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Prediction of Irregular Wave Overtopping

by

John Ahrens

COASTAL ENGINEERING TECHNICAL AID NO. 77-7
DECEMBER 1977

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U.S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING RESEARCH CENTER

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Rates of wave overtopping of structures can be predicted by means of an equation presented in the Shore Protection Manual (SPM)(eg. 7-6, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975; Weggel, 1976). Implicit in the use of this equation is the assumption of monochromatic waves; i.e., waves of uniform height and period. A question ~~that arises is~~ is given on what would the overtopping rate be for irregular wave conditions having a significant height equal to the height of the monochromatic wave used in the SPM
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equation. ~~To develop~~ an answer ~~to this question~~, the irregular wave conditions are assumed to cause the runup to have a Rayleigh distribution of the type commonly associated with wave heights. This technique, which was used by Ahrens (1977) to predict irregular wave runup, appears reasonable but possibly somewhat conservative. The runup with a Rayleigh distribution is used in the SPM's wave overtopping equation to predict average overtopping rates for irregular waves having a particular significant height. This approach generally yields overtopping rates that are considerably lower than the corresponding monochromatic rates except for structures with high relative freeboards where the irregular wave overtopping rates can then exceed the monochromatic rates. This behavior is consistent with the trends observed by Tsuruta and Goda (1968) in their laboratory study of overtopping caused by both monochromatic and irregular waves.

Example problems are given to illustrate how this technique can be used to predict overtopping rates for irregular wave conditions. A table, which can be used to calculate the irregular overtopping rate using the monochromatic rate for equivalent wave conditions is also given.

PREFACE

This report describes a proposed technique for predicting overtopping rates for structures exposed to irregular wind-generated waves by extending the method of predicting overtopping for waves of constant height and period presented in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975). Results produced by the technique should be more representative of conditions in nature than the SPM procedures. However, while the present SPM procedure is based on laboratory tests, the proposed technique has not been directly tested in the laboratory or the field. Therefore, results from the technique should be used for general guidance until results of laboratory tests presently underway become available.

This report was prepared by John Ahrens, Oceanographer, under the general supervision of Dr. R.M. Sorensen, Chief, Coastal Structures Branch.

The author acknowledges the extensive computer programing assistance from M. Titus, and the useful suggestions by Dr. R.M. Sorensen.

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.

JOHN H. COUSINS
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	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

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

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

d_s	water depth at toe of structure (feet)
g	acceleration of gravity (feet per second squared)
H'_o	equivalent deepwater wave height (feet)
$(H'_o)_s$	equivalent deepwater significant wave height (feet)
h	height of the structure crest above the bottom (feet)
K_i	ratio of R_p to R_s for a particular probability of exceedance
p	probability of exceedance
Q_i	overtopping rate associated with a particular probability of exceedance (cubic feet per second per foot)
Q_m	overtopping rate for monochromatic waves (cubic feet per second per foot)
α, Q^*_o	empirical, dimensionless wave overtopping parameters
Q_r	overtopping rate for irregular waves (cubic feet per second per foot)
$Q_{0.5}$	peak overtopping rate (cubic feet per second per foot)
R	runup for monochromatic waves (feet)
R_p	wave runup associated with a particular probability of exceedance (feet)
R_s	wave runup with deepwater significant height and period (feet)

PREDICTION OF IRREGULAR WAVE OVERTOPPING

by

John Ahrens

I. INTRODUCTION

This report gives a proposed technique for predicting the average and peak overtopping rates caused by wind-generated waves acting on coastal structures. No guidance for predicting the overtopping rates for irregular wave conditions is currently available in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975)[1], or other Corps publications. Therefore, this interim guidance is provided until the results of the Coastal Engineering Research Center (CERC) laboratory study of runup and overtopping by irregular waves are available.

The approach is consistent with, relies on, and extends the SPM section on wave overtopping. In addition to the proposed technique, the method provides a simple but plausible means of judging the conservatism or nonconservatism of the traditional approach to predicting overtopping based on monochromatic wave conditions. In applying the procedures described, a word of caution is noted: Some larger waves in the spectrum may be depth-limited and break seaward of the structure. In this case, the rate of overtopping may be overestimated.

II. MONOCHROMATIC WAVE OVERTOPPING EQUATION

Equation 7.6 in the SPM (Sec. 7.22) is given to compute wave overtopping. Weggel (1976)[2] provides the background information on how this equation was developed and gives additional information on its use in supplementing the discussion in SPM. The overtopping equation from the SPM is written as

$$Q_m = \left(g Q_o^* H_o'^3\right)^{1/2} \quad e^{-\left[\frac{0.217}{\alpha} \tanh^{-1}\left(\frac{h-d_s}{R}\right)\right]} \tag{1}$$

in which

$$0 \leq \frac{h - d_s}{R} < 1.0 \ ,$$

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

[2]WEGGEL, J.R., "A Wave Overtopping Equation," *Proceedings of the 15th Conference on Coastal Engineering*, 1976.

where

Q_m = overtopping rate (volume per unit time) per unit structure length

g = gravitation acceleration

H_o' = equivalent deepwater wave height

h = height of the structure crest above the bottom

d_s = water depth at the structure toe

R = runup on the structure that would occur if the structure were high enough to prevent overtopping (corrected for scale effects, SPM Sec. 7.21)

α, Q_o^* = empirically determined coefficients that depend on incident wave characteristics and structure geometry

The SPM (Sec. 7.22) gives values of α and Q_o^* for a wide range of structure types and wave conditions.

Equation (1) provides an unusually good fit to observed overtopping rates from laboratory tests using monochromatic waves (waves of constant height and period). Q_m was used in equation (1) rather than Q to specify overtopping by monochromatic waves. The following section includes some modifications to equation (1) to adapt it to irregular wave conditions so that overtopping rates for irregular waves can be calculated and compared to overtopping rates for monochromatic waves.

III. ADAPTION OF MONOCHROMATIC WAVE OVERTOPPING EQUATION TO IRREGULAR WAVE CONDITIONS

The fundamental assumption in adapting equation (1) to irregular wave conditions is that the runup caused by these conditions has a Rayleigh distribution of the type commonly associated with wave heights. This assumption was made by Ahrens (1977)[3] to predict irregular wave runup and appears reasonable but possibly somewhat conservative; i.e., it will probably yield higher extreme values of runup than are actually observed. The procedure for combining the assumption of a Rayleigh distribution of wave runup with equation (1) for monochromatic wave overtopping is outlined below.

1. The Rayleigh runup distribution is given by

$$\frac{R_p}{R_s} = \left(\frac{\ln\ (1/p)}{2} \right)^{1/2} = K_i \qquad (2)$$

[3] AHRENS, J.P., "Prediction of Irregular Wave Runup," CETA 77-2, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., July 1977.

where R_p is the wave runup associated with a particular probability of exceedance, p; R_s is the wave runup with a given deepwater significant height and period; and K_i is the ratio of R_p to R_s; the index "i" is employed for use in computations shown below. R_s is referred to as the significant runup and is predicted in the conventional manner based on laboratory tests using monochromatic waves as shown in the SPM. Equation (2) provides the transition between monochromatic and irregular conditions.

2. Equation (1) can now be rewritten as

$$Q_i = \left[gQ_0^* (H_0')_s^3 \right]^{1/2} e^{-\left\{ \frac{0.217}{\alpha} \tanh^{-1} \left[\left(\frac{h - d_s}{R_s} \right) \frac{1}{K_i} \right] \right\}} \qquad (3)$$

where Q_i is the overtopping rate associated with a particular value of K_i, and $(H_0')_s$ is the equivalent deepwater significant wave height. $(H_0')_s$ has replaced H_0' in equation (3) to emphasize the distinction between this equation and the monochromatic overtopping equation (eq. 1), and denotes that it is the significant height which is being used in this procedure. The term $(h - d_s)/R_s$ will be referred to as the relative freeboard.

3. The average overtopping rate for runups with a Rayleigh distribution, Q_r, was computed by equation (3) using the following relation:

$$Q_r = \frac{1}{199} \sum_{i=1}^{199} Q_i \qquad (4)$$

for

$$p \doteq 0.005 \times i, \ i = 1, 2, 3 \ . \ . \ . \ 199 \ .$$

The index "i" causes a range of probabilities to be generated; these probabilities when substituted into equation (2) generate a range of values of the parameter K_i. K_i, in turn, is substituted into equation (3) to generate the Q_i's. The 199 values of overtopping are computed for a fixed value of the relative freeboard corresponding to the various values of K_i which are generated by varying the probability of exceedance, p, from 0.005 to 0.995 in increments of 0.005. The average value of the Q_i's (eq. 4) represents the average rate of overtopping expected for a time interval of 199 waves.

4. Using the procedure shown in steps 2 and 3 above, the largest value of Q_i corresponds to a value of p = 0.005. Since the peak rates of overtopping might be of concern in some design situations, the following definition is useful:

$Q_{0.5}$ = Q_i associated with a probability of exceedance of p = 0.005 or 0.5 percent .

If equation (2) is solved for p = 0.005, K_i = 1.628 indicating that $Q_{0.5}$ is the overtopping rate for a runup about 63 percent greater than R_s. $Q_{0.5}$ will be referred to as the peak overtopping rate.

The Appendix is a FORTRAN subroutine which calculates Q_m, Q_r, $Q_{0.5}$, Q_r/Q_m, and $Q_{0.5}/Q_m$ to illustrate how the above procedure can be programed and applied to any situation which might occur.

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

This example is based on the example worked in SPM (Sec. 7.22), modified to account for the irregularity of natural wave and runup conditions.

GIVEN: An impermeable structure with a smooth slope of 1 on 2.5 is subjected to waves having a deepwater height H'_o = 5 feet and a period T = 8 seconds. The depth at the structure toe is d_s = 10 feet and the structure elevation is 5 feet above stillwater level (SWL). Onshore winds of 35 miles per hour are assumed.

FIND: Estimate the overtopping rate for the given wave.

SOLUTION: The wave height and period given are assumed to be the significant values; therefore, the runup obtained in the example is the significant runup, R_s. Using the following values, as given in the example in SPM,

$$\alpha = 0.08$$

$$Q_o^* = 0.035$$

$$H'_o = (H'_o)_s = 5.0 \text{ feet}$$

and

$$\frac{h - d_s}{R_s} = 0.294 \; ;$$

solving equations (3) and (4) for Q_r gives

$$Q_r = 2.70 \text{ cubic feet per second per foot}$$

as compared to the value obtained in SPM of

$$Q_m = 5.1 \text{ cubic feet per second per foot}$$

for monochromatic waves. Thus, the irregular wave overtopping is about one-half of the value given by the monochromatic wave procedure. The peak value of the irregular wave overtopping is

$$Q_{0.5} = 7.2 \text{ cubic feet per second per foot ,}$$

which is about 40 percent greater than the monochromatic rate. The wind effect on overtopping shown in the SPM example is not discussed here, but it can be assumed that it would increase the irregular overtopping by the same percentage (11 percent) as the monochromatic overtopping.

IV. GENERALIZING THE IRREGULAR WAVE OVERTOPPING TECHNIQUE

Example 1 used a specific value of freeboard for the structure (i.e., $h - d_s = 5$ feet); however, the problem could have been worked for any value of freeboard from 0 to 17 feet, which is equivalent to $0.0 \leq (h - d_s)/R_s < 1.0$. The example can be considered in a more general way by plotting the ratio of the average irregular wave overtopping rate, Q_r, to the monochromatic overtopping rate, Q_m, as a function of the relative freeboard (see Fig. 1). The ratio of the peak to monochromatic overtopping rates, $Q_{0.5}/Q_m$, is also shown in Figure 1. When the ratio of overtopping rates is used as in Figure 1, the influence of Q_0^* cancels out and the curves are functions only of α and the relative freeboard. Figure 1 shows the curves for $\alpha = 0.08$, as given in Example 1, and by reading the values off the curves for a relative freeboard of 0.294 the results of the example can be verified.

Figure 2 shows a family of curves of Q_r/Q_m and $Q_{0.5}/Q_m$ for $\alpha = 0.04$, 0.06, 0.08, and 0.10 and demonstrates how α controls the shape of the curves. This range of α's includes most of the α's tabulated in the SPM (Sec. 7.22). Figure 2 also shows that generally Q_m is significantly larger than Q_r for the range of α's presented. The irregular wave overtopping characteristics shown in Figure 2 are consistent with the trends observed by Tsuruta and Goda (1968)[4] in laboratory tests with both monochromatic and irregular waves.

Figure 2 can be used to compute Q_r for various values of α and $(h - d_s)/R_s$ by regarding the ratio Q_r/Q_m as a "correction" factor for Q_m as illustrated in Example 2. Since it is relatively difficult to read the values from Figure 2, the ratios of Q_r/Q_m and $Q_{0.5}/Q_m$ are given as a function of α and $(h - d_s)/R_s$ in tabular form in Tables 1 and 2, respectively.

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

To illustrate the use of the generalization presented, reconsider Example 1, except assume the freeboard is 8 feet rather than 5 feet; therefore, $(h - d_s)/R_s = 0.471$. Using equation (1) for

$$\alpha = 0.08$$

$$Q_0^* = 0.035$$

[4]TSURUTA, S., and GODA, Y., "Expected Discharge of Irregular Wave Overtopping," *Proceedings of the 11th Conference on Coastal Engineering*, 1968, pp. 833-852.

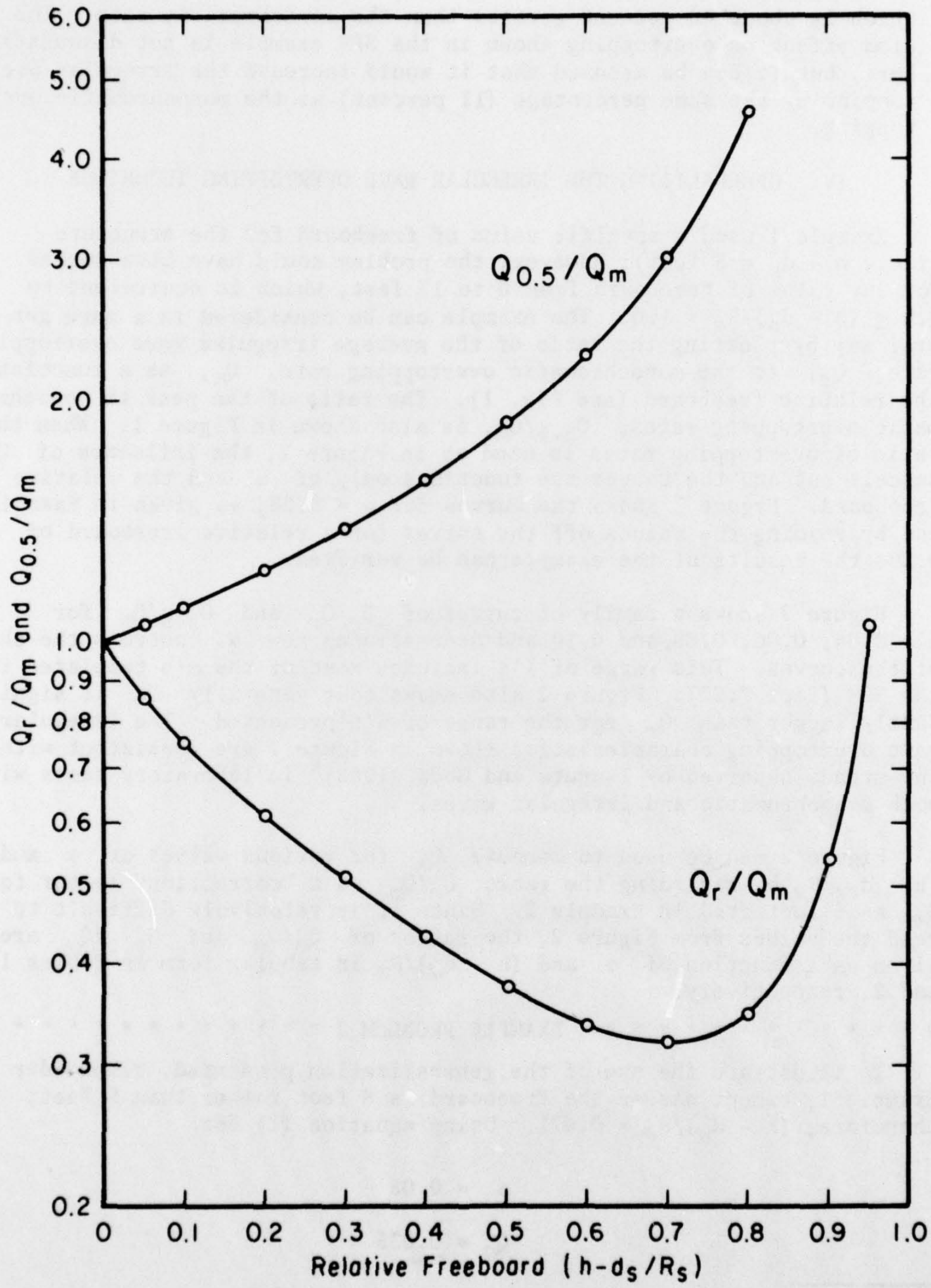

Figure 1. Q_r/Q_m and $Q_{0.5}/Q_m$ curves as a function of the relative freeboard for α = 0.08.

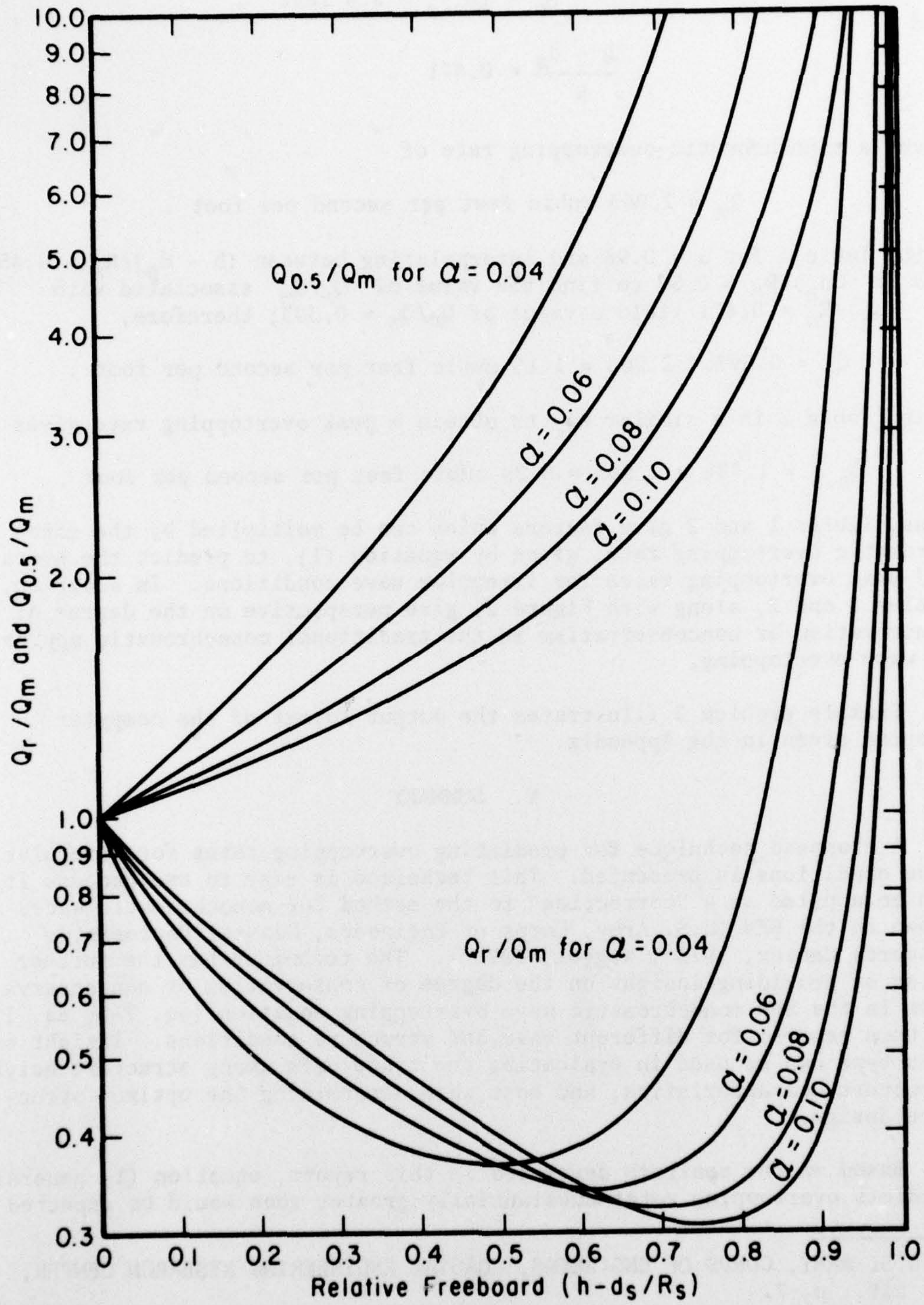

Figure 2. Q_r/Q_m and $Q_{0.5}/Q_m$ curves as a function of the relative freeboard, for α = 0.04, 0.06, 0.08, and 0.10.

$$H_o' = (H_o')_s = 5.0 \text{ feet}$$

and

$$\frac{h - d_s}{R} = 0.471$$

gives a monochromatic overtopping rate of

$$Q_m = 2.963 \text{ cubic feet per second per foot} .$$

Using Table 1 for $\alpha = 0.08$ and interpolating between $(h - d_s)/R_s = 0.45$ and $(h - d_s)/R_s = 0.50$ to find the value of Q_r/Q_m associated with $(h - d_s)/R_s = 0.471$ yield a value of $Q_r/Q_m = 0.393$; therefore,

$$Q_r = 0.393 \times 2.963 = 1.16 \text{ cubic feet per second per foot} .$$

Using Table 2 in a similar way to obtain a peak overtopping rate gives

$$Q_{0.5} = 1.784 \times 2.963 = 5.29 \text{ cubic feet per second per foot} .$$

Thus, Tables 1 and 2 give factors which can be multiplied by the monochromatic overtopping rate, given by equation (1), to predict the average and peak overtopping rates for irregular wave conditions. In addition, Tables 1 and 2, along with Figure 2, give perspective on the degree of conservatism or nonconservatism in the traditional monochromatic approach to wave overtopping.

Example problem 2 illustrates the output format of the computer program given in the Appendix.

V. SUMMARY

A proposed technique for predicting overtopping rates for irregular wave conditions is presented. This technique is easy to use because it can be applied as a "correction" to the method for monochromatic waves shown in the SPM (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975[1]; Weggel, 1976[2]). The technique has the further value of providing insight on the degree of conservatism or nonconservatism in the SPM monochromatic wave overtopping equation (eq. 7-6, eq. 1 in this report) for different wave and structure conditions. Insight of this type can be used in evaluating the trade offs among structure height, structure characteristics, and cost when determining the optimum structure design.

Based on the analysis developed in this report, equation (1) generally predicts overtopping rates substantially greater than would be expected

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[1]U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, op. cit., p. 7.

[2]WEGGEL, op. cit., p. 7.

Table 1. Q_r, Q_m as a function of the relative freeboard, $(h-d_s)/R_s$, and the overtopping parameter, α.

$(h-d_s)/R_s$	α = .03,	.04,	.05,	.06,	.07,	.08,	.09,	.10,	.11,	.12,	.13,	.14
.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
.05	.716	.763	.796	.821	.840	.855	.868	.878	.887	.895	.901	.907
.10	.583	.637	.677	.709	.734	.755	.773	.788	.801	.812	.822	.831
.15	.503	.554	.594	.627	.655	.678	.697	.715	.729	.743	.754	.765
.20	.451	.494	.532	.563	.590	.614	.634	.651	.667	.681	.693	.705
.25	.415	.450	.483	.512	.537	.559	.579	.596	.611	.625	.638	.649
.30	.392	.417	.444	.469	.492	.512	.530	.547	.561	.575	.587	.598
.35	.379	.393	.413	.434	.453	.471	.487	.502	.516	.528	.539	.550
.40	.375	.376	.389	.405	.420	.435	.449	.462	.474	.485	.495	.505
.45	.380	.366	.371	.381	.392	.404	.416	.427	.437	.446	.455	.463
.50	.396	.364	.358	.362	.369	.378	.386	.395	.403	.411	.418	.425
.55	.426	.370	.353	.349	.351	.356	.361	.367	.373	.379	.385	.390
.60	.478	.387	.355	.342	.338	.339	.341	.344	.347	.351	.355	.359
.65	.564	.419	.367	.343	.332	.327	.325	.325	.326	.328	.330	.332
.70	.712	.478	.394	.355	.334	.322	.316	.312	.310	.309	.309	.309
.75	.987	.584	.446	.383	.348	.328	.315	.306	.300	.296	.294	.292
.80	1.569	.789	.548	.441	.384	.349	.327	.312	.301	.293	.287	.282
.85	3.115	1.258	.766	.566	.463	.403	.364	.337	.318	.304	.293	.284
.90	9.345	2.732	1.371	.890	.664	.539	.462	.410	.374	.347	.326	.310
.95	78.173	12.780	4.526	2.329	1.473	1.057	.822	.676	.578	.509	.458	.420

Table 2. $Q_{0.5}$, Q_m as a function of the relative freeboard, $(h-d_g)/R_g$, and the overtopping parameter, α.

$(h-d_g)/R_g$	α = .03	.04	.05	.06	.07	.08	.09	.10	.11	.12	.13	.14
.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
.05	1.150	1.110	1.087	1.072	1.062	1.054	1.048	1.043	1.039	1.036	1.033	1.030
.10	1.324	1.234	1.183	1.151	1.128	1.111	1.098	1.088	1.080	1.073	1.067	1.062
.15	1.529	1.375	1.290	1.237	1.200	1.173	1.152	1.136	1.123	1.112	1.103	1.095
.20	1.774	1.537	1.410	1.332	1.278	1.240	1.210	1.188	1.169	1.154	1.141	1.131
.25	2.070	1.726	1.547	1.439	1.366	1.314	1.274	1.244	1.219	1.199	1.183	1.169
.30	2.436	1.950	1.706	1.561	1.465	1.396	1.345	1.306	1.275	1.249	1.228	1.210
.35	2.896	2.220	1.893	1.702	1.577	1.490	1.425	1.376	1.336	1.304	1.278	1.256
.40	3.489	2.553	2.117	1.868	1.708	1.598	1.517	1.455	1.406	1.367	1.334	1.307
.45	4.275	2.973	2.391	2.069	1.864	1.724	1.623	1.546	1.486	1.438	1.398	1.365
.50	5.350	3.518	2.735	2.313	2.052	1.876	1.749	1.654	1.580	1.521	1.473	1.432
.55	6.881	4.248	3.181	2.623	2.286	2.061	1.902	1.784	1.692	1.620	1.561	1.512
.60	9.167	5.268	3.779	3.028	2.585	2.295	2.093	1.944	1.830	1.740	1.667	1.608
.65	12.796	6.766	4.616	3.577	2.982	2.601	2.339	2.148	2.004	1.891	1.801	1.727
.70	19.034	9.113	5.858	4.363	3.535	3.019	2.670	2.420	2.233	2.089	1.974	1.880
.75	30.975	13.130	7.845	5.566	4.355	3.624	3.141	2.801	2.551	2.359	2.208	2.087
.80	57.668	20.927	11.391	7.594	5.684	4.575	3.863	3.375	3.022	2.756	2.549	2.384
.85	133.637	39.305	18.861	11.560	8.149	6.269	5.113	4.343	3.800	3.400	3.095	2.855
.90	466.563	100.388	39.934	21.600	13.926	10.019	7.756	6.319	5.344	4.648	4.130	3.732
.95	4527.369	551.931	156.138	67.286	36.880	23.493	16.543	12.496	9.932	8.203	6.977	6.073

for the equivalent irregular wave conditions, except for structures with high relative freeboards. For relative freeboards roughly in the range $0.85 < (h - d_s)/R_s < 1.0$, the irregular wave overtopping rate can exceed the monochromatic rate. In addition, there will be a small amount of irregular wave overtopping for $(h - d_s)/R_s \geq 1.0$ which would not be predicted using the SPM monochromatic method. The analysis also shows that the peak irregular wave overtopping rate (defined as $Q_{0.5}$) will exceed the monochromatic rate for all values of the relative freeboard.

Because of the uncertainty in determining the wave height, runup, and parameters α and Q_0^* required to predict the overtopping rate, the design engineer may be justified, in some situations, in using the monochromatic wave overtopping technique, which is generally conservative. The proposed technique should yield a more accurate estimate of the overtopping rate for wind-generated waves; however, it is not necessarily conservative.

APPENDIX

FORTRAN Program to Compute
Irregular Wave Overtopping Rates

```
      SUBROUTINE  IRREGU(  QSTAR,  ALPHA,  RFB,  HS  )
      REAL KI
C
C PART 1  -  INPUT
C     QSTAR AND ALPHA ARE INPUT VALUES FOR WEGGELS CONSTANTS.
C     RFB IS THE INPUT VALUE FOR RELATIVE FREEBOARD.
C     HS IS THE DEEP WATER SIGNIFICANT HEIGHT IN FEET.
      EXP  =  2.71828
C
C PART 2  -  MONOCHROMATIC WAVE CALCULATIONS
C        CHECK THAT REL. FREEBOARD IS WITHIN DOMAIN OF ARCTANH.
         IF( RFB .LE. -1. .OR. RFB .GE. 1. )  RETURN
C        COMPUTE ARCTANH WITH FOLLOWING IDENTITY.
         ARTANH  =  .5*ALOG( (1. + RFB)/(1. - RFB) )
C        COMPUTE OVERTOPPING FOR MONOCHROMATIC WAVES.
         QM = SQRT(32.16*QSTAR*HS**3)*EXP**( ( -.217/ALPHA )*ARTANH )
C
C PART 3  -  IRREGULAR WAVE CALCULATIONS
          SUMQI  =  0.
          DO  1   I = 1, 199
          P  =  FLOAT(I) / 200.
C         KI IS USED TO GENERATE A RAYLEIGH DISTRIBUTION
          KI  =  SQRT( ( ALOG(1./P) )/2. )
          ARG  =  RFB / KI
C         SKIP OUT OF LOOP IF ARG OUT OF RANGE.
          IF(  ARG .GE. 1. )  GO TO 2
          ARTANH  =  .5*ALOG( (1. + ARG)/(1. - ARG) )
C         COMPUTE QI FOR A VALUE OF KI
          QI = SQRT(32.16*QSTAR*HS**3)*EXP**( ( -.217/ALPHA )*ARTANH )
C         STORE THE PEAK QI
          IF( I .EQ. 1 )  QPEAK = QI
          SUMQI  =  SUMQI + QI
    1     CONTINUE
    2     CONTINUE
C
C PART 4  -  AVERAGE AND RATIOS
C        COMPUTE THE AVERAGE QI
         QR  =  SUMQI / 199.
C        COMPUTE QR/QM  AND  QPEAK/QM RATIOS.
         QRQM  =  QR / QM
         QPQM  =  QPEAK / QM
C
C PART 5  -  OUTPUT
      WRITE( 6, 3 )  QSTAR,  ALPHA
      WRITE( 6, 4 )  RFB,    HS
      WRITE( 6, 5 )  QM,     QR,     QRQM
      WRITE( 6, 6 )  QPEAK,  QPQM
    3 FORMAT(1X,/,1X,33HIRREGULAR OVERTOPPING PREDICTION-,/,1X,6HQSTAR=,
     *9X,F9.3,/,1X,6HALPHA=,9X,F9.3)
    4 FORMAT(1X,15HREL. FREEBOARD=,F9.3,/,1X,3HHS=,12X,F9.3,1X,4HFEET)
    5 FORMAT(1X,3HQM=,12X,F9.3,1X,17HFT.3/SEC. PER FT.,/,1X,3HQR=,12X,
     *F9.3,1X,17HFT.3/SEC. PER FT.,/,1X,6HQR/QM=,9X,F9.3 )
    6 FORMAT(1X,6HQPEAK=,9X,F9.3,1X,17HFT.3/SEC. PER FT.,/,1X,9HQPEAK/QM
     *=,6X,F9.3,/)
      RETURN
      END
```

EXAMPLE OUTPUT FORMAT:

```
IRREGULAR OVERTOPPING PREDICTION-
QSTAR=              .035
ALPHA=              .080
REL. FREEBOARD=     .471
HS=                5.000 FEET
QM=                2.963 FT.3/SEC. PER FT.
QR=                1.163 FT.3/SEC. PER FT.
QR/QM=              .393
QPEAK=             5.287 FT.3/SEC. PER FT.
QPEAK/QM=          1.784
```

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A proposed technique is described for predicting overtopping rates for structures exposed to irregular wind-generated waves by extending the method of predicting overtopping for waves of constant height and period presented in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975).

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