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Estimation of Wave Reflection and Energy Dissipation Coefficients for Beaches, Revetments, and Breakwaters

by

William N. Seelig and John P. Ahrens

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More than 4,000 laboratory measurements of wave reflection from beaches, revetments, and breakwaters are used to develop methods for predicting wave reflection and energy dissipation coefficients. Both monochromatic and irregular wave conditions are considered and the prediction techniques apply to both breaking and nonbreaking wave conditions.

PREFACE

This report is published to provide coastal engineers empirical formulas for predicting wave reflection coefficients for beaches, revetments, and breakwaters. The techniques were developed using laboratory data from a number of sources covering a wide range of conditions for both monochromatic and irregular waves. The work was carried out under the coastal processes program of the U.S. Army Coastal Engineering Research Center (CERC).

This report was prepared by William N. Seelig, Hydraulic Engineer, and John P. Ahrens, Oceanographer, both of the Coastal Processes and Structures Branch, under the general supervision of Dr. R.M. Sorensen. J. McTamany, Coastal Oceanography Branch, provided the nonlinear regression analysis used to determine empirical coefficients developed in this report.

Comments on this publication are invited.

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Ted E Bishop

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 (angel)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins

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_i	incident wave amplitude at a spectral line
a_r	reflected wave amplitude at a spectral line
A,B	real and imaginary spectral coefficients from an FFT analysis
d	representative armor diameter = $(W/\gamma)^{1/3}$
d_s	water depth at the toe of the structure
g	acceleration due to gravity
H_b	a representative breaking wave height at the toe of the structure
H_i	incident wave height (use H_s for irregular waves)
H_o	deepwater wave height
H_r	reflected wave height
H_s	significant wave height
H_t	transmitted wave height
K_d	wave dissipation coefficient
K_r	wave reflection coefficient
K_t	wave transmission coefficient
k	wave number = $2\pi/L$
L	wavelength at the toe of the structure
L_o	deepwater wavelength from linear theory = $gT^2/(2\pi)$
m	offshore slope seaward of the structure
n	number of layers of armor
R	wave runup
R_e	Reynolds number
T	wave period (use period of peak energy density for irregular waves)
T_p	period of peak energy density
W	weight of armor material
α, α', β	empirical wave reflection parameters
γ	specific weight of armor unit material
$\Delta \ell$	wave gage spacing
η_{rms}	average root-mean-square surface water level
θ	angle of the seaward structure face
υ	kinematic viscosity of water
ξ	surf similarity parameter = $\tan \theta / \sqrt{H_i/L_o}$

ESTIMATION OF WAVE REFLECTION AND ENERGY DISSIPATION COEFFICIENTS FOR BEACHES, REVETMENTS, AND BREAKWATERS

by
William N. Seelig and John P. Ahrens

I. INTRODUCTION

When a wave encounters a coastal structure or beach, a part of the wave energy is dissipated. The remaining energy is reflected seaward except in the case of a permeable or overtopped structure (Fig. 1), which allows transmission of a part of the energy to the leeward side. Wave reflection may have undesirable effects because the reflected waves are superimposed on the incident waves to increase the magnitude of water particle velocities and water level fluctuations seaward of the structure. These enhanced motions may be a hazard to navigation or may undesirably alter sediment transport patterns. This report presents methods for estimating wave reflection coefficients for beaches, revetments, and breakwaters of waves approaching the structure at a normal angle of incidence (wave crests are parallel to the structure axis).

II. LITERATURE REVIEW

Previous investigators have experimentally and analytically studied wave energy dissipation and reflection characteristics for a variety of structures. Various prediction techniques have been proposed to estimate reflection coefficients for specific types of energy dissipation. Miche (1951) proposed a wave reflection coefficient prediction technique that is often quoted in literature (e.g., Sec. 2.54 in U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). He assumed that there is some critical deepwater wave steepness below which the reflection coefficient is a constant. For conditions where wave steepness is greater than the critical value, the reflection coefficient is proportional to the ratio of the wave steepness to the critical value of wave steepness. Predictions using Miche's approach give the right order of magnitude estimate of the reflection coefficient, but as Ursell, Dean, and Yu (1960) illustrated, predictions may be conservative by a factor of 2.

Moraes (1970) has performed some of the most extensive laboratory tests to date on monochromatic wave reflection from a variety of smooth and rough slopes.

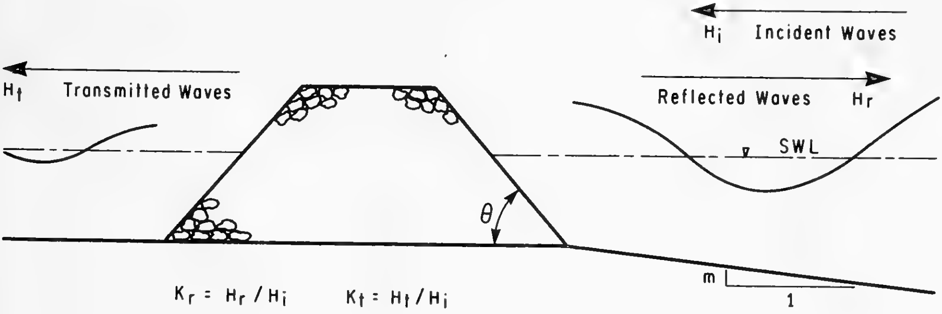


Figure 1. Wave reflection and transmission from a coastal structure.

Madsen and White (1976) made a number of additional carefully controlled reflection measurements for smooth and rough steep-sloped structures under nonbreaking wave action. Based on these data, they developed an analytical-empirical model for predicting reflection coefficients for rough slopes with nonbreaking waves.

Battjes (1974) used Moraes' data to develop an equation for predicting reflection coefficients for smooth slopes where the slope induces wave breaking. This technique is conservative for nonbreaking (surging) waves. Ahrens (1980) has made a number of irregular wave reflection coefficient measurements for overtopped and nonovertopped plane smooth slopes.

A number of wave reflection measurements for laboratory breakwaters have been made. Seelig (1980) investigated rubble-mound and caisson breakwaters using monochromatic and irregular waves. Brunn, Gunbak, and Kjelstrup (1979) measured reflection coefficients for rubble-mound breakwaters and proposed an empirical prediction technique. Additional breakwater reflection data are available in Debok and Sollitt (1978) and Sollitt and Cross (1976). Madsen and White (1976) give a procedure for predicting reflection from rubble-mound breakwaters for nonbreaking waves.

Chesnutt and Galvin (1974) and Chesnutt (1978) have made some of the most detailed measurements available of wave reflection from laboratory sand beaches. Little prototype data are available; however, Munk, et al. (1963) and Suhayda (1974) reported reflection measurements for beaches exposed to extremely low steepness swell waves.

III. EXPERIMENTAL TECHNIQUES

The primary emphasis of this report is on the reanalysis of existing data from a number of published sources. However, some additional laboratory data were taken to supplement the sources; these data are reported in Appendix A.

Goda and Suzuki's (1976) method was used to determine wave reflection coefficients. This method was selected because with the test setup used it gave consistent results which are as reliable as obtainable with other currently used procedures. Experience with this technique suggests that the error is on the order of 5 percent. A typical wave gage setup is illustrated in Figure 2, and a detailed discussion of the analysis method given in Appendix B. The test procedure uses three gages, located a minimum of 6 meters seaward of a test

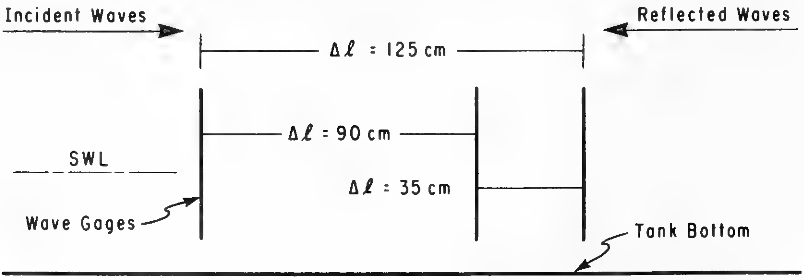


Figure 2. Wave gage array used to measure wave reflection.

structure, to collect simultaneous wave records (incident and reflected waves superimposed), each containing 4,096 data points at a sampling interval of one-sixteenth of a second. A fast Fourier transform (FFT) analysis is made of each record, and each gage pair gives an estimate of the reflection coefficient subject to the criteria discussed in Appendix B. The mean of the three estimates is taken as representative at each spectral line, and an energy-weighted average is taken to characterize reflection for the entire spectrum of irregular waves. The significant incident wave height, H_s, for irregular waves (Goda and Suzuki, 1976) is defined as

$$H_s = \frac{4\ \bar{\eta}_{rms}}{\sqrt{1 + K_r^2}} \tag{1}$$

where $\bar{\eta}_{rms}$ is the average root-mean-square (rms) water surface displacement of the wave records at the three gages, and K_r the reflection coefficient.

Data collection in this study emphasized obtaining additional data on wave reflection on smooth slopes and examining the influence of one or more layers of armor on reducing the reflection coefficient. Monochromatic and irregular waves were tested.

For monochromatic wave conditions (sinusoidal wave generator blade motion), the wave reflection measurement technique was slightly modified. The waveform for monochromatic waves is described by a Fourier series with the entire waveform moving at the speed of the primary wave (Dr. R. Dean, University of Delaware, personal communication, 1980). This allows the wave energy appearing in harmonics of the primary wave to be considered in determining the reflection coefficient (App. B).

IV. FACTORS INFLUENCING WAVE REFLECTION

The conversion of wave energy concept is useful for defining the interrelation between the wave reflection, dissipation, and transmission coefficients. Assuming that the water depth remains constant seaward and leeward of the structure the partition of wave energy is given by

$$1 = K_d^2 + K_r^2 + K_t^2 \tag{2}$$

where K_r is the reflection coefficient, K_d^2 the ratio of wave energy lost through dissipation to the total incident wave energy, and K_t a transmission coefficient including transmission through a permeable structure and transmission by overtopping for a low-crested structure. In an idealized monochromatic wave situation where there are no transfers of wave energy to other wave frequencies,

$$K_r = \frac{H_r}{H_i} \tag{3}$$

and

$$K_t = \frac{H_t}{H_i} \tag{4}$$

where H_i, H_r, and H_t are the incident, reflected, and transmitted wave heights, respectively (see Fig. 1).

Rearranging equation (2) gives

$$K_r = \sqrt{1 - \left(K_d^2 + K_t^2\right)} \tag{5}$$

which clearly shows that any process that increases the sum $\left(K_d^2 + K_t^2\right)$ will cause the reflection coefficient to decrease. Figure 3 illustrates equation (5) and the nonlinear relation of the variables. Note that for a given value of the transmission coefficient the reflection coefficient may be very sensitive to the amount of energy dissipation. In addition, with no transmission large values of energy dissipation will allow the reflection coefficient to be relatively large. For example, with 90-percent energy dissipation and no transmission, the reflection coefficient is 0.31 (see Fig. 3).

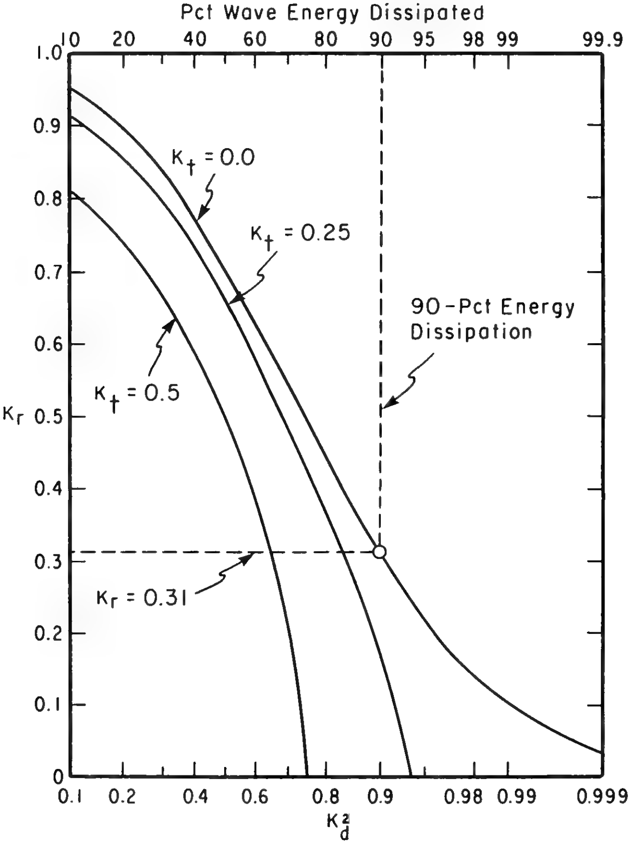


Figure 3. Relation between wave reflection, transmission, and dissipation coefficients.

V. TYPES OF STRUCTURES AND RANGE OF CONDITIONS TESTED

Table 1 summarizes the sources of wave reflection coefficients for structures and beaches and the range of conditions tested. Three types of structure are considered: smooth, impermeable slopes with no overtopping; revetments armored with one or more layers of riprap with no overtopping; and rubble-mound breakwaters armored with stone or dolos.

The water depth at the toe of the structure, d_s, is taken as a characteristic water depth, g is the acceleration due to gravity, and a representative armor unit diameter, d, is determined from

$$d = \left(\frac{W}{\gamma}\right)^{1/3} \tag{6}$$

where W is the armor weight, and γ the specific weight of the armor material. A measure of the wave breaker height that could occur at the toe of the structure, H_b, is given by Goda (1975) as

$$H_b = 0.17\ L_o\left\{1.0 - \exp\left[-4.712\ \frac{d_s}{L_o}\left(1.0 + 15\ m^{1.333}\right)\right]\right\} \tag{7}$$

where L_o is the deepwater wavelength given by linear wave theory, and m the tangent of the slope of the seabed seaward of the structure.

Other variables summarized in Table 1 include dimensionless ratios using H_i, the incident wave height (significant height for irregular waves) at the toe of the structure; T, the wave period (period of peak energy density for irregular waves); and L, the wavelength at the toe of the structure.

Only those tests with fully turbulent hydraulic conditions are considered in order to minimize the influence of viscous effects (Jonsson, 1966). The Reynolds number, R_e, proposed by Madsen and White (1976),

$$R_e = \frac{R^2\ 2\pi}{T\ \upsilon\ \tan\theta} \tag{8}$$

where R is the wave runup and υ the kinematic viscosity of water (about 0.009 square centimeter per second at 20° Celsius), is used to establish which tests are fully turbulent. For smooth slopes only those tests with $R_e > 3 \times 10^4$ are analyzed; for rough slopes only tests with $R_e > 10^4$ are considered (Jonsson, 1966; Madsen and White, 1976).

VI. TECHNIQUES FOR PREDICTING REFLECTION AND ENERGY DISSIPATION COEFFICIENTS

Section IV showed the strong dependence of the magnitude of the reflection coefficient on the amount of wave energy dissipated (also on the amount of wave energy transmitted in the case of a permeable or overtopped structure). In this section, factors that influence the reflection coefficient are systematically investigated, and empirical prediction formulas are developed. Types of wave energy dissipation considered include losses in energy due to structure-induced wave breaking and wave modification, breaking at the toe of a structure or in the surf zone seaward of the structure, structure surface roughness, and internal flow in permeable sections of a structure.

Table 1. Sources of data and range of conditions.

Data set	Reference	Struc types[1]	Cotθ of structure seaward slopes	Wave types[2]	$\frac{d_s}{gT^2}$	$\frac{d}{d_s}$	$\frac{H_i}{H_b}$	$\frac{d}{L}$	n [3]	K_r, calculation method[4]
a	Ahrens (1980)	1	1.5-2.5	I	0.005-0.04	0.0	0.06-1.0	0.0	0	B
b	Ahrens and Seelig (1980)	2	2.0	S,I	0.001-0.025	0.11-0.2	0.16-1.0	0.004-0.02	2.5	B
c	Debok and Sollitt (1978)	3	1.5-2.0	S	0.031-0.14	0.12-0.17	0.28-1.0	0.010-0.024	1	A
d	Gunbak (1979)	3	1.5,2.5	S	---	0.03	---	---	--	A
e	Madsen and White (1976)	1,2	1.5-3.0	S	0.0078-0.012	0.0-0.17	0.07-0.25	0.0-0.02	1	C
f	Moraes (1970)	1,2	0-10.0	S	0.008-0.035	0.002-0.054	0.0-0.34	0.0-0.007	1	A*
g	Seelig (1980)	3	1.5-2.6	S,I	0.002-0.08	0.04-0.61	0.0-1.0	0.0-0.096	1,2	B
h	Hydraulics Research Station (1970)	4	1.5	S,I	0.0067-0.015	0.09	0.3-0.8	0.004-0.013	2	A
i	This study	1,2	2.5,15.0	S,I	0.0018-0.044	0.0-0.22	0.06-0.7	0.0-0.37	0,1,2,3,4	B
j	Ursell, Dean, and Yu (1960)	1	15.0	S	0.0014-0.13	0.0	0.05-0.44	0.0	0	A
k	Chesnutt (1978)	5	5.0-5.9	S	0.005-0.032	0.003	0.2-0.36	0.00008-0.0002	--	A

[1] Structure types:
1, smooth impermeable revetment (nonovertopped);
2, impermeable revetment with one or more layers of armor;
3, rubble-mound breakwaters (rough, permeable);
4, dolos breakwater;
5, laboratory beach.

[2] Wave types tested:
S, sine blade motion;
I, irregular waves.

[3] n = number of layers of armor

[4] Reflection coefficient calculation method:
A, envelope method;
A*, modified envelope method (Goda and Abe, 1968);
B, method of Goda and Suzuki (1976);
C, method of Madsen and White (1976).

1. Modification of the Wave by the Structure (Smooth Slopes).

For a structure with a toe water depth-to-wave height ratio greater than five and wave steepness much less than one-seventh, the interaction of the wave and structure will have dominant control on the magnitude of the reflection coefficient. Miche (1951) proposed that the reflection coefficient for this situation is proportional to the ratio of a critical wave steepness to the incident wave steepness. The critical steepness is

$$\left(\frac{H_o}{L_o}\right)_{crit} = \left(\frac{2\theta}{\pi}\right)^{1/2} \frac{\sin^2\theta}{\pi} \tag{9}$$

where H_o is the deepwater wave height, and θ the angle the structure slope makes with the horizontal, in radians. Miche's equation gives conservative results. For example, it overpredicts monochromatic wave reflection from a 1 on 15 slope by a factor of 2 (Ursell, Dean, and Yu, 1960).

Battjes (1974) recommends the equation,

$$K_r = 0.1\ \xi^2 \ ; \ \xi = \frac{\tan\theta}{\sqrt{\frac{H_i}{L_o}}} \tag{10}$$

which can be written as

$$K_r = \frac{0.1\ \tan^2\theta}{\left(\frac{H_i}{L_o}\right)} \tag{11}$$

Battjes (1974) is assuming an equation similar to the formula proposed by Miche (1951) where the critical steepness is

$$\left(\frac{H_i}{L_o}\right)_{crit} = 0.1\ \tan^2\theta \tag{12}$$

This criterion gives lower and more realistic values of the reflection coefficient than Miche (1951) and is especially useful for $\xi < 2.3$ where breaking is induced by the structure (for plunging breakers). Figure 4 shows the comparison between the equations of Battjes (1974) and Miche (1951).

The following revised equation,

$$K_r = \tanh\ (0.1\ \xi^2), \tag{13}$$

is recommended to give a conservative prediction of reflection coefficients. At small values of the surf similarity parameter ($\xi < 2.3$),

$$0.1\ \xi^2 \simeq \tanh\ (0.1\ \xi^2) \tag{14}$$

and equation (13) gives the same results as equation (10). At larger values of the surf similarity parameter, ξ, equation (13) asymptotically approaches 1.0 and gives an upper bound closer to the data than equation (10) (see Fig. 4).

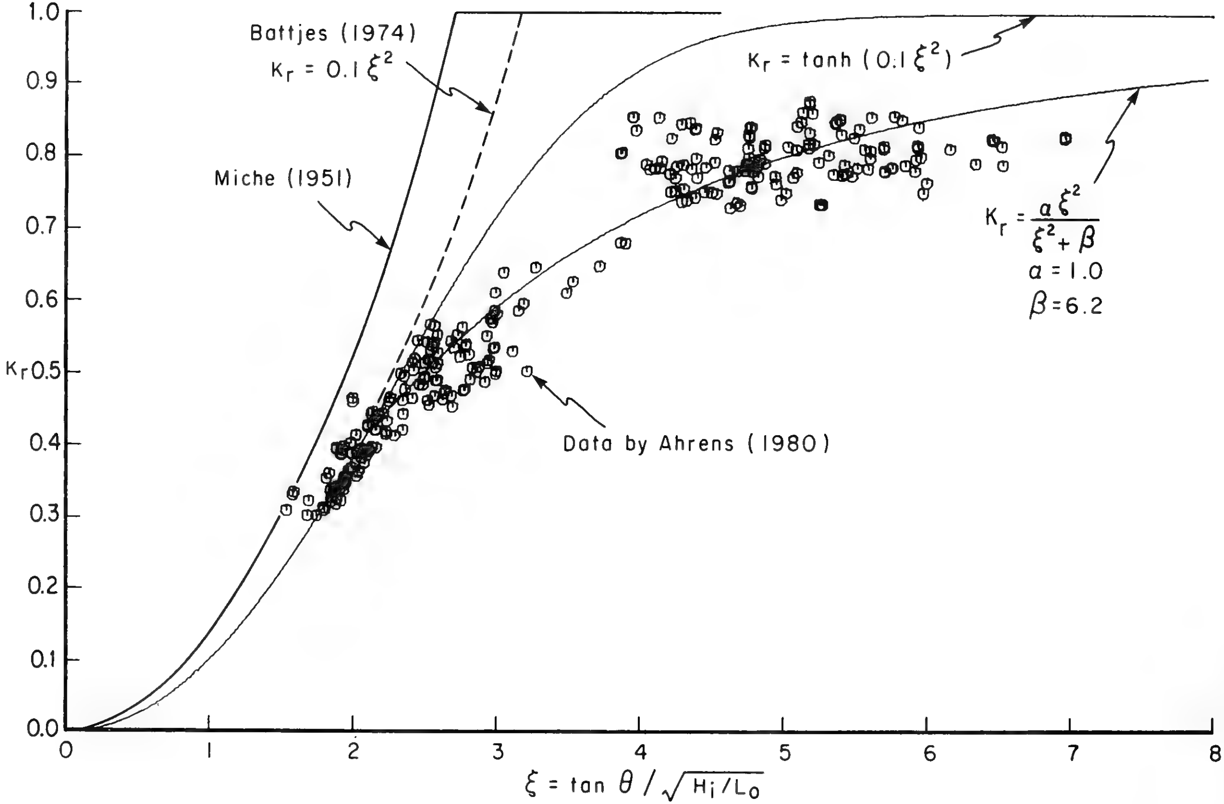


Figure 4. A comparison of wave reflection coefficients for a 1 on 2.5 slope and various equations to predict reflection coefficients.

An improved equation for predicting reflection coefficients with less error in the estimates is

$$K_r = \frac{\alpha\ \xi^2}{\xi^2 + \beta} = \frac{\alpha}{1 + \frac{\beta}{\xi^2}} \tag{15}$$

where α and β are empirical coefficients determined from the laboratory data (e.g., Fig. 4). The value of β increases as the slope becomes flatter and is larger for irregular waves than for monochromatic waves (Fig. 5). For slopes with $\cot\theta \leq 6$, the suggested prediction coefficients are $\alpha = 1.0$ and $\beta = 5.5$ with the equation,

$$\left.\begin{aligned} K_r &= \frac{\alpha\ \xi^2}{\xi^2 + \beta} \\ &\text{or} \\ K_r &= \alpha \tanh\ (0.1\ \xi^2) \end{aligned}\right\} \text{whichever is smaller} \tag{16}$$

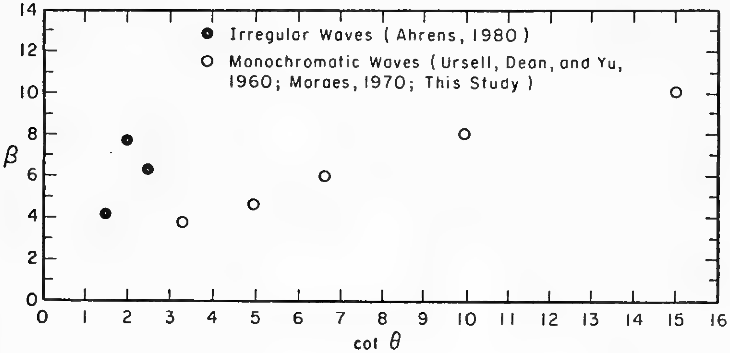


Figure 5. β as a function of structure slope.

2. Breaking at the Toe or Seaward of the Structure.

If the water depth at the toe of the structure is less than five times the incident wave height or if the wave steepness is large, significant additional wave energy loss may result from wave steepness/water depth-limited breaking. The dimensionless ratio describing this type loss is the ratio of the incident wave height to the maximum possible breaker height, (H_i/H_b), where H_b is given by equation (7). This ratio includes the influence of offshore slope, water depth at the toe of the structure, and wave steepness, and gives a measure of breaking at the toe. The suggested empirical coefficient to account for this type energy loss in predicting reflection coefficients is

$$\alpha = \exp\left[-\ 0.5\left(\frac{H_i}{H_b}\right)^{1.3}\right] \tag{17}$$

for use with equation (16), where α is a reflection coefficient reduction factor.

3. Influence of Surface Roughness.

Armor units placed on the surface of a smooth structure will increase the amount of energy loss in a wave encountering the structure, thereby reducing the amount of wave reflection. The suggested prediction equation for a revetment with one layer or armor rock with representative diameter, d, is

$$\alpha = \exp\left[-1.7\sqrt{\frac{d}{L}}\cot\theta - 0.5\left(\frac{H_i}{H_b}\right)^{1.3}\right] \tag{18}$$

for use with equation (16), where L is the wavelength at the toe of the structure. This equation was developed from the data in Table 1.

Figure 6 illustrates the joint influence of a relative armor roughness parameter, $\sqrt{d/L}\cot\theta$, and a relative breaking height parameter, H_i/H_b, on the reflection coefficient reduction factor, α. An examination of equation (18) and Figure 6 indicates that if all other factors remain fixed, the reflection coefficient will decrease as the ratio of the stone size to wavelength, d/L, increases, as the $\cot\theta$ increases (the slope becomes flatter), or as the ratio of the incident wave height to the breaking wave height, (H_i/H_b), increases. Figure 7 shows a comparison between predicted reflection coefficients using equations (18) and (16) versus observed reflection coefficients for monochromatic and irregular waves on a 1 on 2.5 slope armored with one layer of stone with $d/d_s = 0.15$. The correlation coefficient is 0.98 for monochromatic waves and 0.94 for irregular waves.

The ratio of armor stone diameter to incident wave height, d/H_i, on the average has little influence on the reflection coefficient for one layer of armor, so this parameter is not included in equation (18). Some deviation from equation (18) occurs where stone size is much larger than wave height and resulting predictions are conservative. For example, where the stone size-to-wave height ratio is greater than 2.0, equations (16) and (18) overpredict reflection coefficients by an average of 6 percent.

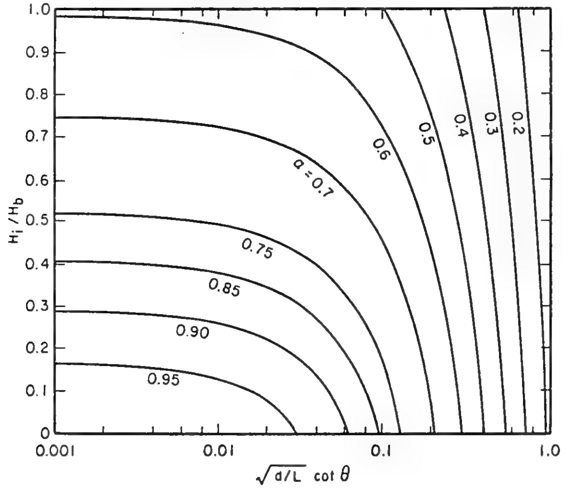
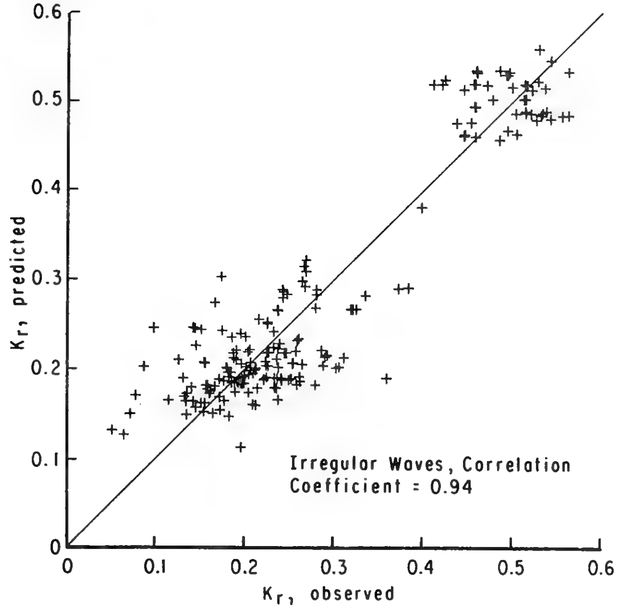


Figure 6. Joint effect on one layer of armor and H_i/H_b on the reflection coefficient reduction factor, α.



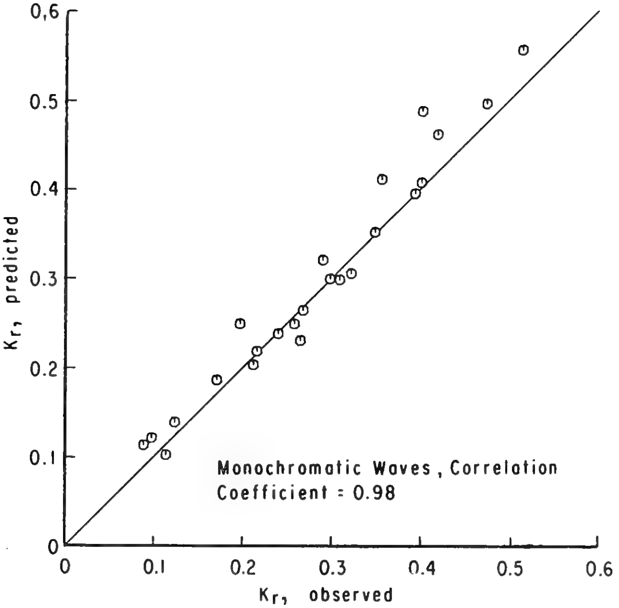


Figure 7. Observed versus predicted reflection coefficients for a revetment armored with one layer of stone.

4. Influence of Multiple Layers of Armor.

As the number of layers, n, of armor on a revetment increases, the amount of wave energy dissipated increases and the reflection coefficient decreases. In addition, as the size of the stone increases relative to the wave height, the roughness becomes more effective and the reflection coefficient decreases. Table 2 gives selected values of a correction factor, α', where

$$\alpha = \alpha' \exp\left[-1.7\sqrt{\frac{d}{L}}\cot\theta - 0.5\left(\frac{H_i}{H_b}\right)^{1.3}\right] \tag{19}$$

Table 2. Correction factor due to multiple layers of armor.[1]

	α'		
	n		
d/H_i	Two	Three	Four
<0.75	0.93	0.88	0.78
0.75 to 2.0	0.71	0.70	0.69
>2.0	0.58	0.52	0.49

[1] $\cot\theta = 2.5$, $d/d_s = 0.15$, $0.004 < d_s/gT^2 < 0.03$.

for multiple layers of armor. These coefficients were obtained by taking the average of the ratios of the measured reflection coefficients for two, three, and four layers of armor to predicted coefficients for a slope with one layer of armor. Only one slope, $\cot\theta = 2.5$, and stone size-to-water depth ratio, $d/d_s = 0.15$, was tested.

5. Wave Reflection from Sand Beaches.

Chesnutt (1978) has the most extensive data set of wave reflection coefficients from laboratory sand beaches. Unfortunately, there are little prototype data available. Chesnutt and Galvin (1974) and Chesnutt (1978) found that many factors influence the magnitude of the reflection coefficient. Their data suggest that

$$K_r = \frac{\alpha\,\xi^2}{\xi^2 + \beta}\ ;\ \beta = 5.5 \tag{20}$$

can be used to estimate reflection coefficients with the beach slope at the stillwater level intercept used to determine ξ. Use $\alpha = 1.0$ for conservative estimates of K_r and $\alpha = 0.5$ to give predictions of the average reflection coefficient measured throughout a test (Fig. 8).

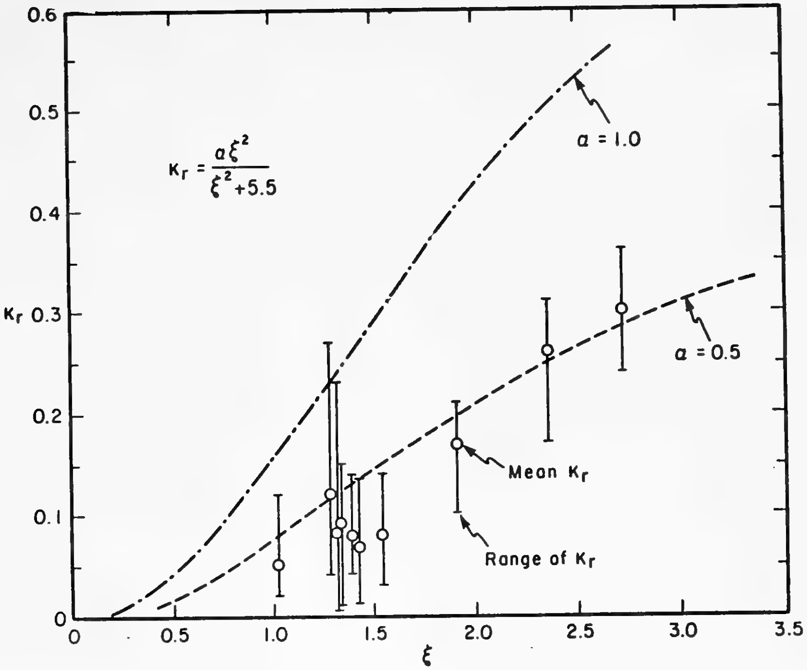


Figure 8. Wave reflection coefficients from laboratory beaches (from Chesnutt, 1978).

6. Rubble-Mound Breakwaters.

An upper limit or conservative estimate of K_r for breakwaters armored with rock or dolos may be obtained using

$$K_r = \frac{\alpha\ \xi^2}{\xi^2 + \beta}\ ;\ \alpha = 0.6,\ \beta = 6.6 \tag{21}$$

Ninety-five percent of all observed laboratory breakwater wave reflection coefficients fall below this prediction equation for data sets c, d, g, and h outlined in Table 1.

More reliable predictions of wave reflection coefficients for rubble-mound breakwaters may be made using the method of Madsen and White (1976) (also see Seelig, 1979). Equations (16) and (18) should be used with the Madsen and White (1976) method to estimate energy dissipation on the seaward face of the breakwater caused by the outer layer of armor units. Figure 9 shows sample laboratory measurements (Sollitt and Cross, 1976) and predicted reflection and transmission coefficients for a rubble-mound breakwater. Observed and predicted reflection coefficients have the best agreement for wave conditions in the turbulent zone, but deviate where the Reynolds number becomes less than 10^4 due to laboratory scale effects.

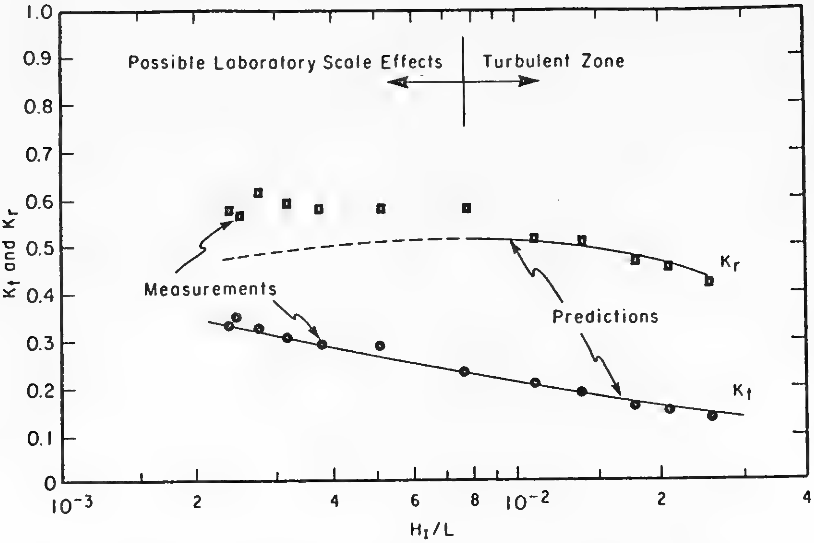


Figure 9. Predicted rubble-mound breakwater wave reflection and transmission coefficients (laboratory data from Sollitt and Cross, 1976).

7. Spectral Resolution of Wave Reflection.

The significant wave height and period of peak energy density are used to characterize irregular wave conditions in this report. However, a more detailed analysis shows that the reflection coefficient varies as a function of wave frequency for irregular waves. Figure 10 illustrates the decrease in reflection coefficient as a function of wave frequency that is typical of waves breaking on a smooth impermeable 1/2 slope ($\xi < 2.3$). Nonbreaking waves have a different characteristic shape of the reflection coefficient as a function of wave frequency. K_r increases as a function of f for frequencies higher than the frequency of peak energy density (Fig. 11). The shift to high frequencies seems to occur because wave energy is transferred from low to higher frequencies due to nonlinear effects when the waves interact with the structure. Note that this energy shift may produce a range of wave frequencies in which more wave energy is moving away from the structure than is incident to the structure, and the local reflection coefficient may be larger than 1.0 over this range of frequencies. Caution should be used when trying to obtain information from the highest frequency part of the spectrum above approximately the 95-percent cumulative energy density level because the signal-to-noise ratio is low and the wave speed is poorly known (Mansard and Funke, 1979).

8. Reflection Coefficient Prediction Equations.

Table 3 summarizes the equations recommended for estimating reflection coefficients for slopes, revetments, rubble-mound breakwaters, and beaches.

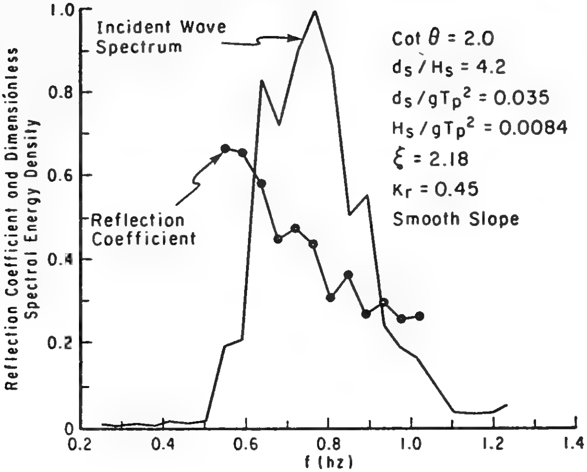


Figure 10. Wave reflection coefficient as a function of wave frequency for an irregular wave condition with breaking waves.

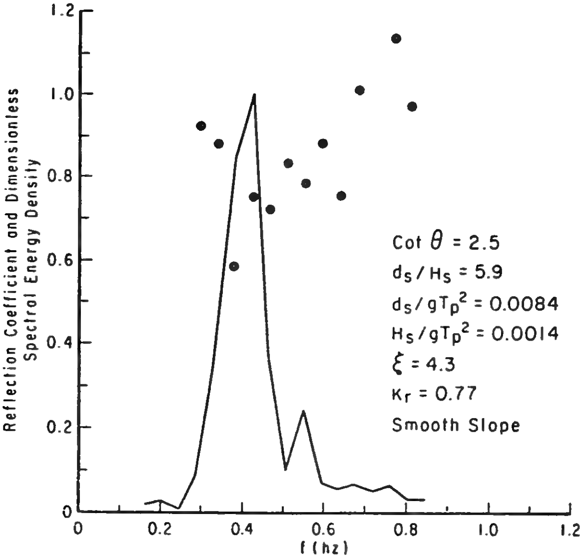


Figure 11. Wave reflection coefficient as a function of wave frequency for an irregular nonbreaking wave condition.

Table 3. Summary of equations for predicting K_r.

Structure type	Prediction equation	α	β	Comments
Revetments	$K_r = \left\{ \begin{array}{l} \dfrac{\alpha\,\xi^2}{\beta + \xi^2} \\ \alpha \tanh\,(0.1\xi^2) \end{array} \right\}$ which-ever is smaller	$\alpha' \exp\left[-1.7\sqrt{\frac{d}{L}}\cot\theta - 0.5\left(\frac{H_i}{H_b}\right)^{1.3}\right]$	5.5 or Fig. 5	H_b from equation (7) $\alpha = 1.0$ for $\frac{d_s}{H_i} > 5$ and $m = 0$ $\alpha' = 1.0$ for $m \le 1$ α' estimated from Table 2 for $\eta > 1$. Use $\alpha' = 1.0$ for a conservative estimate.
Beaches	$K_r = \dfrac{\alpha\,\xi^2}{\beta + \xi^2}$	0.5	5.5	Use $\alpha = 1.0$ for conservative estimate of K_r.
Rubble-mound breakwaters	$K_r = \dfrac{\alpha\,\xi^2}{\beta + \xi^2}$	0.6	6.6	Gives a conservative estimate of K_r. Use Madsen and White (1976) or Seelig (1979) for a more reliable calculation of K_r and K_t.

VII. EXAMPLE PROBLEMS

The following example problems illustrate the methods of predicting reflection coefficients presented in this report.

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

GIVEN: A smooth impermeable revetment (nonovertopped) has a toe water depth, d_s = 7.62 meters, a slope $\cot\theta = 2.0$, and the offshore slope is $m = 0.02$.

FIND: The wave reflection coefficient and fraction of wave energy dissipated for a wave with H_i = 3.05 meters and T = 10 seconds. Illustrate the influence of wave height and period on K_r and show the effect of reducing the slope to $\cot\theta = 5$.

SOLUTION: From equation (7),

$$H_b = 0.17\ L_o \left\{1.0 - \exp\left[-\ 4.712\ \frac{d_s}{L_o}\left(1 + 15\ m^{\ 1.33}\right)\right]\right\}$$

$$H_b = 0.17\left(1.56 \times 10^2\right)\left\{1 - \exp\left[-\ 4.712\ \frac{7.62}{156}\left(1 + 15(0.02)^{1.33}\right)\right]\right\} = 5.85 \text{ m}$$

From equation (17)

$$\alpha = \exp\left[-0.5\left(\frac{H_i}{H_b}\right)^{1.3}\right] = \exp\left[-0.5\left(\frac{3.05}{5.85}\right)^{1.3}\right] = 0.807$$

From equation (10)

$$\xi = \frac{\tan\theta}{\sqrt{\dfrac{H_i}{L_o}}} = \frac{0.5}{\sqrt{\dfrac{3.05}{156}}} = 3.58$$

and from equation (15)

$$K_r = \frac{\alpha\ \xi^2}{\xi^2 + \beta} = \frac{0.807(3.58)^2}{(3.58)^2 + 5.5} = 0.56$$

The energy dissipation coefficient for this example is $K_d^2 = 0.69$, or 69 percent of the incident wave energy is dissipated (from Fig. 3). Other reflection coefficient calculations for 5-, 10-, and 20-second periods for wave heights between 0.3 and 4.4 meters are summarized in Figure 12. Predictions are also shown for a structure with $\cot\theta = 5$. Figure 12 illustrates the influence of wave height, period, and structure slope on K_r.

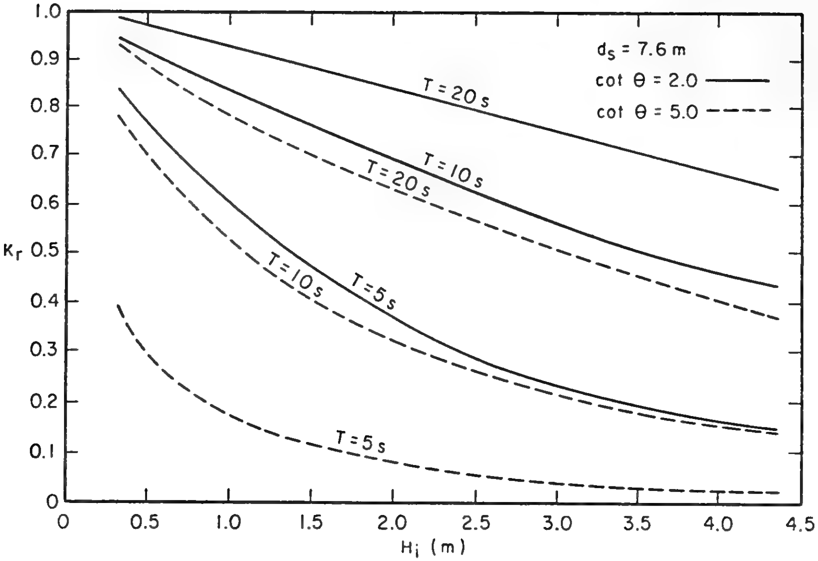


Figure 12. Predicted wave reflection coefficients for smooth impermeable slopes with no overtopping.

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

GIVEN: The wave conditions in example problem 1.

FIND: The wave reflection coefficients if one layer (n = 1) or two layers (n = 2) of 4,500-kilogram (5 tons) rock at 2,700 kilograms per cubic meter (169 pounds per cubic foot) were added as armor to the revetment with cotθ = 2.0.

SOLUTION: The armor material in this example has

$$d = \left(\frac{W}{\gamma}\right)^{1/3} = \left(\frac{4,500}{2,700}\right)^{1/3} = 1.19 \text{ m}$$

using equation (6). For the case of T = 10 seconds and H = 3.05 meters, equation (18) gives

$$\alpha = \exp\left[-1.7\sqrt{\frac{d}{L}}\cot\theta - 0.5\left(\frac{H_i}{H_b}\right)^{1.3}\right]$$

$$\alpha = \exp\left[-1.7\sqrt{\frac{1.19}{82}}\,(2.0) - 0.5\left(\frac{3.05}{5.85}\right)^{1.3}\right] = 0.536$$

and from equation (16)

$$K_r = \frac{\alpha\,\xi^2}{\beta + \xi^2} = \frac{0.536(3.58)^2}{5.5 + (3.58)^2} = 0.37$$

The energy dissipation coefficient from Figure 2 is $K_d^2 = 0.86$, 86-percent dissipation or 17 percent more dissipation than occurred for the smooth slope (see example problem 1). Sample predicted reflection coefficients are given in Figure 13. The preliminary information in Table 2 suggests that further reduction in the reflection coefficients could be achieved by adding a second layer of armor (n = 2) for wave heights less than 3 meters (Fig. 13).

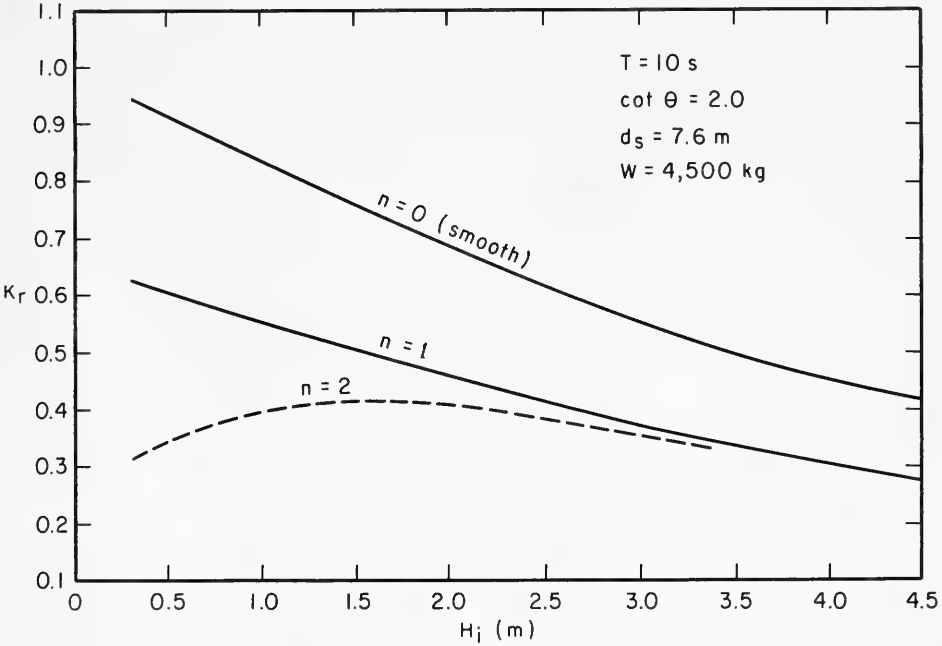


Figure 13. Wave reflection coefficients for a smooth revetment and revetments with one and two layers of armor stone.

VIII. SUMMARY

Methods for predicting wave reflection and dissipation coefficients for beaches, nonovertopped revetments, and breakwaters are presented. Types of wave energy dissipation considered are wave breaking induced by the structure, wave breaking at the toe of the structure, turbulence produced by wave interaction with the outer layer of armor, and flow through additional layers of armor. These techniques are combined with the method of Madsen and White (1976) to estimate reflection and transmission coefficients for permeable rubble-mound breakwaters. Factors considered when making reflection coefficient estimates include structure slope, water depth at the toe of the structure, offshore slope, incident wave height and period, the size and number of layers of armor units, and the type of structure. Techniques presented apply to breaking and nonbreaking (surging) waves and can be used for monochromatic and irregular wave conditions.

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APPENDIX A

LABORATORY WAVE REFLECTION DATA

This appendix includes tables of wave reflection data (Tables A-1 to A-7) obtained as a part of this study. The following variables are used:

ID - an identification code assigned to each data run

H - the incident wave height (centimeter); the significant wave height for irregular waves

T - the wave period (second), the period of peak energy density for irregular waves

SURF - the surf similarity parameter = $\tan\theta/\sqrt{H_i/gT^2}$

H/HB - the incident wave height divided by the maximum breaker height expected at the toe of the structure

D/H - water depth divided by incident wave height

KR - reflection coefficient

QP - the spectral peakedness parameter for irregular wave conditions

Table A-1. Wave reflection from a 1/15.0 smooth slope (monochromatic waves).

```
      WAVE REFLECTION FROM A 1/15.0 SLOPE
        WITH 0 LAYERS OF ARMOR
        A STONE DIAMETER OF 0.00 CM
         WATER DEPTH =    21.5 CM
   ID          H(CM)     T(SEC)     SURF       H/HB     D/H      KR
8006120001      .75       2.00      1.93       .05     28.7    .169
8006120002     1.30       2.00      1.46       .08     16.5    .080
8006120003     1.73       2.00      1.27       .11     12.4    .082
8006120004      .29       2.50      3.90       .02     75.4    .548
8006120005      .83       2.50      2.29       .05     26.1    .283
8006120006     1.15       2.50      1.94       .07     18.6    .171
8006120007     1.37       2.50      1.78       .08     15.7    .125
8006120008     1.78       2.50      1.56       .11     12.1    .082
8006120009     1.81       2.50      1.55       .11     11.9    .079
8006120010     1.45       2.70      1.87       .09     14.8    .238
8006120011     1.16       2.70      2.09       .07     18.5    .326
8006120012     1.70       2.70      1.73       .10     12.7    .185
8006120013      .64       3.00      3.12       .04     33.4    .532
8006120014     1.05       3.00      2.44       .06     20.5    .405
8006120015     1.41       3.00      2.10       .08     15.3    .318
8006120016     1.17       3.50      2.70       .07     18.5    .564
8006120017     1.64       3.50      2.28       .10     13.1    .457
```

Table A-2. Wave reflection from a 1/2.5 smooth slope (monochromatic waves).

```
      WAVE REFLECTION FROM A 1/ 2.5 SLOPE
        WITH 0 LAYERS OF ARMOR
        A STONE DIAMETER OF 0.00 CM
         WATER DEPTH =    53.0 CM
   ID          H(CM)     T(SEC)     SURF       H/HB     D/H      KR
8005221243     2.87       1.25      3.70       .11     18.5    .697
8005221253     6.77       1.25      2.41       .25      7.8    .516
8005221305    12.33       1.25      1.79       .46      4.3    .197
8005221314    12.09       1.25      1.80       .45      4.4    .237
8005221324     9.43       1.50      2.44       .31      5.6    .498
8005221333     8.33       1.50      2.61       .27      6.4    .588
8005221342     5.98       1.50      3.07       .20      8.9    .704
8005221351     3.01       1.50      4.32       .10     17.6    .766
8005221400     1.52       1.83      7.42       .04     34.9    .628
8005221411     1.43       1.83      7.65       .04     37.1    .843
8005221428     7.29       1.83      3.39       .22      7.3    .826
8005221437    12.65       1.83      2.57       .37      4.2    .512
8005221447    18.26       2.37      2.77       .49      2.9    .442
8005221457    14.59       2.37      3.10       .39      3.6    .709
8005221507     8.78       2.37      4.00       .24      6.0    .799
8005221522     4.14       2.37      5.82       .11     12.8    .629
8005221532     3.37       2.88      7.84       .09     15.7    .856
8005291435    13.09       2.88      3.98       .34      4.0    .587
8005291448    19.88       2.88      3.23       .51      2.7    .448
8005291459     1.19       3.50     16.27       .03     44.6    .871
8005291517     3.81       3.50      8.96       .10     13.9    .868
8005291528     6.25       3.50      6.99       .16      8.5    .850
8005291540    10.61       3.50      5.37       .27      5.0    .831
```

Table A-3. Wave reflection from a 1/2.5 slope with one layer of armor (monochromatic waves).

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 1 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 53.0 CM

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR
8001291313	4.93	1.25	2.81	.19	10.7	.258
8001291322	8.16	1.25	2.19	.31	6.5	.171
8001291332	11.94	1.25	1.81	.45	4.4	.124
8001291341	14.86	1.25	1.62	.56	3.6	.089
8001291351	13.86	1.25	1.68	.52	3.8	.098
8001291405	16.40	1.25	1.54	.62	3.2	.114
8001291207	3.66	1.50	3.92	.12	14.5	.348
8001291218	5.68	1.50	3.14	.19	9.3	.298
8001291227	7.40	1.50	2.75	.24	7.2	.208
8001291238	8.91	1.50	2.51	.29	5.9	.240
8001291248	10.21	1.50	2.35	.34	5.2	.216
8001291258	11.33	1.50	2.23	.37	4.7	.212
8001291544	2.24	1.83	6.11	.07	23.7	.418
8001291552	4.67	1.83	4.23	.14	11.3	.393
8001291601	9.63	1.83	2.95	.29	5.5	.309
8001291608	14.69	1.83	2.39	.44	3.6	.265
8001291459	4.26	2.37	5.73	.12	12.4	.401
8001291508	8.34	2.37	4.10	.23	6.4	.356
8001291519	14.67	2.37	3.09	.40	3.6	.290
8001291535	21.47	2.37	2.56	.58	2.5	.197
8001291416	3.38	2.88	7.83	.09	15.7	.513
8001291426	6.91	2.88	5.47	.18	7.7	.473
8001291435	12.99	2.88	3.99	.34	4.1	.400
8001291449	22.21	2.88	3.05	.58	2.4	.322

Table A-4. Wave reflection from a 1/2.5 slope with two layers of armor (monochromatic waves).

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 2 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 53.0 CM

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR
8002121301	2.17	1.25	4.24	.08	24.5	.191
8002121251	5.95	1.25	2.56	.22	8.9	.146
8002121243	13.23	1.25	1.72	.50	4.0	.126
8002121236	14.41	1.25	1.65	.54	3.7	.118
8002121205	4.80	1.50	3.42	.16	11.0	.238
8002121213	9.51	1.50	2.43	.31	5.6	.196
8002121220	12.41	1.50	2.13	.41	4.3	.169
8002121228	12.41	1.50	2.13	.41	4.3	.167
8002121158	2.45	1.83	5.85	.07	21.7	.278
8002121150	5.12	1.83	4.04	.15	10.3	.267
8002121143	10.34	1.83	2.84	.31	5.1	.214
8002121134	15.81	1.83	2.30	.47	3.4	.173
8002121058	3.57	2.37	6.27	.10	14.9	.242
8002121106	7.28	2.37	4.39	.20	7.3	.246
8002121114	13.67	2.37	3.20	.37	3.9	.219
8002121127	20.06	2.37	2.64	.54	2.6	.191
8002121051	2.90	2.88	8.44	.08	18.3	.366
8002121044	6.15	2.88	5.80	.16	8.6	.372
8002120023	12.25	2.88	4.11	.32	4.3	.359
8002120014	21.78	2.88	3.08	.56	2.4	.315

Table A-5. Wave reflection from a 1/2.5 slope with three layers of armor (monochromatic waves).

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 3 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 53.0 CM

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR
8003281253	2.75	1.25	3.76	.10	19.2	.230
8003281301	7.67	1.25	2.26	.29	6.9	.138
8003281310	15.06	1.25	1.61	.57	3.5	.148
8003281244	1.62	1.50	5.89	.05	32.7	.213
8003281235	3.42	1.50	4.05	.11	15.5	.228
8003281224	5.46	1.50	3.21	.18	9.7	.219
8003281214	8.33	1.50	2.60	.27	6.4	.192
8003281205	10.28	1.50	2.34	.34	5.2	.180
8003281154	12.73	1.50	2.10	.42	4.2	.160
8003281135	12.98	1.50	2.08	.43	4.1	.158
8003281052	2.97	1.83	5.30	.09	17.8	.172
8003281102	6.10	1.83	3.70	.18	8.7	.182
8003281113	11.45	1.83	2.70	.34	4.6	.155
8003281125	16.70	1.83	2.24	.49	3.2	.149
8003281039	2.80	2.37	7.07	.08	18.9	.207
8003281029	5.82	2.37	4.91	.16	9.1	.221
8003281019	11.78	2.37	3.45	.32	4.5	.219
8003281009	15.81	2.37	2.98	.43	3.4	.221
8003280922	1.65	2.88	11.20	.04	32.1	.253
8003280931	2.44	2.88	9.22	.06	21.7	.294
8003280940	5.46	2.88	6.16	.14	9.7	.340
8003280950	11.67	2.88	4.21	.30	4.5	.330
8003280957	20.59	2.88	3.17	.53	2.6	.300
8003281333	6.26	3.50	6.99	.16	8.5	.451
8003281320	8.86	3.50	5.87	.22	6.0	.443
8003281343	12.33	3.50	4.98	.31	4.3	.452

Table A-6. Wave reflection from a 1/2.5 slope with four layers of armor (monochromatic waves).

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 4 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 53.0 CM

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR
8004011326	2.39	1.25	4.04	.09	22.2	.262
8004011334	7.22	1.25	2.32	.27	7.3	.168
8004011343	11.88	1.25	1.81	.45	4.5	.114
8004011234	.74	1.50	8.73	.02	71.9	.222
8004011225	1.50	1.50	6.11	.05	35.2	.216
8004011217	3.24	1.50	4.16	.11	16.4	.190
8004011206	7.27	1.50	2.78	.24	7.3	.161
8004011127	1.51	1.83	7.44	.04	35.1	.180
8004011136	3.15	1.83	5.15	.09	16.8	.163
8004011145	6.57	1.83	3.57	.19	8.1	.158
8004011154	12.18	1.83	2.62	.36	4.4	.139
8004011116	.84	2.37	12.91	.02	63.0	.304
8004011107	2.56	2.37	7.40	.07	20.7	.240
8004011058	5.32	2.37	5.13	.14	10.0	.244
8004011047	11.11	2.37	3.55	.30	4.8	.262
8004010958	1.40	2.88	12.18	.04	38.0	.242
8004011007	2.07	2.88	10.01	.05	25.7	.275
8004011019	4.68	2.88	6.65	.12	11.3	.340
8004011034	10.10	2.88	4.53	.26	5.2	.347
8004011258	2.73	3.50	10.59	.07	19.4	.389
8004011249	6.83	3.50	6.69	.17	7.8	.446
8004011307	9.61	3.50	5.64	.24	5.5	.439
8004011316	13.13	3.50	4.83	.33	4.0	.429

Table A-7. Wave reflection from a 1/2.5 slope with one layer of armor (irregular waves).

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 1 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 36.4 CM

IRREGULAR WAVES

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR	QP
8001220925	6.76	1.25	2.40	.32	5.4	.209	2.4
8001220934	7.14	1.37	2.56	.32	5.1	.187	2.9
8001220945	7.33	1.53	2.83	.31	5.0	.225	2.4
8001220955	7.62	.99	1.79	.44	4.8	.196	2.7
8001221007	8.01	1.48	2.61	.35	4.5	.259	2.3
8001221017	7.48	1.25	2.29	.36	4.9	.199	4.2
8001221028	7.22	1.31	2.43	.34	5.0	.212	3.3
8001221038	8.96	1.51	2.53	.39	4.1	.257	2.7
8001221048	8.57	1.50	2.55	.37	4.2	.237	3.3
8001221116	10.60	2.09	4.13	.39	3.4	.597	1.5
8001221126	11.64	1.51	2.22	.50	3.1	.279	2.5
8001221138	11.76	1.68	2.45	.49	3.1	.311	2.2
8001221148	4.77	3.28	7.51	.17	7.6	.495	3.5
8001221158	7.40	3.28	6.03	.27	4.9	.513	2.5
8001221220	9.39	1.79	2.92	.38	3.9	.279	1.6
8001221231	10.43	4.57	7.07	.37	3.5	.527	1.3
8001221241	7.52	3.28	5.98	.27	4.8	.513	2.4

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 1 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 45.0 CM

IRREGULAR WAVES

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR	QP
8001230958	7.89	1.25	2.22	.33	5.7	.192	2.5
8001231008	7.83	1.46	2.61	.29	5.7	.195	2.5
8001231018	8.16	1.15	2.01	.36	5.5	.172	3.0
8001231028	8.35	1.57	2.72	.30	5.4	.215	2.4
8001231038	8.88	1.16	1.94	.39	5.1	.182	2.6
8001231048	9.35	1.48	2.42	.35	4.8	.226	2.3
8001231057	9.40	1.48	2.41	.35	4.8	.224	2.3
8001231108	8.68	1.25	2.12	.36	5.2	.160	4.8
8001231117	8.53	1.25	2.14	.35	5.3	.161	4.8
8001231129	8.50	1.31	2.25	.34	5.3	.199	3.6
8001231139	9.94	1.59	2.52	.36	4.5	.260	3.1
8001231150	9.99	1.45	2.29	.38	4.5	.237	3.7
8001231200	9.87	1.48	2.35	.37	4.6	.235	3.6
8001231210	10.09	1.59	2.50	.36	4.5	.258	3.1
8001231221	8.75	1.31	2.22	.35	5.1	.193	3.6
8001231236	8.60	1.31	2.24	.34	5.2	.196	3.6
8001231248	8.77	1.41	2.39	.34	5.1	.187	2.7
8001231304	13.95	1.08	2.25	.49	3.2	.302	2.5
8001231316	12.25	2.00	2.95	.40	3.7	.383	1.8
8001231330	13.19	1.56	2.15	.48	3.4	.202	3.1
8001231341	5.65	3.01	6.33	.17	8.0	.498	5.2
8001231352	8.33	3.16	5.47	.25	5.4	.519	2.8
8001231403	11.33	1.02	2.40	.40	4.0	.286	2.0
8001231414	12.88	3.94	5.48	.37	3.5	.554	1.8
8001231437	13.87	1.08	2.26	.48	3.2	.306	2.5
8001250924	11.92	1.51	2.18	.44	3.8	.252	3.3
8001250935	12.56	1.67	2.36	.44	3.6	.292	2.6
8001250955	4.65	3.01	6.83	.14	9.3	.493	5.2
8001251005	4.86	3.01	6.82	.15	9.3	.491	5.0
8001251015	12.66	1.62	2.28	.45	3.6	.268	2.6
8001251026	7.53	3.20	5.83	.22	6.0	.476	2.8
8001251036	9.71	1.64	2.95	.33	4.6	.260	2.1
8001251047	11.19	4.41	6.59	.32	4.0	.501	1.6
8001251057	14.00	4.20	5.60	.40	3.2	.502	2.2
8001251108	12.07	1.51	2.17	.45	3.7	.249	3.3
8001251201	9.75	1.82	2.90	.33	4.6	.280	2.1
8001251211	12.72	1.67	2.34	.45	3.5	.290	2.5

Table A-7. Wave reflection from a 1/2.5 slope with one layer of armor (irregular waves).--Continued

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         WAVE REFLECTION FROM A 1/ 2.5 SLOPE
           WITH 1 LAYERS OF ARMOR
           A STONE DIAMETER OF 7.95 CM
            WATER DEPTH =    53.0 CM
      ID        H(CM)    T(SEC)    SURF      H/HB    D/H    KR    QP
              IRREGULAR WAVES

8001271643     8.05      1.53      2.60      .28     6.1   .225   2.0
8001271654     8.92      1.32      2.21      .32     5.9   .204   3.1
8001271703     9.46      1.55      2.52      .31     5.6   .232   2.4
8001271714     9.70      1.41      2.27      .33     5.5   .196   2.9
8001271724    10.38      1.53      2.38      .34     5.1   .232   2.4
8001271734     9.70      1.25      2.00      .37     5.5   .177   4.8
8001271745     9.60      1.30      2.10      .35     5.5   .214   3.6
8001271755    11.02      1.58      2.32      .37     4.6   .244   4.0
8001271807    10.91      1.41      2.14      .37     4.9   .240   4.0
8001271817    10.92      1.41      2.14      .37     4.9   .236   4.0
8001271828    11.61      1.59      2.32      .37     4.6   .246   3.9
8001281104    13.02      1.51      2.04      .45     3.9   .235   3.6
8001281117    14.12      1.55      2.06      .46     3.8   .258   2.8
8001281128     5.37      3.01      6.50      .14     9.9   .484   5.5
8001281138     8.37      2.75      4.75      .22     6.3   .457   3.5
8001281149    10.52      1.98      3.06      .30     5.0   .266   2.2
8001281200    12.33      4.00      5.69      .31     4.3   .535   1.9
8001281211    15.73      4.08      5.12      .39     3.4   .541   2.9
8001281224    13.76      1.51      2.04      .45     3.9   .233   3.8
8001281236    14.31      1.67      2.21      .44     3.7   .204   2.8
8001281248    10.32      1.94      3.02      .30     5.1   .208   2.2
8001281308    15.20      1.51      1.95      .49     3.5   .237   4.1
8001281320    13.69      2.05      2.77      .39     3.9   .335   1.9
8001281333    15.86      1.08      2.11      .48     3.5   .201   2.0
8001281347     6.39      3.01      5.95      .16     8.3   .470   6.7
8001281357     9.32      2.41      4.76      .28     5.7   .503   2.8
8001281408    12.24      2.03      2.90      .35     4.3   .208   2.3
8001281419    14.49      3.94      5.19      .36     3.7   .532   2.4
8001290943    12.09      1.51      2.11      .42     4.2   .221   3.0
8001290955    13.21      1.02      2.23      .42     4.0   .254   2.0
8001291008     7.37      2.75      5.07      .19     7.2   .452   3.4
8001291020     4.87      2.09      6.10      .13    10.9   .444   3.8
8001291030     9.20      1.91      3.15      .27     5.8   .208   2.1
8001291042    11.11      4.27      6.39      .27     4.8   .541   1.8
8001291052    12.88      4.06      5.65      .32     4.1   .520   1.8
8001291105    12.79      1.51      2.10      .42     4.1   .221   3.0
8001291115    13.26      1.02      2.22      .42     4.0   .253   2.0
8001291128     9.24      1.77      2.90      .28     5.7   .267   2.1
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          WAVE REFLECTION FROM A 1/ 2.5 SLOPE
            WITH 1 LAYERS OF ARMOR
            A STONE DIAMETER OF 7.95 CM
             WATER DEPTH =    57.8 CM
      ID        H(CM)    T(SEC)    SURF      H/HB    D/H    KR    QP
7912131116     8.89      1.21      2.03      .33     6.5   .171   2.7
7912131129     9.10      1.51      2.51      .28     6.4   .174   2.7
7912131140     9.96      1.25      1.98      .36     5.8   .136   5.1
7912131149     9.80      1.26      2.01      .35     5.9   .132   4.9
7912131200     9.12      1.27      2.11      .32     6.3   .156   3.1
7912131209     9.12      1.37      2.27      .30     6.3   .155   3.1
7912131219     9.07      1.38      2.22      .32     6.0   .201   2.5
7912131229     9.86      1.53      2.44      .30     5.9   .200   2.4
7912131239     9.60      1.30      2.10      .33     6.0   .159   3.6
7912131247     9.67      1.30      2.09      .33     6.0   .106   3.9
7912131257     9.84      1.41      2.25      .32     5.9   .158   3.0
7912131306     9.91      1.20      1.91      .37     5.8   .154   3.0
7912131316    10.87      1.53      2.32      .33     5.3   .205   2.5
7912131326    10.75      1.51      2.31      .33     5.4   .203   2.6
7912131338    11.73      1.41      2.06      .38     4.9   .196   4.5
7912131347    11.06      1.41      2.07      .38     5.0   .195   4.4
7912131357    12.36      1.51      2.15      .38     4.7   .211   4.0
7912131405    12.32      1.51      2.16      .38     4.7   .211   3.8
7912171051    13.27      1.51      2.07      .41     4.4   .191   3.8
7912171141     7.76      2.91      5.22      .19     7.4   .456   4.5
7912171150     7.80      2.91      5.20      .19     7.4   .457   4.6
7912171251     5.09      2.72      6.03      .12    11.4   .420   4.5
7912171301     5.14      2.78      6.13      .12    11.2   .423   4.7
7912171310     9.95      1.78      2.82      .28     5.8   .242   2.1
7912171321     9.96      1.77      2.79      .28     5.8   .243   2.1
7912171331    11.76      3.82      5.57      .27     4.9   .512   1.7
7912171341    11.63      3.82      5.55      .27     4.9   .515   1.8
7912171351    14.31      4.00      5.28      .33     4.0   .513   1.8
7912171059    12.87      1.51      2.10      .40     4.5   .224   4.0
7912171130    12.93      1.51      2.09      .40     4.5   .233   4.0
7912171403    13.17      4.74      6.53      .30     4.4   .528   1.7
8001091029     5.75      2.98      6.20      .14    10.1   .459   4.2
8001091042    11.33      1.77      2.62      .32     5.1   .236   2.2
8001091055    11.38      1.77      2.62      .32     5.1   .237   2.2
8001091109    11.39      1.77      2.61      .32     5.1   .237   2.2
8001091120    14.28      4.00      5.29      .33     4.0   .513   2.3
8001091132    14.32      4.00      5.28      .33     4.0   .511   2.3
8001091143    14.65      1.51      1.98      .45     3.9   .184   3.7
8001091157    14.46      1.56      2.05      .48     4.0   .188   3.6
8001100841     9.02      2.78      4.63      .22     6.4   .444   4.0
8001100907     8.94      2.78      4.65      .22     6.5   .445   3.9
8001100918    15.14      1.68      2.16      .44     3.8   .223   3.0
8001100931    14.71      1.68      2.19      .43     3.9   .223   2.9
8001100942    15.18      1.68      2.16      .44     3.8   .226   3.1
8001100956    16.42      4.13      5.09      .37     3.5   .536   2.1
8001101009    16.41      4.06      5.01      .37     3.5   .501   2.9
8001101022     5.81      3.01      6.24      .14     9.9   .458   5.1
8001101033     5.86      3.01      6.22      .14     9.9   .458   5.1
8001101056    14.51      1.51      1.98      .45     4.0   .204   3.9
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Table A-7. Wave reflection from a 1/2.5 slope with one layer of armor (irregular waves).--Continued

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 1 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 57.8 CM

IRREGULAR WAVES

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR	QP
8001101116	6.75	3.01	5.79	.16	8.6	.457	4.5
8001101127	6.75	3.01	5.79	.16	8.6	.455	4.6
8001101138	10.08	2.88	4.55	.24	5.7	.484	2.5
8001101150	10.07	2.88	4.53	.24	5.7	.484	2.5
8001101203	13.51	1.98	2.70	.36	4.3	.242	2.2
8001101215	13.20	1.98	2.73	.35	4.4	.247	2.2
8001101228	16.04	3.94	4.91	.37	3.6	.525	2.2
8001101242	15.57	3.94	4.99	.36	3.7	.530	2.6
8001101256	15.30	2.03	2.60	.41	3.8	.325	2.0
8001101312	15.32	2.03	2.59	.41	3.8	.319	2.0
8001101328	15.33	2.03	2.59	.41	3.8	.321	2.0
8001101344	16.23	1.51	1.88	.50	3.6	.212	4.0
8001101358	16.13	1.51	1.88	.50	3.6	.209	4.0
8001101413	16.79	1.68	2.05	.49	3.4	.241	3.3
8001110834	8.88	1.51	2.54	.27	6.5	.142	2.7
8001110845	8.95	1.51	2.53	.28	6.5	.144	2.6
8001110858	9.16	1.24	2.05	.33	6.3	.135	3.2
8001110910	9.90	1.53	2.43	.30	5.8	.185	2.5
8001110920	10.20	1.20	1.88	.38	5.7	.135	3.0
8001110930	10.93	1.53	2.32	.33	5.3	.190	2.5
8001110941	10.11	1.26	1.98	.36	5.7	.115	5.1
8001110952	9.68	1.24	1.99	.35	6.0	.142	3.9
8001111002	12.34	1.51	2.15	.38	4.7	.206	4.0
8001111013	11.61	1.41	2.07	.38	5.0	.185	4.3
8001111026	11.06	1.41	2.12	.36	5.2	.182	4.0
8001111037	12.13	1.51	2.17	.37	4.8	.206	4.0
8001111049	9.55	1.20	1.94	.36	6.1	.145	3.8
8001111104	9.74	1.30	2.08	.34	5.9	.140	3.8

WAVE REFLECTION FROM A 1/ 2.5 SLOPE
WITH 1 LAYERS OF ARMOR
A STONE DIAMETER OF 7.95 CM
WATER DEPTH = 63.0 CM

IRREGULAR WAVES

ID	H(CM)	T(SEC)	SURF	H/HB	D/H	KR	QP
8001111156	9.44	1.50	2.11	.31	6.7	.176	2.8
8001111205	9.58	1.27	2.06	.32	6.6	.160	3.2
8001111216	10.33	1.38	2.15	.32	6.1	.181	2.5
8001111226	10.23	1.20	1.88	.36	6.2	.164	3.0
8001111238	11.37	1.50	2.22	.33	5.5	.190	2.5
8001111251	10.30	1.25	1.94	.35	6.1	.155	5.5
8001111304	10.12	1.30	2.04	.33	6.2	.158	.4.0
8001111316	12.89	1.51	2.11	.38	4.9	.184	3.5
8001111329	12.14	1.50	2.15	.36	5.2	.180	4.5
8001111342	12.07	1.50	2.15	.35	5.2	.179	4.6
8001111355	12.87	1.51	2.11	.38	4.9	.183	3.7
8001111408	10.04	1.24	1.95	.35	6.3	.151	4.1
8001111419	10.12	1.25	1.96	.35	6.2	.134	5.3
8001141005	13.33	1.51	2.06	.39	4.7	.359	3.0
8001141019	14.54	1.56	2.05	.42	4.3	.171	3.4
8001141030	15.22	1.68	2.16	.41	4.1	.206	2.9
8001141042	8.54	2.78	4.76	.19	7.4	.436	4.0
8001141054	5.63	2.75	5.80	.13	11.2	.410	4.8
8001141105	10.06	1.77	2.78	.27	6.3	.372	1.7
8001141115	12.66	3.82	5.37	.27	5.0	.514	1.7
8001141126	15.26	3.56	4.55	.33	4.1	.493	1.9

APPENDIX B

METHOD OF MEASURING WAVE REFLECTION COEFFICIENTS

The method of Goda and Suzuki (1976) is used to determine laboratory reflection coefficients for monochromatic and irregular conditions. Also used is the energy balance approach for both types of waves, so that wave energy transfer between frequencies and variable amounts of reflection over a range of frequencies can be considered. This approach gives a reflection coefficient that is formally defined as the square root of the ratio of the reflected wave energy to incident wave energy. For an idealized case where no energy transfers occur, the reflection coefficient is the ratio of reflected and incident wave heights. Reflection coefficients are determined by placing two or more gages several wavelengths seaward of the structure. Each pair of gages then gives an estimate of reflection coefficients.

In these experiments wave records were sampled simultaneously at three wave gages (Fig. 2) at a rate of 16 times a second to obtain 4,096 data points for each run. An FFT was then performed on each wave gage record to determine real and imaginary spectral coefficients, A and B, at each spectral line j. Let the subscripts $_1$ and $_2$ indicate the landward and seaward gages in a pair. The reflected and incident wave amplitudes for each gage pair for each spectral line are then given by

$$a_i = \frac{1}{2|\sin k\Delta\ell|}\sqrt{(A_2 - A_1 \cos k\Delta\ell - B_1 \sin k\Delta\ell)^2 + (B_2 + A_1 \sin k\Delta\ell - B_1 \cos k\Delta\ell)^2} \qquad \text{(B-1)}$$

$$a_r = \frac{1}{2|\sin k\Delta\ell|}\sqrt{(A_2 - A_1 \cos k\Delta\ell + B_1 \sin k\Delta\ell)^2 + (B_2 - A_1 \sin k\Delta\ell - B_1 \cos k\Delta\ell)^2} \qquad \text{(B-2)}$$

A,B = spectral coefficients

k = wave number $= \frac{2\pi}{L}$ (B-3)

$\Delta\ell$ = gage spacing

Only gage pairs with

$$0.05 \le \frac{\Delta\ell}{L} \le 0.45 \qquad \text{(B-4)}$$

are used in the analysis, and wavelength, L, is determined from linear theory for irregular waves,

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi d}{L}\right), \qquad \text{(B-5)}$$

and may be found using Dean's (1974) stream-function theory for steep monochromatic waves (see App. C).

All estimates of reflection coefficients found using the above procedure are averaged at each spectral line to give an incident wave amplitude and reflection coefficient for line j:

$(a_i)^j$ = average incident wave amplitude at line j

$(K_r)^j$ = average reflection coefficient at line j = $\left(\frac{a_r}{a_i}\right)^i$

The reflection coefficient is then determined by taking

$$K_r = \sqrt{\frac{\sum_{j=12}^{400} \left[(a_i)^j (K_r)^j\right]^2}{\sum_{j=12}^{400} \left[(a_i)^j\right]^2}} \tag{B-6}$$

Irregular wave information is displayed in the form of band spectra, using 11 lines per band and using a variation of equation (B-6) to determine the reflection coefficient for each band.

In the case of monochromatic waves, a nonlinear waveform is described by a Fourier series with each component moving at the speed of the primary wave, and equation (B-6) is used to determine the reflection coefficient.

APPENDIX C

NONLINEAR WAVELENGHTS AND WAVE SPEED

In the real-time analysis of wave reflection it is necessary to know the wavelength or wave speed. Linear theory gives excellent predicitons for low steepness waves, but tends to underestimate both length and speed for large waves.

Dean (1974) gives tabular values of wave speed and wavelength for finite height waves that can be approximated by the empirical relation,

$$\frac{L}{L_o} = \frac{C}{C_o} = \frac{L_A}{L_o} + a\left(\frac{H_i}{L_o}\right)^b \qquad \text{(C-1)}$$

where L and C are wave speed and wavelength, L_o and C_o are deepwater wave speed and wavelength determined from linear theory where

$$L_o = \frac{gT^2}{2\pi} \qquad \text{(C-2)}$$

L_A is the local length determined from linear or Airy theory and a and b are empirical coefficients. Airy wave theory predictions and values of a and b are plotted as a function of d_s/L_o in Figure C-1, where d_s is the water depth.

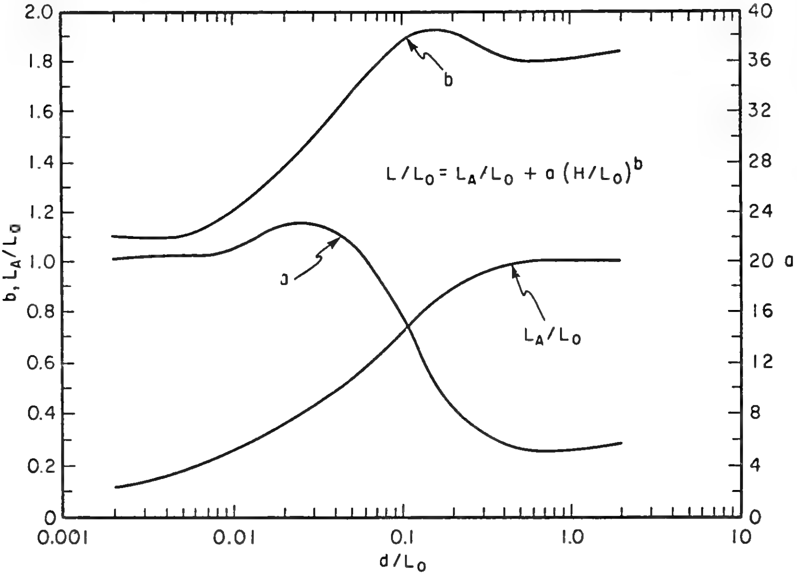

Figure C-1. Coefficients for approximating nonlinear wave speed and wavelength determined from stream-function theory.

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