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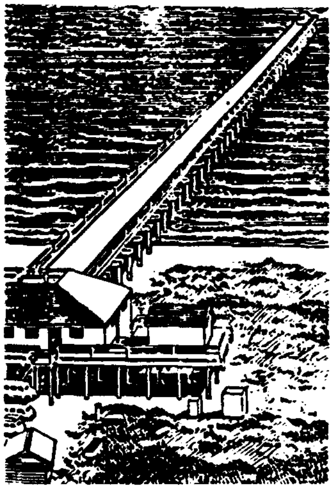

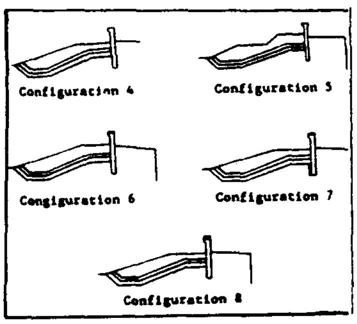

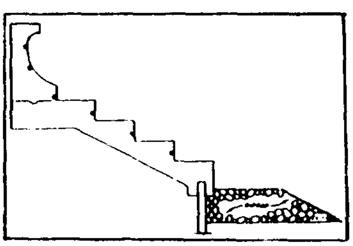

OVERTOPPING RATES FOR SEAWALLS

by

Donald L. Ward, John P. Ahrens

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13. ABSTRACT *(Maximum 200 words)*

Regression analysis is used to develop equations that are easy to use but reasonably accurate in calculating overtopping rates for seawalls. Data are taken from physical model studies and include a wide range of seawall types and wave conditions. The seawalls are divided into seven basic groups, and regression coefficients are determined for each group.

The basic regression model estimates dimensional overtopping and provides a simple means of comparing performance of different seawall designs. An improved model also is developed that provides improved correlation between a dimensionless overtopping variable and the collected data.

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PREFACE

The investigation described in this report was authorized as a part of the Civil Works Research and Development Program by Headquarters, US Army Corps of Engineers (HQUSACE). Work was performed under Work Unit 32432, "Design of Revetments and Seawalls," at the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES). Messrs. John H. Lockhart, Jr., and John G. Housley were HQUSACE Technical Monitors. Dr. C. Linwood Vincent was CERC Program Manager.

The study was conducted by personnel of CERC under the general direction of Dr. James R. Houston, Director, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Director, CERC. Direct supervision was provided by Messrs. C. E. Chatham, Chief, Wave Dynamics Division (WDD), and D. Donald Davidson, Chief, Wave Research Branch (WRB), WDD. This report was prepared by Messrs. Donald L. Ward, Principal Investigator, WRB, and John P. Ahrens, Research Oceanographer, WRB. The models were operated by Messrs. Willie G. Dubose, Engineering Technician, WRB, and John M. Heggins, Computer Technician, WRB. This report was typed by Ms. Myra E. Willis, WRB, and edited by Ms. Janean C. Shirley, Information Technology Laboratory, WES.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

OVERTOPPING RATES FOR SEAWALLS

PART I: INTRODUCTION

Background

1. Seawalls are in common use along the coasts in many parts of the country to protect property from erosion and/or inundation by the seas. Because of continuing coastal development and increasing property values, and possibly from rising sea levels, use of seawalls is likely to continue and expand.

2. Design of a seawall is critically tied to overtopping rate. A structure designed to prevent all overtopping under severe storm conditions will likely be too expensive to build. If occasional overtopping is permitted, rate of overtopping must be calculated to determine expected damages and design of drainage systems. Higher initial cost associated with increased protection must be balanced against greater damages associated with less protection.

3. Local requirements and aesthetics also may affect design of a seawall, and overtopping rates are necessary to assess compromises involved in satisfying these constraints. For example, at Roughan's Point, Massachusetts (Ahrens, Heimbaugh, and Davidson 1986) and Virginia Beach, Virginia (Heimbaugh et al. 1988), standard seawalls of sufficient height to protect against wave action would block the ocean view and were considered unacceptable. Alternative seawall configurations, coupled with improved drainage systems, were designed based on overtopping rates determined through physical model testing.

4. An extensive series of physical model tests has been conducted at the US Army Engineer Waterways Experiment Station's Coastal Engineering Research Center (CERC) to study performance of various seawall configurations. The study was initiated by serious coastal flooding that occurred at Roughan's Point and Revere, MA in February, 1978 (Hardy and Crawford 1986), and has continued due to the widespread problem of coastal flooding in the United States.

The Problem

5. Design of seawalls is commonly based on data in the Shore Protection Manual (SPM) (US Army Corps of Engineers 1984). These data were collected from a series of laboratory tests using monochromatic waves and then plotted in a series of graphs presented in the SPM. A serious problem with this method is that ocean waves are not monochromatic; therefore, the data do not reflect prototype conditions. Also, overtopping coefficients used with the graphs have only been determined for a limited number of cases and interpolation between values is difficult and inaccurate. Studies have indicated that under certain conditions the SPM method will under-predict (Douglass 1986) or over-predict (Gadd, Machemehl, and Maniban 1985) overtopping rates, but it is not clear under which conditions overtopping will be under- or over-predicted.

6. Diversity in seawall designs greatly complicates determination of overtopping rates. Although equations have been developed for simple designs, such as a straight vertical seawall, physical model tests are typically required for more complex geometries. Optimizing a design for a given location then may become a very costly endeavor because of many configurations that may be considered, such as variations in recurve, revetment height and width, and design of caps or parapets.

Purpose of Report

7. The purpose of this report is to present methods for calculating overtopping rates for common seawall types. A series of physical model studies has been conducted using irregular waves and several seawall configurations. Data from 13 configurations tested have been arranged into seven groups with similar configurations within each group. Using regression analysis, equations have been developed for each group to predict overtopping rates. Configurations tested include vertical, stepped, and recurved seawalls, vertical seawalls with recurved parapets, and seawalls fronted by a riprap revetment. In each case, an equation will be presented to quickly estimate overtopping rates. Physical model studies still are required to accurately determine overtopping rates for a given configuration exposed to a specific set of storm conditions. However, the equations presented here will prove useful in preliminary studies and for selecting among alternative

seawall designs, thereby reducing the extent of the physical model study.

8. Final selection of a seawall design will be based on numerous additional factors, such as degree and frequency of wave exposure, foundation conditions, beach use and access, aesthetics, and cost. These factors are beyond the scope of this report.

PART II: THE MODELS

Wave Flume

9. With the exception of the stepped seawall tests, model studies were conducted in CERC's 3.0-ft*-wide by 3.0-ft-deep by 150.0-ft-long wave flume (Figure 1). The test section of the flume was divided into two channels, each 1.5 ft wide, with the model located in one channel and wave absorber material placed in the other channel. Use of the wave absorber reduced reflected wave energy and helped insure an incident wave spectrum with a minimum of contamination. Irregular waves representing Joint North Sea Wave Project spectra (Hasselman et al. 1973) were generated by a hydraulically actuated piston-type wave maker controlled by a computer-generated signal. Wave data were collected for each run using two arrays each consisting of three electronically driven resistance-type wave gages. One array was placed in the channel with the model to record nearshore wave spectra, the other array was located in front of the wave board to record the generated signal. Recorded signals were separated into incident and reflected spectra by the method of Goda and Suzuki (1976).

10. Tests for the model stepped seawall were conducted in CERC's 11.0-ft-wide by 250-ft-long wave flume (Figure 2). A wave absorber comprised of rock with a 1:6 slope was placed in the end of the flume away from the wave generator. The width of the flume in the vicinity of the model was divided into two 3.0-ft-wide outside channels and two 2.5-ft-wide center channels. The center channels were empty and allowed wave energy to pass to the wave absorber at the end of the flume. One of the outside channels was divided into two 1.5-ft-wide channels. The model seawall was placed in one of the 1.5-ft-wide channels and three wave gages were placed in an array in the channel to record water level fluctuations (waves). A single gage was placed across from the model in the second 1.5-ft-wide channel, and a three-gage array was placed across from the model in the other 3-ft-wide channel. Irregular waves representing Texel-Marsen Arsloe (TMA) shallow-water spectra (Hughes 1984) were generated by a hydraulically actuated piston-type wave maker controlled by a computer-generated signal.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

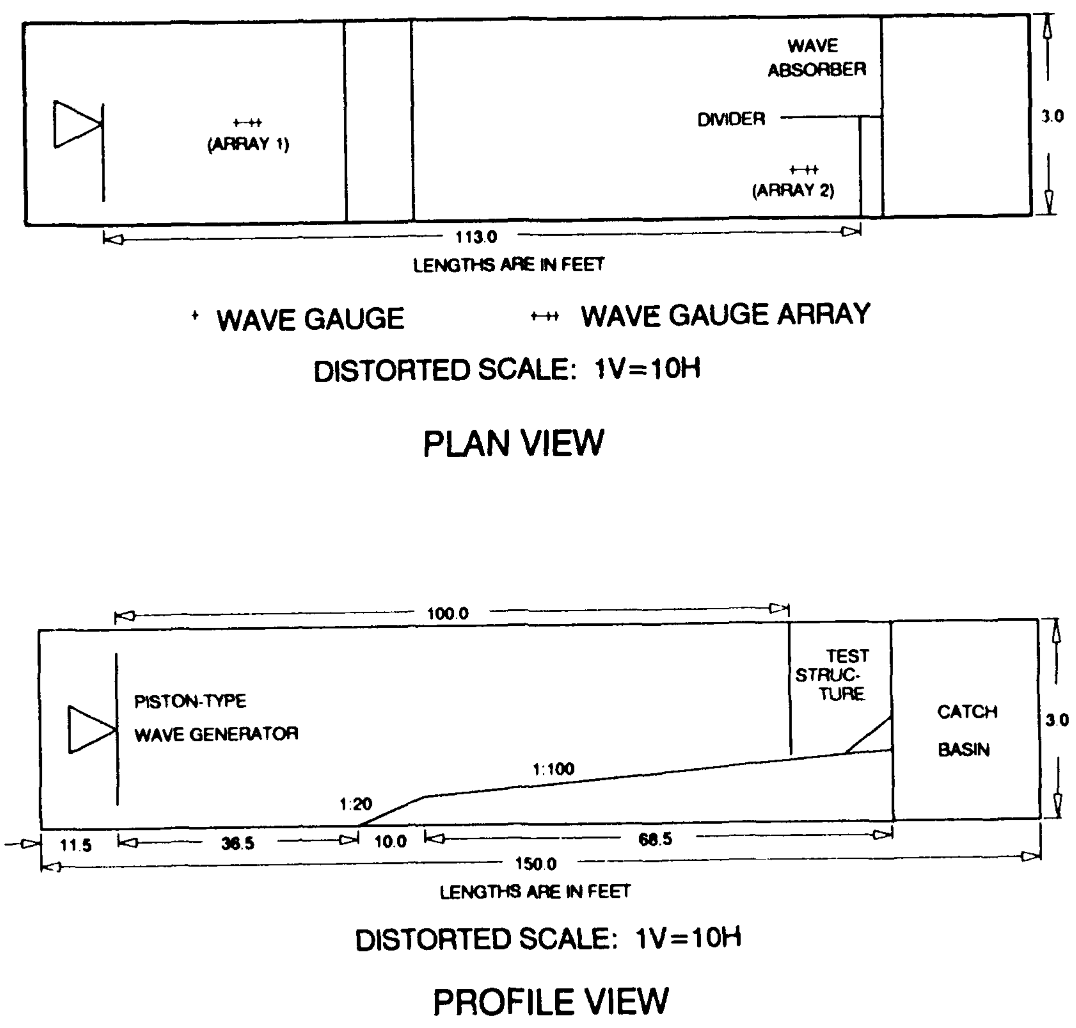


Figure 1. Plan and profile views of wave flume for tests of groups 1 through 6

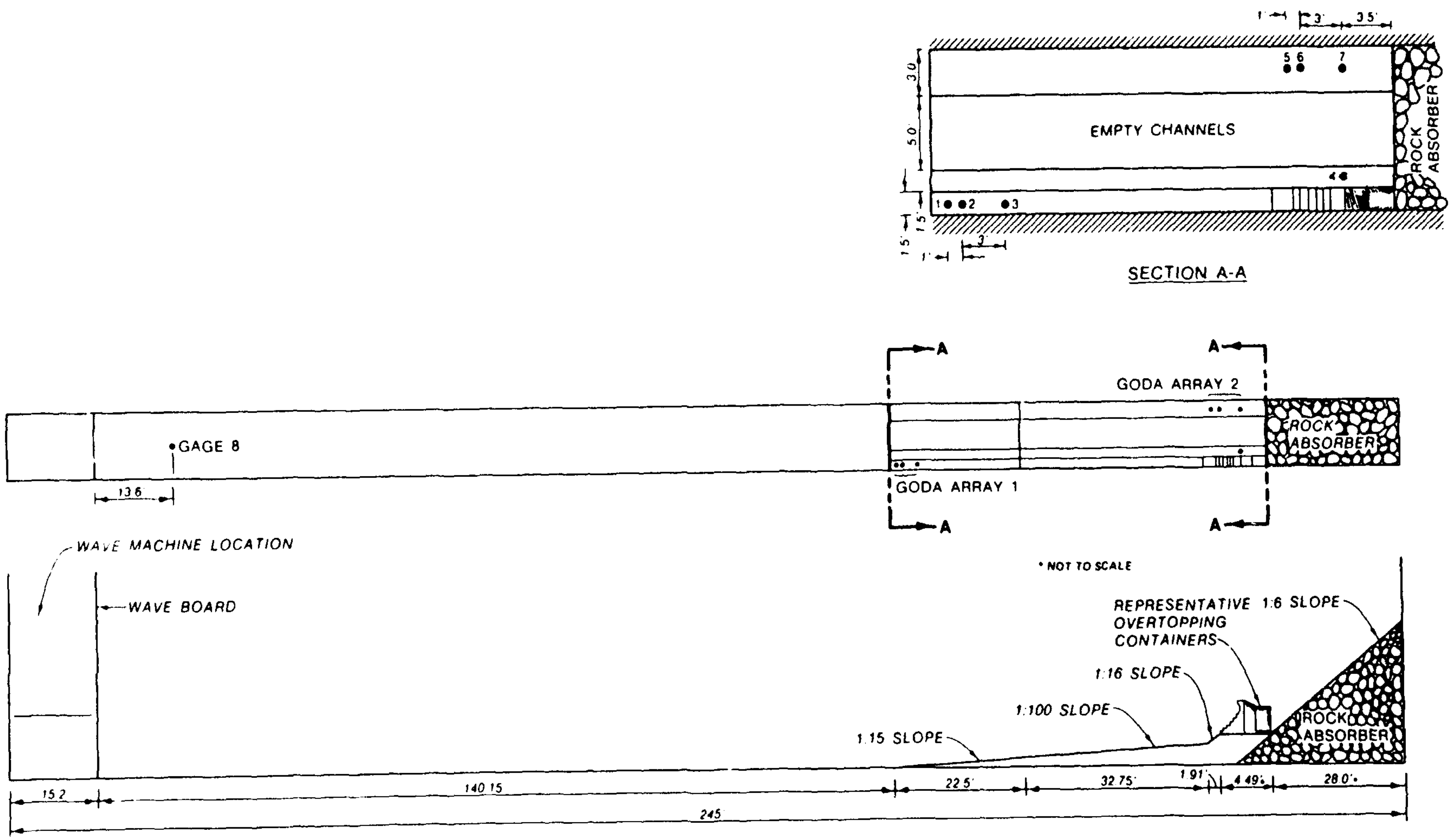


Figure 2. Tank bathymetry and gage arrangement for tests of group 7

Design of Models

11. Recent seawall studies at CERC have included a vertical seawall with parapet at Roughan's Point, MA (Ahrens, Heimbaugh, and Davidson 1986), a recurved seawall at Cape Hatteras, NC (Grace and Carver 1985), and a stepped seawall with recurve at Virginia Beach, VA (Heimbaugh et al. 1988). These seawall types were retested for this study at a 1:16 linear scale except for the stepped seawall, which was tested at a 1:19 linear scale. Based on Froude's model law (Stevens et al. 1942), the following model-to-prototype relations were derived in terms of length (L) and time (T):

Characteristic	Dimension	Model-to-Prototype Scale Relations (1:16)	Model-to-Prototype Scale Relations (1:19)
Length	L	$L_r = 1:16$	$L_r = 1:19$
Area	L^2	$A_r = 1:256$	$A_r = 1:361$
Volume	L^3	$V_r = 1:4,096$	$V_r = 1:6,859$
Time	T	$T_r = 1:4$	$T_r = 1:4.36$

12. Using these relations, the following transference equation may be derived to determine the scale size of armor units used in the studies.

$$\frac{(W_a)_m}{(W_a)_p} = \frac{(\gamma_a)_m}{(\gamma_a)_p}\left(\frac{L_m}{L_p}\right)^3\left[\frac{(S_a)_p - 1}{(S_a)_m - 1}\right]^3$$

where

subscripts m,p = model and prototype values, respectively

W_a = weight of an individual stone, pounds

γ_a = specific weight of an individual stone, pounds per cubic foot

L_m/L_p = linear scale of the model

S_a = specific gravity of an individual stone relative to the water in which the breakwater is constructed, i.e., $S_a = \gamma_a/\gamma_w$

γ_w = specific weight of water, pounds per cubic foot

Scaling in the models assumed specific weights of 62.4 lb/ft^3 for fresh water used in the wave flume, 64.0 lb/ft^3 for sea water at the prototype, and 165 lb/ft^3 for stone used in the model.

13. A calibrated container was placed behind the models to collect water overtopping the structure. Water surface elevation in the overtopping

container was measured with a point gage before and after each test to determine total quantity of overtopping. Total quantity was divided by length of test run to determine overtopping rates.

Description of Seawall Configurations

14. Seawall configurations tested have been divided into seven groups that share similar characteristics. Each group is described and illustrated below.

15. Group 1 seawalls are vertical walls with a recurved parapet and no revetment (Figure 3). Design for this group was taken from configuration 1 in the Roughan's Point, MA, study (Ahrens, Heimbaugh, and Davidson 1986). Configuration 1 modeled the existing eastern seawall at Roughan's Point, which has a crest height of 17.6 ft National Geodetic Vertical Datum (NGVD), with the 1:100 slope beach intersecting the seawall at -0.48 ft NGVD. Water depths at the toe ranged from 8.9 ft to 11.7 ft.

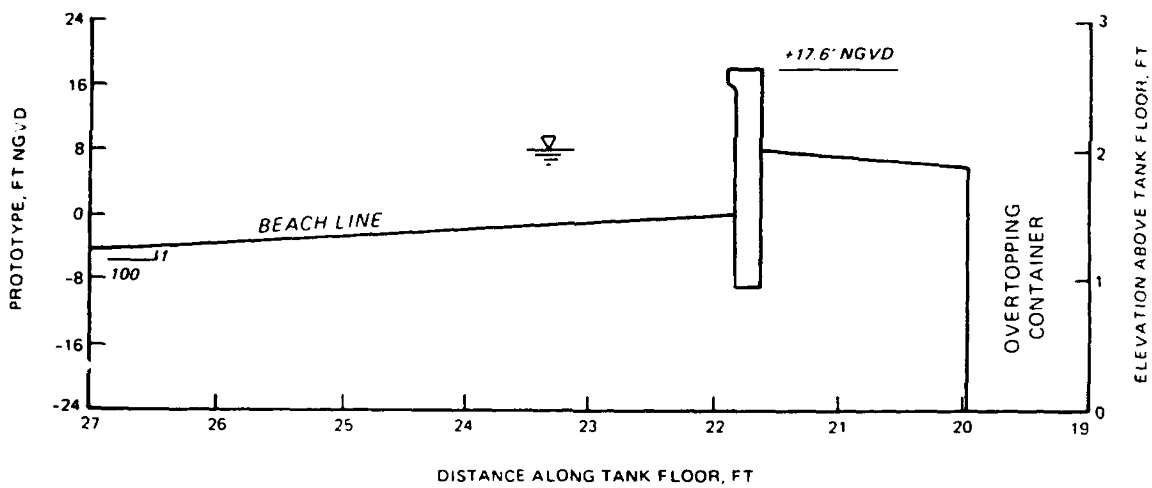
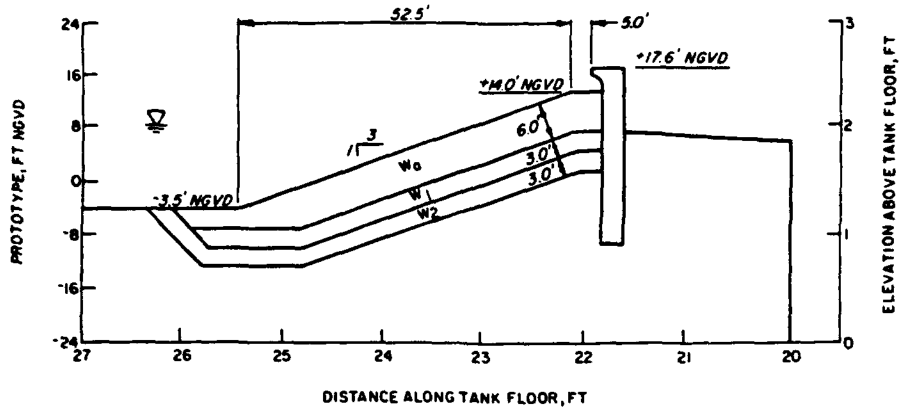
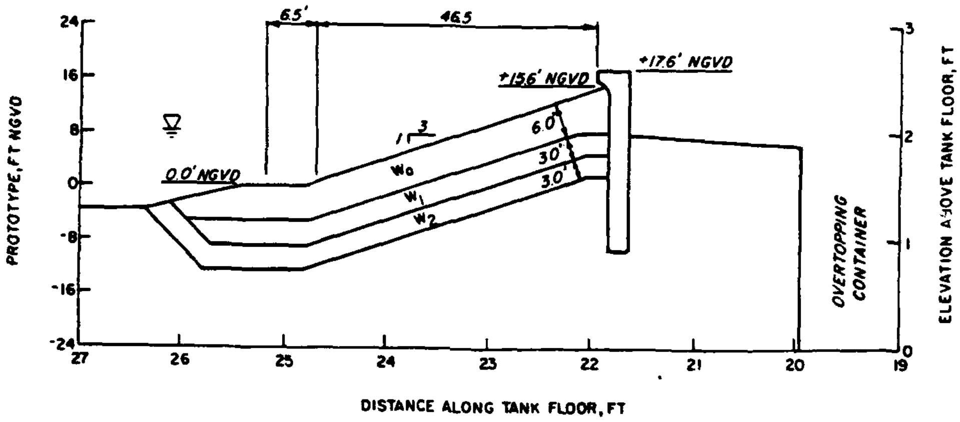


Figure 3. Cross section of group 1 seawalls

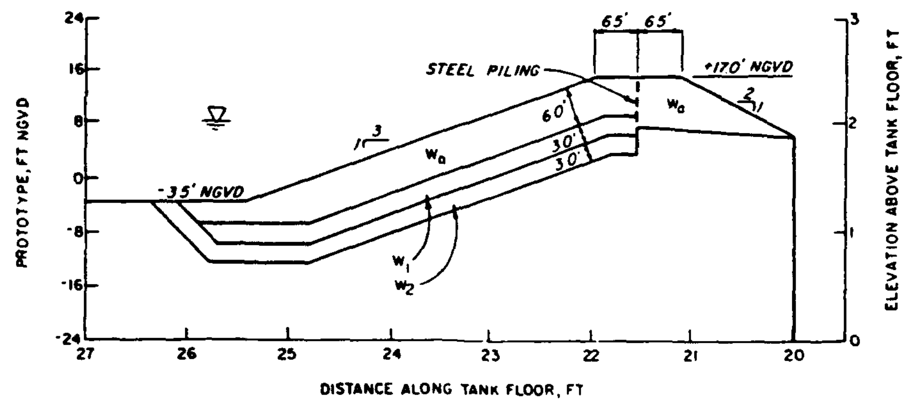
16. Group 2 seawalls are vertical walls with a recurved parapet fronted by a high revetment, or without the parapet if the revetment extends to the top of the seawall (Figure 4). Designs for this group were taken from configurations 2, 3, and 10 in the Roughan's Point study (Ahrens, Heimbaugh, and Davidson 1986). Configuration 2 modeled the existing eastern seawall at Roughan's Point but added a three-layer riprap revetment with a 1:3 slope from -3.5 ft NGVD to +14.0 ft NGVD and a 5-ft crest width. Configuration 3



a. Roughan's Point configuration 2



b. Roughan's Point configuration 3



LEGEND

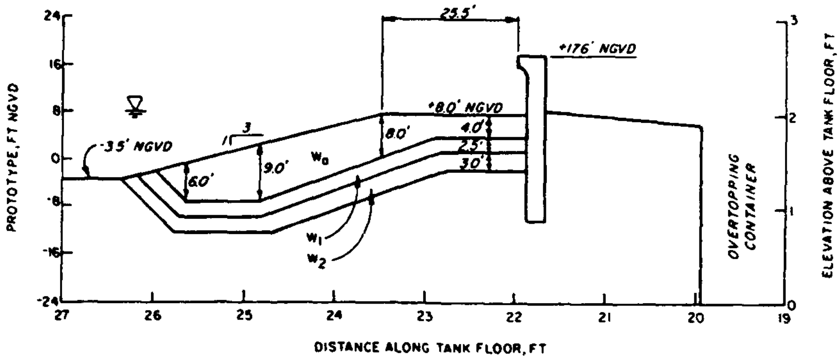
SYMBOL	STONE WEIGHT, W_{50}
W_a	2551 LB
W_1	347 LB
W_2	45 LB

c. Roughan's Point configuration 10

Figure 4. Cross sections of group 2 seawalls

modified the revetment to include a 6.5-ft-wide berm at 0.0 ft NGVD, and extended the revetment slope to intersect the seawall at +15.6 ft NGVD. Configuration 10 replaced the Roughan's Point seawall with a vertical sheet-pile seawall with a crest height of +17.0 ft NGVD. A three-layer, 1:3 riprap revetment extended from -3.5 ft NGVD to the crest of the seawall with a 6.5-ft crest width in front of the seawall.

17. Group 3 seawalls are vertical seawalls with a recurved parapet, a fronting revetment with one or two berms, and may have a cap on the parapet (Figure 5). Designs for this group were taken from configurations 4, 5, 6, 7, and 8 in the Roughan's Point study (Ahrens, Heimbaugh, and Davidson 1986). Configuration 4 had a 1:3, three-layer rubble revetment from -3.5 ft NGVD to +8.0 ft NGVD, with a 25.5-ft-wide berm in front of the seawall. The berm in the armor layer extended well past the horizontal portion of the two underlayers, resulting in an armor layer up to 9.0 ft thick. Configuration 7 was the same as configuration 4, but a 1-ft-high cap was added to the parapet in configuration 7. Configuration 6 was similar to configurations 4 and 7 (included the 1-ft-high cap on the parapet) but the revetment extended to a height of +10.0 ft NGVD, which reduced the berm width to 23.5 ft. Configuration 5 placed a three-layer revetment at a 1:3 slope from -4.0 ft NGVD to +6.0 ft NGVD, followed by a 20-ft-wide berm, a 1:2 slope from +6.0 ft NGVD to +10 ft NGVD, and an 18-ft-wide berm.

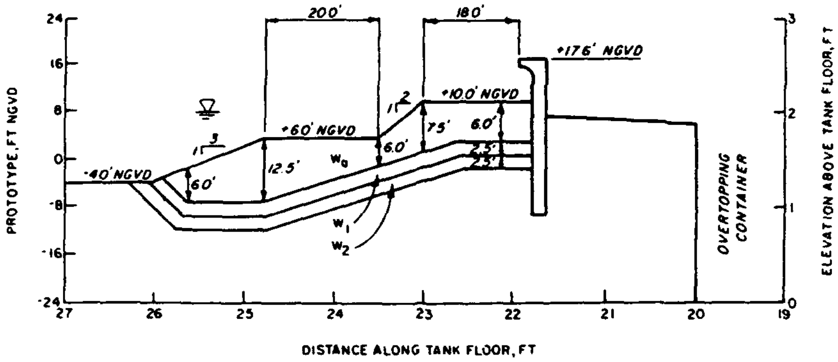


LEGEND

SYMBOL	STONE WEIGHT, W_{50}
W_a	2551 LB
W_1	347 LB
W_2	45 LB

a. Roughan's Point configuration 4

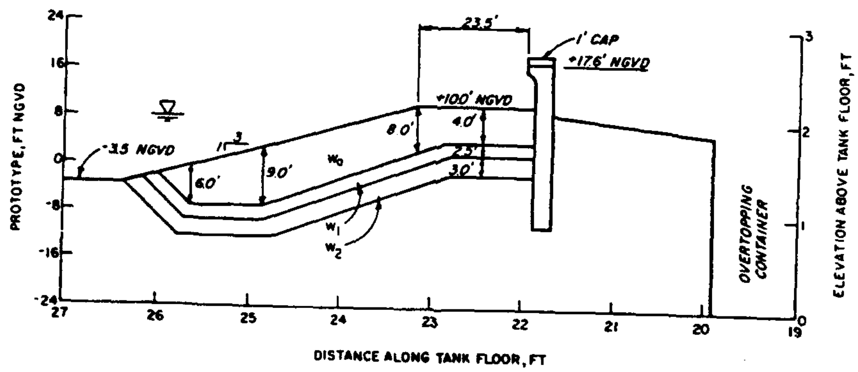
Figure 5. Cross sections of group 3 seawalls (Sheet 1 of 3)



LEGEND

SYMBOL	STONE WEIGHT, W_{50}
W_0	2551 LBS
W_1	347 LBS
W_2	45 LBS

b. Roughan's Point configuration 5

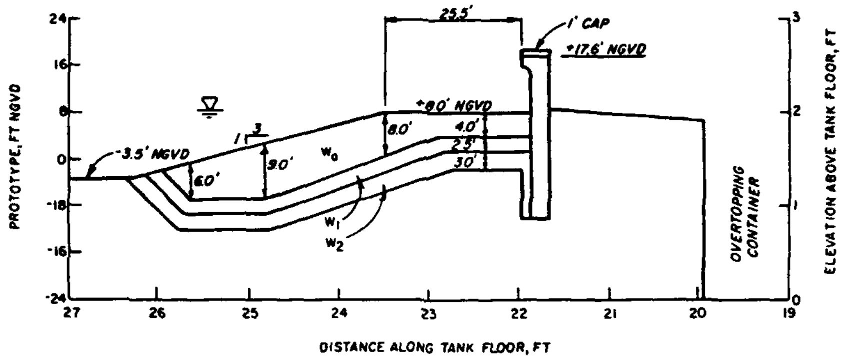


LEGEND

SYMBOL	STONE WEIGHT, W_{50}
W_0	2551 LB
W_1	347 LB
W_2	45 LB

c. Roughan's Point configuration 6

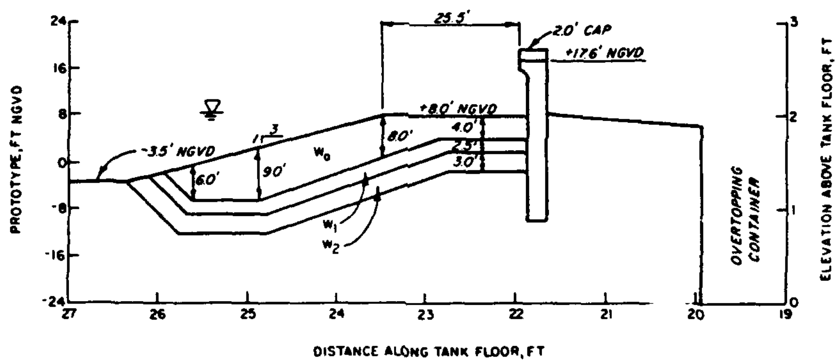
Figure 5. (Sheet 2 of 3)



LEGEND

SYMBOL	STONE WEIGHT, W_{50}
W_0	2551 LB
W_1	347 LB
W_2	45 LB

d. Roughan's Point configuration 7



LEGEND

SYMBOL	STONE WEIGHT, W_{50}
W_0	2551 LB
W_1	347 LB
W_2	45 LB

e. Roughan's Point configuration 8

Figure 5. (Sheet 3 of 3)

18. Group 4 (Figure 6) and group 5 (Figure 7) seawalls are recurved seawalls with revetments. Models of these seawalls were originally used in the Cape Hatteras study (Grace and Carver 1985) as configurations R4S3 and R4S2, respectively. Because the Cape Hatteras study used monochromatic waves and did not include overtopping, the models were retested in a flume with spectral capabilities, and measurements were made of overtopping rates. Results of these tests are reported in Ahrens (1988) as Cape Hatteras seawall configurations 1 and 2, respectively. A riprap revetment in front of a prestressed concrete sheet-pile cutoff wall extended to an elevation of +8.0 ft. The concrete recurved seawall was an additional 11.2 ft high for configuration 1 and 10.9 ft high for configuration 2. Both seawalls have the same recurved section, but configuration 1 has a 1.3-ft seaward extension to the overhang at the crest, and the extension increased the crest height of the seawall by 0.3 ft.

19. Group 6 seawalls are vertical walls with a revetment (Figure 8). This configuration was tested in the Cape Hatteras study (Grace and Carver 1985) as configuration R4S1, and retested with spectral waves and measured overtopping in Ahrens (1988) as Cape Hatteras seawall configuration 3. The model used the same revetment and prestressed concrete sheet-pile cutoff wall that was used for seawall groups 4 and 5, but a vertical wall extending 11.2 ft above the cutoff wall was used in place of the recurved seawall.

20. Group 7 seawalls are stepped seawalls with a recurved parapet and a fronting revetment (Figure 9). This configuration was tested in Phase II of the Virginia Beach study (Heimbaugh et al. 1988) for hurricane and northeaster storm conditions (long wave periods), then retested for this report to provide a wider range of wave conditions.

Test Conditions and Collected Data

21. Tables 1 through 7 list test conditions and collected overtopping rates for seawall groups 1 through 7, respectively.

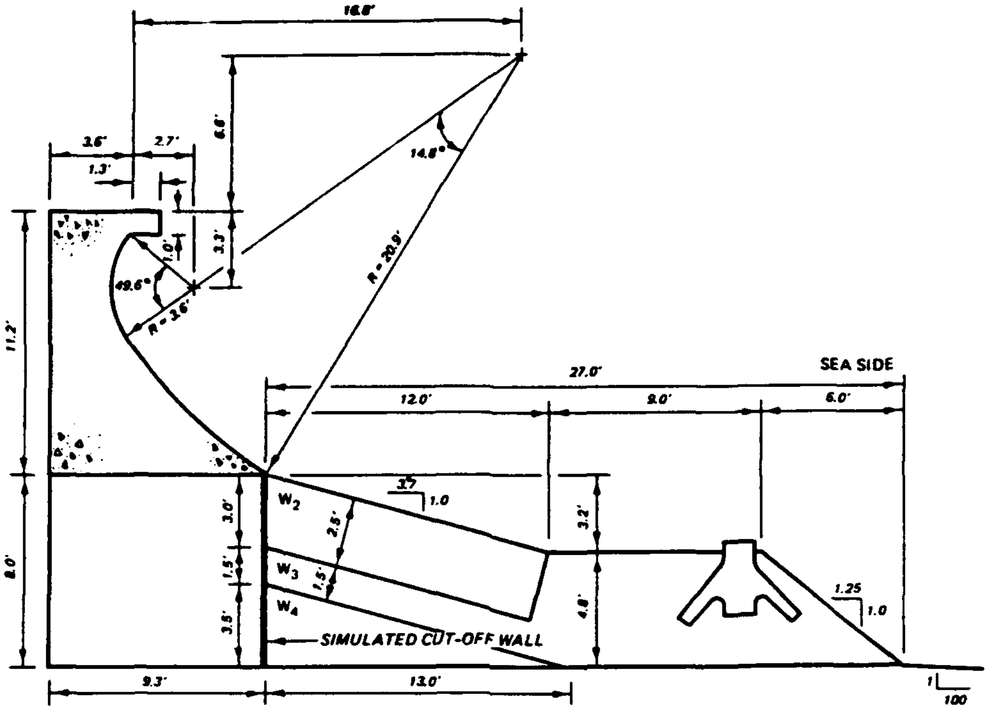


Figure 6. Cross section of group 4 seawalls

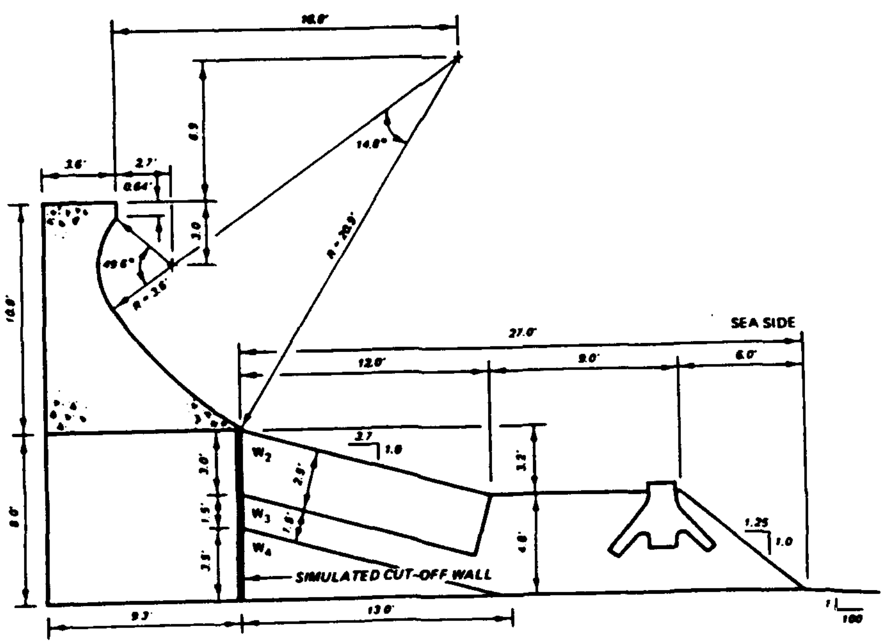


Figure 7. Cross section of group 5 seawalls

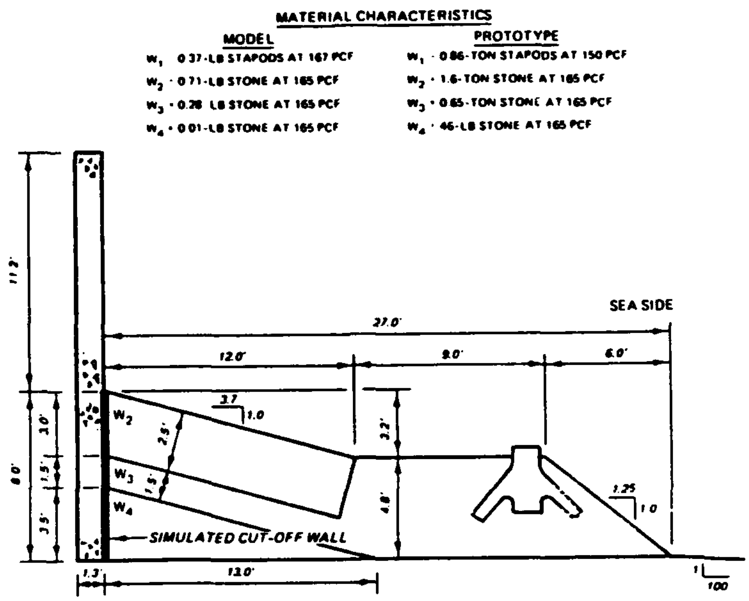


Figure 8. Cross section of group 6 seawalls

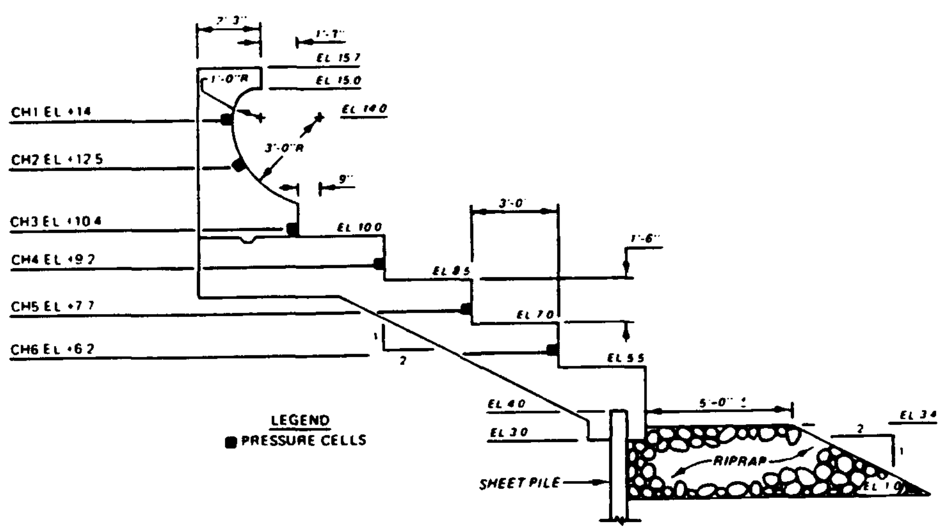


Figure 9. Cross section of group 7 seawalls

Table 1

Test Conditions and Overtopping Rates for Group 1 Seawalls

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate cfs/ft
1	1	5.55	8.00	131.9	8.94	*NA	NA	9.14	0.573	0.033
2	1	6.80	8.00	131.8	8.94	NA	NA	9.14	0.501	0.100
3	1	6.97	8.00	132.3	9.00	NA	NA	9.08	0.488	0.115
4	1	7.15	8.00	131.9	8.95	NA	NA	9.13	0.483	0.131
5	1	5.79	9.00	149.3	8.95	NA	NA	9.13	0.534	0.067
6	1	6.79	9.00	149.1	8.92	NA	NA	9.16	0.482	0.141
7	1	7.22	9.00	149.3	8.94	NA	NA	9.14	0.461	0.160
8	1	7.82	9.00	149.0	8.90	NA	NA	9.18	0.439	0.192
9	1	4.09	10.00	166.9	8.98	NA	NA	9.10	0.647	0.012
10	1	4.08	10.00	166.8	8.97	NA	NA	9.11	0.648	0.014
11	1	5.76	10.00	166.1	8.89	NA	NA	9.19	0.520	0.072
12	1	6.76	10.00	166.5	8.93	NA	NA	9.15	0.465	0.144
13	1	7.21	10.00	166.2	8.90	NA	NA	9.18	0.448	0.192
14	1	7.44	10.00	166.0	8.88	NA	NA	9.20	0.439	0.144
15	1	5.88	7.00	114.4	8.95	NA	NA	9.13	0.577	0.002
16	1	6.58	7.00	114.0	8.93	NA	NA	9.15	0.537	0.041
17	1	6.92	7.00	114.1	8.90	NA	NA	9.18	0.521	0.055
18	1	7.29	7.00	114.0	8.89	NA	NA	9.19	0.504	0.055
19	1	6.21	7.00	114.0	8.90	NA	NA	9.18	0.560	0.034
20	1	6.31	8.00	131.8	8.93	NA	NA	9.15	0.527	0.060
21	1	6.35	9.00	149.2	8.93	NA	NA	9.15	0.503	0.120
22	1	6.51	10.00	166.3	8.91	NA	NA	9.17	0.478	0.118
23	1	7.93	9.00	149.0	8.90	NA	NA	9.18	0.435	0.188
24	1	4.84	7.00	118.7	9.70	NA	NA	8.38	0.596	0.017
25	1	6.24	7.00	118.4	9.66	NA	NA	8.42	0.506	0.048
26	1	6.60	7.00	118.4	9.65	NA	NA	8.43	0.488	0.093
27	1	6.76	7.00	118.3	9.63	NA	NA	8.45	0.481	0.143
28	1	4.56	8.00	137.2	9.73	NA	NA	8.35	0.589	0.038
29	1	6.05	8.00	136.5	9.62	NA	NA	8.46	0.495	0.248
30	1	6.49	8.00	136.7	9.66	NA	NA	8.42	0.470	0.115
31	1	6.87	8.00	136.6	9.64	NA	NA	8.44	0.453	0.222
32	1	4.95	9.00	154.8	9.65	NA	NA	8.43	0.541	0.038
33	1	6.08	9.00	154.7	9.64	NA	NA	8.44	0.472	0.206
34	1	7.16	9.00	154.0	9.55	NA	NA	8.53	0.428	0.316
35	1	7.40	9.00	154.2	9.58	NA	NA	8.50	0.418	0.297

(Continued)

(Sheet 1 of 3)

Table 1 (Continued)

Test No.	Config-uration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Free-board F ft	Relative Free-board F'	Over-topping Rate cfs/ft
36	1	4.96	10.00	172.6	9.63	NA	NA	8.45	0.522	0.079
37	1	6.23	10.00	172.8	9.66	NA	NA	8.42	0.447	0.223
38	1	7.13	10.00	171.5	9.50	NA	NA	8.58	0.417	0.288
39	1	7.33	10.00	172.1	9.57	NA	NA	8.51	0.406	0.354
40	1	6.91	10.00	171.9	9.55	NA	NA	8.53	0.423	0.248
41	1	6.54	9.00	154.1	9.57	NA	NA	8.51	0.454	0.239
42	1	6.44	8.00	136.6	9.64	NA	NA	8.44	0.473	0.147
43	1	7.03	8.00	136.7	9.66	NA	NA	8.42	0.446	0.256
44	1	7.68	9.00	154.1	9.56	NA	NA	8.52	0.408	0.343
45	1	6.15	12.00	208.5	9.64	NA	NA	8.44	0.424	0.293
46	1	6.56	12.00	208.5	9.64	NA	NA	8.44	0.406	0.315
47	1	4.82	7.00	121.5	10.21	NA	NA	7.87	0.557	0.033
48	1	6.22	7.00	121.8	10.27	NA	NA	7.81	0.466	0.100
49	1	6.73	7.00	121.8	10.27	NA	NA	7.81	0.442	0.253
50	1	7.50	7.00	123.5	10.59	NA	NA	7.49	0.392	0.500
51	1	4.74	8.00	141.5	10.39	NA	NA	7.69	0.523	0.098
52	1	6.24	8.00	142.0	10.47	NA	NA	7.61	0.430	0.312
53	1	7.85	8.00	144.5	10.88	NA	NA	7.20	0.347	1.166
54	1	7.55	8.00	143.9	10.78	NA	NA	7.30	0.362	0.642
55	1	5.10	9.00	159.7	10.31	NA	NA	7.77	0.483	0.215
56	1	6.47	9.00	162.4	10.68	NA	NA	7.40	0.391	0.765
57	1	7.69	9.00	163.5	10.84	NA	NA	7.24	0.340	1.055
58	1	7.95	9.00	163.5	10.84	NA	NA	7.24	0.332	1.175
59	1	5.01	10.00	182.9	10.87	NA	NA	7.21	0.434	0.167
60	1	6.55	10.00	181.9	10.74	NA	NA	7.34	0.370	0.609
61	1	7.40	10.00	180.5	10.58	NA	NA	7.50	0.350	0.731
62	1	8.21	10.00	179.4	10.43	NA	NA	7.65	0.333	0.596
63	1	6.97	12.00	214.4	10.21	NA	NA	7.87	0.360	0.361
64	1	6.98	12.00	218.9	10.66	NA	NA	7.42	0.337	0.823
65	1	3.84	7.00	123.9	10.66	NA	NA	7.42	0.607	0.007
66	1	2.68	8.00	141.8	10.44	NA	NA	7.64	0.759	0.002
67	1	6.84	8.00	141.6	10.41	NA	NA	7.67	0.409	0.535
68	1	2.86	9.00	161.1	10.50	NA	NA	7.58	0.692	0.034
70	1	2.70	10.00	180.1	10.52	NA	NA	7.56	0.690	0.022
71	1	7.60	10.00	178.9	10.38	NA	NA	7.70	0.354	0.773

(Continued) (Sheet 2 of 3)

Table 1 (Concluded)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate cfs/ft
72	1	2.51	12.00	217.2	10.48	NA	NA	7.60	0.685	0.000
73	1	8.05	9.00	159.1	10.22	NA	NA	7.86	0.361	0.879
74	1	4.44	7.00	126.8	11.22	NA	NA	6.86	0.506	0.067
75	1	8.11	7.00	125.5	10.98	NA	NA	7.10	0.351	0.376
76	1	7.57	8.00	146.0	11.13	NA	NA	6.95	0.342	0.786
77	1	8.55	8.00	145.1	10.98	NA	NA	7.10	0.323	1.007
78	1	8.82	7.00	128.4	11.54	NA	NA	6.54	0.304	2.377
79	1	4.01	8.00	146.2	11.15	NA	NA	6.93	0.521	0.165
80	1	4.55	9.00	166.2	11.22	NA	NA	6.86	0.454	0.139
81	1	7.83	9.00	164.6	10.98	NA	NA	7.10	0.328	0.920
82	1	9.05	9.00	163.0	10.77	NA	NA	7.31	0.308	1.137
83	1	4.23	10.00	183.1	10.90	NA	NA	7.18	0.484	0.065
84	1	7.86	10.00	181.8	10.73	NA	NA	7.35	0.328	0.744
85	1	8.59	10.00	183.2	10.90	NA	NA	7.18	0.301	1.088
86	1	7.00	12.00	221.3	10.90	NA	NA	7.18	0.325	0.515
87	1	7.83	12.00	221.1	10.87	NA	NA	7.21	0.302	0.889
88	1	3.93	5.00	85.7	11.04	NA	NA	7.04	0.641	0.012
89	1	6.90	5.00	87.7	11.70	NA	NA	6.38	0.396	0.400
90	1	8.38	7.00	127.6	11.37	NA	NA	6.71	0.323	0.843

(Sheet 3 of 3)

Table 2

Test Conditions and Overtopping Rates for Group 2 Seawalls

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
92	2	3.78	8.00	153.9	8.97	5.0	17.5	9.11	0.701	0.046
93	2	7.53	8.00	153.5	8.89	5.0	17.5	9.19	0.447	0.062
94	2	7.81	8.00	153.1	8.82	5.0	17.5	9.26	0.440	0.107
95	2	6.43	7.00	132.3	8.82	5.0	17.5	9.26	0.526	0.000
96	2	7.55	7.00	131.8	8.73	5.0	17.5	9.35	0.477	0.025
97	2	7.35	7.00	131.9	8.74	5.0	17.5	9.34	0.485	0.056
98	2	6.01	9.00	172.7	8.66	5.0	17.5	9.42	0.512	0.040
99	2	6.96	9.00	172.5	8.65	5.0	17.5	9.43	0.465	0.084
100	2	8.12	9.00	173.1	8.74	5.0	17.5	9.34	0.415	0.115
101	2	6.01	10.00	194.1	8.82	5.0	17.5	9.26	0.484	0.024
102	2	6.52	10.00	193.8	8.77	5.0	17.5	9.31	0.461	0.072
103	2	7.29	10.00	193.5	8.73	5.0	17.5	9.35	0.430	0.144
104	2	5.78	5.00	89.5	8.82	5.0	17.5	9.26	0.643	0.004
105	2	4.74	12.00	234.0	8.74	5.0	17.5	9.34	0.537	0.020
106	2	5.80	12.00	234.0	8.74	5.0	17.5	9.34	0.470	0.087
107	2	6.50	12.00	234.8	8.82	5.0	17.5	9.26	0.431	0.224
108	2	7.30	8.00	153.0	8.81	5.0	17.5	9.27	0.461	0.032
109	2	6.14	7.00	132.6	8.89	5.0	17.5	9.19	0.538	0.005
110	2	7.21	7.00	132.6	8.89	5.0	17.5	9.19	0.483	0.030
111	2	6.21	8.00	153.5	8.90	5.0	17.5	9.18	0.508	0.013
112	2	7.56	8.00	153.5	8.89	5.0	17.5	9.19	0.446	0.094
113	2	6.11	9.00	174.6	8.96	5.0	17.5	9.12	0.488	0.037
114	2	8.21	9.00	173.7	8.82	5.0	17.5	9.26	0.408	0.105
115	2	5.50	7.00	136.2	9.66	5.0	17.5	8.42	0.525	0.027
116	2	7.09	7.00	136.3	9.69	5.0	17.5	8.39	0.442	0.098
117	2	5.57	8.00	157.6	9.63	5.0	17.5	8.45	0.498	0.049
118	2	7.12	8.00	157.2	9.56	5.0	17.5	8.52	0.427	0.188
119	2	5.82	9.00	179.0	9.64	5.0	17.5	8.44	0.463	0.125
120	2	7.86	9.00	178.6	9.58	5.0	17.5	8.50	0.382	0.310
121	2	6.03	10.00	200.2	9.64	5.0	17.5	8.44	0.436	0.104
122	2	7.45	10.00	199.4	9.54	5.0	17.5	8.54	0.383	0.286
123	2	6.05	7.00	139.2	10.33	5.0	17.5	7.75	0.450	0.056
124	2	7.61	7.00	139.0	10.29	5.0	17.5	7.79	0.389	0.215
125	2	5.71	8.00	161.8	10.41	5.0	17.5	7.67	0.441	0.101
126	2	8.54	8.00	161.6	10.38	5.0	17.5	7.70	0.339	0.366

(Continued)

(Sheet 1 of 4)

Table 2 (Continued)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
127	2	6.42	9.00	183.2	10.32	5.0	17.5	7.76	0.396	0.176
128	2	8.43	9.00	183.4	10.35	5.0	17.5	7.73	0.328	0.389
129	2	6.40	10.00	205.5	10.40	5.0	17.5	7.68	0.378	0.186
130	2	8.11	10.00	205.8	10.44	5.0	17.5	7.64	0.321	0.609
131	2	6.53	7.00	142.8	11.17	5.0	17.5	6.91	0.378	0.132
132	2	7.68	7.00	142.2	11.02	5.0	17.5	7.06	0.348	0.229
133	2	8.11	7.00	140.9	10.72	5.0	17.5	7.36	0.350	0.340
134	2	6.06	8.00	165.6	11.15	5.0	17.5	6.93	0.380	0.194
135	2	7.63	8.00	165.6	11.15	5.0	17.5	6.93	0.325	0.415
136	2	8.31	8.00	163.3	10.69	5.0	17.5	7.39	0.330	0.356
137	2	6.89	9.00	185.3	10.66	5.0	17.5	7.42	0.359	0.280
138	2	7.81	9.00	186.0	10.77	5.0	17.5	7.31	0.325	0.468
139	2	9.17	9.00	185.8	10.74	5.0	17.5	7.34	0.294	0.956
141	2	7.76	10.00	208.6	10.84	5.0	17.5	7.24	0.311	0.601
142	2	9.09	10.00	207.3	10.66	5.0	17.5	7.42	0.288	0.884
143	2	5.35	12.00	255.1	11.14	5.0	17.5	6.94	0.358	0.354
144	2	6.90	12.00	255.8	11.23	5.0	17.5	6.85	0.298	0.669
145	2	7.71	12.00	255.8	11.22	5.0	17.5	6.86	0.277	0.585
146	2	6.98	5.00	95.2	11.00	5.0	17.5	7.08	0.425	0.025
147	2	6.49	10.00	208.1	10.78	5.0	17.5	7.30	0.354	0.078
1	3	5.17	5.00	94.9	10.88	6.5	0.0	7.20	0.528	0.002
2	3	5.70	5.00	94.7	10.80	6.5	0.0	7.28	0.500	0.002
3	3	6.26	5.00	94.7	10.81	6.5	0.0	7.27	0.470	0.010
4	3	5.78	7.00	141.5	10.85	6.5	0.0	7.23	0.431	0.000
5	3	6.79	7.00	141.5	10.85	6.5	0.0	7.23	0.387	0.036
6	3	7.38	7.00	141.5	10.86	6.5	0.0	7.22	0.366	0.084
7	3	5.43	8.00	164.0	10.84	6.5	0.0	7.24	0.428	0.005
8	3	7.35	8.00	164.1	10.85	6.5	0.0	7.23	0.349	0.105
9	3	7.63	8.00	164.0	10.82	6.5	0.0	7.26	0.342	0.129
10	3	6.07	9.00	186.6	10.87	6.5	0.0	7.21	0.379	0.074
11	3	6.91	9.00	186.2	10.81	6.5	0.0	7.27	0.351	0.170
12	3	8.41	9.00	185.9	10.75	6.5	0.0	7.33	0.310	0.321
13	3	6.51	10.00	208.8	10.87	6.5	0.0	7.21	0.349	0.014
14	3	7.61	10.00	208.7	10.86	6.5	0.0	7.22	0.315	0.172
15	3	8.23	10.00	208.1	10.77	6.5	0.0	7.31	0.303	0.225

(Continued)

(Sheet 2 of 4)

Table 2 (Continued)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
16	3	5.51	12.00	252.6	10.84	6.5	0.0	7.24	0.367	0.022
17	3	6.88	12.00	252.3	10.81	6.5	0.0	7.27	0.318	0.214
18	3	7.57	12.00	252.3	10.81	6.5	0.0	7.27	0.298	0.324
148	10	5.86	5.00	91.7	14.84	13.0	20.5	6.26	0.427	0.001
149	10	7.00	7.00	135.6	14.73	13.0	20.5	6.37	0.339	0.172
150	10	7.08	8.00	157.1	14.75	13.0	20.5	6.35	0.319	0.543
151	10	7.54	9.00	177.8	14.67	13.0	20.5	6.43	0.297	0.524
152	10	7.13	10.00	198.8	14.67	13.0	20.5	6.43	0.297	0.463
153	10	6.03	12.00	241.7	14.80	13.0	20.5	6.30	0.306	0.575
154	10	6.89	7.00	135.6	14.75	13.0	20.5	6.35	0.341	0.148
155	10	6.99	8.00	156.7	14.68	13.0	20.5	6.42	0.326	0.224
156	10	7.14	9.00	175.8	14.36	13.0	20.5	6.74	0.325	0.276
157	10	6.71	10.00	198.8	14.66	13.0	20.5	6.44	0.310	0.242
158	10	7.28	7.00	132.0	13.97	13.0	20.5	7.13	0.373	0.061
159	10	7.52	8.00	152.4	13.91	13.0	20.5	7.19	0.351	0.221
160	10	7.87	9.00	173.3	13.97	13.0	20.5	7.13	0.323	0.273
161	10	7.32	10.00	193.5	13.94	13.0	20.5	7.16	0.328	0.157
162	10	6.63	7.00	132.6	14.09	13.0	20.5	7.01	0.390	0.000
163	10	6.90	8.00	152.6	13.95	13.0	20.5	7.15	0.369	0.110
164	10	6.78	9.00	173.2	13.96	13.0	20.5	7.14	0.357	0.176
165	10	6.54	10.00	193.4	13.93	13.0	20.5	7.17	0.354	0.272
166	10	6.76	7.00	133.5	14.28	13.0	20.5	6.82	0.373	0.038
168	10	7.35	9.00	161.9	12.32	13.0	20.5	8.78	0.426	0.134
169	10	7.04	10.00	182.7	12.55	13.0	20.5	8.55	0.410	0.134
170	10	6.45	7.00	127.8	13.12	13.0	20.5	7.98	0.457	0.013
171	10	6.57	8.00	148.1	13.17	13.0	20.5	7.93	0.427	0.044
172	10	7.03	9.00	168.2	13.21	13.0	20.5	7.89	0.389	0.088
173	10	6.80	10.00	187.7	13.18	13.0	20.5	7.92	0.386	0.098
174	10	7.03	8.00	148.7	13.28	13.0	20.5	7.82	0.403	0.097
175	10	5.52	5.00	87.5	13.34	13.0	20.5	7.76	0.559	0.000
176	10	6.60	7.00	128.6	13.27	13.0	20.5	7.83	0.441	0.030
177	10	6.72	8.00	148.6	13.26	13.0	20.5	7.84	0.415	0.081
178	10	7.19	9.00	167.3	13.09	13.0	20.5	8.01	0.390	0.085
179	10	6.78	10.00	183.9	12.70	13.0	20.5	8.40	0.412	0.151
180	10	6.16	12.00	227.1	13.20	13.0	20.5	7.90	0.385	0.187

(Continued)

(Sheet 3 of 4)

Table 2 (Concluded)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
181	10	5.18	5.00	87.5	13.34	13.0	20.5	7.76	0.584	0.000
182	10	6.19	7.00	128.5	13.25	13.0	20.5	7.85	0.461	0.015
183	10	6.55	8.00	148.6	13.27	13.0	20.5	7.83	0.423	0.042
184	10	6.63	9.00	169.1	13.35	13.0	20.5	7.75	0.397	0.050
185	10	5.41	5.00	85.2	12.58	13.0	20.5	8.52	0.628	0.000
186	10	6.06	7.00	125.1	12.59	13.0	20.5	8.51	0.512	0.007
187	10	6.66	8.00	144.1	12.52	13.0	20.5	8.58	0.462	0.021
188	10	6.93	9.00	163.0	12.48	13.0	20.5	8.62	0.435	0.033
189	10	6.82	10.00	178.4	12.03	13.0	20.5	9.07	0.448	0.036
190	10	5.30	12.00	220.9	12.56	13.0	20.5	8.54	0.465	0.034
191	10	4.82	5.00	85.2	12.59	13.0	20.5	8.51	0.677	0.000
192	10	5.64	7.00	125.1	12.59	13.0	20.5	8.51	0.537	0.005
193	10	6.24	8.00	144.5	12.58	13.0	20.5	8.52	0.479	0.013
194	10	6.44	9.00	163.2	12.51	13.0	20.5	8.59	0.454	0.029
195	10	6.27	10.00	182.9	12.58	13.0	20.5	8.52	0.442	0.015
196	10	5.19	12.00	218.7	12.35	13.0	20.5	8.75	0.485	0.052

(Sheet 4 of 4)

Table 3

Test Conditions and Overtopping Rates for Group 3 Seawalls

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
19	4	6.00	8.00	163.0	10.64	25.5	11.5	7.44	0.412	0.044
20	4	5.84	8.00	163.0	10.64	25.5	11.5	7.44	0.420	0.059
21	4	6.01	8.00	163.7	10.78	25.5	11.5	7.30	0.404	0.075
22	4	5.08	5.00	94.8	10.87	25.5	11.5	7.21	0.535	0.001
23	4	6.05	5.00	95.0	10.94	25.5	11.5	7.14	0.472	0.004
24	4	6.75	5.00	94.8	10.87	25.5	11.5	7.21	0.442	0.004
25	4	6.63	7.00	141.2	10.79	25.5	11.5	7.29	0.397	0.029
26	4	7.24	7.00	141.5	10.86	25.5	11.5	7.22	0.370	0.084
27	4	7.86	7.00	141.2	10.78	25.5	11.5	7.30	0.355	0.113
28	4	6.23	9.00	185.7	10.72	25.5	11.5	7.36	0.381	0.226
29	4	7.00	9.00	185.2	10.64	25.5	11.5	7.44	0.357	0.078
30	4	8.13	9.00	185.4	10.68	25.5	11.5	7.40	0.321	0.227
31	4	5.93	10.00	207.7	10.72	25.5	11.5	7.36	0.379	0.094
32	4	6.99	10.00	207.7	10.72	25.5	11.5	7.36	0.340	0.161
33	4	7.73	10.00	206.8	10.58	25.5	11.5	7.50	0.324	0.188
34	4	4.77	12.00	251.0	10.66	25.5	11.5	7.42	0.415	0.017
35	4	6.07	12.00	252.2	10.80	25.5	11.5	7.28	0.346	0.167
36	4	6.76	12.00	249.9	10.53	25.5	11.5	7.55	0.335	0.354
37	4	6.52	8.00	159.9	10.06	25.5	11.5	8.02	0.424	0.058
39	4	7.19	8.00	159.9	10.05	25.5	11.5	8.03	0.397	0.101
40	4	4.87	5.00	92.8	10.06	25.5	11.5	8.02	0.617	0.001
41	4	5.99	5.00	92.9	10.08	25.5	11.5	8.00	0.536	0.001
42	4	6.46	5.00	92.9	10.08	25.5	11.5	8.00	0.509	0.001
43	4	6.11	7.00	138.1	10.08	25.5	11.5	8.00	0.463	0.007
44	4	6.94	7.00	138.1	10.08	25.5	11.5	8.00	0.425	0.017
45	4	7.46	7.00	138.0	10.06	25.5	11.5	8.02	0.406	0.045
46	4	6.32	9.00	181.3	10.01	25.5	11.5	8.07	0.417	0.064
47	4	7.12	9.00	181.4	10.02	25.5	11.5	8.06	0.385	0.094
48	4	7.76	9.00	180.8	9.93	25.5	11.5	8.15	0.368	0.133
49	4	5.71	10.00	203.0	10.04	25.5	11.5	8.04	0.428	0.016
50	4	6.80	10.00	202.8	10.01	25.5	11.5	8.07	0.383	0.073
51	4	6.82	10.00	203.0	10.03	25.5	11.5	8.05	0.381	0.073
52	4	4.66	12.00	246.0	10.08	25.5	11.5	8.00	0.458	0.000
53	4	5.76	12.00	245.7	10.04	25.5	11.5	8.04	0.399	0.063

(Continued)

(Sheet 1 of 4)

Table 3 (Continued)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
54	4	6.32	12.00	246.0	10.07	25.5	11.5	8.01	0.374	0.141
55	5	5.96	8.00	164.3	10.88	38	12	7.20	0.400	0.036
56	5	6.99	8.00	163.9	10.81	38	12	7.27	0.364	0.097
57	5	7.37	8.00	163.3	10.69	38	12	7.39	0.357	0.151
58	5	4.88	5.00	94.9	10.88	38	12	7.20	0.549	0.000
59	5	5.81	5.00	94.8	10.87	38	12	7.21	0.489	0.004
60	5	6.46	5.00	94.9	10.88	38	12	7.20	0.455	0.000
61	5	6.27	7.00	141.5	10.86	38	12	7.22	0.408	0.017
62	5	7.16	7.00	141.5	10.85	38	12	7.23	0.374	0.053
63	5	7.97	7.00	141.6	10.87	38	12	7.21	0.347	0.112
64	5	6.41	9.00	186.6	10.87	38	12	7.21	0.365	0.071
65	5	7.28	9.00	186.1	10.78	38	12	7.30	0.340	0.161
66	5	8.01	9.00	184.7	10.56	38	12	7.52	0.330	0.287
67	5	5.70	10.00	208.3	10.80	38	12	7.28	0.385	0.035
68	5	6.82	10.00	208.6	10.84	38	12	7.24	0.340	0.160
69	5	7.67	10.00	207.7	10.72	38	12	7.36	0.319	0.114
70	5	4.71	12.00	252.9	10.88	38	12	7.20	0.405	0.052
71	5	5.97	12.00	251.9	10.76	38	12	7.32	0.352	0.133
72	5	7.28	12.00	251.5	10.72	38	12	7.36	0.310	0.251
73	5	5.73	8.00	160.0	10.08	38	12	8.00	0.460	0.013
74	5	6.88	8.00	159.5	9.98	38	12	8.10	0.413	0.036
76	6	5.83	8.00	164.3	10.88	23.5	13.5	7.20	0.406	0.087
77	6	7.04	8.00	164.0	10.84	23.5	13.5	7.24	0.360	0.074
78	6	7.81	8.00	164.0	10.83	23.5	13.5	7.25	0.336	0.098
79	6	5.16	5.00	94.9	10.88	23.5	13.5	7.20	0.529	0.001
80	6	6.24	5.00	94.9	10.88	23.5	13.5	7.20	0.466	0.001
81	6	6.95	5.00	94.5	10.72	23.5	13.5	7.36	0.444	0.049
82	6	6.78	7.00	141.6	10.88	23.5	13.5	7.20	0.386	0.011
83	6	7.51	7.00	141.6	10.88	23.5	13.5	7.20	0.360	0.029
84	6	8.25	7.00	140.8	10.69	23.5	13.5	7.39	0.348	0.159
85	6	6.47	9.00	185.8	10.74	23.5	13.5	7.34	0.371	0.048
86	6	7.55	9.00	185.6	10.71	23.5	13.5	7.37	0.336	0.108
87	6	8.45	9.00	185.7	10.72	23.5	13.5	7.36	0.311	0.177
88	6	6.20	10.00	208.3	10.80	23.5	13.5	7.28	0.364	0.027

(Continued)

(Sheet 2 of 4)

Table 3 (Continued)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
89	6	7.24	10.00	208.3	10.81	23.5	13.5	7.27	0.328	0.104
90	6	7.95	10.00	207.8	10.73	23.5	13.5	7.35	0.312	0.120
91	6	4.95	12.00	252.1	10.78	23.5	13.5	7.30	0.398	0.027
92	6	5.92	12.00	251.5	10.72	23.5	13.5	7.36	0.356	0.116
93	6	6.79	12.00	251.8	10.74	23.5	13.5	7.34	0.324	0.158
121	7	8.10	9.00	176.6	9.27	25.5	11.5	8.81	0.389	0.024
122	7	7.26	7.00	134.1	9.20	25.5	11.5	8.88	0.463	0.005
123	7	6.05	5.00	90.7	9.26	25.5	11.5	8.82	0.591	0.005
124	7	7.30	8.00	155.5	9.24	25.5	11.5	8.84	0.437	0.015
125	7	5.88	12.00	239.0	9.28	25.5	11.5	8.80	0.435	0.009
126	7	6.45	10.00	197.4	9.26	25.5	11.5	8.82	0.437	0.019
127	7	7.18	9.00	176.5	9.25	25.5	11.5	8.83	0.423	0.008
128	7	7.73	8.00	164.0	10.84	25.5	11.5	7.24	0.338	0.098
129	7	6.84	8.00	163.8	10.79	25.5	11.5	7.29	0.370	0.077
130	7	5.89	8.00	164.4	10.90	25.5	11.5	7.18	0.402	0.035
131	7	6.46	5.00	95.0	10.92	25.5	11.5	7.16	0.452	0.001
132	7	5.93	5.00	94.8	10.86	25.5	11.5	7.22	0.483	0.001
133	7	5.20	5.00	94.8	10.86	25.5	11.5	7.22	0.528	0.001
134	7	7.84	7.00	141.4	10.84	25.5	11.5	7.24	0.352	0.069
135	7	7.31	7.00	141.2	10.78	25.5	11.5	7.30	0.372	0.039
136	7	6.31	7.00	141.3	10.80	25.5	11.5	7.28	0.409	0.023
137	7	6.29	9.00	186.6	10.88	25.5	11.5	7.20	0.370	0.044
138	7	7.39	9.00	185.7	10.72	25.5	11.5	7.36	0.340	0.114
139	7	8.14	9.00	186.0	10.77	25.5	11.5	7.31	0.317	0.169
140	7	7.66	10.00	208.0	10.75	25.5	11.5	7.33	0.318	0.033
141	7	7.09	10.00	208.2	10.79	25.5	11.5	7.29	0.333	0.202
142	7	6.01	10.00	208.6	10.85	25.5	11.5	7.23	0.369	0.021
143	7	6.90	12.00	251.9	10.76	25.5	11.5	7.32	0.320	0.179
144	7	5.90	12.00	252.1	10.78	25.5	11.5	7.30	0.354	0.105
145	7	4.88	12.00	252.5	10.83	25.5	11.5	7.25	0.399	0.023
146	8	6.48	5.00	94.9	10.89	25.5	11.5	7.19	0.454	0.026
147	8	8.04	7.00	141.4	10.84	25.5	11.5	7.24	0.346	0.020
148	8	7.96	8.00	163.7	10.77	25.5	11.5	7.31	0.335	0.062
149	8	8.60	9.00	185.9	10.76	25.5	11.5	7.32	0.305	0.110

(Continued)

(Sheet 3 of 4)

Table 3 (Concluded)

Test No.	Configuration No.	Wave Height H_{mo} ft	Wave Period T_p sec	Wave Length L_p ft	Depth At Toe d_s ft	Berm Width W_B ft	Berm Height h_B ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
150	8	7.75	10.00	208.2	10.78	25.5	11.5	7.30	0.314	0.115
151	8	6.87	12.00	252.4	10.82	25.5	11.5	7.26	0.318	0.138
152	8	5.88	12.00	252.4	10.82	25.5	11.5	7.26	0.353	0.072
153	8	7.07	10.00	208.1	10.77	25.5	11.5	7.31	0.335	0.060
154	8	7.09	9.00	185.5	10.70	25.5	11.5	7.38	0.351	0.081
155	8	6.92	8.00	163.8	10.80	25.5	11.5	7.28	0.366	0.052
156	8	7.77	7.00	141.4	10.83	25.5	11.5	7.25	0.355	0.023
157	8	5.98	5.00	94.9	10.88	25.5	11.5	7.20	0.479	0.000
158	8	4.86	12.00	252.8	10.86	25.5	11.5	7.22	0.398	0.015
159	8	6.02	10.00	208.5	10.83	25.5	11.5	7.25	0.369	0.015
160	8	6.45	9.00	185.9	10.76	25.5	11.5	7.32	0.370	0.031
161	8	5.91	8.00	163.8	10.80	25.5	11.5	7.28	0.407	0.012
162	8	6.70	7.00	141.6	10.88	25.5	11.5	7.20	0.389	0.000
163	8	5.19	5.00	94.9	10.88	25.5	11.5	7.20	0.526	0.000

(Sheet 4 of 4)

Table 4 (Concluded)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
38	1	7.53	10.00	213.7	12.08	15.3	9.2	8.14	0.354	0.239
39	1	8.54	10.00	213.3	12.02	15.3	9.2	8.20	0.329	0.390
40	1	8.49	9.00	191.1	12.11	15.3	9.2	8.11	0.338	0.359
41	1	4.89	5.00	92.9	10.56	15.3	9.2	9.66	0.740	0.000
42	1	5.91	5.00	92.9	10.56	15.3	9.2	9.66	0.653	0.002
43	1	6.10	5.00	92.9	10.56	15.3	9.2	9.66	0.640	0.000
44	1	5.62	7.00	138.1	10.55	15.3	9.2	9.67	0.592	0.002
45	1	6.75	7.00	138.1	10.56	15.3	9.2	9.66	0.523	0.008
46	1	7.16	7.00	138.1	10.55	15.3	9.2	9.67	0.504	0.018
47	1	5.62	8.00	160.0	10.56	15.3	9.2	9.66	0.563	0.008
48	1	6.77	8.00	160.0	10.54	15.3	9.2	9.68	0.498	0.026
49	1	7.48	8.00	159.8	10.52	15.3	9.2	9.70	0.468	0.038
50	1	6.24	9.00	181.6	10.54	15.3	9.2	9.69	0.505	0.026
51	1	7.23	9.00	182.2	10.64	15.3	9.2	9.58	0.452	0.050
52	1	8.37	9.00	181.8	10.58	15.3	9.2	9.65	0.413	0.078
53	1	6.38	10.00	202.8	10.50	15.3	9.2	9.73	0.481	0.016
54	1	7.41	10.00	203.3	10.56	15.3	9.2	9.66	0.432	0.054
55	1	8.01	10.00	203.3	10.56	15.3	9.2	9.66	0.410	0.066
56	1	5.31	12.00	246.0	10.56	15.3	9.2	9.66	0.507	0.014
57	1	6.79	12.00	245.6	10.50	15.3	9.2	9.72	0.433	0.072
58	1	7.03	12.00	246.0	10.55	15.3	9.2	9.67	0.421	0.106
59	1	8.38	9.00	185.7	11.20	15.3	9.2	9.02	0.384	0.165
60	1	5.34	5.00	96.8	12.18	15.3	9.2	8.05	0.574	0.000
61	1	7.84	7.00	144.8	12.13	15.3	9.2	8.10	0.391	0.064
62	1	8.74	10.00	213.6	12.07	15.3	9.2	8.15	0.321	0.357
63	1	7.77	12.00	258.8	12.07	15.3	9.2	8.15	0.326	0.331
64	1	5.09	5.00	92.9	10.58	15.3	9.2	9.65	0.719	0.000
65	1	7.69	8.00	160.0	10.56	15.3	9.2	9.66	0.457	0.116

Table 5

Test Conditions and Overtopping Rates for Group 5 Seawalls

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
66	2	5.91	5.00	94.9	11.38	*NA	NA	8.51	0.571	0.010
67	2	5.27	5.00	94.6	11.26	NA	NA	8.63	0.625	0.101
68	2	6.73	5.00	94.9	11.37	NA	NA	8.52	0.524	0.000
69	2	6.14	7.00	141.6	11.35	NA	NA	8.54	0.488	0.026
70	2	7.15	7.00	141.3	11.30	NA	NA	8.59	0.444	0.092
71	2	7.87	7.00	141.4	11.32	NA	NA	8.57	0.416	0.169
72	2	5.81	8.00	164.0	11.31	NA	NA	8.58	0.485	0.052
73	2	7.37	8.00	164.0	11.32	NA	NA	8.57	0.413	0.209
74	2	8.11	8.00	163.8	11.26	NA	NA	8.62	0.390	0.277
75	2	5.99	9.00	186.6	11.35	NA	NA	8.54	0.453	0.139
76	2	6.94	9.00	186.3	11.31	NA	NA	8.58	0.413	0.303
77	2	8.53	9.00	186.1	11.27	NA	NA	8.62	0.361	0.408
78	2	6.24	10.00	208.5	11.31	NA	NA	8.58	0.427	0.162
79	2	7.40	10.00	208.5	11.30	NA	NA	8.58	0.381	0.328
80	2	8.41	10.00	207.1	11.10	NA	NA	8.78	0.359	0.376
81	2	5.29	12.00	252.6	11.33	NA	NA	8.56	0.446	0.102
82	2	6.60	12.00	251.6	11.21	NA	NA	8.68	0.391	0.293
83	2	7.65	12.00	252.3	11.29	NA	NA	8.60	0.350	0.438
85	2	6.40	5.00	96.9	12.22	NA	NA	7.67	0.485	0.006
86	2	7.01	5.00	96.7	12.17	NA	NA	7.72	0.459	0.012
87	2	6.48	7.00	145.1	12.20	NA	NA	7.69	0.421	0.072
88	2	7.38	7.00	144.6	12.06	NA	NA	7.82	0.393	0.191
89	2	8.02	7.00	144.6	12.08	NA	NA	7.81	0.371	0.361
90	2	5.89	8.00	168.3	12.17	NA	NA	7.72	0.429	0.150
91	2	7.18	8.00	167.6	12.02	NA	NA	7.87	0.384	0.408
92	2	8.02	8.00	167.7	12.04	NA	NA	7.85	0.355	0.610
93	2	6.09	9.00	191.4	12.16	NA	NA	7.73	0.402	0.272
95	2	8.62	9.00	189.1	11.77	NA	NA	8.12	0.337	0.686
96	2	4.79	10.00	213.6	12.07	NA	NA	7.82	0.460	0.132
97	2	7.66	10.00	213.4	12.03	NA	NA	7.86	0.338	0.587
98	2	8.47	10.00	212.6	11.92	NA	NA	7.97	0.321	0.786
99	2	5.37	12.00	259.2	12.12	NA	NA	7.77	0.397	0.165
100	2	6.70	12.00	257.8	11.94	NA	NA	7.94	0.351	0.496
101	2	7.49	12.00	256.6	11.81	NA	NA	8.08	0.332	0.743

(Continued)

Table 5 (Concluded)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
102	2	7.51	9.00	187.4	11.49	NA	NA	8.40	0.383	0.564
104	2	8.49	7.00	144.4	12.02	NA	NA	7.86	0.360	0.350
105	2	5.26	5.00	92.9	10.58	NA	NA	9.31	0.680	0.000
106	2	6.05	5.00	92.9	10.57	NA	NA	9.32	0.620	0.014
107	2	6.22	5.00	92.9	10.56	NA	NA	9.33	0.609	0.000
108	2	5.64	7.00	138.7	10.69	NA	NA	9.20	0.561	0.018
109	2	6.80	7.00	138.3	10.61	NA	NA	9.28	0.500	0.030
110	2	7.23	7.00	137.7	10.47	NA	NA	9.42	0.488	0.064
111	2	7.11	7.00	137.9	10.50	NA	NA	9.38	0.491	0.064
112	2	7.77	8.00	159.7	10.50	NA	NA	9.38	0.441	0.147
113	2	6.76	8.00	159.7	10.49	NA	NA	9.40	0.484	0.090
114	2	5.67	8.00	159.7	10.49	NA	NA	9.40	0.545	0.042
115	2	6.37	9.00	178.7	10.08	NA	NA	9.81	0.507	0.068
117	2	7.19	9.00	181.6	10.54	NA	NA	9.35	0.443	0.163
118	2	8.10	9.00	181.2	10.46	NA	NA	9.42	0.413	0.169
119	2	7.73	8.00	159.7	10.49	NA	NA	9.40	0.443	0.170
120	2	6.32	10.00	203.3	10.56	NA	NA	9.33	0.464	0.090
121	2	7.57	10.00	198.7	9.92	NA	NA	9.97	0.443	0.162
122	2	8.16	9.00	182.3	10.65	NA	NA	9.24	0.402	0.256
123	2	8.11	10.00	202.2	10.41	NA	NA	9.48	0.400	0.230
124	2	5.19	12.00	246.5	10.61	NA	NA	9.28	0.494	0.000
125	2	6.42	12.00	246.0	10.56	NA	NA	9.33	0.431	0.265
126	2	6.95	12.00	245.1	10.46	NA	NA	9.43	0.414	0.251

Table 6

Test Conditions and Overtopping Rates for Group 6 Seawalls

Test No.	Config-uration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Free-Board F ft	Relative Free-board F'	Over-topping Rate Q cfs/ft
135	3	4.96	5.00	92.8	10.54	9.0	4.8	9.98	0.758	0.086
136	3	5.84	5.00	92.8	10.54	9.0	4.8	9.98	0.680	0.103
137	3	6.34	5.00	92.9	10.57	9.0	4.8	9.96	0.642	0.142
138	3	5.85	7.00	137.9	10.52	9.0	4.8	10.01	0.596	0.178
139	3	6.67	7.00	137.8	10.49	9.0	4.8	10.04	0.549	0.286
140	3	7.65	7.00	137.7	10.46	9.0	4.8	10.06	0.502	0.380
141	3	6.15	8.00	159.5	10.46	9.0	4.8	10.06	0.553	0.238
142	3	7.39	8.00	159.2	10.40	9.0	4.8	10.13	0.493	0.410
143	3	7.60	8.00	159.4	10.45	9.0	4.8	10.08	0.481	0.525
144	3	5.84	10.00	202.6	10.46	9.0	4.8	10.07	0.529	0.339
145	3	7.30	10.00	202.1	10.39	9.0	4.8	10.14	0.459	0.529
146	3	7.69	10.00	202.2	10.41	9.0	4.8	10.12	0.443	0.657
147	3	5.36	12.00	245.6	10.50	9.0	4.8	10.02	0.522	0.226
148	3	6.37	12.00	244.4	10.38	9.0	4.8	10.15	0.472	0.492
149	3	7.30	12.00	244.4	10.38	9.0	4.8	10.15	0.431	0.627
150	3	6.63	9.00	181.5	10.51	9.0	4.8	10.02	0.501	0.326
151	3	7.52	9.00	180.6	10.38	9.0	4.8	10.15	0.468	0.523
152	3	8.17	9.00	180.7	10.39	9.0	4.8	10.14	0.442	0.618
153	3	4.83	5.00	94.9	11.38	9.0	4.8	9.15	0.702	0.098
154	3	5.69	5.00	94.7	11.27	9.0	4.8	9.26	0.637	0.155
155	3	6.22	5.00	94.7	11.30	9.0	4.8	9.23	0.599	0.220
156	3	6.01	7.00	141.2	11.26	9.0	4.8	9.26	0.538	0.271
157	3	6.77	7.00	141.3	11.29	9.0	4.8	9.24	0.496	0.477
158	3	7.87	7.00	143.7	11.86	9.0	4.8	8.67	0.419	0.652
159	3	6.29	9.00	185.8	11.22	9.0	4.8	9.31	0.479	0.515
160	3	7.12	9.00	184.7	11.04	9.0	4.8	9.49	0.450	0.762
161	3	8.60	9.00	185.4	11.16	9.0	4.8	9.37	0.391	1.010
162	3	4.70	5.00	90.6	9.70	9.0	4.8	10.82	0.859	0.045
163	3	6.08	5.00	90.9	9.78	9.0	4.8	10.74	0.718	0.086
164	3	6.75	8.00	155.2	9.68	9.0	4.8	10.85	0.565	0.162
165	3	8.98	8.00	155.5	9.72	9.0	4.8	10.81	0.465	0.320
166	3	8.77	9.00	176.5	9.74	9.0	4.8	10.79	0.452	0.311
167	3	10.10	9.00	176.1	9.66	9.0	4.8	10.86	0.415	0.392
168	3	7.99	10.00	197.0	9.68	9.0	4.8	10.85	0.467	0.193

(Continued)

Table 6 (Concluded)

Test No.	Config-uration No.	Wave Height Hmo ft	Wave Period Tp sec	Wave Length Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height hB ft	Free-Board F ft	Relative Free-board F'	Over-topping Rate Q cfs/ft
169	3	9.01	12.00	238.5	9.70	9.0	4.8	10.82	0.403	0.362
170	3	7.15	12.00	239.1	9.77	9.0	4.8	10.76	0.467	0.150
171	3	10.11	10.00	197.3	9.73	9.0	4.8	10.80	0.397	0.368

Table 7

Test Conditions and Overtopping Rates for Group 7 Seawalls

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec.	Wave Leight Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height Wb ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
1	1	4.61	6.0	99.6	8.04	*NA	NA	5.83	0.454	0.079
2	1	4.24	5.2	85.6	8.12	NA	NA	5.75	0.498	0.050
3	1	3.14	5.3	86.1	8.22	NA	NA	5.65	0.596	0.001
4	1	2.13	4.8	76.7	8.25	NA	NA	5.62	0.798	0.000
5	1	2.57	6.9	116.4	8.17	NA	NA	5.70	0.623	0.000
6	1	4.01	7.1	119.9	8.12	NA	NA	5.75	0.462	0.089
7	1	5.03	7.3	124.0	8.09	NA	NA	5.78	0.395	0.267
8	1	6.20	7.6	129.8	8.30	NA	NA	5.57	0.326	0.504
9	1	2.82	7.7	131.4	8.36	NA	NA	5.51	0.544	0.013
10	1	4.46	7.7	131.3	8.29	NA	NA	5.58	0.406	0.170
11	1	5.74	7.6	130.0	8.30	NA	NA	5.57	0.343	0.494
12	1	6.10	7.8	132.7	8.42	NA	NA	5.45	0.320	0.599
13	1	4.21	9.1	156.4	8.36	NA	NA	5.51	0.392	0.153
14	1	5.70	8.6	147.8	8.32	NA	NA	5.55	0.329	0.500
15	1	6.24	8.6	147.8	8.53	NA	NA	5.34	0.298	0.804
16	1	6.23	10.4	180.5	8.63	NA	NA	5.24	0.274	1.224
17	1	3.23	10.1	174.4	8.26	NA	NA	5.61	0.459	0.064
18	1	5.04	10.1	174.4	8.24	NA	NA	5.63	0.343	0.443
19	1	6.04	10.1	174.4	8.27	NA	NA	5.60	0.302	0.636
20	1	5.99	10.6	184.3	8.49	NA	NA	5.38	0.287	0.906
21	1	3.69	11.8	205.4	8.32	NA	NA	5.55	0.394	0.001
22	1	5.23	11.4	198.0	8.47	NA	NA	5.40	0.307	0.625
23	1	5.68	12.5	218.6	8.61	NA	NA	5.26	0.274	1.045
24	1	5.89	12.1	209.8	8.77	NA	NA	5.10	0.263	1.202
25	1	3.68	12.6	220.2	8.28	NA	NA	5.59	0.388	0.256
26	1	5.19	12.3	214.9	8.25	NA	NA	5.62	0.313	1.107
27	1	5.70	14.4	252.6	8.36	NA	NA	5.51	0.273	1.160
28	1	5.82	14.7	256.9	8.49	NA	NA	5.38	0.261	1.698
29	1	2.90	5.2	83.6	7.55	NA	NA	6.32	0.711	0.000
30	1	4.13	5.2	83.6	7.47	NA	NA	6.40	0.568	0.015
31	1	4.84	6.0	96.9	7.48	NA	NA	6.39	0.486	0.050
32	1	5.05	6.0	96.9	7.48	NA	NA	6.39	0.473	0.091
33	1	2.89	6.9	113.2	7.79	NA	NA	6.08	0.619	0.000
34	1	4.40	7.1	116.6	7.72	NA	NA	6.15	0.469	0.051
35	1	5.60	7.1	116.6	7.79	NA	NA	6.08	0.395	0.174

(Continued)

Table 7 (Concluded)

Test No.	Configuration No.	Wave Height Hmo ft	Wave Period Tp sec.	Wave Leight Lp ft	Depth At Toe ds ft	Berm Width WB ft	Berm Height Wb ft	Freeboard F ft	Relative Freeboard F'	Overtopping Rate Q cfs/ft
36	1	5.96	7.7	127.2	7.85	NA	NA	6.02	0.364	0.253
37	1	4.47	8.3	139.0	7.82	NA	NA	6.05	0.431	0.153
38	1	5.65	8.3	137.4	7.86	NA	NA	6.01	0.368	0.297
39	1	5.97	7.8	129.0	7.92	NA	NA	5.95	0.358	0.397
40	1	4.98	9.1	151.9	7.86	NA	NA	6.01	0.386	0.221
41	1	5.82	8.6	143.6	7.75	NA	NA	6.12	0.361	0.455
42	1	5.97	10.3	173.9	7.86	NA	NA	6.01	0.327	0.316
43	1	4.85	10.1	169.4	7.68	NA	NA	6.19	0.391	0.259
44	1	5.71	10.1	169.4	7.79	NA	NA	6.08	0.344	0.516
45	1	5.79	10.6	179.0	7.90	NA	NA	5.97	0.329	0.610
46	1	5.02	11.8	199.0	7.73	NA	NA	6.14	0.358	0.269
47	1	5.48	12.1	203.7	7.90	NA	NA	5.97	0.327	0.623
48	1	5.59	12.1	203.7	8.05	NA	NA	5.82	0.314	1.130
49	1	4.85	12.8	215.9	7.72	NA	NA	6.15	0.358	0.415
50	1	5.23	14.7	249.4	7.90	NA	NA	5.97	0.315	0.713
51	1	5.35	14.7	249.4	8.05	NA	NA	5.82	0.302	0.850
52	1	3.35	5.3	77.5	6.21	NA	NA	7.66	0.803	0.000
53	1	4.32	5.2	77.3	6.25	NA	NA	7.62	0.674	0.009
54	1	4.68	6.0	89.3	6.18	NA	NA	7.69	0.615	0.009
55	1	4.42	7.1	107.1	6.11	NA	NA	7.76	0.607	0.001
56	1	5.27	7.1	107.1	6.16	NA	NA	7.71	0.536	0.037
57	1	5.37	8.0	122.2	6.29	NA	NA	7.58	0.498	0.064
58	1	4.48	8.4	128.1	6.19	NA	NA	7.68	0.560	0.018
59	1	4.66	8.4	128.1	6.28	NA	NA	7.59	0.539	0.001
60	1	4.73	8.5	129.2	6.38	NA	NA	7.49	0.526	0.019
61	1	4.87	8.6	131.0	6.20	NA	NA	7.67	0.526	0.000
62	1	5.38	8.7	134.0	6.32	NA	NA	7.55	0.480	0.044
63	1	5.46	9.7	149.4	6.46	NA	NA	7.41	0.450	0.059
64	1	4.79	9.9	151.5	6.21	NA	NA	7.66	0.505	0.023
65	1	5.22	11.5	178.0	6.34	NA	NA	7.53	0.445	0.082
66	1	5.34	11.5	178.0	6.47	NA	NA	7.40	0.431	0.121
67	1	4.19	11.8	182.1	6.17	NA	NA	7.70	0.523	0.045
68	1	4.39	12.1	186.4	6.37	NH	NA	7.50	0.490	0.078

* NOT APPLICABLE

PART III: DISCUSSION

Basic Overtopping Equation

22. Using a simplified theoretical analysis, Jensen and Juhl (1987) determined that a reasonable conceptual model for wave overtopping rate Q and dimensionless freeboard F' for breakwaters could be described by a simple exponential relationship of the form

$$Q = Q_o \exp(C_1 F') \qquad (1)$$

where Q_o and C_1 are determined from regression analysis, and dimensionless freeboard is defined as

$$F' = F/H_s \qquad (2)$$

where F is freeboard (vertical distance from still-water level (SWL) to top of structure), and H_s is incident significant wave height.

23. Although the analysis in Jensen and Juhl (1987) was based on laboratory data for breakwaters, the data included breakwaters with crown-walls, which are hydraulically similar to seawalls with revetments. It is interesting that Owen (1980, 1982a, 1982b) used a nondimensional equation of the same basic form as Equation 1, and Jensen reported overtopping rates in nondimensional form in an earlier paper (Jensen 1984). However, Jensen and Juhl (1987) were unable to determine a nondimensional form that worked well for all configurations tested, and therefore used a dimensional overtopping rate. Similarly, Ahrens and Heimbaugh (1988) were unable to normalize Q to improve correlation over use of a dimensional Q for all seawall configurations tested with Equation 1.

24. One advantage of using a dimensional overtopping rate is that it allows easy correlation with potentials for flooding or structural damage such as those tabulated in Fukuda, Uno, and Irie (1974) or Goda (1985). Fukuda, Uno, and Irie measured and filmed waves overtopping coastal structures during severe storms. The films then were shown to a panel of coastal experts who determined the degree of danger posed by the overtopping to a person, a car, or a house located 10 ft behind the structure. Averaging the results of the panel, it was determined that overtopping rates greater than 0.002 cfs/ft were dangerous for a walking person, greater than 0.0002 cfs/ft would prohibit a

vehicle from driving past at high speed, and damage to a house could be expected at overtopping rates greater than 0.0007 cfs/ft. These rates could be increased by a factor of 10 for a location 30 ft behind the structure. Goda studied storm damage to coastal structures and found that overtopping rates in excess of 0.5 cfs/ft were dangerous to structures with concrete sides and crest.

25. Ahrens and Heimbaugh (1988) defined dimensionless freeboard as

$$F' = F/(H_{mo}^2 L_p)^{1/3} \tag{3}$$

where H_{mo} is zeroth moment wave height measured near the toe (groups 1 through 6) or at the toe (group 7), and L_p is local wavelength at the toe of the structure calculated from linear wave theory using depth of water at the toe (d_s) and incident wave period of peak energy (T_p). For all data groups except stepped seawalls (group 7), incident T_p was an assumed period based on the known peak period generated at the wave board, which was assumed constant in the wave flume. In the stepped seawall tests, incident T_p was determined from the three-gage array located across from the structure. F' is seen to be a ratio of structure freeboard to a form of wave severity.

26. Equation 3 is an efficient definition of relative freeboard because it includes information about water level, structure height, and wave conditions in just one term. An interesting and useful consequence of this definition is that it provides an easy reference to inundation of the structure. Observations made during the test runs indicated that as wave conditions became more severe for a given freeboard, the structure would become flooded and changes in structure geometry had little effect on overtopping rates. This inundation effect was observed with dimensionless freeboards less than 0.3.

27. Equation 1 was linearized for the regression analysis by taking the natural logarithm of each side, which tends to decrease the relative importance of tests with high overtopping rates. Also, measurements of overtopping volume have a greater percent error for low overtopping rates. A weight function was therefore employed to reflect the greater importance of tests which produced high overtopping rates. The weight function is defined as

$$\textit{weight function} = \int (Q \times 100) + 1 \tag{4}$$

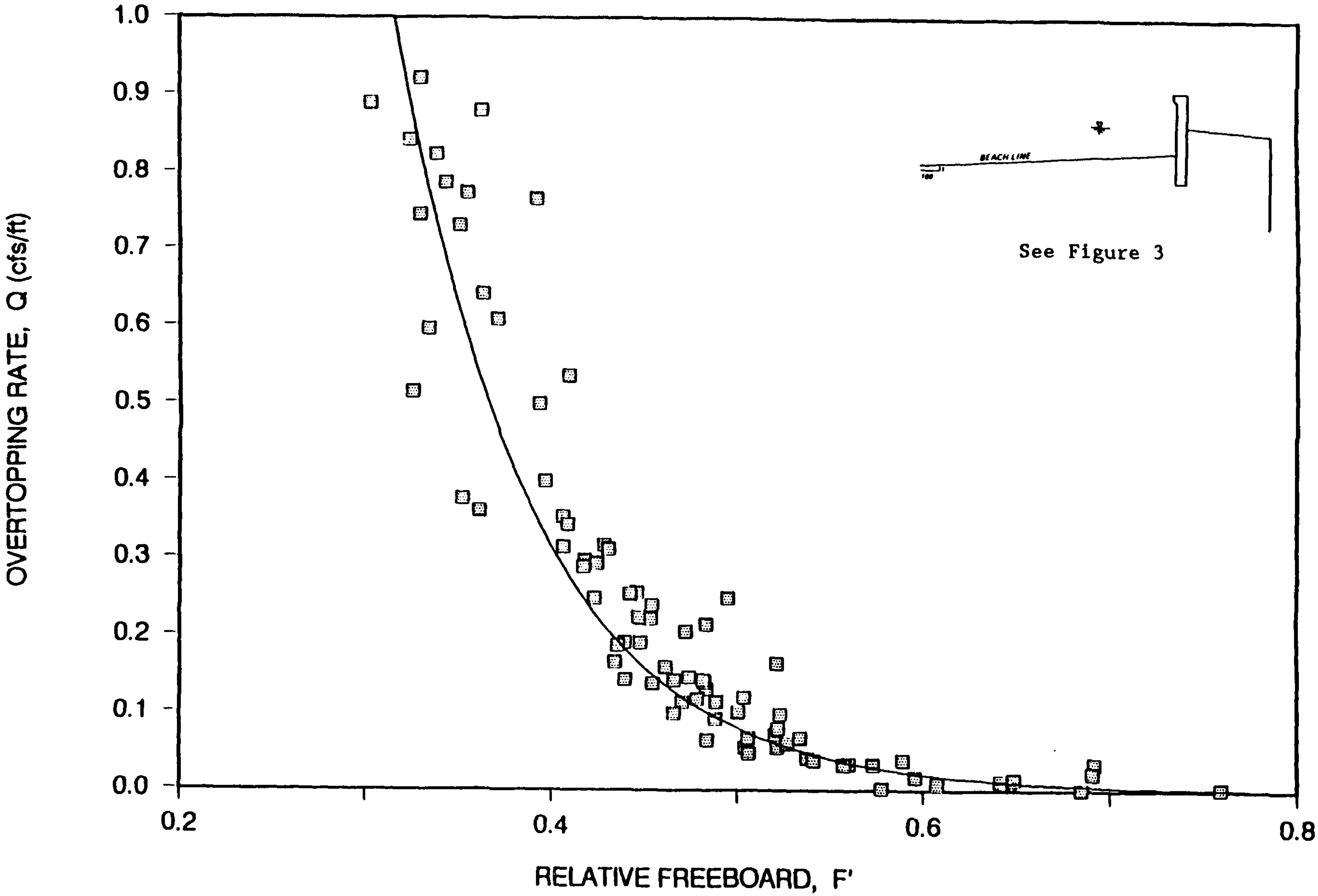


Figure 10. Regression curve and measured overtopping for group 1 seawalls

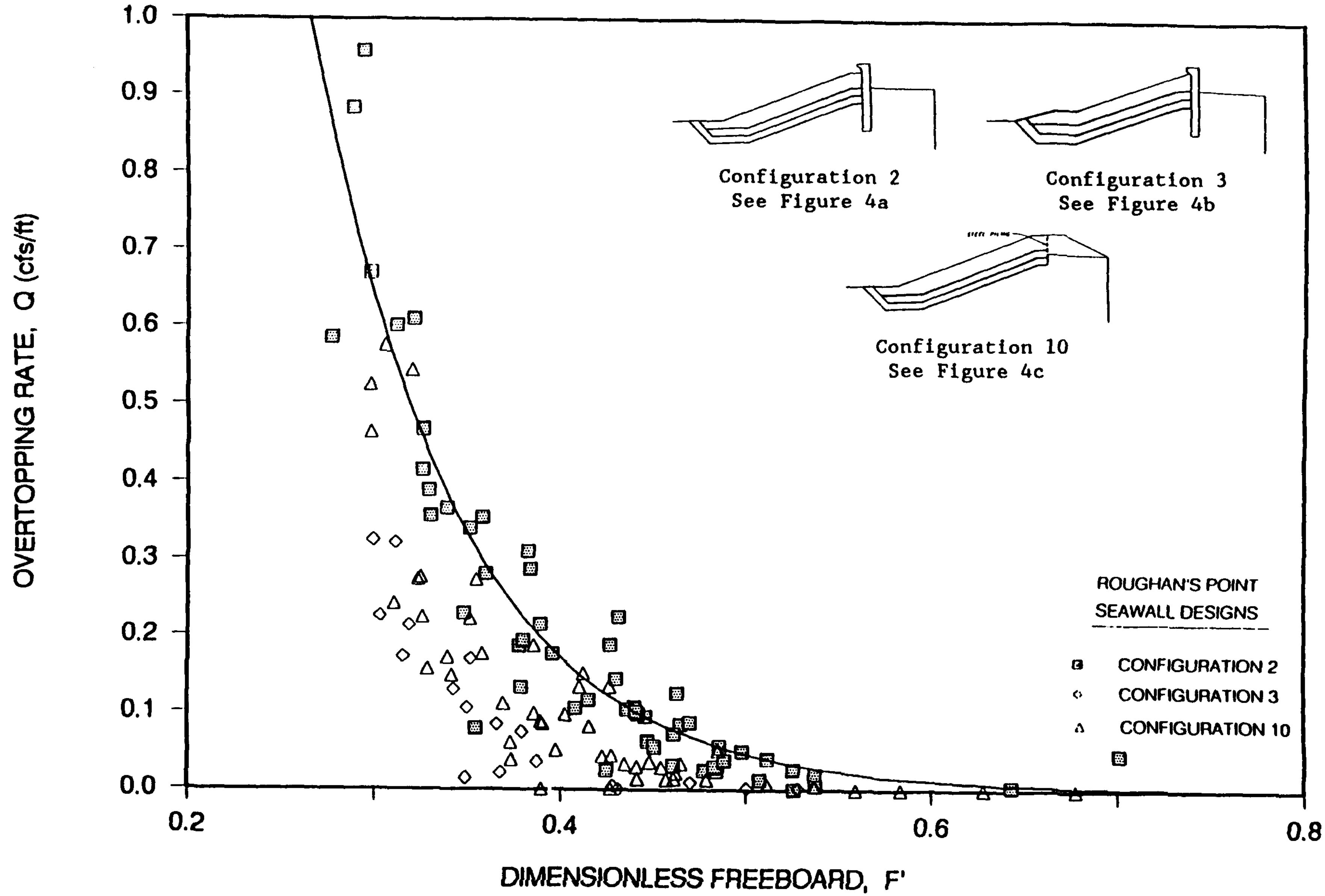


Figure 11. Regression curve and measured overtopping for group 2 seawalls

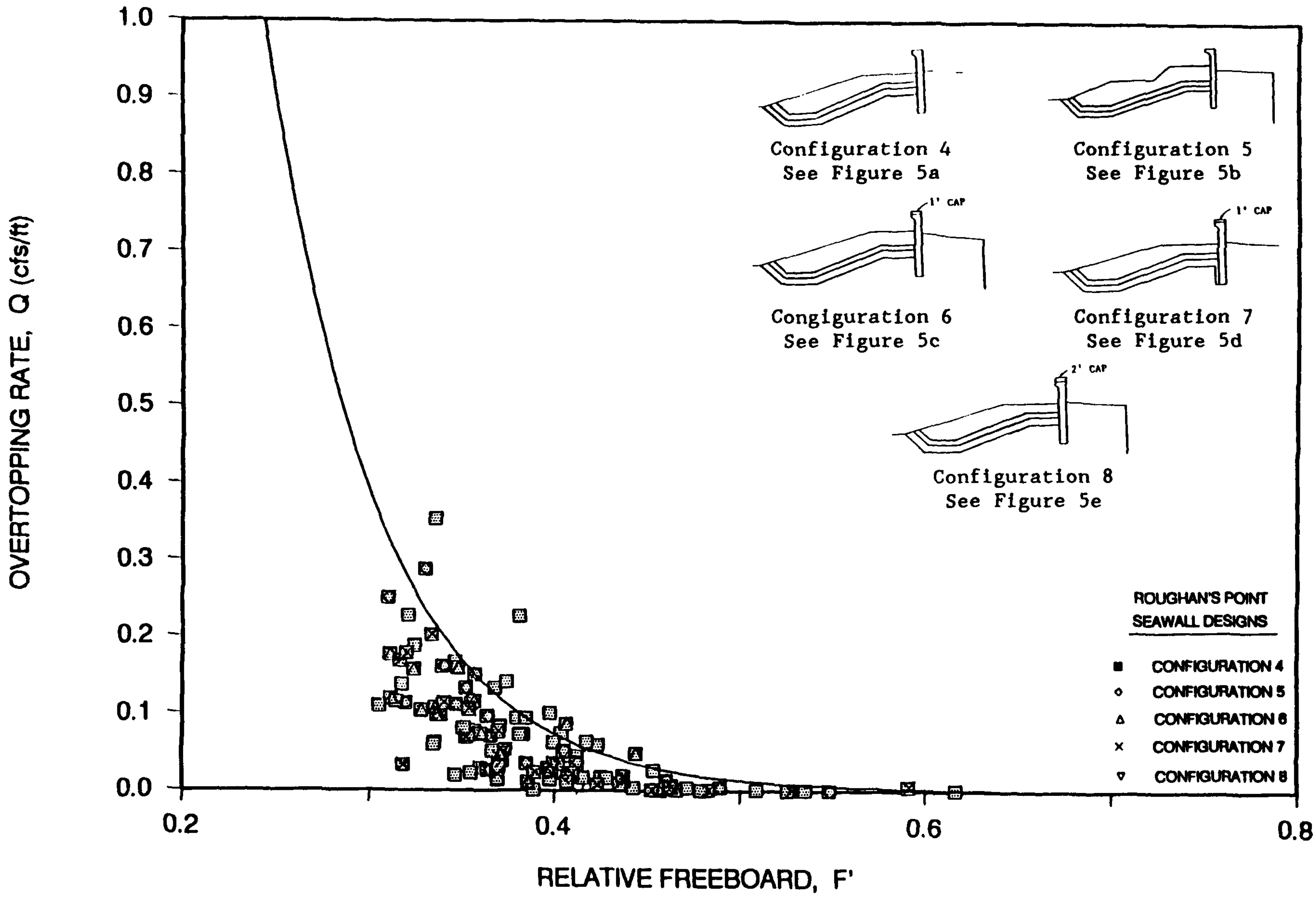


Figure 12. Regression curve and measured overtopping for group 3 seawalls

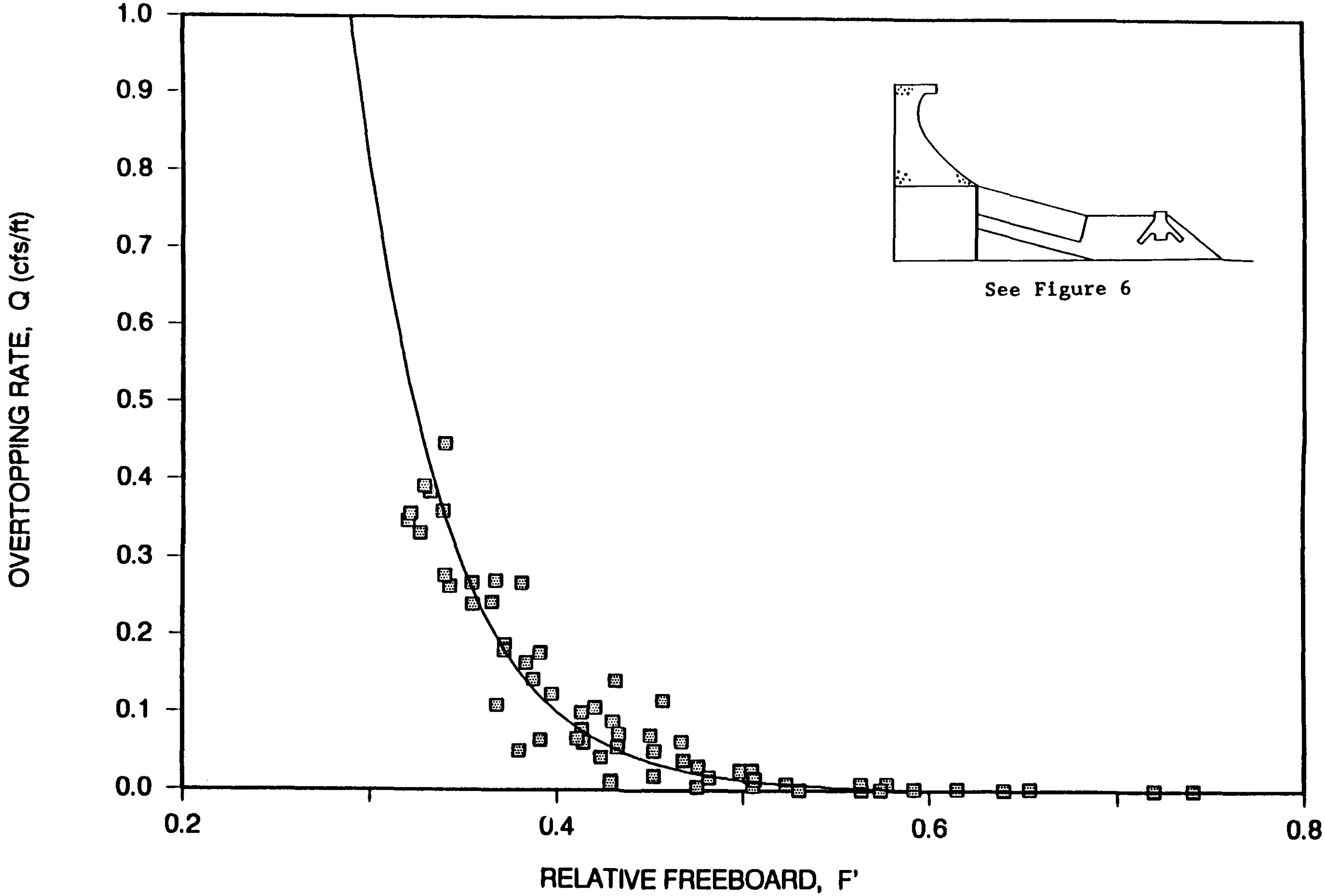


Figure 13. Regression curve and measured overtopping for group 4 seawalls

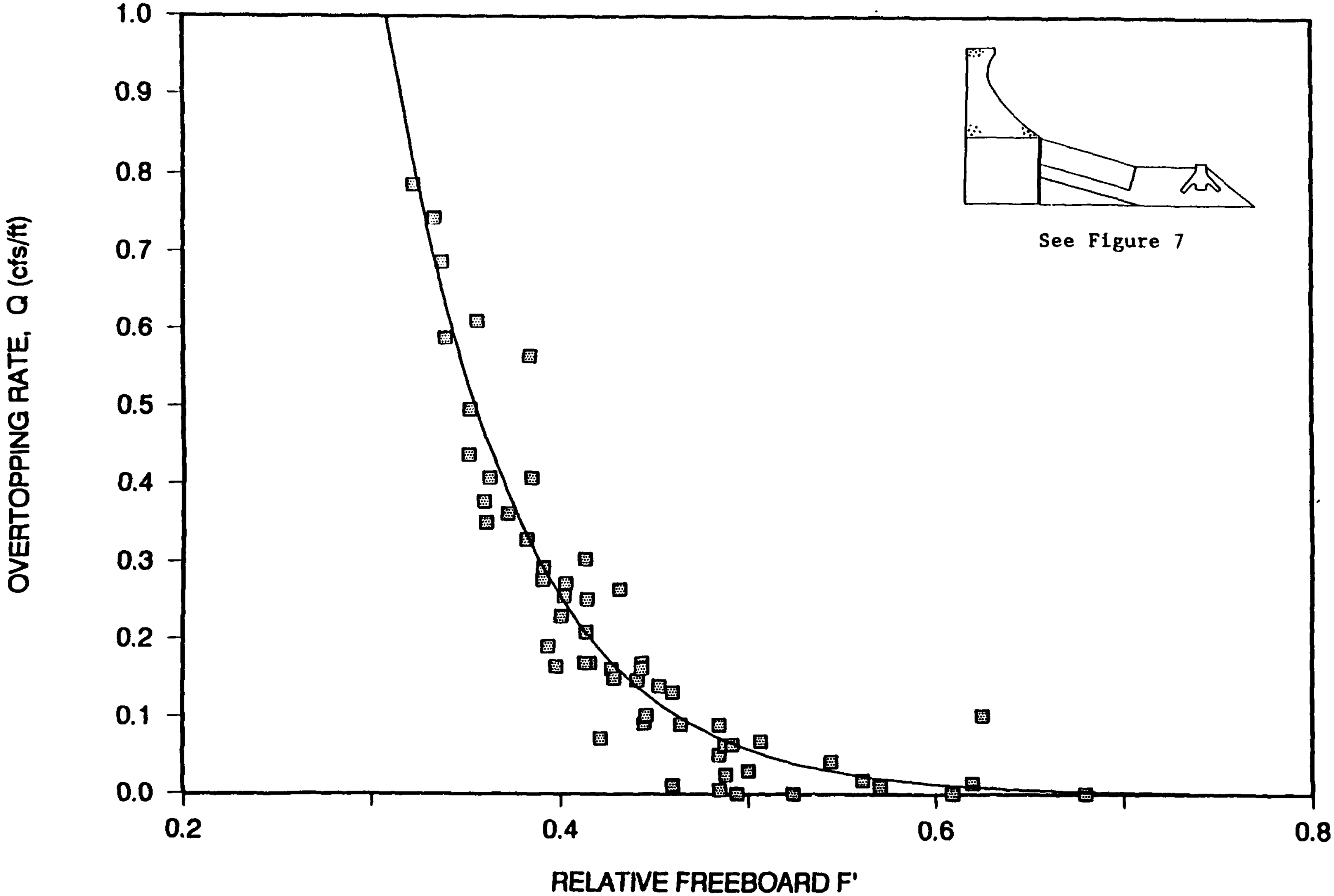


Figure 14. Regression curve and measured overtopping for group 5 seawalls

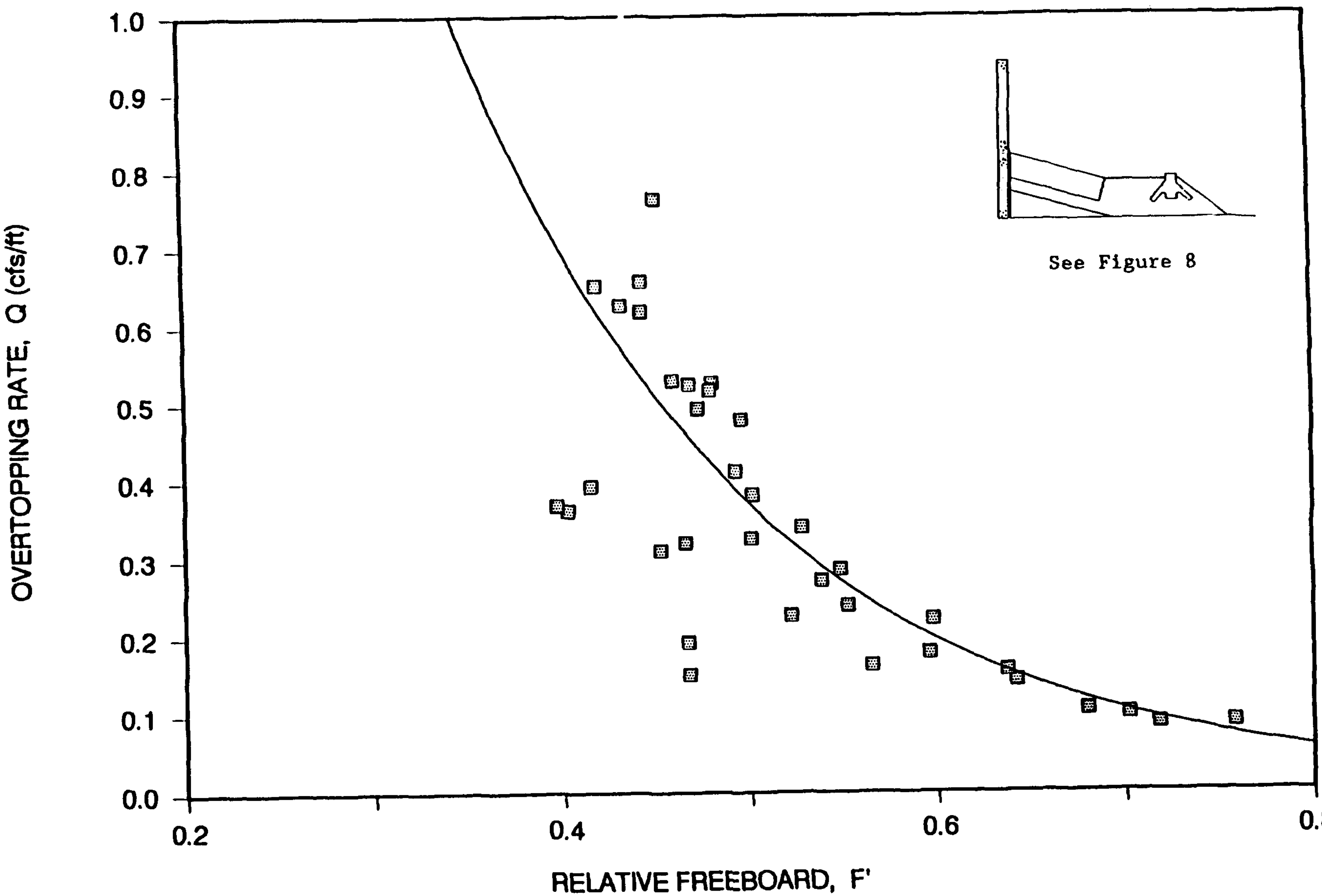


Figure 15. Regression curve and measured overtopping for group 6 seawalls

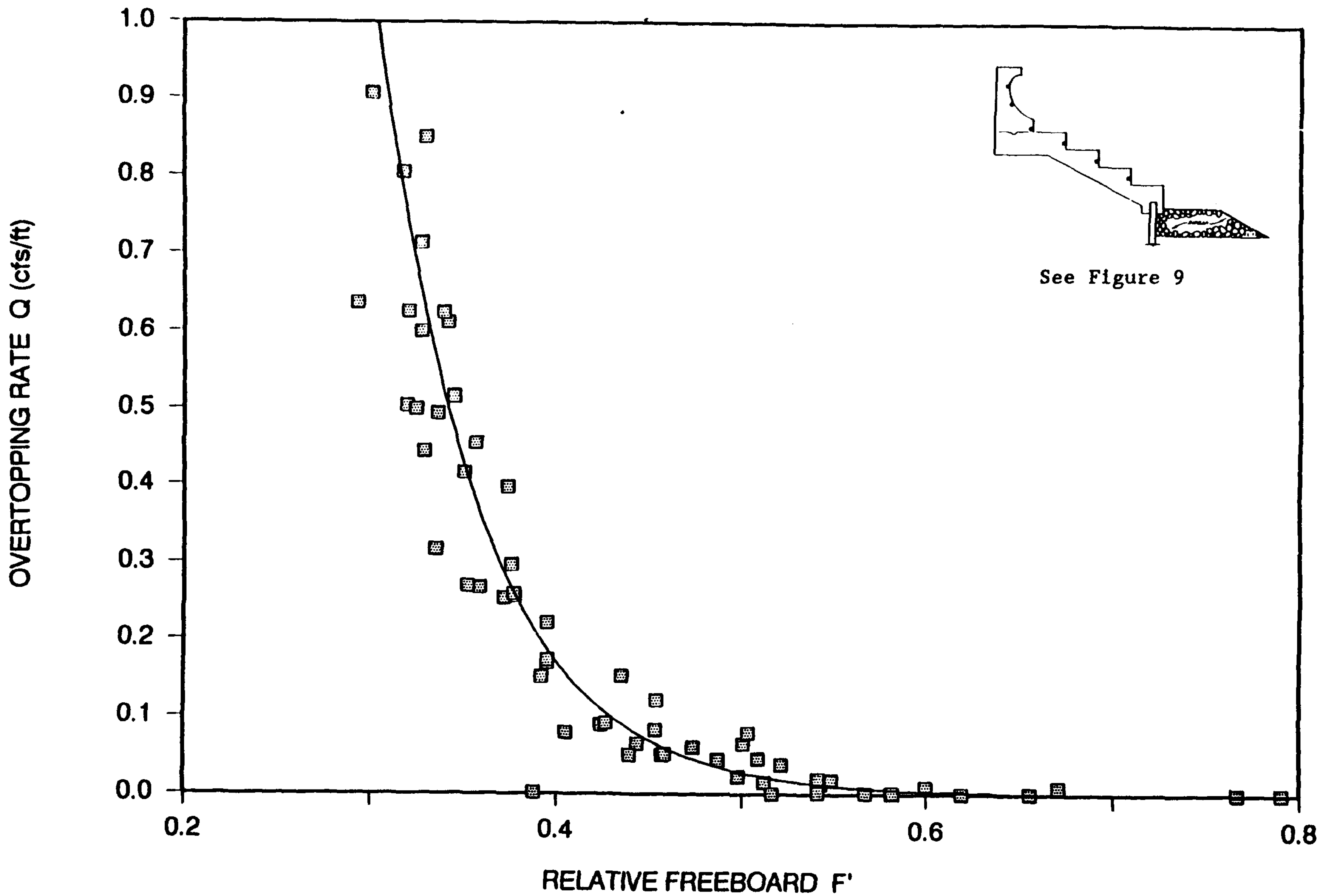


Figure 16. Regression curve and measured overtopping for group 7 seawalls

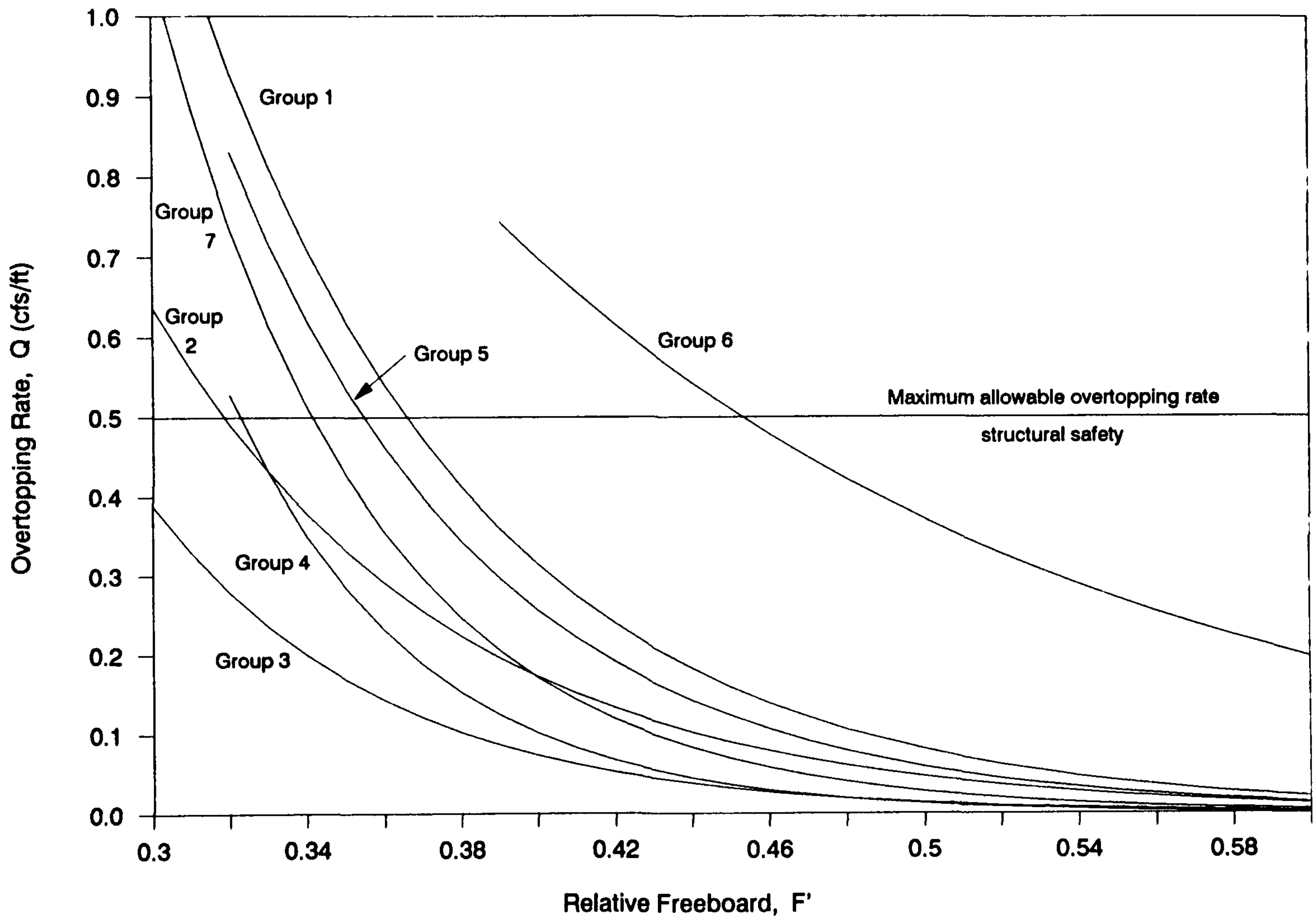


Figure 17. Comparison of regression curves for seawall groups 1 through 7

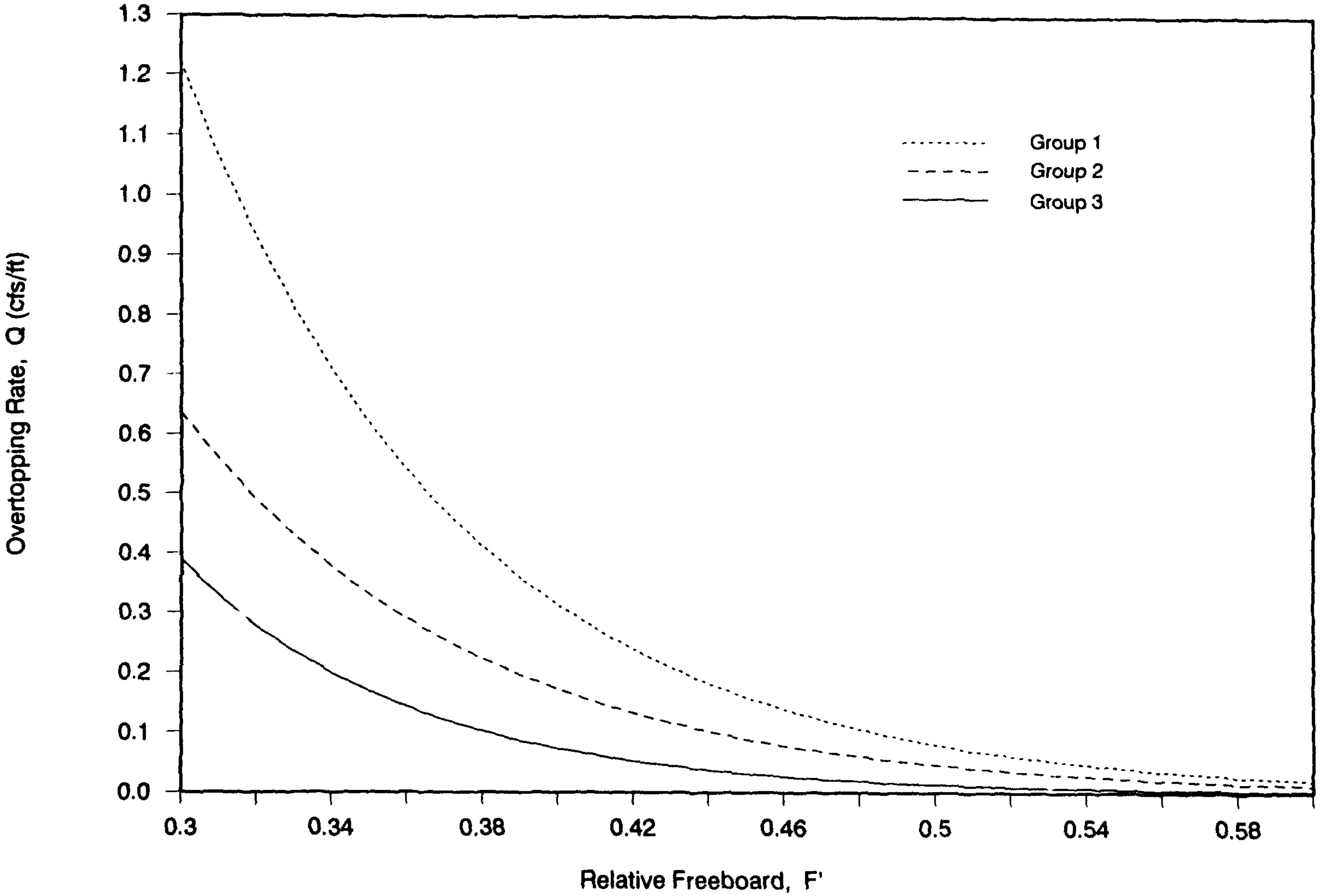


Figure 18. Effect of revetment in front of seawall

(group 1), a vertical seawall with a high revetment (group 2), and a vertical seawall with a berm revetment (group 3). The seawalls were all topped with a recurved parapet with the exception of one configuration in group 2 in which the revetment extended to the top of the seawall.

31. Dissipation of wave energy by a rubble revetment is very difficult to predict quantitatively due to the turbulent flow regime, nonlinear wave forms, and complicated boundary conditions. Several qualitative effects should be noted, however. As a wave runs up a revetment, the water penetrates into the rubble mound. Damping of wave energy occurs within the rubble due to friction with the rock surfaces, and expansion, contraction, and eddy diffusion losses due to irregularities in the interstices. Energy losses also occur along the surface of the rubble both from surface friction and the increase in turbulence caused by surface roughness. After the rubble has filled with water, a "ramp effect" occurs whereby succeeding wave bores may more readily flow up the revetment (Goda 1985) although mixing within the rubble continues due to penetration of wave energy into the rubble.

32. In Figure 18, it is clear that revetments aid in the dissipation of wave energy, as expected. Less obvious, however, are the comparative effects of a wide bermed revetment versus a higher revetment without a berm. While both revetments may contain similar quantities of stone, the bermed revetment was found in these tests to reduce overtopping more effectively than the high revetment. Clearly, runup reaching the top of the high revetment flowed over the seawall, as the revetment extended to the top of the seawall. The berm revetment was lower and more water reached the top of the revetment, but overtopping was impeded by the portion of the seawall extending higher than the revetment.

Effect of Recurve on Seawalls

33. Figure 19 illustrates overtopping rates based on Equation 1 for the three configurations of the Cape Hatteras study (Grace and Carver 1985; Ahrens 1988) reported herein as groups 4, 5, and 6, and the stepped seawall with recurve used in the Virginia Beach study (Heimbaugh et al. 1988) and reported herein as group 7. The revetment fronting the Cape Hatteras seawalls was the same for each group, but group 4 had a recurved seawall with overhang, group 5 had the same recurved seawall but without the overhang, and group 6 was just a

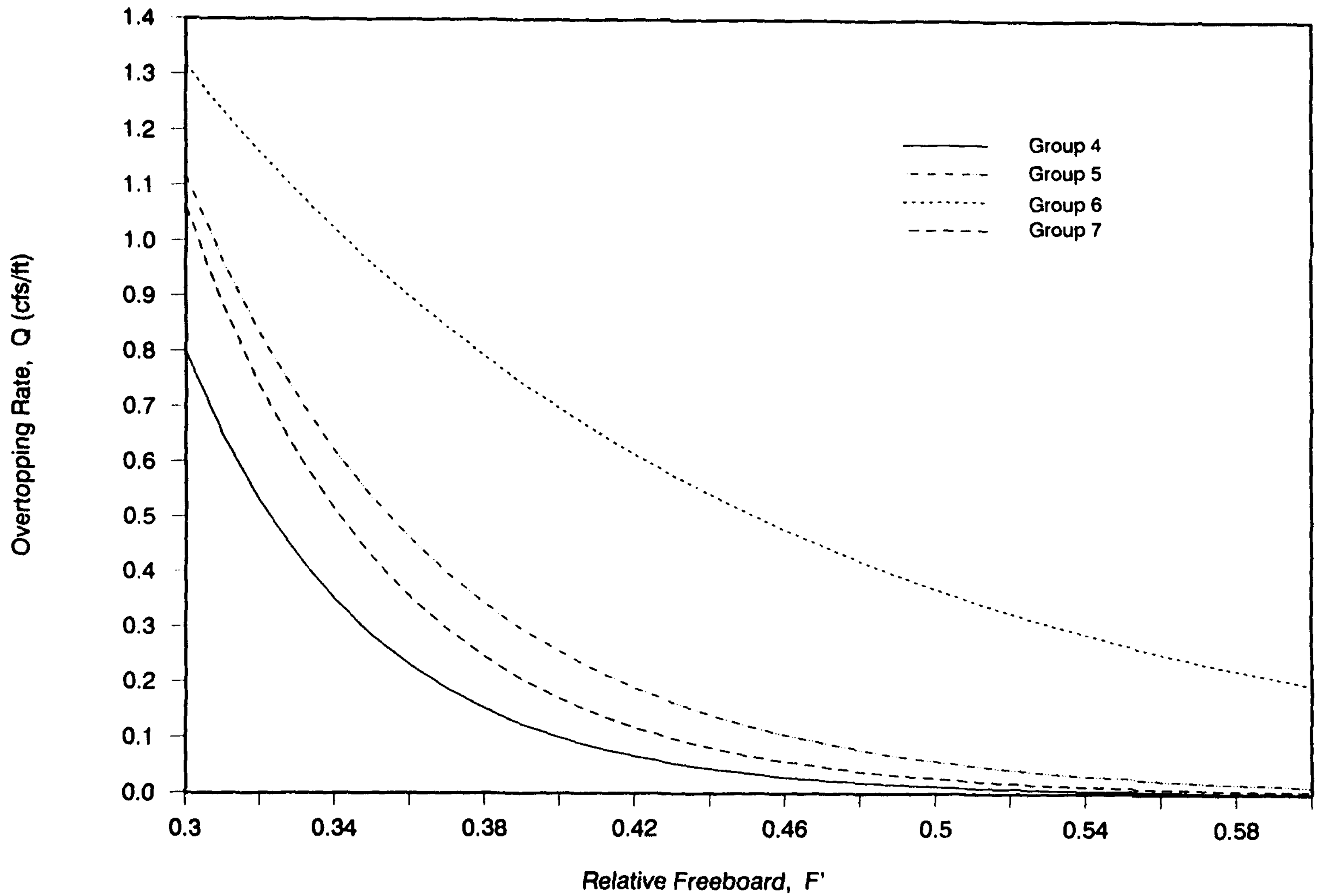


Figure 19. Effect of recurve on seawall

vertical wall. The group 7 seawall was similar to group 4 (with the overhang), but used a smaller revetment and added a series of steps between the revetment and the recurve.

34. The improvement in use of a recurved seawall over a vertical wall is obvious in Figure 19. The addition of the overhang on group 4 also substantially reduced the quantity of overtopping. Both the recurve and the overhang were effective at impeding the horizontal, shoreward progression of wave energy by redirecting the energy vertically and/or seaward.

35. Figure 19 also compares the effectiveness of the large revetment in group 4 to the small revetment and steps in group 7. Although it is difficult to make direct comparisons due to differences in configuration of the recurves, it appears that the larger revetment is more effective at dissipating wave energy than the stepped seawall. A stepped seawall is intended to dissipate energy by disrupting the runup and increasing losses due to turbulence. Observations made during testing of the stepped seawall indicated the steps may have been too small to effectively disrupt the flow, therefore the stepped seawall may have compared more favorably if larger steps had been tested. Revetments have an advantage over steps in that the stones not only disrupt flow along the surface of the revetment, but wave energy is also damped within the rubble mound.

Improved Model

36. Equation 1 is recommended for its ease of use and ready correlation to tabulated values of inundation and damage. However, improved regression correlation was obtained by using an equation of the form

$$Q' = Q_o' \exp(C_1 F' + C_2 X) \tag{5}$$

where Q_o' and C_2 are dimensionless regression coefficients, X may be any of several dimensionless variables which improve the predictive ability of the model, and Q' is a dimensionless overtopping rate defined as

$$Q' = Q/\sqrt{(g * H_{mo}3)} \tag{6}$$

where g is gravitational acceleration, and other terms were defined for Equation 1. Many different terms were tried for X and the terms that offered the best correlation coefficients are listed in Table 9. By comparing

Table 9

Regression Coefficients, Secondary Variables, and Correlation Coefficients for Seawall Groups 1 Through 7

Group No.	X	Q_o'	C_1	C_2	Correlation Coefficient
1	F/d_s	0.338	- 7.385	- 2.178	0.923
2	$(H_{mo}/L_o)^{1/2}$	0.308	-10.732	- 6.629	0.794
3	$(H_{mo}/L_o)^{1/2}$	1.000	-14.371	-11.411	0.841
4	W_B/L_p	1.000	-12.690	-20.870	0.943
5	$(H_{mo}/L_o)^{1/2}$	0.541	-11.702	- 5.771	0.947
6	H_{mo}/D_B	1.000	- 7.558	- 1.366	0.918
7	$(H_{mo}/L_o)^{1/2}$	1.000	-11.174	-10.664	0.948

the correlation coefficients in Table 9 for the improved model to the correlation coefficients in Table 8 for the basic model, the improvement offered by this model is evident. Only data sets 2 and 3 have correlation coefficients less than 0.9, which is reasonable considering the range of structure configurations included in these two groups.

37. In four of the data sets, a wave steepness parameter was chosen for the secondary variable, defined by

$$X = (H_{mo}/L_o)^{1/2} \tag{7}$$

where L_o is deepwater Airy wavelength based on the wave period of peak energy. The influence of wave steepness indicates that surf conditions play an important role in the runup and overtopping of these structures. For two of the data sets (4 and 6), the rubble berm plays an important role, as indicated by the secondary variables. For data sets 4 and 6, the secondary variables that best improved the correlation between observed and predicted values were W_B/L_p and H_{mo}/d_B, respectively, where W_B is berm width and d_B is water depth over the berm. It was found that if water depth over the berm was small, then changes in water depth were quite important (data set 6), but for deeper water the berm width was more critical (data set 4).

38. Figures 20 through 26 illustrate dimensionless overtopping rates for a range of freeboards for each of the seven data groups. The three curves

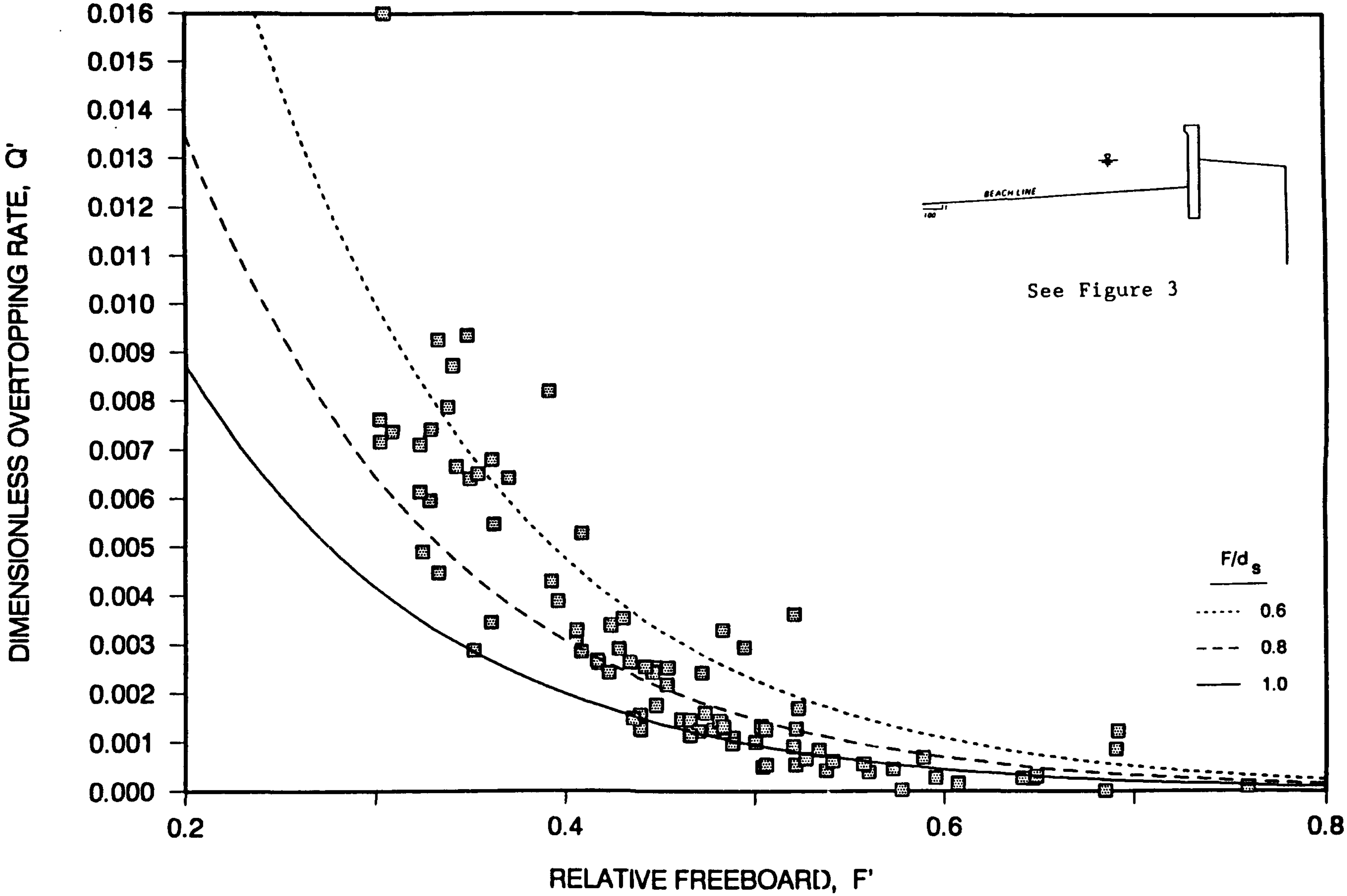


Figure 20. Group 1 measured overtopping and regression curves for improved overtopping model

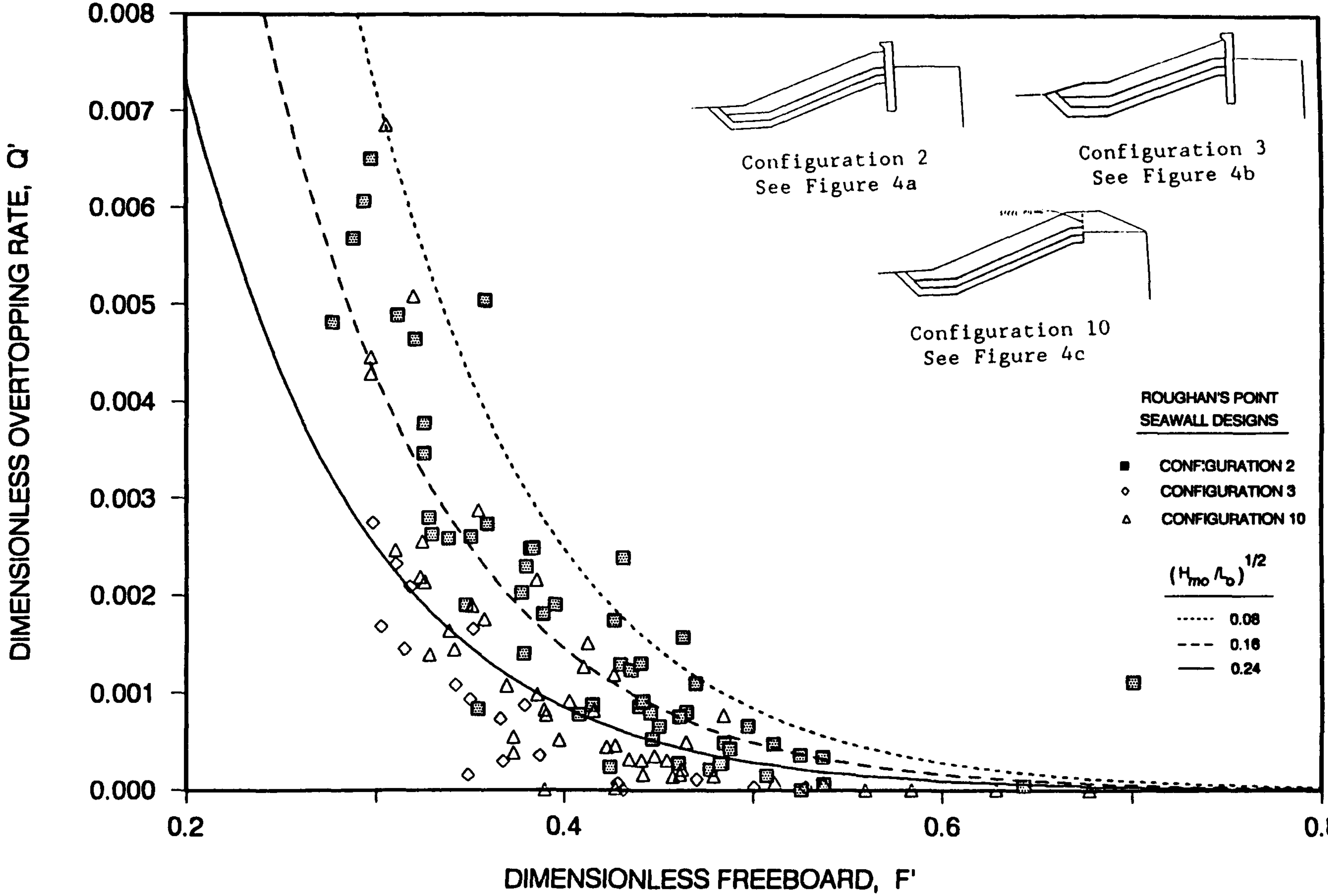


Figure 21. Group 2 measured overtopping and regression curves for improved overtopping model

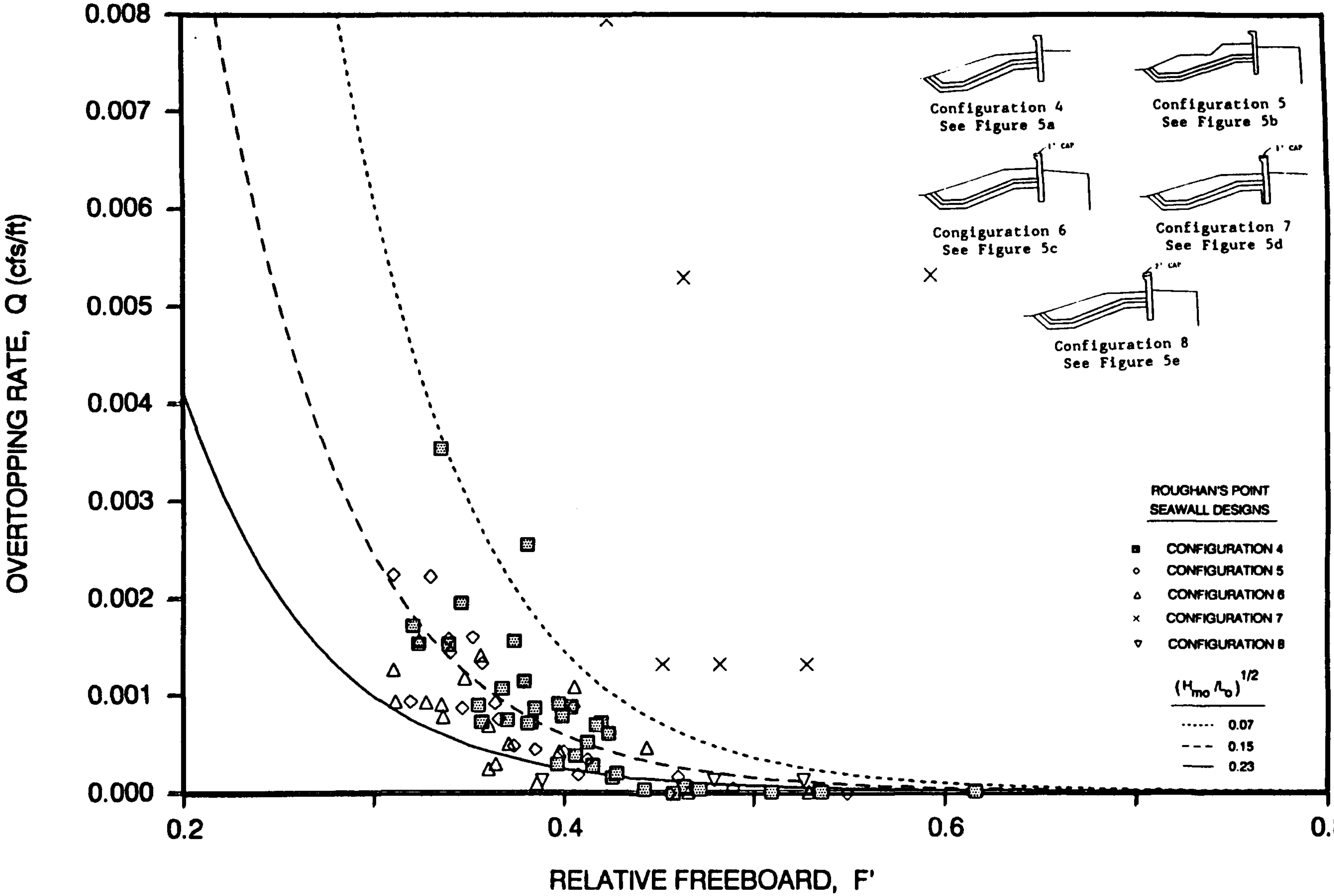


Figure 22. Group 3 measured overtopping and regression curves for improved overtopping model

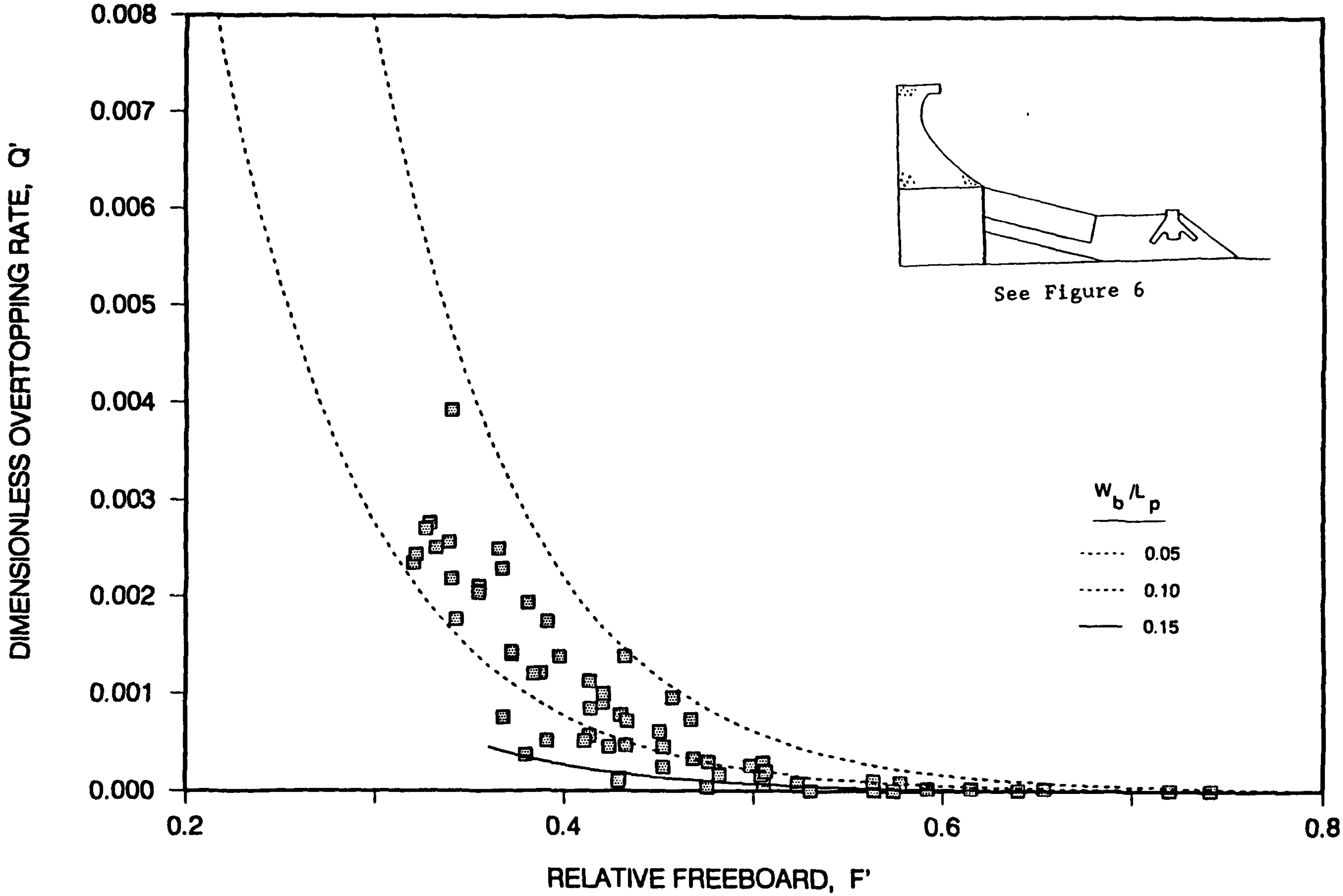


Figure 23. Group 4 measured overtopping and regression curves for improved overtopping model

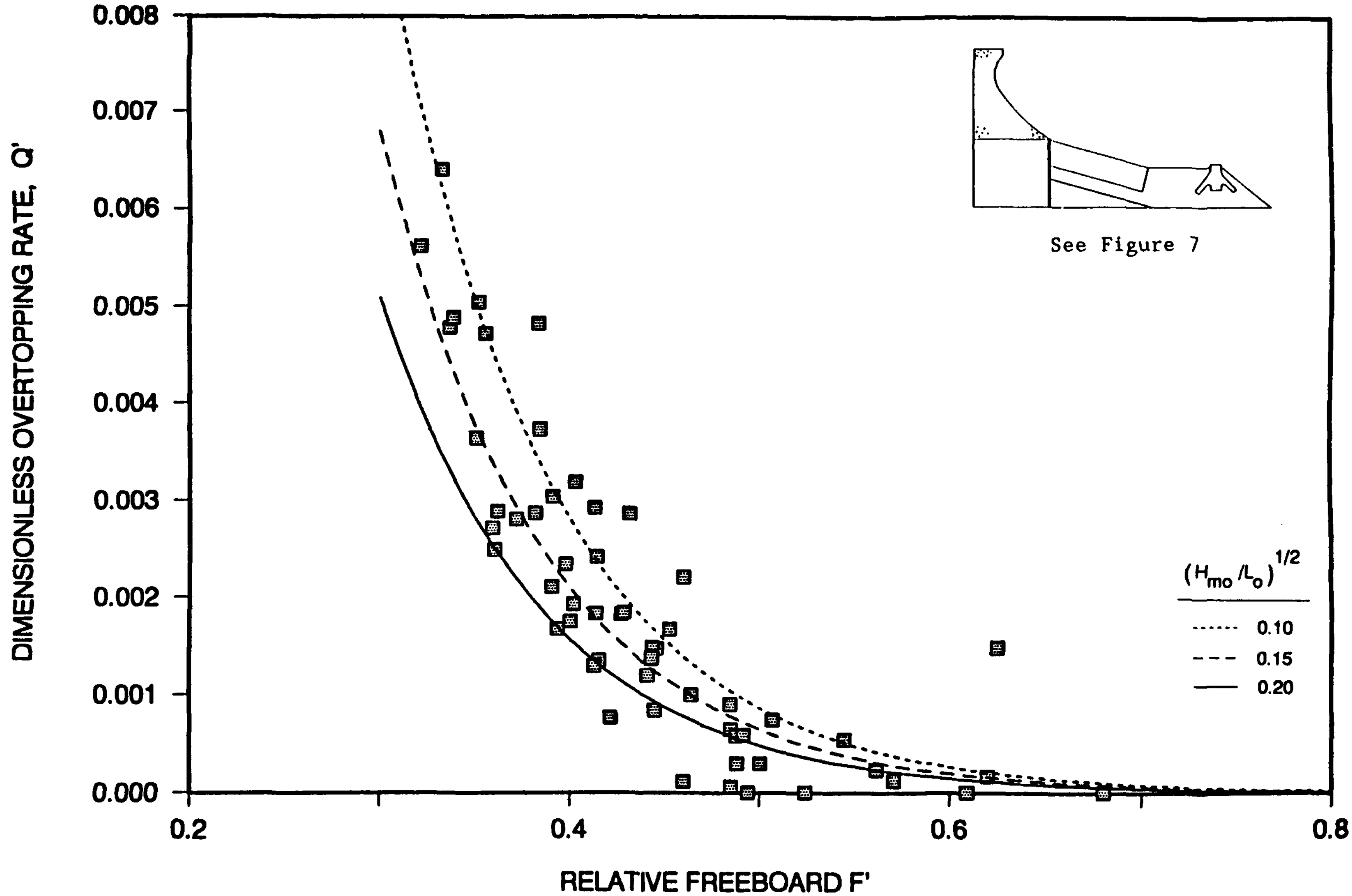


Figure 24. Group 5 measured overtopping and regression curves for improved overtopping model

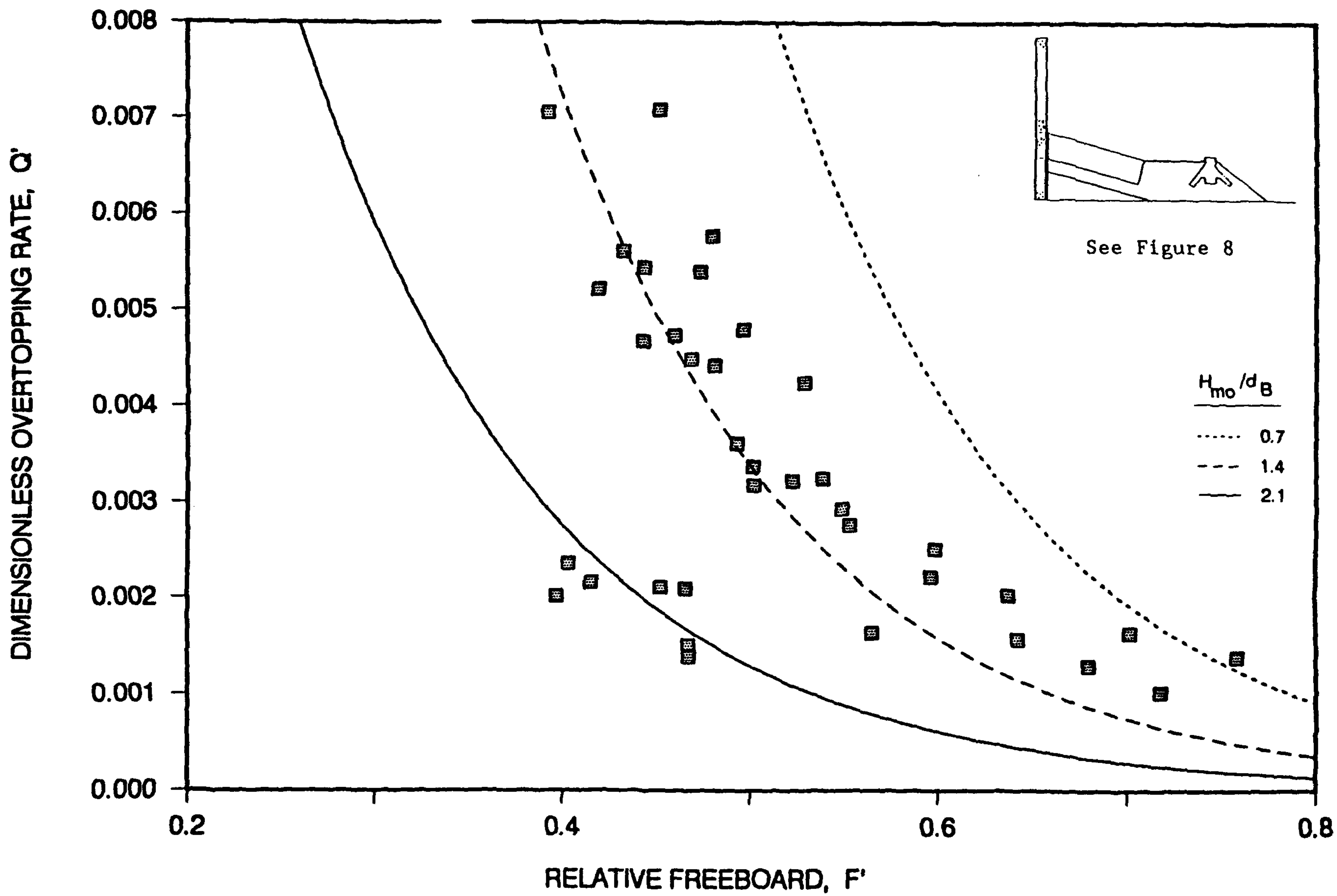


Figure 25. Group 6 measured overtopping and regression curves for improved overtopping model

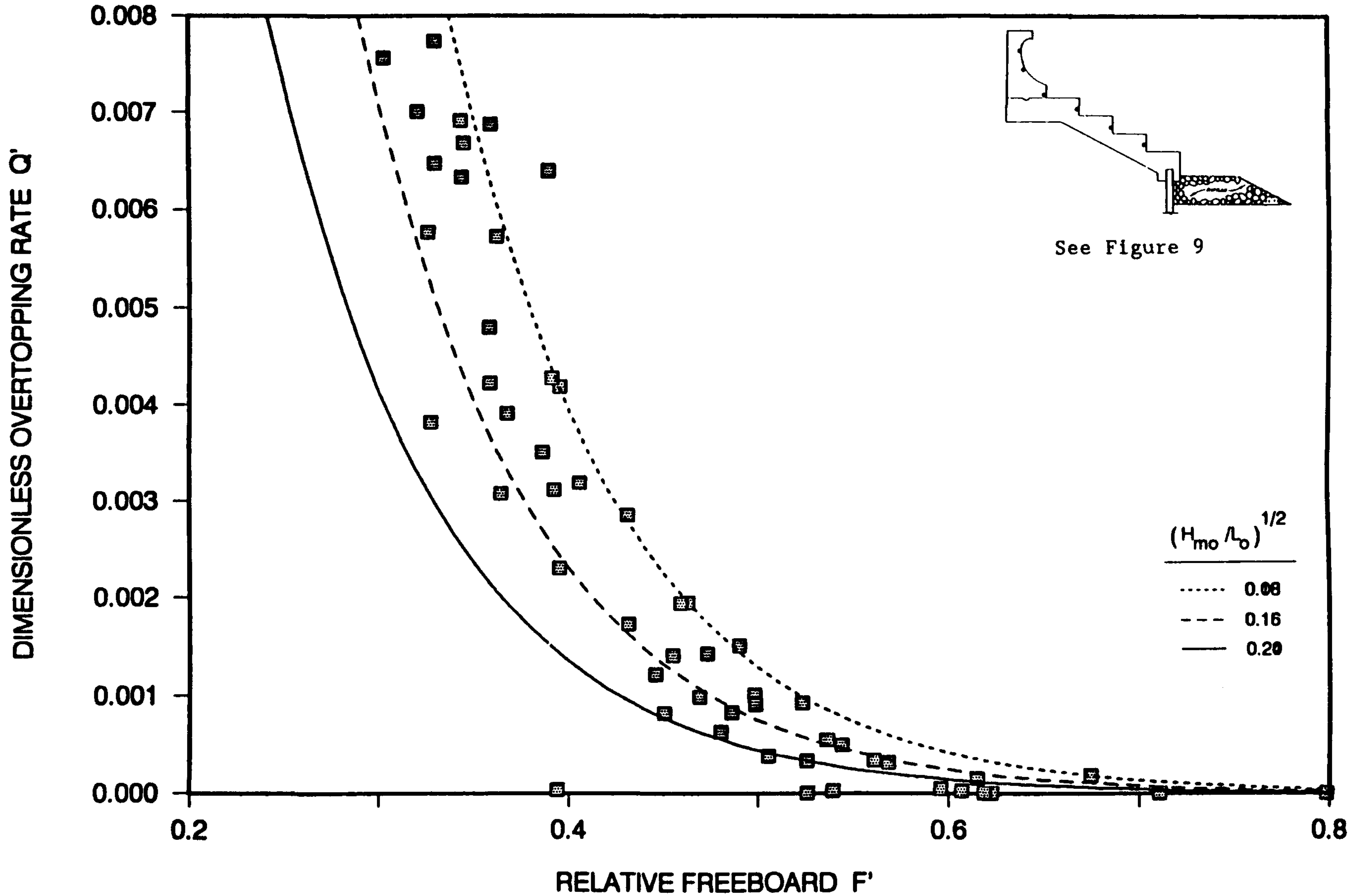


Figure 26. Group 7 measured overtopping and regression curves for improved overtopping model

shown on each figure illustrate a range of values of the secondary variables. It is important to note that several of the curves are extended beyond the range of the test data. This is only for illustrative purposes to demonstrate the effects of the secondary variable. In practice, the regression curves presented herein should not be used beyond the range of the test data from which the equations were obtained.

PART IV: CONCLUSIONS

39. A conceptually simple yet efficient equation has been developed which incorporates information on wave conditions, structure height, and water level in the determination of overtopping rates. This equation has been used with regression analysis to determine overtopping rates for a variety of seawall types over a wide range of sea conditions with reasonable accuracy. Although physical model testing is still recommended for final stages in the design of a structure, these equations are sufficient for preliminary stages in the design process and for comparing the effects of different structure types.

40. An improved model also is presented which provides a somewhat better correlation with the data. Although the secondary variable in the improved equation makes it difficult to compare results from different structure types, this equation may be used to provide an improved estimate of overtopping rates for a specific structural design and a given set of sea conditions.

41. Although the test conditions employed in this analysis cover a wide range of sea conditions, it must be emphasized that the equations should not be used outside the ranges tested unless physical model tests are used to confirm the results.

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Appendix A: NOTATION

C_1	Regression coefficient
C_2	Regression coefficient
d_B	Water depth over berm
d_s	Depth at the structure toe
F	Dimensional freeboard
F'	Dimensionless freeboard
g	Gravitational acceleration
H_{mo}	Wave height of the zeroth moment
H_s	Significant wave height
L_m/L_p	Linear scale of the model
L_o	Deepwater Airy wavelength
L_p	Local wavelength at the structure toe
Q	Dimensional overtopping rate per unit length of seawall
Q'	Dimensionless overtopping rate
Q_o	Regression coefficient
S_a	Specific gravity of an individual stone relative to the water in which the breakwater is constructed
T_p	Wave period of peak energy density
W_a	Weight of an individual stone, lb
W_B	Width of berm
X	Secondary variable
γ_a	Specific weight of an individual stone, pcf
γ_w	Specific weight of water, pcf
$\int$	Indicates quantity in parentheses is a truncated integer