CHAPTER 59

SEAWALL OVERTOPPING MODEL

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ABSTRACT

Results from an extensive series of laboratory tests of irregular wave overtopping for a number of seawall and seawall/revetment configurations is presented. Data for 13 configurations has been collected and grouped into 7 data sets representing relatively similar geometrical characteristics. All data sets showed an approximately exponential relationship between the overtopping rate and a dimensionless freeboard parameter which is the ratio of the seawall freeboard to the local wave severity. This finding logically led to the development of three progressively more complex overtopping models. The models provide a relatively simple way to estimate overtopping rates and an objective way to evaluate the hydraulic performance of seawalls/revetments. Advantages and disadvantages of the models are discussed and their ability to predict overtopping rates is compared.

INTRODUCTION

Wave runup and overtopping are two of the most important factors influencing the design of coastal structures. Current methods to predict overtopping rates, such as given in the Shore Protection Manual (SPM, 1984), rely on a data base composed of laboratory tests using monochromatic waves. In addition, problems arise in using the SPM method because of uncertainty in choosing proper overtopping coefficients and treating wave runup as an independent variable. Studies have been conducted which indicate that the SPM method can, for some circumstances, under predict overtopping rates (Douglass, 1986) and for other circumstances greatly over predicts the rates Gadd, et al. 1985). When these over estimates or underestimates of overtopping rates might be expected is unclear. Recent laboratory work using irregular waves has produced an alternative to the SPM method of calculating overtopping rates.

Data for 13 different seawall and seawall/revetment configurations has been collected and collated into 7 representative data sets. Examination of these data sets revealed that all had the common property that the overtopping rate could be expressed as an exponential function of a dimensionless freeboard parameter. This characteristic

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held regardless of whether the overtopping rate was expressed as a dimensional or dimensionless variable. Similar findings have been reported by Owen (1982) and Jensen and Juhl (1987). This paper will develop three exponential overtopping models which represent a logical extension of the general relation. Each model has characteristics which are useful and the advantages and disadvantages of each model will be discussed. A criteria for comparing the models will be presented and their ability to predict overtopping rates will be compared.

DATA COLLECTION

Laboratory tests were conducted in the Coastal Engineering Research Center's (CERC) 45.73m long, 0.91m wide, and 0.91m deep wave tank and the 76.20m long, 3.35m wide, and 1.83m deep wave tank. All tests used irregular waves generated by computer controlled, hydraulically actuated, piston type wave boards.

Data sets were compiled from three separate CERC studies. One study tested three seawall/revetment configurations which have been proposed to protect the historic lighthouse at Cape Hatteras, North Carolina (Grace and Carver 1985). A second study tested a number of seawall/revetment configurations proposed to improve the performance of existing seawalls at Roughans Point, Massachusetts, (Ahrens, et al. 1986). The third study tested a seawall proposed to protect Virginia Beach, Virginia, (Heimbaugh, et al. 1988). Research funds were used to extend the range of conditions tested to allow the development of more general relationships.

Each test consisted of approximately 30 minutes of irregular wave generation during which wave conditions were measured using resistance type wave gages. Incident and reflected wave spectra were resolved using the method of Goda and Suzuki (1976). Water was allowed to pass over the seawalls and collected in a calibrated container. Elevations in the container were measured with a point gage before and after each test. Figure 1 shows simple profiles of each seawall/revetment configuration used to compile the seven data sets, and Table 1 summarizes test conditions for each data set. More detailed descriptions of test conditions and testing procedures can be found in references cited above.

METHOD OF ANALYSIS AND FINDINGS

One of the most important findings to date is the development of an effective dimensionless freeboard parameter, denoted F'. F' can consolidate all of the overtopping data for similar structure configurations into a single, well defined trend. F' is defined

$$F' = \frac{F}{\left(H_{mo}^{2}\, L_{p}\right)^{1/3}} \tag{1}$$

where F, the freeboard, is the average vertical distance from the mean local water level to the crest of the seawall, H_{mo} is the energy based zero-moment wave height either measured near the structure (data sets 1 through 6) and assumed to be representative of H_{mo} at the toe of the seawall/revetment, or measured at the toe (data set 7). L_p is the Airy wave length calculated using the nominal T_p (data sets 1 through 6) and the water depth at the

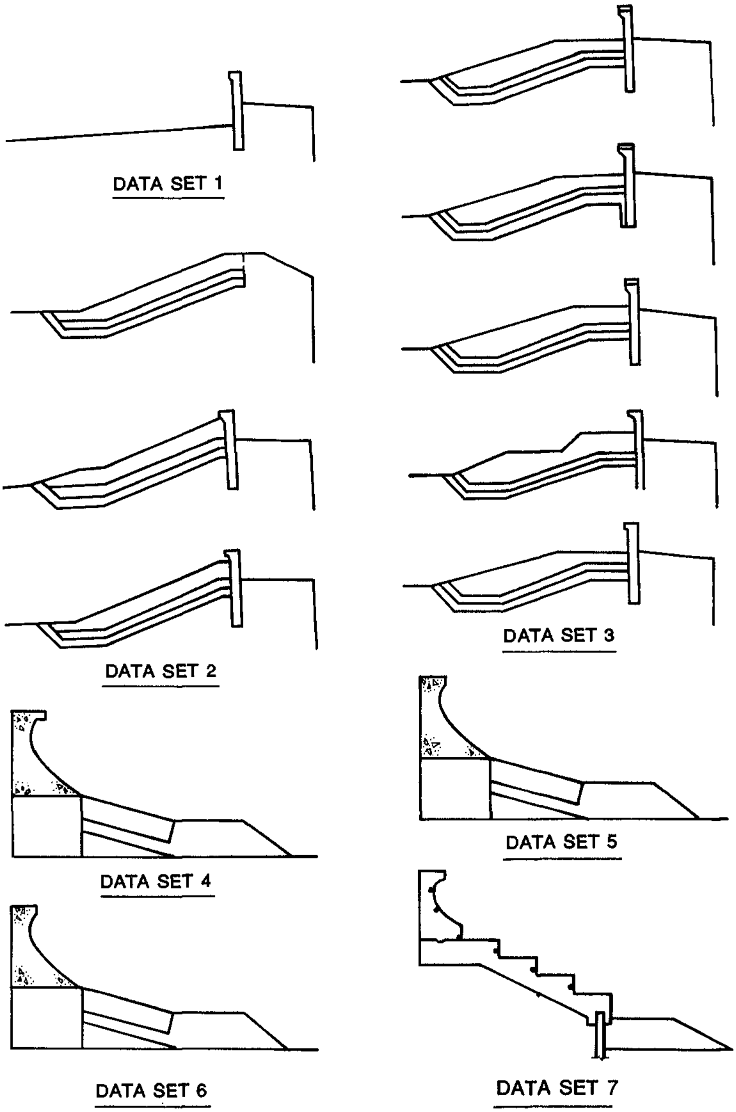

Figure 1. Simple geometric profiles used in each data set

Table 1

Seawall Test Conditions Summary Table

Data Set No.	Description	Model Scale	Wave Tank Dimensions	Spectrum Type	Offshore Slope Near Structure	Range of			
						Nominal T_p sec	H_{mo} cm.	d_s cm.	Water Depth at Wave Board, m
1	Roughans Point Seawall Configuration 1 Vertical wall w/recurved parapet No revetment	1:16	0.91x0.91x76.20m	JONSWAP	1:100	1.25-3.0	4.77-16.81	16.92-22.30	0.619-0.648
2	Roughans Point Seawall/ Revetment Configurations 2,3,10 Seawall w/high revetment	1:16	0.91x0.91x76.20m	JONSWAP	1:100	1.25-3.0	7.20-17.47	22.23-28.28	0.576-0.662
3	Roughans Point Seawall/ Revetment Configurations 4,5,6,7,8 Seawall w/bermed revetment and wall caps of 0.3 and 0.6m	1:16	0.91x0.91x76.20m	JONSWAP	1:100	1.25-3.0	8.88-16.39	23.28-28.38	0.624-0.655
4	Cape Hatteras Type Seawall Seawall/Revetment Configuration 1 Severe Recurve	1:16	0.91x0.91x76.20m	JONSWAP	1:100	1.25-3.0	9.32-17.16	19.99-23.26	0.639-0.672
5	Cape Hatteras Type Seawall Seawall/Revetment Configuration 2 Moderate Recurve	1:16	0.91x0.91x76.20m	JONSWAP	1:100	1.25-3.0	9.13-16.42	18.99-23.36	0.626-0.673
6	Cape Hatteras Type Seawall Seawall/Revetment Configuration 3 Vertical Wall	1:16	0.91x0.91x76.20	JONSWAP	1:100	1.25-3.0	8.96-19.26	18.50-22.68	0.623-0.665
7	Virginia Beach Seawall Seawall/Riprap Stepped wall with recurved parapet	1:19	3.35x1.83x76.20m	TMA-shallow water	1:16 and 1:100	1.15-2.98	3.42-10.01	9.80-14.07	0.713-0.747

structure toe, d_s , or the measured T_p (data set 7), where T_p is the period of peak energy density of the wave spectrum. The nominal T_p used in data sets 1 through 6 was an assumed period based on the known peak period generated at the wave board and T_p for data set 7 was the measured peak period using a three gage Goda array.

The relative freeboard, F' , is the ratio of the freeboard to the severity of the local wave conditions. For energy based wave conditions the severity seems to be better characterized by variables containing L_p than by just H_{mo} (Ahrens 1987). The overtopping parameter F' is efficient since it contains in one term information about the water level, structure height, and wave conditions. During a test series on a seawall/revetment configuration, as wave conditions become more severe, a point is reached where details of the structure's geometery seem to have little influence on the overtopping rate. This point occurs when a combination of a high water level and large waves causes the structure to be virtually swamped or inundated by wave action. Inundation occurs when $F' \lesssim 0.3$.

Three exponential models have been found useful in estimating overtopping rates and evaluating the performance of seawalls and seawall/revetment configurations. The models in order of increasing complexity are:

$$\text{Model 1, } Q = Q_o \exp (C_1 F') \tag{2}$$

$$\text{Model 2, } Q' = Q'_o \exp (C_1 F') \tag{3}$$

$$\text{Model 3, } Q' = Q'_o \exp (C_1 F' + C_2 X_2) \tag{4}$$

where Q is the overtopping rate in cubic meters per second per meter length of seawall crest and Q' is the dimensionless overtopping rate given by

$$Q' = \frac{Q}{\sqrt{g\, H_{mo}^{3}}} \tag{5}$$

where g is the acceleration of gravity. Q_o is an overtopping coefficient having the same units as Q . Overtopping coefficients Q'_o , C_1 , and C_2 are dimensionless coefficients determined by regression analysis. The term "X_2" in Model 3 can be any one of several dimensionless variables which improve the predictive ability of Model 3 over Model 2.

During regression analysis of the data a weight function was used to reflect the greater importance of tests which produced high overtopping rates. The weight function used is defined as

$$\text{weight function} = \text{Int } (Q \times 100) + 1 \tag{6}$$

where, Int, indicates that the quantity in parenthesis is a truneated integer and Q is the overtopping rate in English units, i.e. $ft^3/ft\text{-}sec$, converted to prototype values. Taking the logrithim of the models in order to linearize them and determine overtopping coefficients tends to decrease the relative influence of tests with high overtopping rates. In addition, tests with low rates have a higher percent error associated with measuring the overtopping volume. The weight function given by Equation 6 is an attempt to balance these undesirable effects on the regression process.

Each of the models has certain advantages and disadvantages which will be illustrated using data set 1 (Table 1) as an example. Figure 2 shows a detailed profile of the seawall configuration for data set 1. The seawall is basically a vertical wall without a fronting revetment and a small recurve at the crest (see Ahrens, et al. 1986

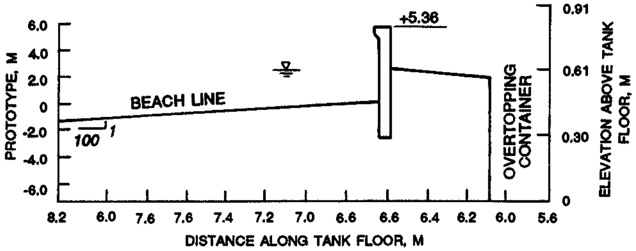

Figure 2. Data set 1 seawall configuration

for further details). Figures 3a through 3c compare predicted versus observed overtopping rates using Models 1 through 3 for predicted values, respectively. Figures 4a through 4c show the observed and predicted values of Q or Q' as a function of F' for Models 1 through 3, respectively. In Figure 4c a horizontal line indicates an overtopping rate of 0.05 m^3 /m-sec which represents the approximate upper limit of overtopping for structure safety, Goda (1987). Figure 4c illustrates an advantage of Model 1, overtopping is given in dimensional units which can be directly related to potential flooding, levels of damage, or levels of danger, such as discussed by Fukuda et al. (1974) and tabulated in Owen (1982).

By intercomparing Figures 3a, 3b, and 3c, it can be seen that Model 3 is best at predicting Q . The same conclusion is reached using the correlation coefficients for data set 1 given in Table 2. This finding would be expected since Model 3 has the second variable, X_2 , which improves the prediction based on just F' . Table 2 shows that the secondary variable for data set 1 is F/d_s . Considerable trial and error effort went into the selection of the secondary variable for each data set. In Table 2 the secondary variable which worked best with F' in predicting Q' is listed by data set. In four of the seven data sets the most important second independent variable to use with F' is the wave steepness parameter,

$$x_2 = \left(\frac{H_{mo}}{L_o}\right)^{1/2}$$

where,

$$L_o = \frac{g\,T_p^2}{2\pi}$$

The influence of steepness in predicting Q' indicates that surf conditions and their affect on potential runup are quite important to the overtopping process on some structures. For data sets 4 and 6 the influence of the rubble berm in front of the wall is important and the secondary variables reflect this fact. The secondary variables which improve the prediction of Q' for data sets 4 and 6 are W_B/L_p and H_{mo}/d_B respectively, where W_B is the width of the berm and d_B is the water depth over the berm. Review of the data and test conditions suggest that when the water depth over the berm is small the berm depth is quite important, e.g. data set 6, but a relatively modest

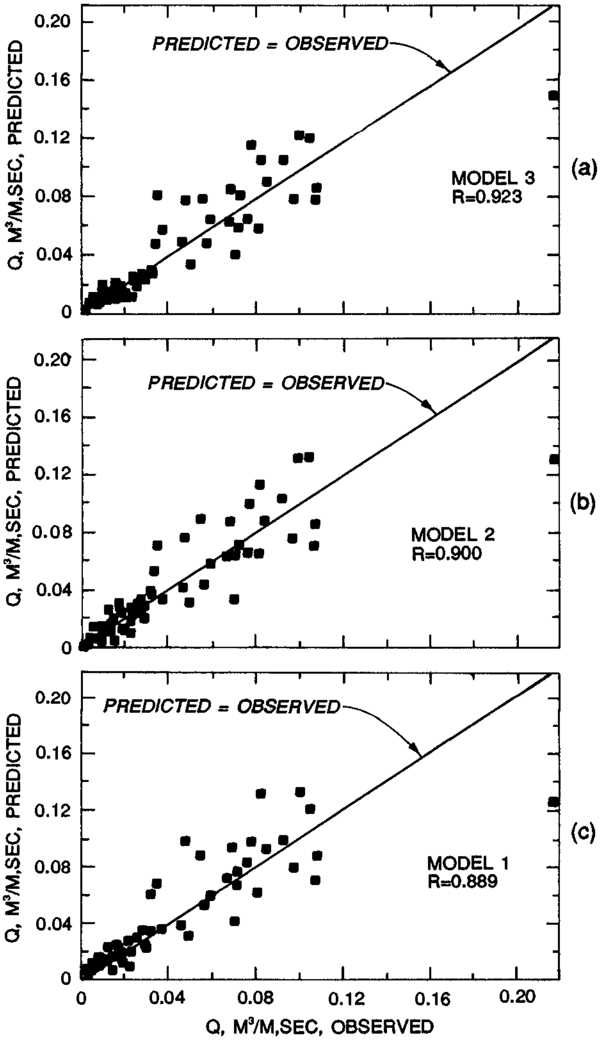

Figure 3. Predicted versus observed overtopping rates, Models 1-3

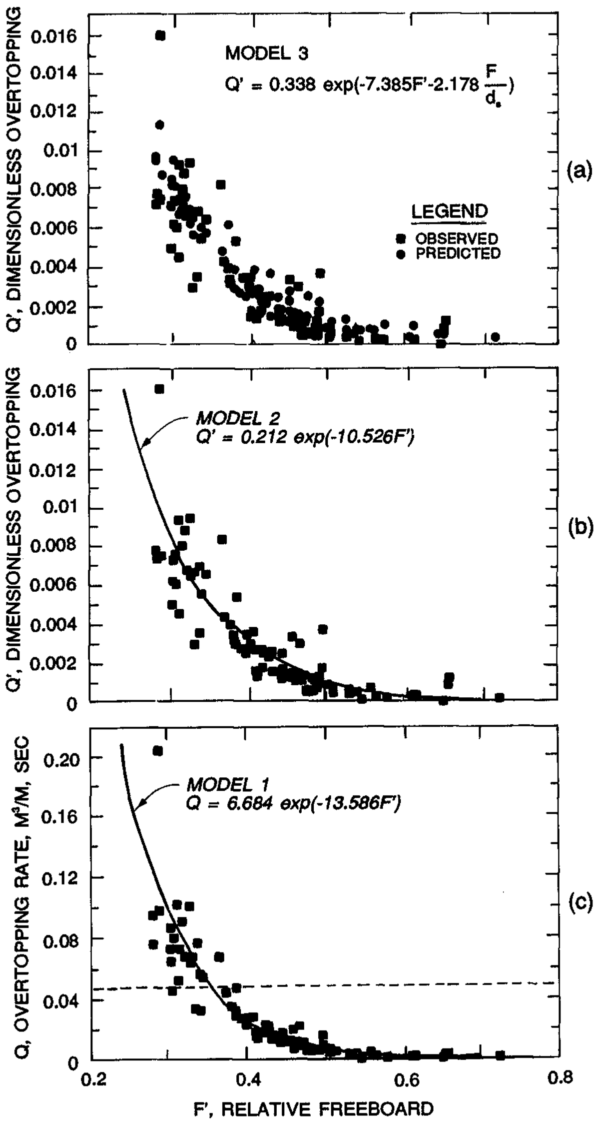

Figure 4. Observed and predicted values of Q and Q' as a function of F'

Table 2
Seawall Revetment Summary Chart*

Data Set No.	Model	Regression Coefficient	Overtopping Variables	No. of Observations	Correlation Coefficient (Q pred. vs Q obs.)	A'_q
1	1	71.952 -13.586	Q_o F'	89	0.889	
	2	0.212 -10.526	Q'_o F'		0.90	0.0008564
	3	0.338 -7.385 -2.178	Q'_o F' F/d_s		0.923	
2	1	32.357 -13.091	Q_o F'	118	0.777	
	2	0.1472 -11.138	Q'_o F'		0.789	0.0004677
	3	0.308 -10.732 -6.629	Q'_o F' $(H_{mo}/L_o)^{1/2}$		0.794	
3	1	58.71 -16.723	Q_o F'	111	0.825	
	2	0.279 -14.885	Q'_o F'		0.811	.0002155
	3	1 -14.371 -11.411	$(H_{mo}/L_o)^{1/2}$		0.841	
4	1	394.625 -20.676	Q_o F'	62	0.93	
	2	1 -17.555	Q'_o F'		0.915	.000294
	3	1 -12.69 -20.87	Q'_o F' W_b/L_p		0.943	
5	1	93.251 -14.749	Q_o F'	57	0.953	
	2	0.332 -12.414	Q'_o F'		0.934	.0006454
	3	0.541 -11.702 -5.771	Q'_o F' $(H_{mo}/L_o)^{1/2}$		0.947	
6	1	8.798 -6.334	Q_o F'	37	0.771	
	2	0.0232 -3.791	Q'_o F'		0.615	.0019625
	3	1 -7.558 -1.366	Q'_o F' H_{mo}/D_B		0.918	
7	1	253.93 -18.26	Q_o F'	68	0.927	
	2	0.348 -11.232	Q'_o F'		0.923	.0010659
	3	1 -11.174 -10.664	Q'_o F' $(H_{mo}/L_o)^{1/2}$		0.948	

*NOTE Q_o in Model 1 is dimensional while Models 2 and 3 are dimensionless.

increase in water depth causes the width of the berm to be the more important characteristic, e.g. data set 4. In some instances it was not clear why one choice of a secondary variable was better than another choice. Since the secondary variables are partly dependent on the conditions tested the model 3 approach should not be regarded as producing an overly general formula.

In Table 2 a correlation coefficient is given for each model for each data set. This coefficient is the correlation between the predicted and observed dimensional overtopping rates. Using this correlation coefficient provides a fair way to compare the effectiveness of the three models. For some data sets Model 2 has a lower correlation coefficient than Model 1, which suggest that the method of normalizing Q was not optimum for that data set. In one case, data set 5, Model 1 even had a higher correlation coefficient than model 3. It is assumed that normalizing Q interfered with the surprisingly high correlation between Q and F'. Of course, it was necessary to normalize Q the same way for all data sets in order to make comparisons. Quite a few different ways to normalize Q were tried. Ideally it would be advantageous to normalize Q using wave condition variables H_{mo}, L_p, and T_p and use characteristics of the geometery of the seawall/revetment and water depth to formulate the dimensionless independent variables. Attempts to develop an effective overtopping prediction method based on separating wave and structure variables was unsuccessful. Experience from this study indicates that there does not seem to be a conspicuously superior way to normalize Q ; this finding is consistent with those of Jensen and Juhl (1987).

Inspection of Table 2 indicates that Model 3 does a substantially better job predicting overtopping rates for data sets 1, 4, 5, 6, and 7 than for data sets 2 and 3. Data sets 2 and 3 were the only ones with the correlation between predicted and observed overtopping rates less than 0.90. Data sets 2 and 3 were also the only data sets where tests of seawall/revetment configurations with slightly different geometries were lumped together. In all of the other data sets the wave heights, wave periods, and water depths were varied but there were no changes in the geometry of the structure. The conclusion is that small changes in geometry of a seawall/revetment configuration can have an important influence on the overtopping rate but is difficult to properly account for the change in a simple overtopping model. This finding is consistent with Owen (1980) who tabulates different overtopping coefficients for each different profile tested of embankment type seawalls, Jensen and Juhl (1987) who show different overtopping curves for each breakwater and sea dike tested, and Bradbury and Allsop (1988) who tabulate different overtopping coefficients for each breakwater crown wall configuration tested.

One of the useful characteristics of model 2 is that it can be easily used to generate a hydraulic inefficiency coefficient, A_q', for a seawall/revetment configuration. A_q' is defined as the area under the curve, such as shown in Figure 4b, between $F' = 0.30$ and infinity. The lower limit of integration has been set at the approximate value of F' where wave inundation of the structure becomes the dominant mode of overtopping. Symbolically we have

$$A_q' = Q_o' \int_{0.30}^{\infty} \exp\,(C_1 F')\, dF' = -\frac{Q_o'}{C_1} \exp\,(0.30\, C_1)$$

Values of A_q' are given in Table 2. Generally the ranking of the structures using A_q' seems logical with some small surprises. The stepped seawall with a moderate recurve, data set 7, seems to perform below expectations. When the data sets based on seawalls with recurved parapets are examined, data sets 4, 5, and 7, the vertical scale of the recurves for data sets 4 and 5 are larger in relation to the incident H_{mo} than the recurve for data set 7. It may be that the recurves used for data sets 3 and 4 are more effective than the one used for data set 7, partly because they represent a larger discontinuity to the runup flow, even though they are partly submerged at high water levels. Table 3 summarizes the relavent information on discontinuity effects for recurved parapets on seawalls for heavy overtopping conditions and long period waves. Ranking seawalls on the basis of A_q' values also indicates that the small curve at the crest of the wall tested for data set 1 is effective despite its small size.

Table 3. Discontinuity effects for recurved parapets on seawalls for heavy overtopping conditions, F' = 0.30, and long waves, T_p = 3.0 sec

Data Set	d_s for a High Water Level cm	Freeboard cm	Vertical Height of Recurved cm	H_{mo} for Heavy Overtop cm	Discontinuity/ H_{mo}
4	23.1	13.5	21.3	14.3	1.49
5	23.1	12.9	20.8	13.4	1.55
7	14.0	9.6	9.1	9.7	0.94

SUMMARY AND CONCLUSION

Results from an extensive series of laboratory tests of irregular wave overtopping of a number of seawall and seawall/revetment configurations are presented. Overtopping rates were found to be strongly dependent on a dimensionless freeboard parameter, F' , which is the ratio of the freeboard to a measure of the local wave severity, Equation 1. There is an approximately exponential relation between Q and F' which logically leads to the development of three progressively more complex overtopping models, Equations 2, 3, and 4. The primary purpose of the models is to predict overtopping rates but they are also useful for evaluating various strategies to reduce overtopping and ranking the hydraulic performance of the structures. Model 3 is the most complex and usually makes the best estimates of overtopping rates, however, no completely satisfactory approach has been developed which will provide a good generalized overtopping model for a variety of seawall and seawall/revetment configurations.

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