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# Energy Losses of Waves in Shallow Water

by

William G. Grosskopf and C. Linwood Vincent

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This report presents a method for predicting nearshore significant wave height given the straight-line fetch length, the windspeed, and the nearshore water depth. The prediction curves were generated by numerically propagating offshore JONSWAP spectra shoreward while applying shoaling and wave steepness limitation criteria to each spectral component. Example problems are included.

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# PREFACE

This report presents a method for predicting nearshore significant wave height given the straight-line fetch length, the windspeed, and the nearshore water depth. The wave height prediction curves were generated by numerically propagating offshore JONSWAP spectra shoreward while applying shoaling and wave steepness limitation criteria to each spectral component. The report provides an alternate approach to the problem of shallow-water wave estimation. The work was carried out under the shallow-water wave transformation program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was written by William G. Grosskopf, Hydraulic Engineer, and Dr. C. Linwood Vincent, Chief, Coastal Oceanography Branch, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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FIGURES

## 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 | 1.852 | kilometers per hour |
| acres | 0.4047 | hectares |
| foot-pounds | 1.3558 | newton meters |
| millibars | $1.0197 \times 10^{-3}$ | 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) | 0.01745 | 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

$C_h$ wave steepness limitation factor

$d$ water depth

$E$ energy density

$E_T$ total energy in the wave spectrum

$F$ straight-line fetch length (for irregularly shaped water bodies, this should be based on an average over a 24° quadrant)

$f$ frequency of spectral component

$f_m$ frequency of spectral peak

$g$ acceleration due to gravity

$H_o$ deepwater significant wave height

$H_s$ significant wave height

$\tilde{H}$ dimensionless wave height

$K_s$ shoaling coefficient

$L$ wavelength

$R$ land-wat^r windspeed correction factor

$R_T$ air-sea temperature difference windspeed correction factor

$T_p$ peak wave period

$U_A$ windspeed to be used in wave height estimation

$U_A'$ overwater windspeed corrected for wind instabilities

$U_w$ overwater windspeed

$U_z$ windspeed measured Z meters above land or water surface

$U_{10}$ 10-meter (33 foot) windspeed

$\tilde{x}$ dimensionless fetch length

$\alpha$ Phillips equilibrium constant

$\gamma$ ratio of maximal spectral energy to the maximum of the corresponding Pierson-Moskowitz spectrum

$\pi$ 3.14159

$\sigma_a$ left-side width of the spectral peak

$\sigma_b$ right-side width of the spectral peak

$\phi$ wave steepness limitation factor

$\omega_h$ wave steepness limitation factor

# ENERGY LOSSES OF WAVES IN SHALLOW WATER

*by*
*William G. Grosskopf and C. Linwood Vincent*

## I. INTRODUCTION

The energy in an irregular wave train changes as the waves propagate from deep water toward shore. Estimates of the total change in wave energy have traditionally been made by multiplying a shoaling, refraction and friction coefficient by an offshore significant wave height to yield the nearshore wave height. Recent studies of wave spectra have provided a more detailed view of the wave field and indicate that additional processes should be considered. This report presents finite-depth wave height estimation curves, given an initial JONSWAP type of offshore spectral wave condition (Hasselmann, et al., 1973) generated over a short fetch and incorporating finite-depth steepness effects based on a study by Kitaigorodskii, Krasitskii, and Zaslavskii (1975). These curves represent energy changes due to shoaling and an upper limit of energy spectral density as a function of wave frequency and water depth.

Research at the Coastal Engineering Research Center (CERC) and elsewhere indicates steepness effects that lead to breaking in a shoaling wave field lead to a major loss of energy in addition to that lost by bottom friction and percolation. These effects can be incorporated into wave estimation curves in a fashion similar to shoaling because the effects can be made a function of depth. The effects of refraction, bottom friction, and percolation are not included in these curves because they are site specific. The effects of bottom friction and percolation will always be to reduce the estimated wave height. These curves should be applied only in areas of nearly parallel bottom contours. Consequently, refraction will also only reduce wave height.

This report presents a method for estimating the significant wave height, $H_s$, given the fetch length, F, the overwater windspeed, $U_W$ (see U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1981), and the water depth, d, neglecting any additional wave growth in shallow water due to the wind. The method differs from two recently reported methods--Seelig (1980), who presents a method for predicting shallow-water wave height given deepwater wave height, $H_o$, peak period, $T_p$, and bottom slope, m, and Vincent (1981), who presents a method for calculating the depth-limited significant wave height based on knowledge of the deepwater wave spectrum--but it does not supersede the use of these other two methods. The report provides an alternate approach to the problem of shallow-water wave estimation given the four quantities mentioned above.

## II. WAVE HEIGHT PREDICTION CURVES

A series of JONSWAP spectra was generated numerically in deepwater conditions for varying windspeeds and fetch length, and propagated into shallow water over parallel bottom contours. A frequency-by-frequency calculation was made at various depths shoreward applying independently the wave steepness limitation criterion (Kitaigorodskii, Krasitskii, and Zaslavskii, 1975) and a shoaling coefficient to each spectral component. If the shoaled wave energy exceeded the limiting value, the limiting value was retained. A detailed explanation of the methodology involved in this computation is presented in the

Appendix. Resulting spectra at gradually decreasing depths for a given case are shown in Figure 1. This analysis provides the wave height prediction curves shown in Figure 2. These curves provide the nearshore significant wave height, $H_s$, at a given water depth which is related to the total energy, $E_T$, in the nearshore wave spectrum by

$$H_s = 4\sqrt{E_T}$$

given the fetch length, the overwater windspeed, and the deepwater wave height. Note that in Figure 1 there is a slight shift in the wave period toward lower frequencies as the spectrum moves into shallow water. Later work will attempt to quantify this shift and incorporate bottom friction effects.

## III. USE OF CURVES

There are certain restraints on the use of the curves which are as follows:

(1) Curves are designed to be used for fetch-limited, wind-generated waves in deep water over short fetches, i.e., up to 62 miles (100 kilometers).

(2) This analysis includes only the wave steepness criterion and shoaling. It does not reflect other energy losses such as refraction, friction, or percolation (parallel bottom contours are assumed).

(3) The fetch length, F, is strictly the straight-line fetch unless the water body is irregularly shaped where the fetch would be based on an average over a 24° quadrant.

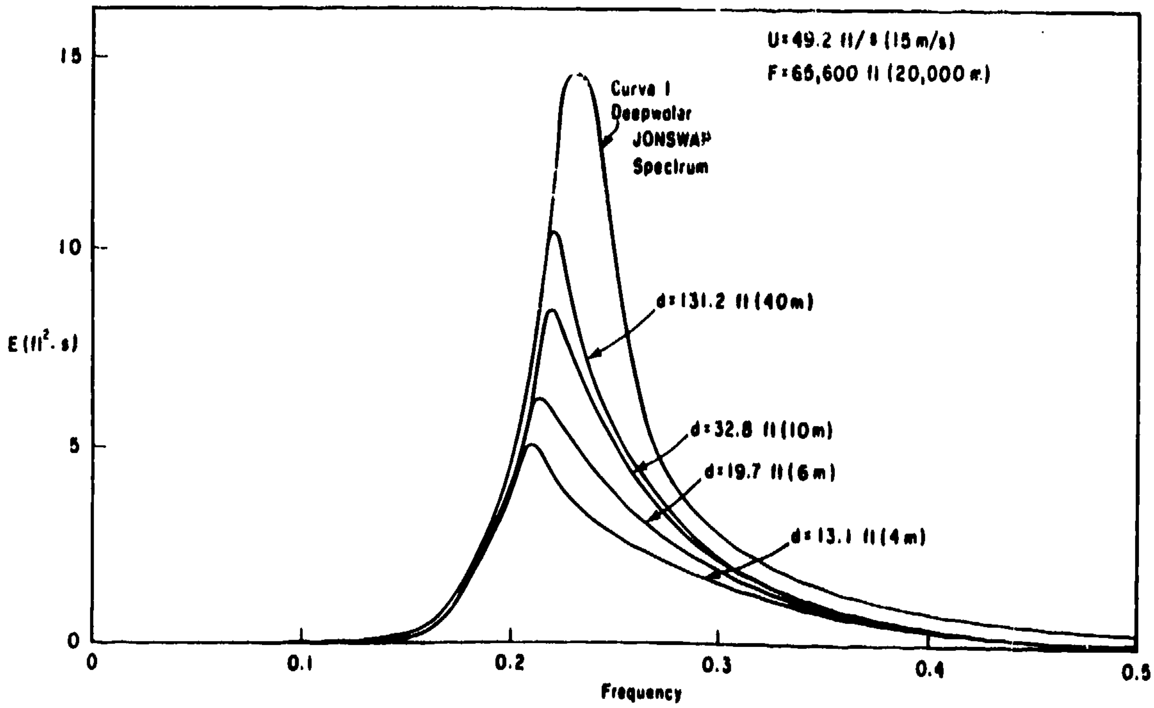


Figure 1. Transformation of JONSWAP spectrum in shallow water.

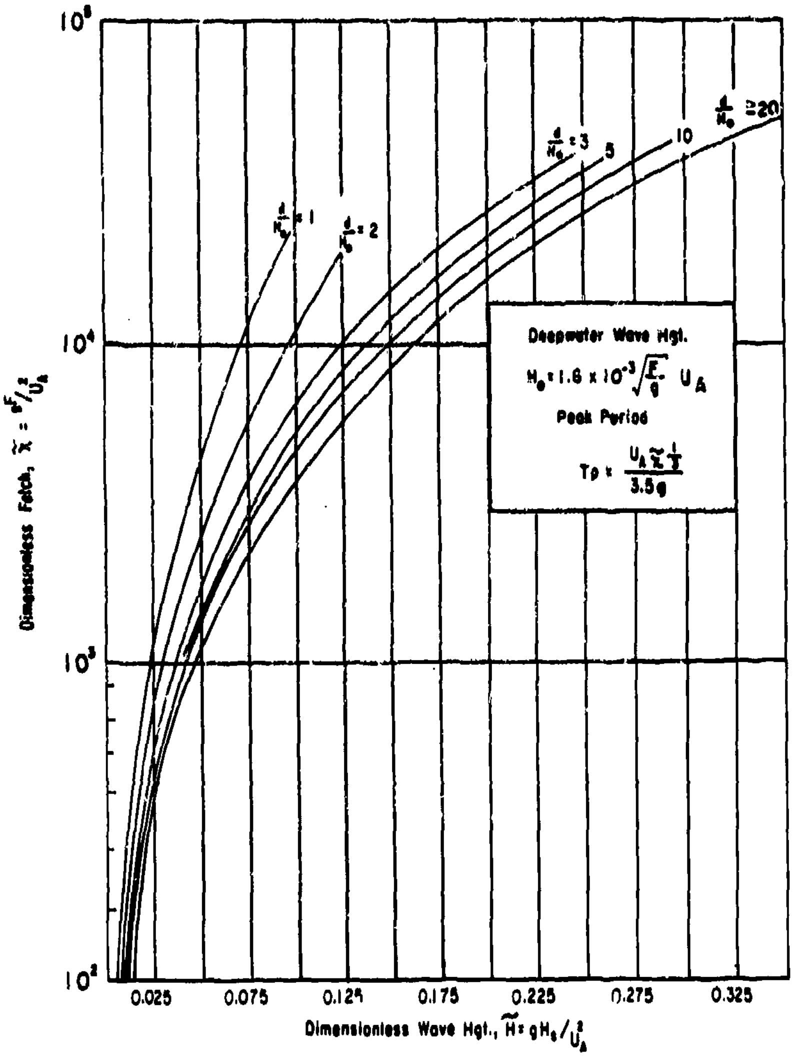


Figure 2. Dimensionless fetch versus dimensionless wave height as a function of $d/H_o$.

(4) To calculate the adjusted windspeed, $U_A$, the following procedure should be used:

(a) If windspeed is observed at any level other than 33 fect (10 meters) windspeed on land or water, the adjustment to the 33-foot level is approximated by:

$$U_{10} = \left(\frac{10}{Z}\right)^{1/7} U_z$$

where $U_{10}$ is the 10-meter windspeed in meters per second, Z the height of wind measurement above the surface in meters, and $U_z$ the measured windspeed in meters per second. This method is valid up to about Z = 66 feet (20 meters). If the windspeed was measured at 33 feet, $U_{10} = U_z$.

(b) If windspeed was measured overland, correct to overwater windspeed by

$$U_W = 1.1U_{10} \text{ for } F \leq 10 \text{ miles (16 kilometers)}$$

$$U_W = RU_{10} \text{ for } F > 10 \text{ miles}$$

where $U_W$ is the overwater windspeed in meters per second; R is given in Figure 3. If windspeed was measured overwater and adjusted to a 10-meter height, $U_W = U_{10}$.

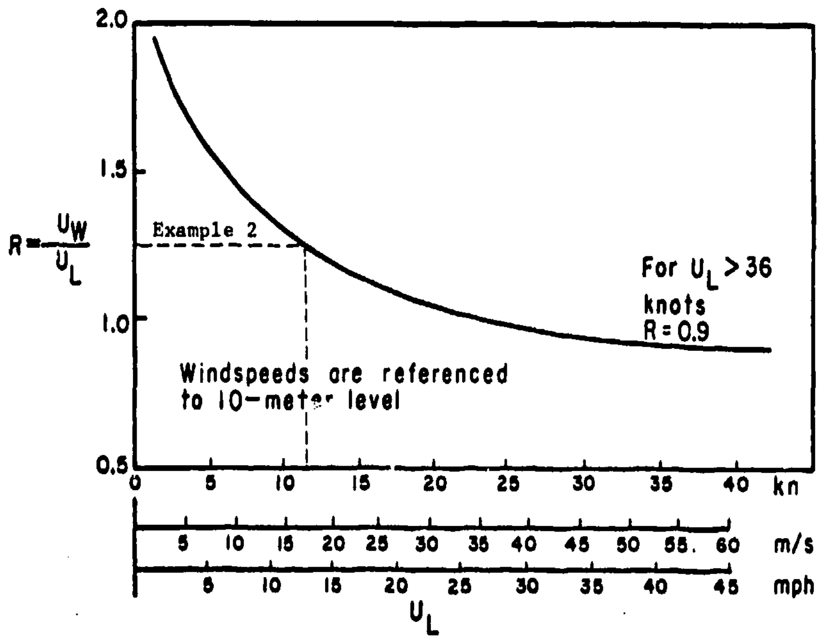


Figure 3. Ratio, R, of windspeed overwater, $U_W$, to windspeed overland, $U_L$, as a function of windspeed overland, $U_L$ (after Resio and Vincent, 1976).

(c) To correct for wind instabilities over fetch lengths greater than 10 miles:

$$U_A' = 0.71\, U_W^{1.23}$$

where $U_A'$ is the adjusted windspeed in meters per second. If the $F \leq 10$ miles, $U_A' = U_W$.

(d) To correct for air-sea temperature differences,

$$U_A = R_T\, U_A' \text{ for } F > 10 \text{ miles}$$

$$U_A = U_A' \text{ for } F \leq 10 \text{ miles}$$

where $U_A$ is the new windspeed adjusted for the temperature difference; $R_T$ is given in Figure 4.

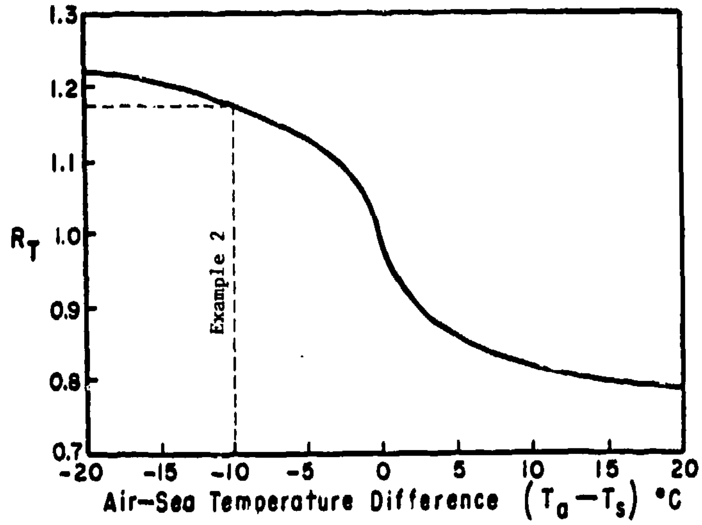


Figure 4. Amplification ratio, $R_T$, accounting for effects of air-sea temperature difference (Resio and Vincent, 1976).

## IV. EXAMPLE PROBLEMS

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

GIVEN: Deepwater fetch, F = 24.9 miles (40 kilometers), adjusted 33-foot (10 meter) windspeed, $U_A$ = 65.6 feet (20 meters) per second (an example of computation of the adjusted windspeed can be found in U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1981).

FIND: Significant wave height and peak period of the wave spectrum at depths of 23 and 9.8 feet (7 and 3 meters).

SOLUTION: The dimensionless fetch, $\tilde{x}$ is

$$\tilde{x} = \frac{gF}{U_A^2} \frac{(9.8 \text{ m/s}^2)(40{,}000 \text{ m})}{(20 \text{ m/s})^2} = 980 = 9.8 \times 10^2$$

The deepwater significant wave height and peak period are

$$H_o = 1.6 \times 10^{-3} \sqrt{\frac{F}{g}}\, U_A = 1.6 \times 10^{-3} \sqrt{\frac{40{,}000}{9.8}}\ (20 \text{ m/s}) = 2.04 \text{ meters}$$

$$T_p = \frac{U_A \tilde{x}^{1/3}}{3.5g} = \frac{20(980)^{1/3}}{3.5(9.8)} = 5.79 \text{ seconds}$$

at a depth of 7 meters

$$\frac{d}{H_o} = \frac{7}{2.04} = 3.43$$

In Figure 2 at $\tilde{x} = 0.8 \times 10^2$ and interpolated between curves for $d/H_o$ of 3 and 5, reading down for $\tilde{H}$,

$$\tilde{H} = \frac{gH_s}{U_A^2} = 0.037$$

$$H_s = 1.51 \text{ meters}$$

At a depth of 3 meters, $d/H_o = 1.47$, providing an $\tilde{H} = 0.025$ or $H_s = 1.02$ meters. The peak period, $T_p$, and the local wavelength would increase over that at a 7-meter depth and currently must be calculated by the tables given in Appendix C of the Shore Protection Manual (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977).

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

GIVEN: The wind direction is predominantly from the southwest over the deep, irregularly shaped water body shown in Figure 5. The windspeed to be considered is 49.2 feet (15 meters) per second measured on top of an instrument shack at 13 feet (4 meters) from the ground. The air temperature when these conditions occur is 50° Fahrenheit (10° Celsius) and the water temperature is 60° Fahrenheit (16° Celsius).

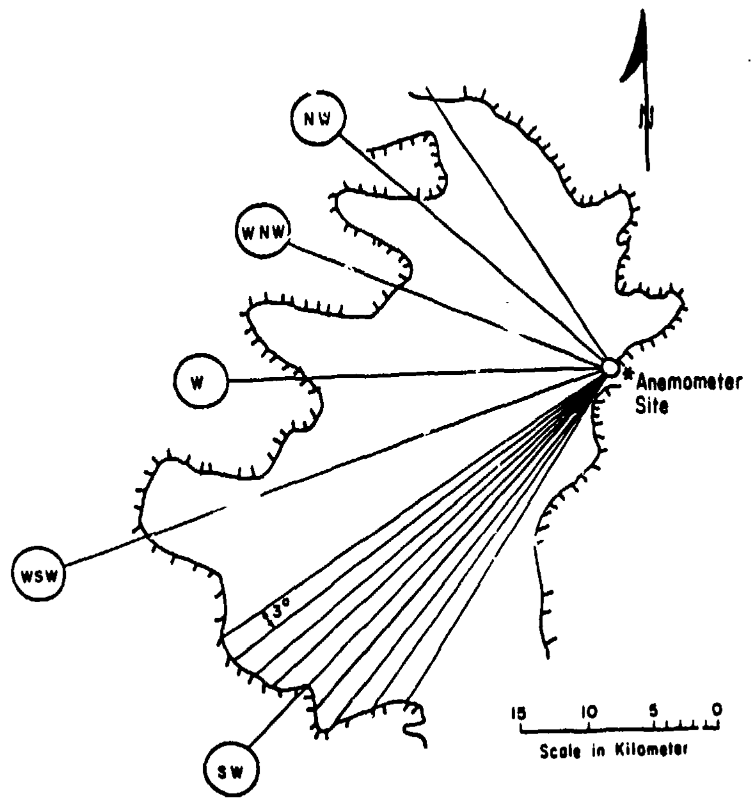


Figure 5. The fetch length for this irregularly shaped water body in the wind direction is determined by drawing nine radials at 3° increments centered on the wind direction and arithmetically averaging the radial lengths as illustrated. The average fetch in this example is approximately 22.2 miles (36 kilometers).

FIND: The significant wave height at a 16.4-foot (5 meter) depth just off the coast near the anemometer site.

SOLUTION: The fetch is found by averaging over a 24° quadrant since the body of water is *irregularly* shaped. As shown in Figure 5, nine radials are constructed at 3° increments and the average fetch length of 22 miles (36 kilometers) is found.

The adjusted windspeed is found following the steps outlined previously:

(a) Adjust wind from the 4-meter to the 10-meter level

$$U_{10} = \left(\frac{10}{Z}\right)^{1/7} U_Z = \left(\frac{10}{4m}\right)^{1/7} (15) = 17.1 \text{ meters per second}$$

(b) Adjust overland wind to overwater wind with R from Figure 3

$$U_w = RU_{10} = 1.25(17.1) = 21.4 \text{ meters per second}$$

(c) Correct wind for instabilities

$$U_A' = 0.71\, U_w^{1.23} = 0.71(21.4)^{1.23} = 30.7 \text{ meters per second}$$

(d) Correct for air-sea temperature difference with $R_T$ from Figure 4

$$U_A' = R_T\, U_A' = 1.17(30.7) = 35.9 \text{ meters per second}$$

The dimensionless fetch, $\tilde{x}$, is

$$\tilde{x} = \frac{gF}{U_A^2} = \frac{(9.8\ m/s^2)(36,000\ m)}{(35.9\ m/s)^2} = 273.7$$

The deepwater significant wave height and peak period are

$$H_o = 1.6 \times 10^{-3} \sqrt{\frac{36,000}{9.8}}\,(35.9\ m/s) = 3.5 \text{ meters}$$

$$T_p = \frac{35.9(273.7)^{1/3}}{3.5(9.8)} \quad 6.80 \text{ seconds}$$

At a 5-meter depth

$$\frac{d}{H_o} = \frac{5}{3.5} = 1.43$$

In Figure 2 at $\tilde{x} = 273.7$ and $d/H_o = 1.43$

$$\tilde{H} = \frac{gH_s}{U_A^2} = 0.012$$

and

$$H_s = \frac{\tilde{H}\, U_A^2}{g} = \frac{(0.12)(35.9)^2}{9.8} = 1.58 \text{ meters}$$

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## APPENDIX

## METHODOLOGY AND GOVERNING SPECTRAL EQUATIONS

### 1. Deepwater Representation of Fetch-Limited Wave Spectrum.

A spectrum of wind waves, generated in deep water for a long period of time, is limited by the length of the fetch over which the wind is blowing. The wind will generate a spectrum with a shape which has been parameterized by Hasselmann, et al. (1973). The parameterization, or JONSWAP spectrum, provides a functional relationship between energy and frequency as well as the windspeed, fetch length, and width of the spectral peak:

$$E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_m}\right)^{-4}\right] \gamma^{\exp \frac{(f-f_m)^2}{2\sigma^2 f_m^2}} \qquad \text{(A-1)}$$

and

$$\sigma = \begin{cases} \sigma_a \text{ for } f \le f_m \\ \sigma_b \text{ for } f > f_m \end{cases}$$

where

$E$ = energy density

$F$ = fetch length

$f$ = frequency of wave component

$f_m$ = frequency of spectral peak = $3.5g/(U_{10} \times {}^{1/3})$

$g$ = acceleration due to gravity

$U_A$ = adjusted 10-meter windspeed

$\tilde{x}$ = dimensionless fetch = $gF/U_A^2$

$\alpha$ = Phillips equilibrium constant = $0.076 \times^{-0.22}$

$\gamma$ = ratio of maximal spectral energy to the maximum of the corresponding Pierson-Moskowitz spectrum = 3.3

$\sigma_a$ = left-side width of the spectral peak = 0.07

$\sigma_b$ = right-side width of the spectral peak = 0.09

This equation provides a wave spectrum as shown in curve 1 (Fig. 1), with a total energy equal to the deepwater significant wave height, squared over 16.

2. Energy Reduction in Shallow Water.

As an irregular wave train enters transitional and shallow-water depths, the presence of the sea bottom causes changes in wave steepness which, due to the limitation on wave steepness, lead to a loss of wave energy. Kitaigorodskii, Krasitskii, and Zaslavskii (1975) suggest that an upper limit of energy exists at a given frequency which is a function of depth and α:

$$E(f) = \alpha g^2 f^{-5} (2\pi)^{-4} \phi \quad \text{(A-2)}$$

where

$$C_h \tanh (\omega_h^2 C_h) = 1$$

$d$ = water depth

$\alpha$ = 0.0081

$$\phi = C_h^2 \{1 + [2\omega_h^2 C_h/\sinh(2\omega_h^2 C_h)]\}^{-1}$$

$$\omega_h = 2\pi f \sqrt{d/g}$$

This equation represents a stability limit or "limiting form criterion" on a wave component. Kitaigorodskii, Krasitskii, and Zaslavskii used a value of α of 0.0081 based on field data. Recent work at the U.S. Army Engineer Waterways Experiment Station (WES) has indicated that another mechanism, nonlinear wave-wave interaction, has an equivalent effect but that α would vary with dimensionless fetch ($gF/U_A^2$). The application of this theory is further outlined by Vincent (1981).

Shoaling of a wave in shallow water also changes wave energy. A shoaling coefficient can be calculated as in the Shore Protection Manual (App. C in U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977) for each frequency component according to linear theory:

$$K_s(f) = \left(\left[\tanh \frac{2\pi d}{L(f)}\right]\left[1 + \frac{4\pi d/L(f)}{\sinh 4\pi d/L(f)}\right]\right)^{-1} \quad \text{(A-3)}$$

and can be multiplied by the deepwater energy at each frequency band to obtain a "shoaled" spectrum,

$$E(f) \text{ shoaled} = K_s(f)\, E(f) \text{ deep} \quad \text{(A-4)}$$

3. Determination of Shallow-Water Energy Spectrum.

Figure A-1 is a flow chart describing the solution process used in producing the design curves presented in this paper.

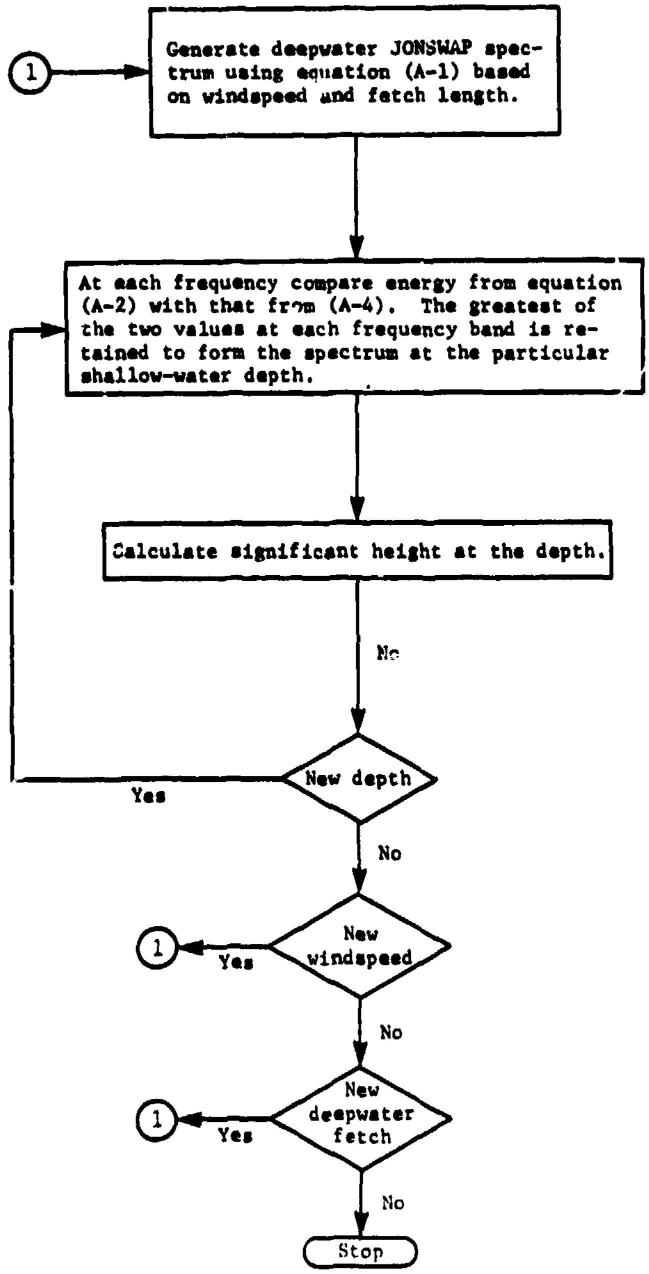


Figure A-1. Flow chart illustrating the use of equations (A-1) to (A-4) in generating the curves presented in Figure 2.

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