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Calculation of Wave Attenuation Due to Friction and Shoaling : An Evaluation

by
William G. Grosskopf

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An evaluation of the Bretschneider and Reid (1954) technique for calculating wave attenuation due to friction and shoaling is presented. Data used in this evaluation were collected at CERC's Field Research Facility (FRF), Duck, North Carolina. The results, using Kamphuis' (1975) friction factor diagram, show slightly underpredicted wave heights with an average deviation of 6 percent. Poor correlation with observed wave heights is illustrated when bottom contours are not straight and parallel, indicating the presence of other mechanisms.

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PREFACE

This report presents an evaluation of the Bretschneider and Reid (1954) technique for calculating wave attenuation due to friction and shoaling using data collected at the Coastal Engineering Research Center's (CERC) Field Research Facility (FRF), Duck, North Carolina. The work was carried out under CERC's coastal engineering research program.

The report was prepared by William G. Grosskopf, Hydraulic Engineer, under the general supervision of Dr. C.L. Vincent, Chief, Coastal Oceanography Branch, Research Division.

Comments on this publication are invited.

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

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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	1.0197×10^{-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

A horizontal displacement amplitude of water particles

C_f friction coefficient

d water depth

d_{90} sand grain size of 90th percentile of sediment samples

H_s significant wave height

H_{sn} significant wave height at location n

K_s shoaling coefficient

K_{sn} shoaling coefficient at location n

k wave height

k_s roughness height

L wavelength

L_n wavelength at location n

L_o deepwater wavelength

m bottom slope

R_e Reynolds number

T wave period

u_b maximum horizontal water particle velocity

ν kinematic viscosity

ϕ integral of the dimensionless shoaling factor, ϕ_f

ϕ_f dimensionless shoaling factor

CALCULATION OF WAVE ATTENUATION DUE TO FRICTION AND SHOALING: AN EVALUATION

by
William G. Grosskopf

I. INTRODUCTION

Many processes are responsible for variations in the energy of nearshore waves including breaking, friction, shoaling, refraction, percolation, and nonrigid bottom effects. However, in an area where nearshore bottom contours are straight and parallel, and bottom conditions indicate a nonpermeable and nonelastic sea floor, wave breaking, shoaling, refraction, and friction remain dominant. The area seaward of the pier end at U.S. Army Coastal Engineering Research Centers's (CERC) Field Research Facility (FRF), Duck, North Carolina, meets these conditions. Data from FRF can be used to evaluate different formulations of these processes.

This report evaluates the Bretschneider and Reid (1954) theory recommended in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977) for calculating the effect of bottom friction and shoaling on incoming waves, using data gathered from two offshore Waverider buoy gages (manufactured by Datawell, Haarlem, The Netherlands) located off the pier end at FRF. The two Waveriders operate in depths of approximately 18 and 10 meters, at 2,880 and 680 meters from shore, respectively. These instruments are located far enough offshore to avoid the possibility of wave breaking, other than whitecapping, as a dissipative mechanism between Waveriders for the data set used. Simultaneously observed wave spectra from these two gages during 1978 and 1979 were compared to calculated wave characteristics, using Bretschneider and Reid's (1954) prediction for waves traveling over an impermeable bottom of constant slope. It is found that Bretschneider and Reid's method provides a close correlation with observed data, especially in cases where the wave spectrum is narrow and single-peaked.

II. CALCULATING CHANGES IN WAVE HEIGHT DUE TO BOTTOM FRICTION AND SHOALING

Attenuation of wave height due to bottom friction and shoaling can be calculated using equation (1), for waves with significant wave height, H_s, wave period, T, traveling over a bottom of slope, m, and depth, d, at the outer gage 1. Shoaling effects are calculated using linear theory. The relation is

$$H_{s2} = K_s \, H_{s1} \left(\frac{C_f \, H_{s1}}{mT^2} \, \phi + 1 \right)^{-1} \qquad (1)$$

where

C_f = friction coefficient

K_s = shoaling coefficient

m = bottom slope

H_{s2} = significant wave height at nearshore gage 2 (Waverider gage 610)

H_{s1} = significant wave height at outer gage 1 (Waverider gage 620)

The shoaling coefficient can be calculated from

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

and

$$\phi = \int_{\infty}^{d/T^2} \phi_f \; \delta\left(\frac{d}{T^2}\right) \qquad (3)$$

The term ϕ can be evaluated from Figure 1.

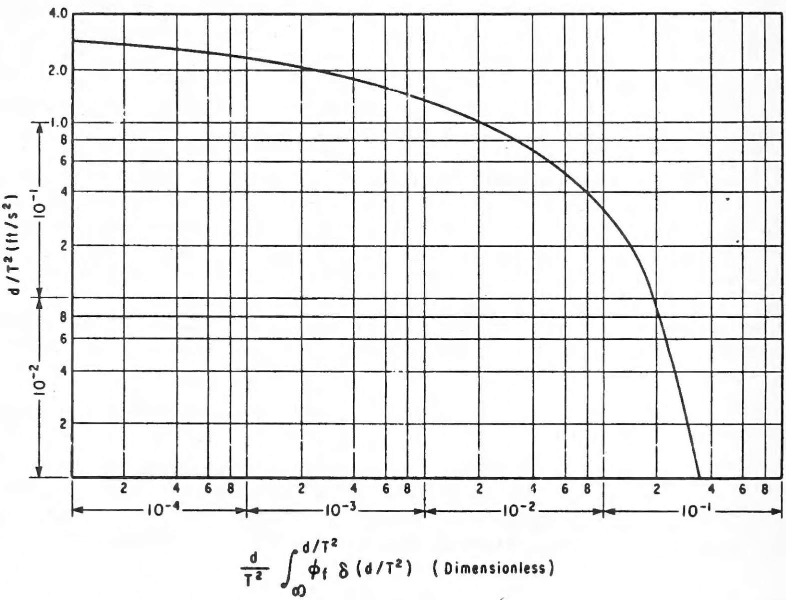

Figure 1. Graph used in determining the integral of the bottom dissipation function, ϕ_f, for waves passing over a constantly sloping bottom.

The friction coefficient, C_f, has been given considerable attention in laboratory and theoretical studies in recent years. Bretschneider and Reid (1954) recommend using a constant value of 0.01. More recent laboratory work has indicated a dependence of friction factor on the Reynolds number and dimensionless bottom roughness height. Jonsson (1966) and Kamphuis (1975) produced and refined a friction factor diagram, as shown in Figure 2, where the friction factor, C_f, can be found if the Reynolds number at the sea

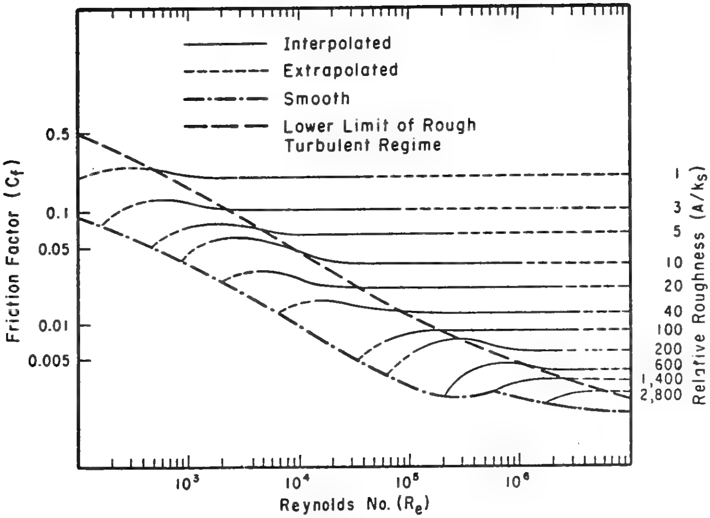

Figure 2. Friction factor diagrams (after Kamphuis, 1975).

floor, R_e, and the relative roughness height, A/k_s, are known. The Reynolds number is related to the bottom velocity under the wave by

$$R_e = \frac{u_b A}{\nu} \quad (4)$$

where

u_b = maximum horizontal water particle bottom velocity is

$$\frac{\pi H_{s1}}{T \sinh \frac{2\pi d}{L}}$$

L = wavelength

ν = kinematic viscosity of seawater equals 6.25×10^{-7} meters per second

A = horizontal displacement amplitude of water particles is

$$\frac{H_{s1}}{2 \sinh \frac{2\pi d}{L}}$$

k = wave number ($2\pi/L$)

T = wave period

This technique, which is explained and illustrated in CERC Field Guidance Letter 79-4 (Esteva, 1979), is used to determine C_f in the present study.

III. COMPARISON WITH FIELD DATA

Simultaneous observations of a variety of significant wave heights, periods, and energy spectrum shapes were chosen from available field data to illustrate possible weaknesses or strengths of Bretschneider and Reid's (1954) theory in all types of wave climate. The wave data selected were obtained from two Waverider buoy gages located in an area outside the breaker zone where sediment characteristics indicate that bottom friction is the predominant dissipation mechanism. Using conditions at the outer gage (Waverider gage 620) as input for Bretschneider and Reid's predictive equations, resulting calculated wave characteristics at the nearshore gage (Waverider gage 610) are compared to observed wave height values. Results are shown in Table 1 and Figure 3. Negative deviations from observed wave heights indicate the predicted value is lower than actually observed; i.e., the theory predicts more frictional energy loss than is observed. The range of friction coefficients used is 0.004 to 0.07. Most of the large underpredictions occur when no change or an actual increase in wave height is observed from offshore to inshore, possibly due to strong wind-wave generation. Overprediction indicates that other dissipation processes are occurring. Table 2 summarizes the results of this study. Figure 3 indicates that negative deviations are more pronounced for broad or multipeaked spectra, while narrow or single-peaked spectra correspond to slightly overpredicted wave heights. General trends show that the theory corresponds closely to observed wave conditions with maximum deviations of 60 percent but most conditions are within 15 percent. Examining only the data points for the narrow, single-peaked spectra, overprediction occurs for lower wave heights; underprediction occurs for larger waves which tend to be more nonlinear at the same shallow depth.

Table 3, which presents the results of Bretschneider and Reid's theory using Baylor staff gages (manufactured by Baylor Company, Houston, Texas) along the pier at FRF, provides an example of the theory's inapplicability where bottom contours are not straight and parallel. The irregular pier-induced topography causes the theory to overpredict wave height at Baylor gage 665 (located 350 meters from shore), inshore of Baylor gage 625 (located 630 meters from shore), indicating that other processes (e.g., refraction, bottom scattering) are affecting wave heights. As shown in the table, preliminary runs of a more advanced, nonlinear model indicate that the additional observed losses are likely due to refraction. This example shows that caution must be taken in applying the Bretschneider and Reid theory near manmade structures or in areas of irregular bathymetry.

* * * * * * * * * * * * * * * * * * IV. EXAMPLE PROBLEM * * * * * * * * * * * * * * * * * *

GIVEN: A wave with the following wave height and period at gage 620 at an 18-meter depth:

$$H_{s620} = 2.0 \text{ meters}$$

$$T = 10 \text{ seconds}$$

FIND: The wave height 2,200 meters closer to shore in a depth of 10 meters. Assume a d_{90} of the sediment to be 0.3 millimeter.

Table 1. Comparison of predicted and observed wave heights.

Data file No.	Date	Time	Observed significant wave conditions (gage 620)		Wave height (gage 610)		Shoaling coefficient K_s	Friction coefficient C_f	Deviation from observed wave height (pct)	Wave spectra
			Height (m)	Period (s)	Observed (m)	Predicted (m)				
1	13 Sept. 1978	1920	2.7	08	2.5	2.4	0.93	0.004	-4.0	Narrow
2	13 Sept. 1978	2020	2.4	08	2.4	2.2	0.93	0.004	-8.3	Broad
3	13 Sept. 1978	2120	2.5	07	2.3	2.2	0.92	0.004	-4.3	Narrow
4	10 Sept. 1978	1020	1.2	09	1.3	1.1	0.96	0.004	-15.4	Broad
5	13 Sept. 1978	1120	1.5	04	1.3	0.6	0.98	0.070	-53.8	Multipeaked
6	13 Sept. 1978	1220	1.6	04	1.5	0.6	0.98	0.070	-60.0	Broad
7	25 Sept. 1978	1020	0.9	09	0.8	0.9	0.96	0.004	+12.5	Narrow
8	03 Sept. 1978	2020	0.9	09	0.8	0.9	0.96	0.004	+12.5	Narrow
9	03 Sept. 1978	2120	0.8	10	0.8	0.8	0.98	0.004	0.0	Multipeaked
10	03 Sept. 1978	2220	0.8	08	0.7	0.7	0.93	0.004	0.0	Multipeaked
11	09 Sept. 1978	1820	1.2	10	1.3	1.2	0.98	0.004	-7.7	Multipeaked
12	10 Sept. 1978	0920	1.4	10	1.2	1.4	0.98	0.004	+16.7	Narrow
13	12 Sept. 1978	0920	1.3	10	1.3	1.3	0.98	0.004	0.0	Narrow
14	12 Sept. 1978	1920	1.2	14	1.0	1.3	1.10	0.004	+13.0	Narrow
15	14 Sept. 1978	0720	2.3	06	2.1	1.9	0.91	0.004	-9.5	Multipeaked
16	01 Aug. 1978	1920	0.6	07	0.6	0.5	0.92	0.008	-16.7	Broad
17	01 Aug. 1978	2020	0.6	08	0.6	0.6	0.93	0.006	0.0	Broad
18	13 Nov. 1978	1520	1.8	08	1.9	1.6	0.93	0.004	-15.7	Broad
19	27 June 1979	0820	1.6	06	1.8	1.4	0.91	0.005	-22.2	Broad
20	12 Nov. 1979	2120	1.9	05	1.7	1.5	0.93	0.010	-11.8	Broad
21	20 June 1979	1420	1.7	08	1.8	1.5	0.93	0.004	-16.7	Multipeaked
22	25 Sept. 1979	0519	1.8	09	1.8	1.7	0.96	0.004	-5.6	Broad
23	25 Sept. 1979	0319	1.8	09	1.8	1.7	0.96	0.004	-5.6	Multipeaked
24	18 Oct. 1979	1320	2.1	10	2.1	2.0	0.98	0.004	-4.7	Narrow
25	18 Oct. 1979	1120	2.2	12	2.3	2.3	1.04	0.004	0.0	Narrow
26	18 Oct. 1979	0720	2.2	12	2.4	2.3	1.04	0.004	-4.2	Narrow
27	17 Oct. 1979	1420	2.9	06	2.7	2.5	0.91	0.004	-7.4	Narrow
28	25 Sept. 1979	0419	2.0	08	1.8	1.8	0.93	0.004	0.0	Narrow
29	12 Nov. 1979	0840	2.1	06	1.7	1.8	0.91	0.005	+5.8	Narrow
30	12 Nov. 1979	2140	1.9	08	1.6	1.7	0.93	0.004	+6.3	Narrow
31	25 Sept. 1979	0339	1.8	07	1.8	1.6	0.92	0.004	-11.1	Broad

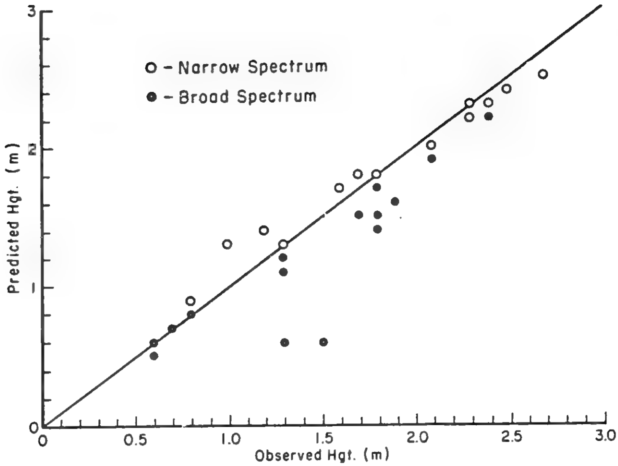

Figure 3. Comparison of observed and predicted wave heights at the nearshore gage (Waverider gage 610), Duck, North Carolina.

Table 2. Average deviation of Bretschneider and Reid's theory from observed wave heights.[1]

Wave spectra	Deviation (pct)	Regression line
Narrow	+4.2	y = 0.83x + 0.33
Broad	-15.3	y = 0.87x - 0.05
All spectra (multipeaked)	-6.5	y = 0.91x + 0.03

[1]Correlation coefficient for all spectra equals 0.926.

Table 3. Illustration of the inapplicability of Bretschneider and Reid's theory in areas of irregular bottom topography.

Date	Time	Wave height (m)			Deviation from observed (pct)	Estimated H_{s665} by including refraction (m)
		Observed		Predicted		
		H_{s625}	H_{s665}	H_{s665}		
13 Sept. 1978	0300	0.9	0.5	0.96	91.2	0.50
13 Sept. 1978	2100	2.5	1.6	2.33	45.8	1.50
13 Sept. 1978	2300	2.4	1.4	2.24	60.3	1.44
14 Sept. 1978	1100	2.1	1.3	1.97	51.2	1.26
15 Sept. 1978	1600	1.3	0.7	1.29	85.1	0.78
18 Oct. 1978	0700	2.2	1.6	2.5	55.1	1.32
18 Oct. 1978	1100	2.1	1.4	2.2	59.1	1.26

SOLUTION:

(1) Determine friction coefficient. From SPM Table C-1 (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977) for $(d/L_o)_{620} = 0.115$,

$$\left(\frac{d}{L}\right)_{620} = 0.154 \quad \text{and} \quad L_{620} = 116.9 \text{ meters}$$

Using linear theory,

$$A = \frac{H_{s620}}{2 \sinh kd} = \frac{2.0}{2(1.126)} = 0.89 \text{ meter}$$

$$u_b = \frac{\pi H_{s620}}{T \sinh kd} = \frac{\pi(2.0)}{10(1.126)} = 0.56 \text{ meter per second}$$

From equation (4),

$$R_e = \frac{u_b A}{\nu} = \frac{(0.56)(0.89)}{(6.25 \times 10^{-7})} \cong 8.3 \times 10^5$$

$$\frac{A}{k_s} = \frac{A}{2d_{90}} = \frac{0.89}{0.0006} = 1{,}483$$

Figure 2 then yields the friction coefficient at gage 620 to be

$$C_f = 0.004$$

(2) Determine predicted wave height. The average depth in the traverse is 14 meters:

$$\frac{d}{T^2} = \frac{14}{(10)^2} = \frac{14}{100} = 0.14$$

From Figure 1,

$$\frac{d}{T^2}\phi = 0.180 \quad \text{or} \quad \phi = 1.29$$

The bottom slope, m, is (8.0/2,200) = 0.0036, and the shoaling coefficient is determined at gage 610 where the wave height is unknown:

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

$$K_{s610} = \left[(0.591)\left(1 + \frac{1.360}{1.819}\right)\right]^{-1/2} = 0.984$$

The predicted wave height at gage 610 is then found by equation (1) to be

$$H_{s610} = (0.984)(2.0)\left[\frac{(0.004)(2.0)}{(0.0036)(100)}(1.29) + 1\right]^{-1} = 1.91 \text{ meters}$$

* *

V. SUMMARY AND CONCLUSIONS

The combined effect of shoaling and bottom friction is underpredicted an average deviation of 6 percent by Bretschneider and Reid's (1954) theory, based on 31 observations. This study indicates that care must be taken in applying the predictive theory when wave spectra are broad or multipeaked, or when the bathymetry is irregular and the bottom contours are not straight and parallel.

For parallel bottom contour cases, the largest deviations from observed wave conditions arise when the wave spectrum which corresponds to the significant wave characteristics is broad or multipeaked. These large deviations, due to the presence of large amounts of energy relative to the total energy of the spectrum in many wave components, indicate that the significant wave height may not be a representative number to use for calculations in the equations when the spectrum is not narrow and single-peaked.

The calculations in Table 3 show that caution must be taken when using the equations in areas of irregular bathymetry or near coastal structures where the bathymetry may not be uniform. Other types of wave attenuation processes become important in these cases, with refraction being particularly dominant when the contours are not parallel and other bottom irregularities such as holes and shoals are present.

The choice of the friction coefficient will also play a role in compounding the predicted wave height deviation from actual observations. The coefficients used here are a result of controlled laboratory studies and, therefore, may not be a true representation of field coefficients. The presence of bottom ripples is not considered in this analysis, but has been shown to be a variable in determining the friction coefficient. Also, linear theory is used to calculate bottom velocity and horizontal water particle displacement; higher order calculations may lower present deviations.

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