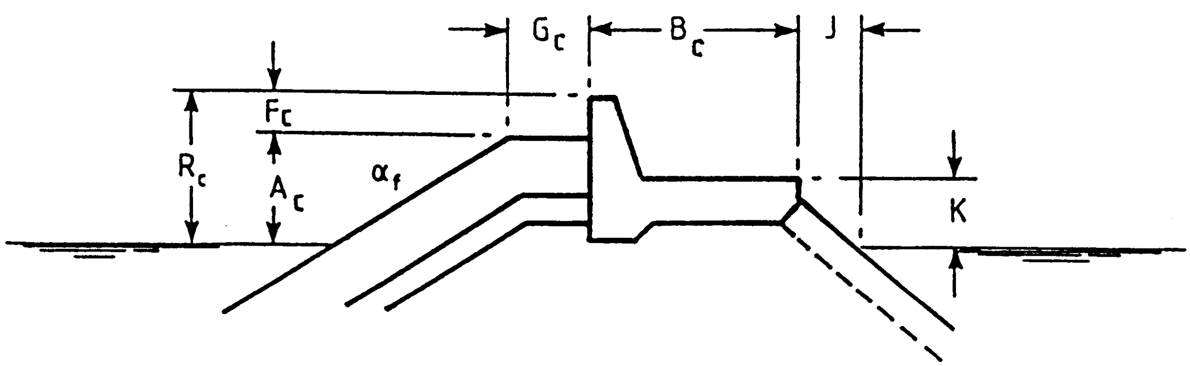
REMR TECHNICAL NOTE CO-RR-1.5

REDUCTION OF WAVE OVERTOPPING BY PARAPETS

PURPOSE: To present a mathematical method for predicting the design of a parapet at the top of a riprap protected embankment to reduce wave overtopping rates and for evaluating the effectiveness of the parapet.

BACKGROUND: The method for designing a parapet to reduce wave overtopping rates presented herein is based on laboratory tests conducted by Hydraulics Research Limited, Wallingford, England (Ref a). Additional analysis was performed at CERC to extend the range of strategies that can be used to reduce wave overtopping on coastal structures. The original research was used to determine the effectiveness of various breakwater crown-wall configurations to reduce irregular wave overtopping rates. However, the test setup and some of the configurations are useful for estimating overtopping of riprap revetments.

METHOD OF ANALYSIS: Figure 1 shows a generalized cross section of the crown-walls tested in the 1988 study. Data suitable for evaluating the performance of a vertical parapet in reducing wave overtopping rates on a riprap revetment are designated Test Sections 4, 5, 6, and 7 (Figure 2) and for a recurved parapet, Test Section 13 (Figure 3.)



Crown wall geometry : $A_cB_cF_cR_c, G_c$ J, K
Rear armour : D_{s50}, D_{s85}, D_{s15}

Figure 1. Geometry of breakwater cross sections

The approach used in this analysis is to create a synthetic data set based on the data given in Tables 1 and 2.

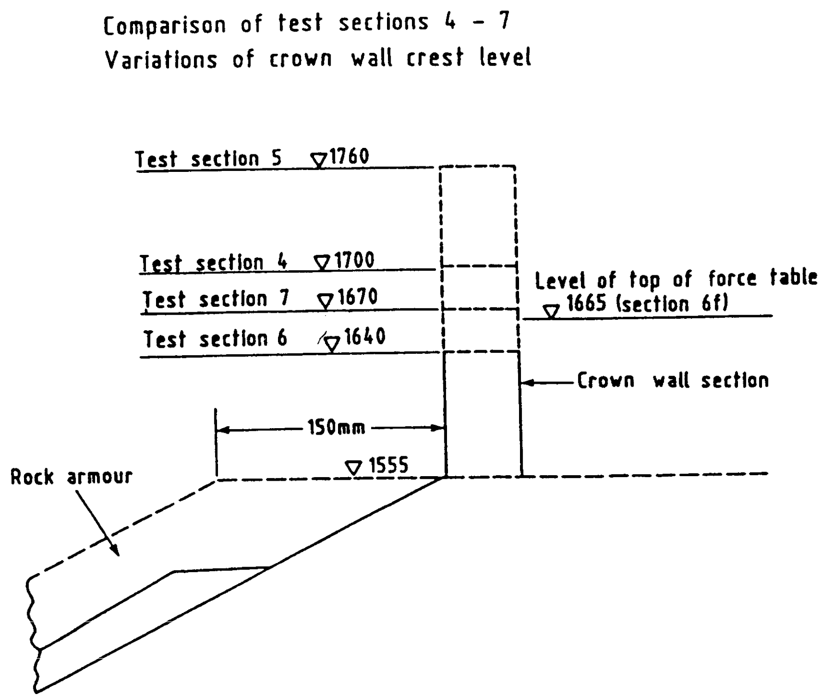


Figure 2. Test sections 4-7

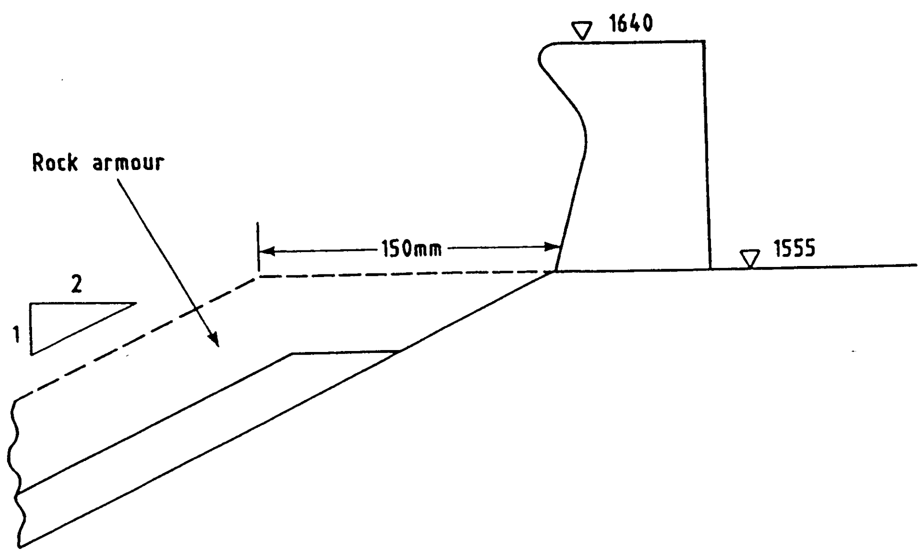


Figure 3. Test section 13 - recurved wall

Regression coefficients "A" and "B" given in Table 2 are used to generate a synthetic data set using the equation

$$Q^* = A(F^*)^B \tag{1}$$

where

$$Q^* = Q/(T_m \, g \, H_s)$$

and

$$F^* = (R_c/H_s)^2 \left[\frac{s_m}{2\pi}\right]^{1/2}$$

Q is the average overtopping volume per unit length of structure per unit time, T_m is the mean wave period, H_s is the significant wave height, R_c is the freeboard of the crest of structure (Figure 1), g is the acceleration of gravity, and s_m is the deep water wave steepness defined,

$$S_m = \frac{2\pi \, H_s}{g T_m^2} = \frac{H_s}{L_o}$$

The synthetic data set consists of 15 values of overtopping for each of the five Test Sections considered, giving a total of 75 values. These values were generated from the following ranges:

$$H_s \le 25.0 \text{ cm}$$
$$1.0 \le T_m \le 2.0 \text{ sec}$$
$$8.5 \le F_c \le 20.5 \text{ cm}$$
$$14.0 \le R_c \le 26.0 \text{ cm}$$

$$0.77 \le R_c/H_s \le 2.00$$
$$0.035 \le H_s/L_o \le 0.065$$
$$1.0 \le -\ln(F^*) \le 3.0$$

where F_c is the parapet height (Figure 1). The above ranges are consistent with the original laboratory tests. Values of dimensional variables were selected within these ranges, and the values of the dimensionless variables generated were checked to see that they were within the desired range. Analysis was conducted with the use of a spread sheet, and the basic data generated is shown in Table 3.

RESULTS: Using regression analysis, the "best" simple model for predicting the values of Q, actually $-\ln(Q^*)$, given in Table 3 for Test Sections 4, 5, 6, and 7 is

$$-\ln(Q^*) = 5.14 + 17.68\left[\frac{F_c}{(H_s L_o)^{0.5}}\right] + 38.79\left[\frac{A_c}{(H_s L_o)^{0.5}}\right] \tag{2}$$

where $A_c/(H_s*L_o)^{0.5}$ is referred to as the relative berm height, and $F_c/(H_s*L_o)^{0.5}$ as the relative parapet height. The correlation, R2 = 0.925, obtained for Equation 2 is within the range obtained by Bradbury, Allsop, and Stephens for Test Sections 4, 5, 6, and 7. One of the convenient aspects of Equation 2 is that it provides an easy, logical way to evaluate the performance of a parapet in reducing overtopping rates on a riprap protected embankment. However, it is not clear how well Equation 2 might fit the original data or how good it would be outside the range of variables tested.

Figures 4, 5, 6, and 7 compare data trends of -ln(Q*) versus -ln(F*) as given by Bradbury, Allsop, and Stephens with values predicted by Equation 2 for Test Sections 4, 5, 6, and 7, respectively. Consistent with Bradbury et al., -ln(Q*) is referred to as the dimensionless discharge and -ln(F*) is referred to as the dimensionless freeboard. Figures 4 through 7 show that Equation 2 generally does a good job of following the original data trends.

Test Section 13 used a recurved parapet (Figure 3) with the same height as the standard vertical parapet used in Test Section 6. The recurved parapet is surprisingly effective. Equation 2 can be used to estimate overtopping rates for recurved parapets if the constant term for the relative parapet height is changed from 17.68 to 20.0. This change indicates that overtopping rates over the recurved parapet are only about 9 percent the rates for a vertical parapet. The recurved parapet may be so successful because it is located well above the water line on a berm where the riprap has already greatly reduced the intensity of the wave uprush. Figure 8 shows that the modified version of Equation 2 does a good job of following the data trend for Test Section 13.

EXAMPLE PROBLEM:

a. Given: Assume that the wave overtopping rate, Q, on a riprap revetment must be reduced to .05 cfs/ft or below. The freeboard of the riprap, A_c, is 4.5 ft above the design water depth. Either a vertical wall parapet or a recurved parapet is to be used to reduce overtopping, H_s, of 10.0 ft and a mean wave period, T_m, of 8.0 sec. Determine the required parapet height.

b. Approach: In Figure 9, Equation 2 for vertical parapets and the modified Equation 2 for recurved parapets are used to estimate Q as a function of parapet height, F_c. Also, in Figure 9, the relative freeboard height, R_c/H_s, and the relative parapet height, F_c/H_s, are shown so that a parapet height that is outside the range of test conditions used by Bradbury, Allsop, and Stephens will not be selected; the total correct ranges are about

$$0.77 \le R_c/H_s \le 2.00$$
$$0.50 \le F_c/H_s \le 1.50$$

Obviously, that portion of the generated data outside the referenced data base should not be used to predict parapet heights. The minimum value of the relative freeboard height of $F_c/H_s = 0.50$ in Figure 9 indicates that a recurved parapet with a height of 5.0 ft will reduce the overtopping rate to considerably below the maximum acceptable value of Q = 0.05 cfs/ft. Also, Figure 9

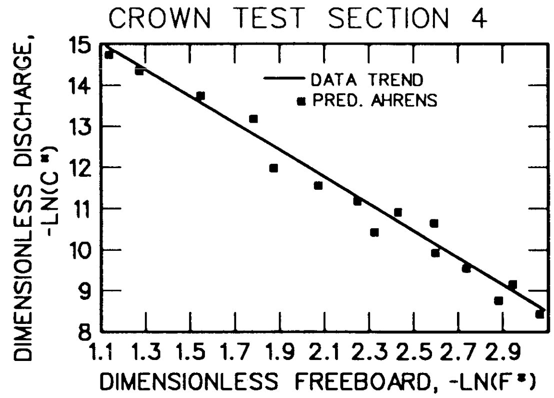


Figure 4. Discharge rate versus freeboard for test section 4*

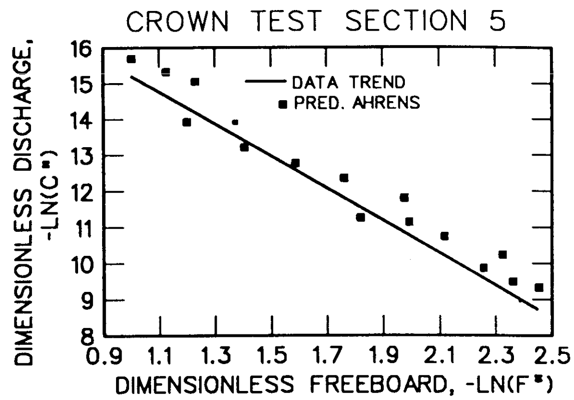


Figure 5. Discharge rate versus freeboard for test section 5*

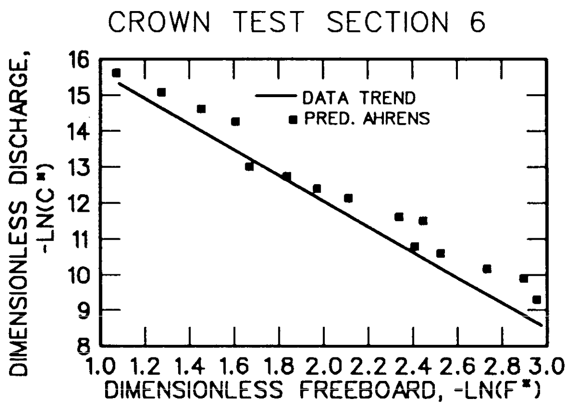


Figure 6. Discharge rate versus freeboard for test section 6*

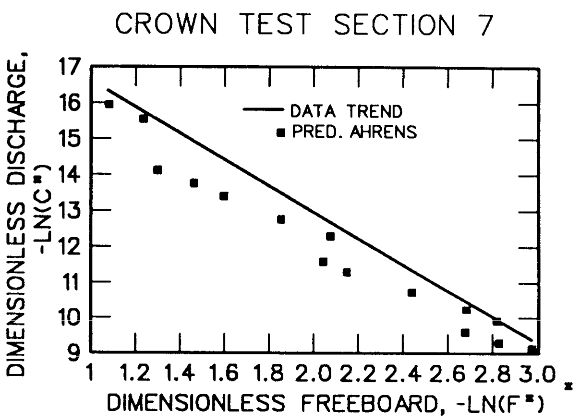


Figure 7. Discharge rate versus freeboard for test section 7*

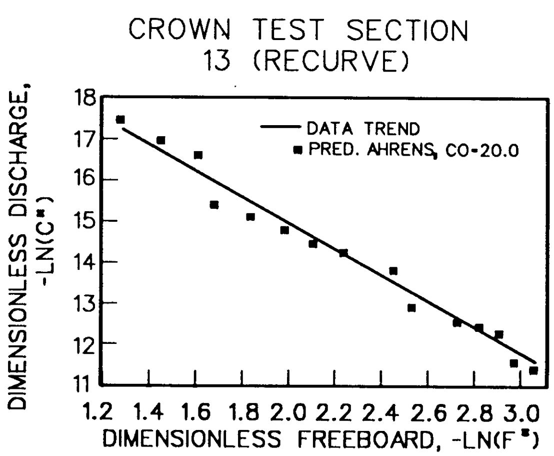


Figure 8. Discharge rate versus freeboard for test section 13*

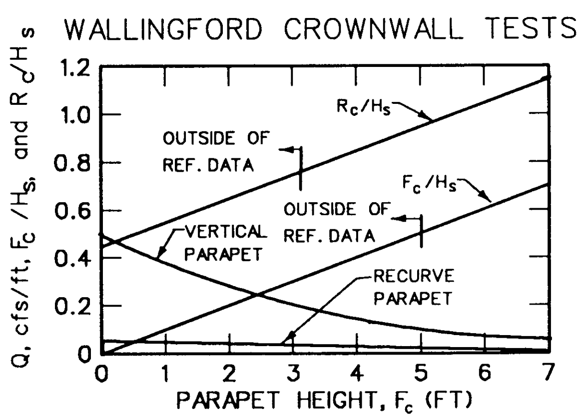


Figure 9. Computed discharge as a function of parapet height for the sample problem (based on Bradbury, Allsop, & Stephens (1988))

* Figures by Bradbury, Allsop, & Stephens (1988)

shows that the vertical parapet would not have reduced the overtopping rate sufficiently to meet the specified standard. On this basis a recurved parapet with a height of 5.0 ft is tentatively selected for the structure. Physical model tests should be conducted to ascertain that the selected wall will perform properly and to fine tune the geometry of the structure.

CONCLUSIONS: The analysis presented herein is based on an extensive series of physical model tests conducted by Bradbury, Allsop, and Stephens. All tests were conducted with irregular waves. It appears that the approach adopted in this paper has an advantage over the original analysis since it can consider a continuous range of parapet heights within the bounds of the test conditions rather than just the specific heights tested.

REFERENCE: Bradbury, A. P., Allsop, N. W. H., and Stephens, R. V. 1988 (Mar). "Hydraulic Performance of Breakwater Crown Walls," Report SR146, Hydraulics Research, Wallingford, England.

Table 1. Model Test Section Construction (after Bradbury, Allsop, and Stephens, 1988)

TEST SECTION	SLOPE TYPE (Cot = 2)	SLOPE CREST LEVEL*	WALL CREST LEVEL*	R_c (m)	F_c (m)	A_c (m)	G_c (m)
4	armoured	0.555	0.70	0.20	0.145	0.055	0.15
5	armoured	0.555	0.76	0.26	0.205	0.055	0.15
6	armoured	0.555	0.64	0.14	0.085	0.055	0.15
7	armoured	0.555	0.67	0.17	0.115	0.055	0.15
13	armoured	0.555	0.64	0.14	0.085	0.055	0.15

* All levels are relative to the toe of the section (m)

Table 2. Summary of Empirical Coefficients (after Bradbury, Allsop, and Stephens, 1988)

Test Section	Coefficients A	Coefficients B	Correlation R^2
4	6.7×10^{-9}	-3.457	0.81
5	3.6×10^{-9}	-4.368	0.93
6	5.3×10^{-9}	-3.514	0.84
7	1.8×10^{-9}	-3.600	0.96
13	5.9×10^{-10}	-3.154	0.71

Table 3. Synthetic Data Set Generated from Laboratory Tests by Bradbury, Allsop, and Stephens (1988)

Wallingford Test Section	Berm Elevation AC (cm)	Parapet Height FC (cm)	Total Freeboard Ac+Fc=Rc (cm)	Selected Significant Wave Height Hs(cm)	Rc/Hs	Selected Mean Wave Period Tm(sec)	Wave Steepness Hs/Lo	Dimensionless Freeboard F* F(star)	Negative ln F*	Dimensionless Overtopping Rate Q*	Negative ln Q*	Fc/Hs	Ac/Hs
4	5.5	14.5	20	13	1.54	1.25	0.053	0.218	1.523	1.30E-06	13.56	1.12	0.42
4	5.5	14.5	20	11	1.82	1.25	0.045	0.280	1.272	5.45E-07	14.42	1.32	0.50
4	5.5	14.5	20	10	2.00	1.25	0.041	0.323	1.129	3.32E-07	14.92	1.45	0.55
4	5.5	14.5	20	15	1.33	1.25	0.062	0.176	1.738	2.72E-06	12.81	0.97	0.37
4	5.5	14.5	20	14	1.43	1.50	0.040	0.163	1.816	3.57E-06	12.54	1.04	0.39
4	5.5	14.5	20	20	1.00	1.50	0.057	0.095	2.351	2.27E-05	10.69	0.73	0.28
4	5.5	14.5	20	16	1.25	1.50	0.046	0.133	2.017	7.14E-06	11.85	0.91	0.34
4	5.5	14.5	20	22	0.91	1.50	0.063	0.083	2.494	3.72E-05	10.20	0.66	0.25
4	5.5	14.5	20	18	1.11	1.50	0.051	0.112	2.193	1.32E-05	11.24	0.81	0.31
4	5.5	14.5	20	22	0.91	1.75	0.046	0.071	2.648	6.34E-05	9.67	0.66	0.25
4	5.5	14.5	20	20	1.00	1.75	0.042	0.082	2.506	3.87E-05	10.16	0.73	0.28
4	5.5	14.5	20	17	1.18	1.75	0.036	0.104	2.262	1.67E-05	11.00	0.85	0.32
4	5.5	14.5	20	25	0.80	1.75	0.052	0.058	2.840	1.23E-04	9.00	0.58	0.22
4	5.5	14.5	20	22	0.91	2.00	0.035	0.062	2.782	1.01E-04	9.20	0.66	0.25
4	5.5	14.5	20	25	0.80	2.00	0.040	0.051	2.974	1.95E-04	8.54	0.58	0.22
5	5.5	20.5	26	14	1.86	1.25	0.057	0.330	1.109	4.58E-07	14.60	1.46	0.39
5	5.5	20.5	26	13	2.00	1.25	0.053	0.369	0.998	2.82E-07	15.08	1.58	0.42
5	5.5	20.5	26	15	1.73	1.25	0.062	0.297	1.213	7.19E-07	14.14	1.37	0.37
5	5.5	20.5	26	22	1.18	1.50	0.063	0.140	1.970	1.96E-05	10.84	0.93	0.25
5	5.5	20.5	26	17	1.53	1.50	0.048	0.205	1.583	3.62E-06	12.53	1.21	0.32
5	5.5	20.5	26	13	2.00	1.50	0.037	0.307	1.180	6.25E-07	14.29	1.58	0.42
5	5.5	20.5	26	15	1.73	1.50	0.043	0.248	1.395	1.60E-06	13.35	1.37	0.37
5	5.5	20.5	26	19	1.37	1.50	0.054	0.174	1.750	7.51E-06	11.80	1.08	0.29
5	5.5	20.5	26	22	1.18	1.75	0.046	0.120	2.124	3.85E-05	10.17	0.93	0.25
5	5.5	20.5	26	18	1.44	1.75	0.038	0.162	1.823	1.03E-05	11.48	1.14	0.31
5	5.5	20.5	26	20	1.30	1.75	0.042	0.138	1.981	2.06E-05	10.79	1.03	0.28
5	5.5	20.5	26	25	1.04	1.75	0.052	0.099	2.316	8.89E-05	9.33	0.82	0.22
5	5.5	20.5	26	25	1.04	2.00	0.040	0.086	2.449	1.59E-04	8.74	0.82	0.22
5	5.5	20.5	26	23.5	1.11	2.00	0.038	0.095	2.356	1.06E-04	9.15	0.87	0.23
5	5.5	20.5	26	22	1.18	2.00	0.035	0.105	2.257	6.89E-05	9.58	0.93	0.25
6	5.5	8.5	14	7	2.00	1.00	0.045	0.338	1.085	2.40E-07	15.24	1.21	0.79
6	5.5	8.5	14	9	1.56	1.00	0.058	0.232	1.461	9.01E-07	13.92	0.94	0.61
6	5.5	8.5	14	8	1.75	1.00	0.051	0.277	1.285	4.84E-07	14.54	1.06	0.69
6	5.5	8.5	14	10	1.40	1.00	0.064	0.198	1.620	1.57E-06	13.36	0.85	0.55
6	5.5	8.5	14	12	1.17	1.25	0.049	0.120	2.116	8.99E-06	11.62	0.71	0.46
6	5.5	8.5	14	9	1.56	1.25	0.037	0.186	1.685	1.97E-06	13.14	0.94	0.61
6	5.5	8.5	14	10	1.40	1.25	0.041	0.158	1.843	3.44E-06	12.58	0.85	0.55
6	5.5	8.5	14	14	1.00	1.25	0.057	0.096	2.347	2.03E-05	10.81	0.61	0.39
6	5.5	8.5	14	11	1.27	1.25	0.045	0.137	1.986	5.68E-06	12.08	0.77	0.50
6	5.5	8.5	14	15	0.93	1.25	0.062	0.086	2.451	2.91E-05	10.44	0.57	0.37

Table 3 (Concluded)

Wallingford Test Section	Berm Eleva-tion AC (cm)	Parapet Height FC (cm)	Total Freeboard Ac+Fc=Rc (cm)	Selected Signif-icant Wave Height Hs(cm)	Rc/Hs	Selected Mean Wave Period Tm(sec)	Wave Steep-ness Hs/Lo	Dimension-less Freeboard F* F(star)	Nega-tive ln F*	Dimension-less Overtop-ping Rate Q*	Nega-tive ln Q*	Fc/Hs	Ac/Hs
6	5.5	8.5	14	13	1.08	1.50	0.037	0.089	2.419	2.60E-05	10.56	0.65	0.42
6	5.5	8.5	14	16	0.88	1.50	0.046	0.065	2.730	7.77E-05	9.46	0.53	0.34
6	5.5	8.5	14	14	1.00	1.50	0.040	0.080	2.530	3.85E-05	10.17	0.61	0.39
6	5.5	8.5	14	18	0.78	1.50	0.051	0.055	2.907	1.45E-04	8.84	0.47	0.31
6	5.5	8.5	14	17	0.82	1.75	0.036	0.051	2.975	1.84E-04	8.60	0.50	0.32
7	5.5	11.5	17	9	1.89	1.00	0.058	0.342	1.073	8.57E-08	16.27	1.28	0.61
7	5.5	11.5	17	10	1.70	1.00	0.064	0.292	1.231	1.51E-07	15.70	1.15	0.55
7	5.5	11.5	17	13	1.31	1.25	0.053	0.158	1.848	1.39E-06	13.48	0.88	0.42
7	5.5	11.5	17	15	1.13	1.25	0.062	0.127	2.063	3.02E-06	12.71	0.77	0.37
7	5.5	11.5	17	10	1.70	1.25	0.041	0.234	1.454	3.38E-07	14.90	1.15	0.55
7	5.5	11.5	17	11	1.55	1.25	0.045	0.202	1.597	5.66E-07	14.39	1.05	0.50
7	5.5	11.5	17	9	1.89	1.25	0.037	0.274	1.296	1.91E-07	15.47	1.28	0.61
7	5.5	11.5	17	22	0.77	1.50	0.063	0.060	2.819	4.61E-05	9.99	0.52	0.25
7	5.5	11.5	17	14	1.21	1.50	0.040	0.117	2.141	4.01E-06	12.43	0.82	0.39
7	5.5	11.5	17	17	1.00	1.50	0.048	0.088	2.433	1.14E-05	11.38	0.68	0.32
7	5.5	11.5	17	20	0.85	1.50	0.057	0.069	2.676	2.75E-05	10.50	0.58	0.28
7	5.5	11.5	17	13	1.31	1.50	0.037	0.131	2.030	2.69E-06	12.83	0.88	0.42
7	5.5	11.5	17	20	0.85	1.75	0.042	0.059	2.831	4.79E-05	9.95	0.58	0.28
7	5.5	11.5	17	22	0.77	1.75	0.046	0.051	2.974	8.02E-05	9.43	0.52	0.25
7	5.5	11.5	17	18	0.94	1.75	0.038	0.069	2.673	2.71E-05	10.51	0.64	0.31
13	5.5	8.5	14	9	1.56	1.00	0.058	0.232	1.461	5.93E-08	16.64	0.94	0.61
13	5.5	8.5	14	10	1.40	1.00	0.064	0.198	1.620	9.76E-08	16.14	0.85	0.55
13	5.5	8.5	14	8	1.75	1.00	0.051	0.277	1.285	3.39E-08	17.20	1.06	0.69
13	5.5	8.5	14	15	0.93	1.25	0.062	0.086	2.451	1.34E-06	13.52	0.57	0.37
13	5.5	8.5	14	9	1.56	1.25	0.037	0.186	1.685	1.20E-07	15.94	0.94	0.61
13	5.5	8.5	14	11	1.27	1.25	0.045	0.137	1.986	3.10E-07	14.99	0.77	0.50
13	5.5	8.5	14	13	1.08	1.25	0.053	0.107	2.236	6.82E-07	14.20	0.65	0.42
13	5.5	8.5	14	12	1.17	1.25	0.049	0.120	2.116	4.67E-07	14.58	0.71	0.46
13	5.5	8.5	14	10	1.40	1.25	0.041	0.158	1.843	1.97E-07	15.44	0.85	0.55
13	5.5	8.5	14	16	0.88	1.50	0.046	0.065	2.730	3.24E-06	12.64	0.53	0.34
13	5.5	8.5	14	17	0.82	1.50	0.048	0.060	2.821	4.31E-06	12.35	0.50	0.32
13	5.5	8.5	14	18	0.78	1.50	0.051	0.055	2.907	5.65E-06	12.08	0.47	0.31
13	5.5	8.5	14	14	1.00	1.50	0.040	0.080	2.530	1.72E-06	13.27	0.61	0.39
13	5.5	8.5	14	17	0.82	1.75	0.036	0.051	2.975	7.02E-06	11.87	0.50	0.32
13	5.5	8.5	14	18	0.78	1.75	0.038	0.047	3.061	9.19E-06	11.60	0.47	0.31