feet, H_i = 3.27 feet, f_f = 0.13 (from Fig. 16)

$$\Delta x = 2,000 \text{ feet, } T = 3.41 \text{ seconds, and } 2\pi d/(gt^2) = 0.235 ,$$

$K_{f.01}$ = 0.98 for f_f = 0.01 and f_f H_i $\Delta x/d^2$ = 0.334

K_{fa} = 0.80 for f_f = 0.13 and f_f H_i $\Delta x/d^2$ = 4.34 .

Using equation (10), α = 0.1 and

$$F_a = \alpha \Delta x = 0.1 \ (2,000) = 200 \text{ feet}$$

$$F = F_e + F_a = 7,200 + 200 = 7,400 \text{ feet} .$$

For d = 14 feet, U = 70 miles per hour, and F = 7,400 feet (from Figs. 1 and 2)

$$H_f = 3.34 \text{ feet and } T = 3.51 \text{ seconds} .$$

Note.--For a sandy bottom f_f = 0.01, the wave would have increased to a height of approximately 4.26 feet, a 42-percent increase from

the initial wave height of 3 feet. For the thick stands of tall grass,
the predicted increase in wave height is only 11 percent using the
approximate method of solution discussed in this report.

* *

V. WAVE DECAY IN SHALLOW WATER

Values of wind-generated significant wave heights and wave periods
as a function of windspeed and water depth are shown in Figures 1 to 12.
If the initial significant wave height at the seaward or beginning edge
of a segment of fetch exceeds the maximum significant wave height for
the given water depth of the segment of fetch and the given windspeed,
the effects of the bottom friction may be assumed to exceed the effects
of the wind stress. Therefore, the wave is assumed to decay, lose height,
and over a long distance to approach a height equal to the maximum sig-
nificant wave height.

The higher waves at the beginning of the fetch will actually repre-
sent a spectrum of waves. Waves of various periods could break at dif-
ferent points approaching the shallow-water fetch area from deep water.
As shown in Figure 16, the method used here predicts that the longer
period wind waves would decay faster than shorter period waves passing
through the shallow water (see Fig. 18). As discussed previously, the
effects of vegetation near the surface may have a strong influence on
very short-period waves. However, these waves are considered to be less
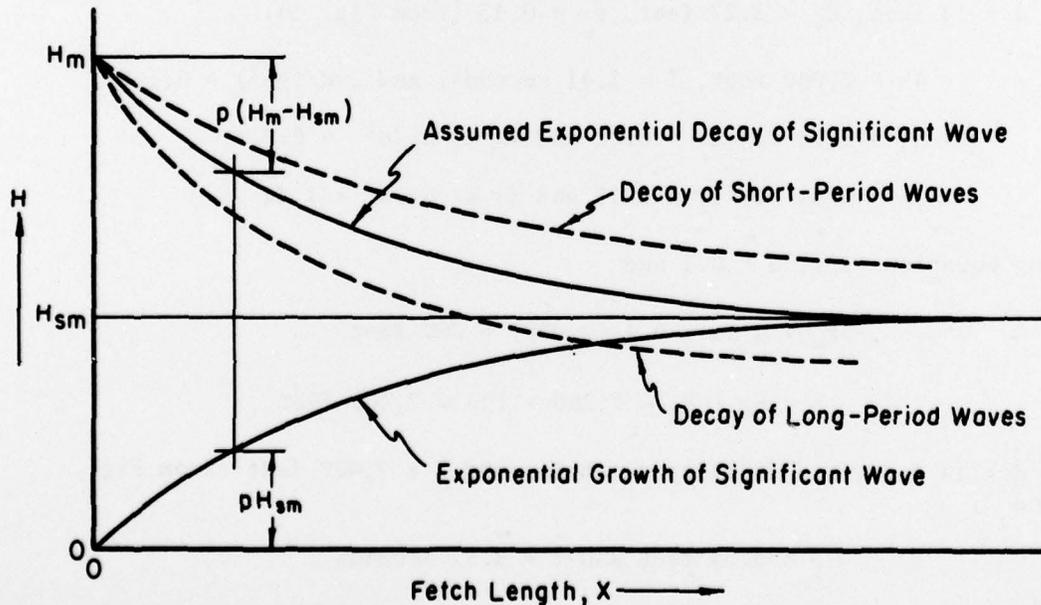important for design purposes, and this influence is ignored.

Figure 18.   Exponential wave growth and decay.

36

As a first approximation, the wave decay may be assumed to occur exponentially at a rate similar to the rate of wave growth; i.e., the wave height will decay from a maximum stable wave height given by the shallow-water condition

$$H_m = 0.78 \, d \tag{15}$$

to a height equal to the maximum significant height in a distance approximately equal to the shallow-water fetch length required for a wave to grow from a zero height to the maximum generated significant wave height (the fetch length defined by the long dashlines in Fig. 1).

1. <u>Wave Height</u>.

The means of determining the decayed wave height is shown schematically in Figure 19. Steps to predict the decay of a wave are:
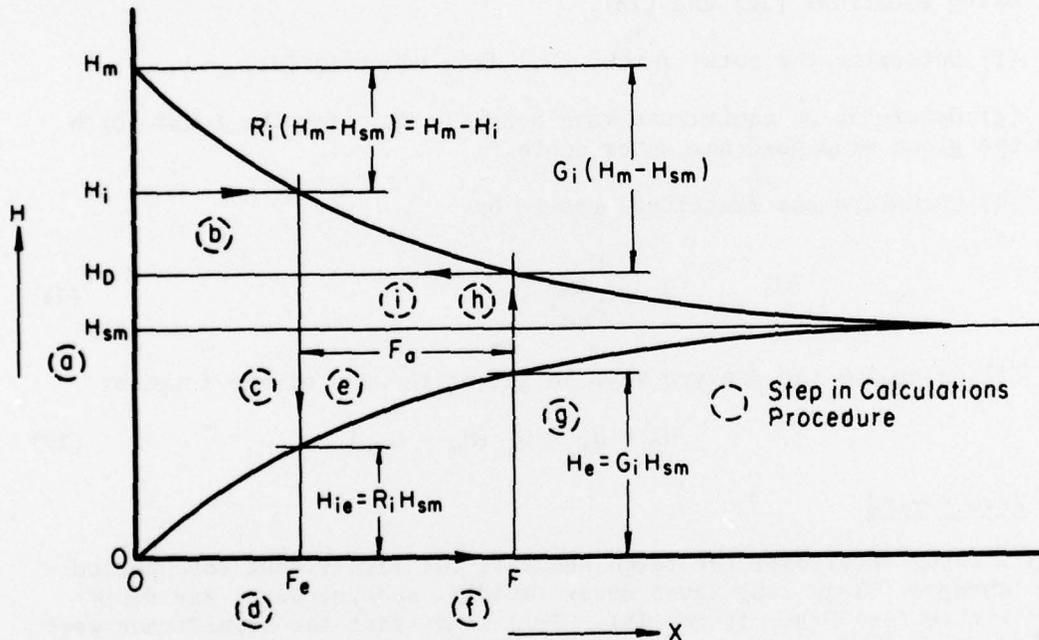
Figure 19. Schematic of wave decay calculations.

(a) Determine the maximum significant wave height that would be generated for the given windspeed and water depth, assuming an unlimited fetch, and using Figures 1 to 12 or equation (3).

(b) Determine the fractional reduction, R_i, represented by the initial wave at the seaward edge of the segment of fetch under consideration given by

37

$$R_i = \frac{H_m - H_i}{H_m - H_{sm}} \, , \qquad\qquad (16)$$

where H_m is the maximum stable wave height given by equation (15), H_i the incident wave height at the seaward edge of the fetch segment, and H_{sm} the maximum significant wave height.

(c) Determine the equivalent initial wave height, H_{ie}, for wave growth by

$$H_{ie} = R_i H_{sm} \, . \qquad\qquad (17)$$

(d) Determine the equivalent fetch length, F_e, for the wave height, H_{ie}.

(e) Determine an adjusted fetch length, F_a, for the segment length, Δx, using equations (12) and (13).

(f) Determine the total fetch, F, from equation (14).

(g) Determine an equivalent wave height, H_e, for the total fetch and the given windspeed and water depth.

(h) Calculate the fractional growth by

$$G_i = \frac{H_e}{H_{sm}} \, . \qquad\qquad (18)$$

(i) Calculate the decayed wave height at the end of the fetch by

$$H_D = H_m - G_i \, (H_m - H_{sm}) \, . \qquad\qquad (19)$$

2. <u>Wave Period.</u>

As waves decay over the fetch segment, the significant wave period also changes. Very long waves decay rapidly; shorter waves may decay very little (see Figs. 16 and 18). This means that the significant wave period may be reduced. As a conservative estimate, it will be assumed that the wave period remains constant. This is a conservative estimate since longer period waves would produce higher runup on a structure, all other variables being the same.

* * * * * * * * * * * * * * * EXAMPLE PROBLEM 2 * * * * * * * * * * * * * *

<u>GIVEN</u>: A coastal area is flooded by a storm surge so that the water depth over the area is 10 feet (3.05 meters). The actual fetch across the area, in the direction of wave travel, is 3,000 feet (914 meters). The area is covered with thick stands of tall grass and a small to moderate amount of brush or low bushy trees in an even distribution.

38

The windspeed is 90 miles per hour (132 feet or 40.2 meters per second) and the initial wave height at the seaward edge of the area of 6 feet (1.83 meters); the wave period is 4.5 seconds.

FIND: The decayed wave height at the end of the fetch.

SOLUTION: From the long dashline in Figure 1, for the windspeed of 90 miles per hour and the water depth of 10 feet

$$\frac{gd}{U^2} = \frac{32.2 \times 10}{(132)^2} = 0.0185$$

giving (at the intersection of the above line with the long dashline)

$$\frac{gH}{U^2} = 0.0075$$

so that the maximum significant wave height

$$H_{sm} = \frac{0.0075\ U^2}{g} = \frac{0.0075\ (132)^2}{32.2} = 4.1 \text{ feet .}$$

From equation (15),

$$H_m = 0.78d = 0.78\ (10) = 7.8 \text{ feet}$$

and from equation (16), the fractional reduction is

$$R_i = \frac{H_m - H_i}{H_m - H_{sm}} = \frac{7.8 - 6}{7.8 - 4.1} = 0.486 \text{ .}$$

From equation (17), the equivalent initial wave height

$$H_{ie} = R_i\ H_{sm} = 0.486 \times 4.1 = 1.99 \text{ feet ;}$$

from Figure 1, for

$$\frac{gH}{U^2} = \frac{32.2\ (1.99)}{(132)^2} = 0.00368$$

and

$$\frac{gd}{U^2} = 0.0185$$

the fetch is given by

$$\frac{gF}{U^2} = 1.4$$

39

F = 760 feet for the 90-mile per hour windspeed, so that the equivalent fetch is

$$F_e = 760 \text{ feet} \quad .$$

The vegetation does not match any of the curves in Figure 15, but falls between curves B and C. Assuming that a moderate amount of brush will give a friction effect about halfway between the two curves, from curve B, where d = 10 feet, f_f = 0.20, and from curve C, where d = 10 feet, f_f = 0.485. The bottom friction is then taken, in this case, as the average of the two values

$$f_f = \frac{0.20 + 0.485}{2} = 0.343 \quad .$$

For f_f = 0.01,

$$\frac{f_f \, H_i \, \Delta x}{d^2} = \frac{0.01 \times 6 \times 3,000}{10^2} = 1.8 \quad ;$$

for f_f = 0.343,

$$\frac{f_f \, H_i \, \Delta x}{d^2} = \frac{0.343 \times 6 \times 3,000}{10^2} = 61.7 \quad ;$$

for T = 4.5 seconds and d = 10 feet,

$$\frac{2\pi d}{gT^2} = \frac{2\pi \, (10)}{g \, (4.5)^2} = 0.096 \quad .$$

From Figure 16,

$$K_{f.01} = 0.80 \text{ for } f_f = 0.01 \text{ and } f_f \, H_i \, \Delta x/d^2 = 1.8$$

$$K_{fa} = 0.105 \text{ for } f_f = 0.343 \text{ and } f_f \, H_i \, \Delta x/d^2 = 61.7 \quad .$$

From Equation (13),

$$\alpha_r = \frac{1 - K_{fa}}{1 - K_{f.01}} = \frac{1 - 0.105}{1 - 0.80} = \frac{0.895}{0.20} = 4.48 \quad ;$$

from equation (12),

$$F_a = \alpha_r \, \Delta x = 4.48 \, (3,000) = 13,440 \text{ feet}$$

(i.e., the wave decay over 3,000 feet of tall grass with some brush is equal to the wave decay over 13,440 feet of a sand bottom for this water depth and windspeed).

$$F = F_e + F_a = 760 + 13,440 = 14,200 \text{ feet} \quad .$$

40

For a windspeed of 90 miles per hour and a fetch of 14,200 feet (from Fig. 1)

$$\frac{gd}{U^2} = 0.0185 \text{ (as previously determined)}$$

$$\frac{gF}{U^2} = \frac{32.2 \times 14,200}{(132)^2} = 26.24$$

giving

$$\frac{gH}{U^2} = 0.0071 \ .$$

From which the equivalent wave height,

$$H_e = \frac{0.0071\ U^2}{g} = \frac{0.0071\ (132)^2}{32.2} = 3.84 \text{ feet} \ .$$

From equation (18), the fractional growth is

$$G_i = \frac{H_e}{H_{sm}} = \frac{3.84}{4.1} = 0.937 \ .$$

The decayed wave height is then given by equation (19) as

$$H_D = H_m - G_i \ (H_m - H_{sm}) = 7.8 - 0.937 \ (7.8 - 4.1) = 4.33 \text{ feet} \ .$$

At the end of the fetch segment, the wave height and period are approximated by

$$H_D = 4.33 \text{ feet}$$

$$T = 4.5 \text{ seconds}$$

* *

VI. SUMMARY AND CONCLUSIONS

The method presented in this report gives a first approximation for estimating wave heights at the end of a fetch with a high value of bottom friction (e.g., a flooded area with dense stands of grass or brush). Only limited data are available for wave height growth or reduction for waves passing over areas with dense bottom vegetation. The method has not been verified.

A substantial amount of data is needed for waves passing over areas of flooded vegetation. The method should be verified and modified as required. The shoaling coefficients (Fig. 16) and the friction factors (Fig. 15) should also be compared with values from actual measurements.

LITERATURE CITED

BRETSCHNEIDER, C.L., "Revised Wave Forecasting Relationships," *Proceedings of the Second Conference on Coastal Engineering*, Council on Wave Research, 1952, pp. 1-5.

BRETSCHNEIDER, C.L., "Modification of Wave Height Due to Bottom Friction, Percolation, and Refraction," TM-45, U.S. Army, Corps of Engineers, Beach Erosion Board, Washington, D.C., Oct. 1954.

BRETSCHNEIDER, C.L., "Revisions in Wave Forecasting; Deep and Shallow Water," *Proceedings of the Sixth Conference on Coastal Engineering*, Council on Wave Research, 1958, pp. 30-67.

BRETSCHNEIDER, C.L., Department of Ocean Engineering, University of Hawaii, Honolulu, Hawaii, unpublished correspondence, 1970-71.

CHOW, V. T., *Open-Channel Hydraulics*, McGraw-Hill, New York, 1959.

IJIMA, T., and TANG, F.L.W., "Numerical Calculation of Wind Waves in Shallow Water," *Proceedings of the 10th Conference on Coastal Engineering*, 1966, pp. 38-45.

PUTNAM, J.A., and JOHNSON, J.W., "The Dissipation of Wave Energy of Bottom Friction," *Transactions of the American Geophysical Union*, Vol. 30, No. 1, 1949, pp. 67-74.

SAVILLE, T., Jr., "Wind Setup and Waves in Shallow Water," TM-27, U.S. Army, Corps of Engineers, Beach Erosion Board, Washington, D.C., June 1952.

U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, *Shore Protection Manual*, 2d ed., Vols. I, II, and III, Stock No. 008-022-00077-1, U.S. Government Printing Office, Washington, D.C., 1975, 1,160 pp.

WAYNE, C.J., "Sea and Marsh-Grasses: Their Effect on Wave Energy and Near-Shore Sand Transport," M.S. Thesis, Florida State University, Tallahassee, Fla., Sept. 1975.

WHITAKER, R.E., REID, R.O., and VASTANO, A.C., "An Analysis of Drag Coefficient at Hurricane Windspeeds from a Numerical Simulation of Dynamical Water Level Changes in Lake Okeechobee, Florida," TM-56, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Oct. 1975.

Camfield, Frederick E.

Wind-wave propagation over flooded, vegetated land / by Frederick E.
Camfield.--Ft. Belvoir, Va. : U.S. Coastal Engineering Research
Center ; Springfield, Va. : available from National Technical Informa-
tion Service, 1977.
   42 p. : ill. (Technical paper - U.S. Coastal Engineering Research
Center ; no. 77-12)
   Bibliography: p. 42.
   Report describes a method for estimating wind-wave growth and decay
over flooded areas where there is a major friction effect because of
dense vegetation. These technical guidelines are an extension of the
procedures given in the SPM which limits the design curves to waves
passing over a sandy bottom.
   1. Wave generation. 2. Wind waves. 3. Shallow water waves. I.
Title. II. Series: U.S. Coastal Engineering Research Center. Techni-
cal paper no. 77-12.

TC203   .U581tp   no. 77-12   627

Camfield, Frederick E.

Wind-wave propagation over flooded, vegetated land / by Frederick E.
Camfield.--Ft. Belvoir, Va. : U.S. Coastal Engineering Research
Center ; Springfield, Va. : available from National Technical Informa-
tion Service, 1977.
   42 p. : ill. (Technical paper - U.S. Coastal Engineering Research
Center ; no. 77-12)
   Bibliography: p. 42.
   Report describes a method for estimating wind-wave growth and decay
over flooded areas where there is a major friction effect because of
dense vegetation. These technical guidelines are an extension of the
procedures given in the SPM which limits the design curves to waves
passing over a sandy bottom.
   1. Wave generation. 2. Wind waves. 3. Shallow water waves. I.
Title. II. Series: U.S. Coastal Engineering Research Center. Techni-
cal paper no. 77-12.

TC203   .U581tp   no. 77-12   627

Camfield, Frederick E.

Wind-wave propagation over flooded, vegetated land / by Frederick E.
Camfield.--Ft. Belvoir, Va. : U.S. Coastal Engineering Research
Center ; Springfield, Va. : available from National Technical Informa-
tion Service, 1977.
   42 p. : ill. (Technical paper - U.S. Coastal Engineering Research
Center ; no. 77-12)
   Bibliography: p. 42.
   Report describes a method for estimating wind-wave growth and decay
over flooded areas where there is a major friction effect because of
dense vegetation. These technical guidelines are an extension of the
procedures given in the SPM which limits the design curves to waves
passing over a sandy bottom.
   1. Wave generation. 2. Wind waves. 3. Shallow water waves. I.
Title. II. Series: U.S. Coastal Engineering Research Center. Techni-
cal paper no. 77-12.

TC203   .U581tp   no. 77-12   627

Camfield, Frederick E.

Wind-wave propagation over flooded, vegetated land / by Frederick E.
Camfield.--Ft. Belvoir, Va. : U.S. Coastal Engineering Research
Center ; Springfield, Va. : available from National Technical Informa-
tion Service, 1977.
   42 p. : ill. (Technical paper - U.S. Coastal Engineering Research
Center ; no. 77-12)
   Bibliography: p. 42.
   Report describes a method for estimating wind-wave growth and decay
over flooded areas where there is a major friction effect because of
dense vegetation. These technical guidelines are an extension of the
procedures given in the SPM which limits the design curves to waves
passing over a sandy bottom.
   1. Wave generation. 2. Wind waves. 3. Shallow water waves. I.
Title. II. Series: U.S. Coastal Engineering Research Center. Techni-
cal paper no. 77-12.

TC203   .U581tp   no. 77-12   627