Appendix C: Habitat Bench Design Issues for Areas Offshore of ASB

1.0 Introduction

As part of habitat enhancement planning for Bellingham Bay, the area offshore of the Aerated Stabilization Basin (ASB) facility and in between the Whatcom and I&J Waterways has been considered for development of a nearshore habitat bench. The nearshore habitat bench would enhance the existing migration corridors for juvenile salmonids, by increasing the quantity and quality of shallow subtidal habitat along these corridors. Similar benches have been incorporated into the design concept for the interior faces of the ASB should it be cleaned out and converted to a marina with integrated public access and habitat enhancement features.

This memo summarizes some of the coastal engineering design issues that would apply to the development of a subtidal habitat bench offshore of the ASB area. The principal issue is the stability of the bench materials under anticipated wind and wave conditions, and the design choices made to optimize stability while preserving the habitat functions of the bench.

The design issues described in this memorandum will also apply to sediment capping which is contemplated in portions of this area as part of the Whatcom Waterway RI/FS. Selected project alternatives evaluated in the RI/FS include the placement of a nominal 3-foot thick sediment cap in portions of the habitat bench area. The design issues described in this memorandum have been incorporated into the RI/FS document.

2.0 Physical Setting and Conceptual Bench Design

The ASB currently operates as a wastewater treatment facility. However, it is contemplated for future use as a marina with integrated public access and habitat enhancement features. The sediments immediately offshore of the ASB (sediment site unit 5-B) currently consist of sandy material, up to the toe of the ASB berm. The ASB berm begins at elevations of approximately -6 feet MLLW in this area. The ASB berm is constructed of large armor stone with a slope of approximately 3H:1V.

During the Bellingham Bay Demonstration Pilot, the area offshore of the ASB was identified as a priority location for the development of submerged habitat benches to enhance migration corridors for juvenile salmonids. These benches would increase the quantity of shallow subtidal habitat, particularly the premium depth areas, typically considered those in elevations of -4 ft MLLW or shallower.

The shallower sediments nearest the ASB are subject to wind and wave action that will affect the design of future habitat benches. The existing bay floor near the ASB transitions from a fine silt in deepwater areas, to silty sand at elevations shallower than about 20 feet. The highest wind and wave energies are expected in the shallowest elevations, particularly those that are exposed at low tides.

Conceptually a habitat bench in front of the ASB would be constructed as part of the cleanup of the Whatcom Waterway site and redevelopment of the ASB facility. The outer ASB berm would be retained as part of future land uses, with some reconfiguration of the face of the berm as part of site transition. The toe of the berm will continue to be in about -6 feet MLLW. The interior of the berm will be modified significantly to optimize public access and habitat features, and to provide for future navigation uses of the ASB. Materials used for the construction of the outer bench will include some stone and berm sands obtained from ASB berm reconfiguration, as well as additional materials procured from other sources. The berm sand is coarse, with a median diameter of 0.8 mm. The berm stones vary in size.

Wave action inside the modified berm will be less substantial than on the outer face, and will have fewer of the design considerations applicable to the outer bench area. The optimum bench design would maximize the footprint of shallow subtidal sediments in the elevation range -6 ft MLLW to -4 ft MLLW. The conceptual design evaluated in this memorandum includes a bench that would begin offshore approximately 300 feet from the existing ASB berm toe. The average thickness of applied material would be approximately 3 feet, with additional thicknesses provided if desired to maximize shallow habitat elevations. The final side slopes would be similar to that of the current bay floor currently slopes at about 0.014, or about 70 feet horizontal for every 1 foot vertical.

3.0 Design Basis and Site-Specific Data

In designing a habitat bench, the potential for physical disturbance and erosion must be considered. In doing so, weather data for the area are combined with coastal surveys to define anticipated typical storm conditions. These are the storms that are frequent to the area and that shape the design of most coastal structures. The design process also considers the impacts of extreme storm conditions. Extreme are those that occur very infrequently (i.e., one or two times in a 100-year period). Typically these storm conditions are of short duration in comparison with the typical storms, but can cause shifting of bay sediments not experienced in typical storms.

The final design is based on the typical storm, with design enhancements to minimize shifting of sediments during infrequent extreme storm events. Some sediment shifting is tolerable and expected. However, mass material loss through erosion is to be avoided in order to ensure long-term viability of the habitat bench, and to minimize additional sedimentation in nearby areas including the I&J Waterway. If the habitat bench is integrated with a sediment cap, the design should also maintain sufficient bench material thickness to ensure containment of capped sediments. The key site-specific data used to assess bench/cap design include the following:

Tide Data: The tides in Bellingham Bay are semi-diurnal mixed, meaning that there are two unequal highs and lows each day. The mean tide range is 5.43 feet and the diurnal range is 7.79 feet. The tidal datums for the 1983-2001 tidal epoch are given in Table 1. The tides determine the varying water depth in front of the breakwater.

Wind Data: The dominant disturbance to the sediment of a habitat bench cap is expected to be wind-generated waves. A literature search indicates that there are no known wave data for Bellingham Bay. Therefore, waves will have to be forecast/hindcast from wind data. The wind parameters that influence wave generation include: wind speed, wind direction, wind duration, and fetch (the distance over which the wind blows). Wave growth is directly proportional to wind speed, wind duration, and fetch. Fetch was obtained by scaling off the nautical chart (NOAA-NOS Chart No. 18424) for Bellingham Bay. The fetches associated with each principle wind direction are presented in Tables 2 and 3. Wind data for Bellingham Bay are sparse. The plan is to assess both typical storm waves and extreme storm waves in addressing the issue of a stable armor cap on the habitat bench. The wind-to-wave analyses are done for typical storm conditions and extreme storm conditions.

Design (Typical) Storm Information: The typical storm conditions are obtained from a wind rose for Bellingham Bay prepared by the U.S. Army Corps of Engineers – Seattle District Figure A-1 (See Attachment A). The maximum wind speed from each direction is assumed to be representative of a typical storm from that direction. The duration of a typical storm by directions was obtained from a U.S. Army Corps of Engineers – Seattle District Figure A-2 Wind Duration Curves for Bellingham Bay (see Attachment B). The typical storm wind conditions to be used in the wave analysis are summarized in Table 2. The longest fetch is from the SE with typical storm winds up to 24 mph for up to 24 hours duration.

Extreme Storm Information: Extreme storm winds representative of Bellingham Bay are collected from a variety of sources. The storm of 21 October 1934 (Read, 2003) produced a sustained wind in Bellingham from the SSE at 60 mph with a peak wind at 70 mph. The 4 December 1945 storm (Read, 2004) produced a peak wind from the SSE at 66 mph and a gust to 80+ mph. The 12 October 1962 (Columbus Day Storm) storm (Lynott and Cramer, 1966) recorded a gust of 92 mph from the S. And a storm on 24 November 1998 (http://www.usatoday.com/weather/news/1998/w1124rpt.html) produced a gust of 76 mph, believed to be from the S. Sustained winds (with 1-hour duration) are obtained from the U.S. Army Corps of Engineers – Seattle District Figure A-2 Wind Duration Curves for Bellingham. Peak winds (1-minute duration) and gusts (1-second duration) were obtained from storm reports. The extreme storm wind data for Bellingham Bay is summarized on Table 3. The extreme storms winds are out of the south, but the fetch in that direction is a relatively short 4,000 feet. The longest fetch of 41,000 feet is to the southwest, but there are no recorded peak winds or gusts from that direction; however, the sustained wind speed of 52 mph is relatively high.

Wave Estimation Methods: The wind data is used to calculate the typical and extreme (storm) wind-generated waves in Bellingham Bay using the methods presented in the *Coastal Engineering Manual* (U.S. Army Corps of Engineers, 2002). Waves are calculated along the longest fetch for the typical storm (SW wind at 24 mph for 24 hours), the extreme sustained storm (SW wind at a speed of 52 mph and duration of 1 hour), and the maximum sustained, peak, and gust wind speeds (from the south with a fetch of 4,000 feet). The results of the wind-generated wave calculations (Attachment C) are presented in Tables 4 and 5. The largest typical storm waves are from the southwest (SW) with a wave height of 3.2 feet and a period of 2.9 seconds. The largest extreme storm waves appear to be from the southwest (SW) with a wave period of 3.6 seconds, and a significant wave height of 6.1 feet. Extreme storm waves from the south (S) are fetch limited and the expected wave periods and wave heights are about half that for winds from the SW. The wave parameters for SW wind-generated wave are used for further analysis of the habitat bench surface materials.

Vessel Wake Evaluation: The habitat bench will be situated near navigation areas, and so for completeness, an assessment of boat wakes are calculated. Generally, boat wake parameters lie within the envelope of wind-generated wave parameters. The largest boats transiting the waterway between the bay and the marina entrance will generate the largest wakes. A conservative evaluation was conducted assuming a 110-foot long motor yacht, transiting in 30 feet of water and passing within 300 feet of the habitat bench, and approaching the marina at a speed of 7 knots (11.8 feet /sec). The wake calculation (Attachment D) indicates a wake period of 1.9 seconds and a wake height of 0.3 feet. These parameters are well within the storm wave parameters given above.

4.0 Evaluation of Bench Material Stability

The simplest design for a habitat bench or sediment cap would consist of a 3-feet thick layer of sand or a graded mixture of sand and stones placed directly on the silty sands of the bay floor. The size of material that is expected to be physically stable is dependent on the magnitude of the wave-generated currents impinging on top of the bench. The use of larger stones in the surface layers of the bench will increase the stability of the cap and habitat bench, but the use of very large stones or armor stone reduces the incremental benefits of the bench creation.

The water depth over the habitat bench will be controlled by the tides. Using MLLW as the controlling tide datum, the minimum depth of water over the cap is assumed to be 3 feet. Storm waves will break and reform at the outer edges of the habitat bench and in about 9 feet of water depth. The methods in the Shore Protection Manual are used to size stable stone exposed to storm waves.

The calculations (see Attachment E) indicate that under typical storm conditions, stable sediment in front of the berm/breakwater should range from coarse silt in deep (greater than -12 feet MLLW) to medium gravel in shallow water, respectively. Under extreme storm wave conditions, stable bottom sediments range from coarse sand in deep water, to coarse gravel in shallow water, respectively. Based on current composition of the sediments, the deeper sediment conditions seem to prevail in front of the berm/breakwater; that is, coarse silt to coarse sand.

Adding a habitat bench or sediment cap that reduces the water depth by at least 3 feet out to 300 feet in front of the berm/breakwater will reduce water depths within the bench area and will subject the cap surface to higher wave energies than the current bay floor is experiencing. When storm waves shoal on the habitat bench, the wave motion will generate bottom currents. These currents have the ability to erode and suspend the bench sediments. The currents associated with storm waves were used to assess the size of a stable bench surface layer. The maximum horizontal currents range from about 6 ft/sec for a typical storm to about 13 ft/sec for an extreme storm. To ensure that significant shifting of the materials is not experienced will require use of either 1) a coarse surface mix, or 2) a protective offshore submerged wave break.

The final bench design will depend on the level of design stability selected, and whether an off-shore wave break was included in the design. Under typical storm conditions, a stable capping mix would grade from fine to coarse gravel. If a single material size is desired to be stable over the entire habitat bench, the median cap stone size should be 2-1/2 inches. Alternately, finer material could be used in deeper water portions of the bench, and the coarser material used only in the shallow portions of the bench. If the bench is designed to be stable without the use of an offshore wave break and avoid shifting under extreme storm conditions, the cap mix should grade from coarse gravel to cobbles, with the shallowest portions of the bench containing a median stone size of 12 inches. Finer materials could be used in deeper portions of the bench and would be stable under extreme storm conditions.

If an offshore wave break is included in the design of the habitat bench, then the final cap can be constructed using Grade A materials as listed in Table 5. With a properly constructed wave break, the mix with median stone size of 2-1/2 inches will maintain bench stability even under the extreme storm. This would allow use of standard "fish mix" materials in the top layers of the cap and habitat bench. Sand materials can be used in bench subgrade. The impact of the offshore wave break on project cost should be minimal given the planned availability of stone from reconfiguration of the ASB berms. Navigation impacts of the wave break would not be substantially different than those of the habitat bench itself and would be addressed by providing "shoal" markers at the outer edges of the bench.

5.0 Preferred Design and Discussion

The preferred design concept for the construction of a habitat bench and/or sediment cap in unit 5-B includes the use of sand materials below -12 ft MLLW and in bench subgrades. An offshore submerged wave break would be constructed using recycled ASB berm stone. The wave break would be placed in water depths of approximately -8 feet and would extend to approximately -3 feet MLLW. The wave break would be exposed only in extreme low tides. Behind the submerged wave break, the topping material for the habitat bench would consist of material similar to the Grade A materials listed in Table 5. These materials can be readily obtained from local sources. The bench area would range in elevation from -6 feet MLLW to -3 feet MLLW.

The preferred design described above provides maximum habitat benefits, while maintaining the greatest bench stability. The design allows the use of premium habitat mix as topping materials for the bench. These materials would be stable with or without the submerged wave break in a typical storm used as the basis for design. The addition of the wave break provides for enhanced stability, minimizing the shifting of bench materials that could occur in extreme storm events. These extreme storms are not typically used for design basis, but are provided here given the goal of ensuring long-term function of the created habitat. The submerged wave break provides this increased stability, while maintaining the premium particle size mix for habitat function.

References

Lynott, Robert E. and Owen P Cramer. "Detailed Analysis of the 1962 Columbus Day Windstorm in Oregon and Washington". *Monthly Weather Review*, Vol. 94, No. 2, February 1966, Pages 105-117.

Read, Wolf. *The Major Windstorm of October 21,1934*. Found at http://oregonstate.edu/~readw/October1934.html, February 24, 2003.

Read, Wolf. *The Major Sou'wester of December 4,1945*. Found at http://oregonstate.edu/~readw/December1945.html, April 16, 2004.

U. S. Army Corps of Engineers. *Coastal Engineering Manual*. Engineer Manual 1110-2-1100 (Part II), 30 April 2002.

U.S. Army Corps of Engineers. *Shore Protection Manual*. Two Volumes, Coastal Engineering Research Center, Waterways Experiment Station, Vicksburg, MS, 1984.

Tables

Table 1. The 1983-2001 Tidal Datums for Bellingham Bay.

Tidal Datum	Meters	Feet
Highest Observed Tide	3.177	10.42
Mean Higher High Water	2.594	8.51
Mean High Water	2.375	7.79
Mean Tide Level	1.546	5.07
Mean Sea Level	1.510	4.95
Mean Low Water	0.718	2.36
NAVD 88	0.147	0.48
Mean Lower Low Water	0.0	0.0
Lowest Observed Tide	-1.057	-3.47

Table 2. Typical Storm Winds in Bellingham Bay from Wind Rose (1948-1954).

Direction	Fetch (ft)	Wind Speed (mph)	Duration (hours)
N	0	38	3
NE	0	38	3
E	0	24	8
SE	1,000	38	5
S	4,000	24	24
SW	41,000	24	24
W	27,000	24	2
NW	24,000	24	6

Table 3. Extreme Strom Wind Data for Bellingham Bay from Storm Reports.

Direction	Fetch (ft)	Sustained (1-hour) Wind Speed (mph)	Peak (1-minute) Wind Speed (mph)	Gust (1-second) Wind Speed (mph)
N	0	44		
NE	0	44		
E	0	42		
SE	1,000	56		
S	4,000	60	70	92
SW	41,000	52		
W	27,000	26		
NW	24,000	NA		

Table 4. Typical Storm Wave Summary for Bellingham Bay.

Wind Direction (from)	SE	S	SW	W	NW
Wind Speed (mph)	38	24	24	24	24
Wind Duration (seconds)	18,000	86,400	86,400	7,200	21,600
Fetch (feet)	1,000	4,000	41,000	27,000	21,600
Wave period (second)	0.9	1.3	2.9	2.3	2.3
Significant (33-Percentile) Wave Height (feet)	0.7	0.9	3.2	2.1	2.1
10-Percentile Wave Height (feet)	0.9	1.2	4.0	2.7	2.7
1-Percentile Wave Height (feet)	1.1	1.6	5.3	3.5	3.6

Table 5. Extreme Storm Wave Summary for Bellingham Bay

Wind Direction (from)	S	S	S	SW
Wind Speed (mph)	**60**	**70**	**92**	**52**
Wind Duration (seconds)	**3600**	**60**	**1**	**3600**
Fetch (feet)	**4,000**	**4,000**	**4,000**	**41,000**
Wave period (second)	**1.7**	**1.7**	**1.8**	**3.6**
Significant (33-Percentile) Wave Height (feet)	**2.2**	**2.1**	**2.4**	**6.1**
10-Percentile Wave Height (feet)	**2.7**	**2.7**	**3.0**	**7.8**
1-Percentile Wave Height (feet)	**3.6**	**3.5**	**4.0**	**10.2**

Table 6. Stable Capping Mix Properties (No offshore wave-break)

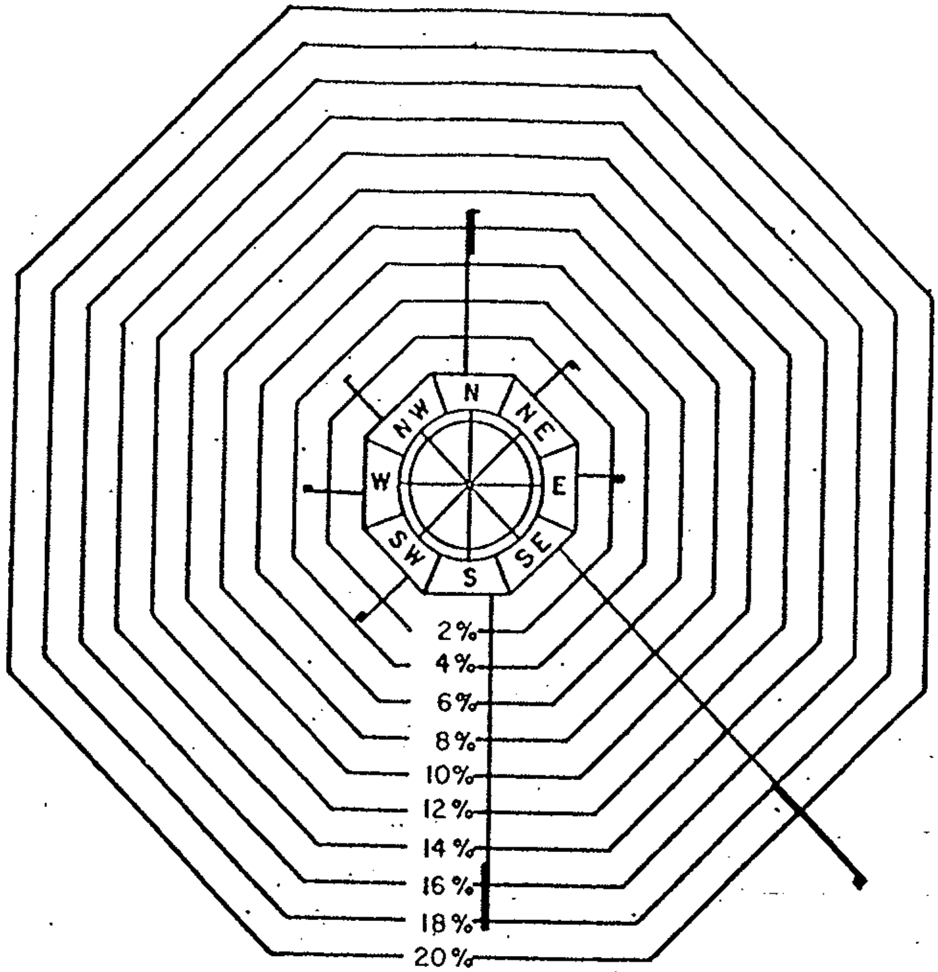
Percent Finer Than by Weight	Grade A Mix Size (inches) Stable Under Typical Storm Without Wave Break	Grade B Mix Size (inches) Stable Under Extreme Storm Without Wave Break
100	1 ½	7
85	2	9
50	**2 ½**	**12**
15	3	15
0	4	18

Attachment A
Annual Wind Rose – Bellingham, Washington

Attatchment A

CORPS OF ENGINEERS

U. S. ARMY



CALM (less than 4mph) = 33%

LEGEND

VELOCITY RANGE
M.P.H.

4 TO 12

OVER 13 TO 24

OVER 25 TO 38

OVER 38

SOURCE

Climatological Handbook,
Columbia Basin States
Published June 1968

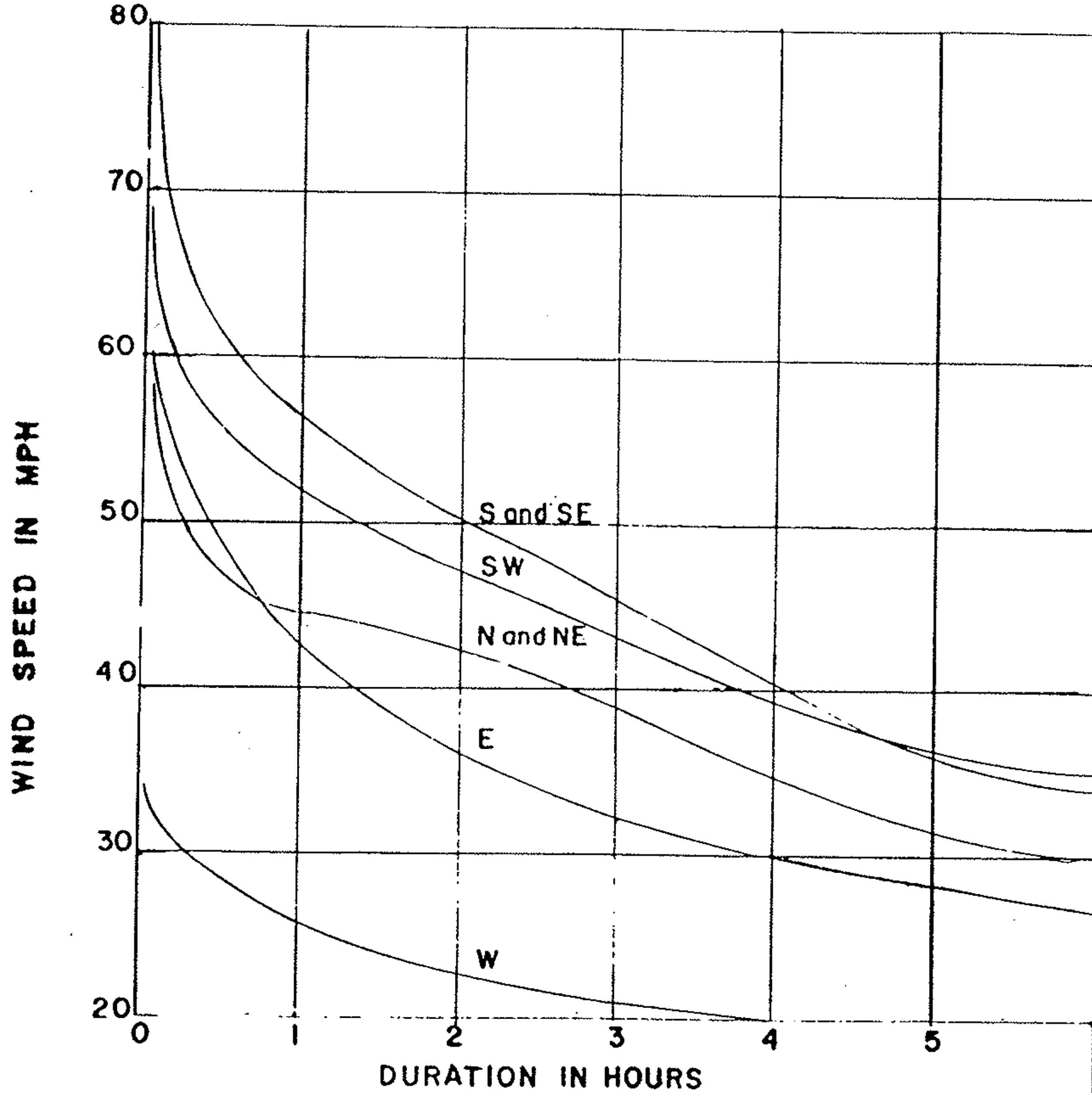
BELLINGHAM, WASH.
ANNUAL
WIND ROSE
FROM 1948 TO 1954
U.S. Army Engr. District, Seattle, Wash.

Comp.: FLS
Drawn: FLS
Checked: NJM Date: 8/13/71

Figure A-1

Attachment B
Wind Duration Curves – Bellingham, Washington

Attachment B



NOTE:

CURVES ARE ESTIMATED ON BASIS OF SUMMARY OF STRONG WINDS AT BELLINGHAM FOR PERIOD 1930 THRU 1959 AND FROM DETAILED WIND RECORD FRIDAY HARBOR FROM 21 NOV. 1959 THRU 17 DEC. 1970.

BELLINGHAM, WASH.

WIND DURATION CURVES

Sheet of Scale: As shown

U. S. Army Engr. District, Seattle, Wash.

Dr.: Transmitted with report

Tr.: dated 196

Ck.: File No.

Figure A-2

Attachment C
Typical Storm Waves – Bellingham, Washington

Typical Storm Waves for Bellingham Bay

Wind-generated Wave Calculations Per the Coastal Engineering Manual (CEM)*

Step		Unit	Symbol	SE	S	SW	W	NW
	Observed wind speed units	-	-	mph	mph	mph	mph	mph
1	Observed wind speed	-	U_z	38	24	24	24	24
2	Observed wind height	ft	z	33	33	33	33	33
3	Observed wind duration	sec	t	18,000	86,400	86,400	7,200	21,600
4	Observation over land (L) or water (W)	-	L,W	L	L	L	L	L
5	Fetch length	ft	X	1,000	4,000	41,000	27,000	24,000
6	Air-sea temperature difference	Deg.C	Δ_T	0	0	0	0	0
7	Observed wind speed	ft/sec	U_z	55.7	35.2	35.2	35.2	35.2
8	Wind speed corrected for height	ft/sec	U_{10}	55.7	35.2	35.2	35.2	35.2
9	Wind speed corrected for duration	ft/sec	U_{3600}	62.3	44.4	44.4	36.9	39.9
10	Wind speed corrected for location	ft/sec	U_{water}	74.7	53.3	53.3	44.2	47.8
11	Wind speed corrected for temp difference	ft/sec	U_c	74.7	53.3	53.3	44.2	47.8
12	Wind drag coefficient	-	C_D	0.0017	0.0015	0.0015	0.0015	0.0015
13	Fetch-limited generation duration	sec	$t_{X,U}$	576	1,626	7,672	6,178	5,565
14	Duration corrected wind speed	ft/sec	U	71.0	52.5	56.0	45.9	49.2
15	Friction velocity	ft/sec	u	2.924	2.016	2.153	1.761	1.891
16	Energy-based significant wave height	ft	H_{m0}	0.67	0.93	3.17	2.11	2.13
17	Energy-based peak wave period	sec	Tp	0.9	1.3	2.9	2.3	2.3
18	33-Percentile Wave Height	ft	$H_{1/3}$	0.7	0.9	3.2	2.1	2.1
19	10-Percentile Wave Height	ft	$H_{1/10}$	0.9	1.2	4.0	2.7	2.7
20	1-Percentile Wave Height	ft	$H_{1/100}$	1.1	1.6	5.3	3.5	3.6
21	Maximum Wave Height	ft	H_{max}	1.3	1.7	5.9	3.9	4.0

* *Coastal Engineering Manual (Part II)*. U.S. Army Corps of Engineers, Engineering Manual EM 1110-2-1100, 31 January 2002.

Calculations based on CEM Figure II-2-20:

1-6 Input observed wind speed, observation height, observation duration, observation location, fetch, and air-water temperature difference

7 U_z [ft/sec] = (6080/3600)[knots] = (5280/3600)[mph] = (3281/3600)[km/hr] = = (5280/3600)[FM]/(1.277+0.296tanh(0.9log0.0125[FM]) = (3.281)[m/s]

8 $U_{10} = U_z(33/z)^{1/7}$

9 $U_{3600} = U_{10}/\{1.277 + 0.296 \tanh[0.9\log(45/t)]\}$ for t<3,600 sec

$= U_{10}/[-0.15 \log(t) + 1.533]$ for t>3,600 sec

10 $U_{water} = 1.2U_{3600}$ if L; otherwise $U_{water} = U_{3600}$

11 $U_c = 0.9U_{water}$ if $T_{air}>T_{water}$

$= U_{water}$ if $T_{air}=T_{water}$

$= 1.1U_{water}$ if $T_{air}<T_{water}$

12 $C_D = 0.001(1.1+0.01067U_{10})$

13 $t_{X,U} = 77.23(0.3048X)^{2/3}/[(0.3048U_c9.81)]^{1/3}$

14 $U = U_c/\{1.277 + 0.296 \tanh[0.9\log(45/t_{X,U})]\}$ for $t_{X,U}$<3,600 sec

$= U_c/[-0.15 \log(t_{X,U}) + 1.533]$ for $t_{X,U}$>3,600 sec

15 $u = (C_DU^2)^{1/2}$

16 $H_{m0} = [(0.3048u)^2/9.81]\{0.0413[9.81(0.3048X)/(0.3048u)^2]^{1/2}\}(1/0.3048)$

17 $T_p = [(0.3048u)/9.81]\{0.651[9.81(0.3048X)/(0.3048u)^2]^{1/3}\}$

18 $H_{1/3} = H_{m0}$

19 $H_{1/10} = 1.27\ H_{1/3}$

20 $H_{1/100} = 1.67\ H_{1/3}$

21 $H_{max} = 1.86\ H_{1/3}$

Extreme Storm Waves for Bellingham Bay

Wind-generated Wave Calculations Per the Coastal Engineering Manual (CEM)*

Step		Unit	Symbol	SW	S	S	S
	Observed wind speed units	-	-	mph	mph	mph	mph
1	Observed wind speed	-	U_z	52	60	70	92
2	Observed wind height	ft	z	33	33	33	33
3	Observed wind duration	sec	t	3,600	3,600	60	1
4	Observation over land (L) or water (W)	-	L,W	L	L	L	L
5	Fetch length	ft	X	41,000	4,000	4,000	4,000
6	Air-sea temperature difference	Deg.C	Δ_T	0	0	0	0
7	Observed wind speed	ft/sec	U_z	76.3	88.0	102.7	134.9
8	Wind speed corrected for height	ft/sec	U_{10}	76.3	88.0	102.7	134.9
9	Wind speed corrected for duration	ft/sec	U_{3600}	76.3	88.0	82.5	87.4
10	Wind speed corrected for location	ft/sec	U_{water}	91.5	105.6	99.0	104.9
11	Wind speed corrected for temp difference	ft/sec	U_c	91.5	105.6	99.0	104.9
12	Wind drag coefficient	-	C_D	0.0019	0.0020	0.0022	0.0025
13	Fetch-limited generation duration	sec	$t_{X,U}$	6,406	1,294	1,322	1,297
14	Duration corrected wind speed	ft/sec	U	95.1	103.4	97.1	102.7
15	Friction velocity	ft/sec	u	4.160	4.671	4.548	5.176
16	Energy-based significant wave height	ft	H_{m0}	6.13	2.15	2.09	2.38
17	Energy-based peak wave period	sec	Tp	3.6	1.7	1.7	1.8
18	33-Percentile Wave Height	ft	$H_{1/3}$	6.1	2.2	2.1	2.4
19	10-Percentile Wave Height	ft	$H_{1/10}$	7.8	2.7	2.7	3.0
20	1-Percentile Wave Height	ft	$H_{1/100}$	10.2	3.6	3.5	4.0
21	Maximum Wave Height	ft	H_{max}	11.4	4.0	3.9	4.4

* *Coastal Engineering Manual (Part II)*. U.S. Army Corps of Engineers, Engineering Manual EM 1110-2-1100, 31 January 2002.

Calculations based on CEM Figure II-2-20:

1-6 Input observed wind speed, observation height, observation duration, observation location, fetch, and air-water temperature difference

7 U_z [ft/sec] = (6080/3600)[knots] = (5280/3600)[mph] = (3281/3600)[km/hr] = = (5280/3600)[FM]/(1.277+0.296tanh(0.9log0.0125[FM]) = (3.281)[m/s]

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10 $U_{water} = 1.2U_{3600}$ if L; otherwise $U_{water} = U_{3600}$

11 $U_c = 0.9U_{water}$ if $T_{air} > T_{water}$
$= U_{water}$ if $T_{air} = T_{water}$
$= 1.1U_{water}$ if $T_{air} < T_{water}$

12 $C_D = 0.001(1.1 + 0.01067U_{10})$

13 $t_{X,U} = 77.23(0.3048X)^{2/3}/[(0.3048U_c 9.81)]^{1/3}$

14 $U = U_c/\{1.277 + 0.296 \tanh[0.9\log(45/t_{X,U})]\}$ for $t_{X,U}$<3,600 sec
$= U_c/[-0.15 \log(t_{X,U}) + 1.533]$ for $t_{X,U}$>3,600 sec

15 $u = (C_D U^2)^{1/2}$

16 $H_{m0} = [(0.3048u)^2/9.81]\{0.0413[9.81(0.3048X)/(0.3048u)^2]^{1/2}\}(1/0.3048)$

17 $T_p = [(0.3048u)/9.81]\{0.651[9.81(0.3048X)/(0.3048u)^2]^{1/3}\}$

18 $H_{1/3} = H_{mo}$

19 $H_{1/10} = 1.27\ H_{1/3}$

20 $H_{1/100} = 1.67\ H_{1/3}$

21 $H_{max} = 1.86\ H_{1/3}$

Attachment D
Vessel-Generated Waves

Vessel Generated Waves
Blaauw et al (1984)

Vessel Type	Yacht
Vessel Speed, kt (V_s)	7
Water Depth, ft (h)	30
Side Distance, ft (S)	300
Interference Peak Coefficient (a)*	0.25
Wave Height, ft (H_i)	0.3
Wave Length, ft (L_i)	18
Wave Period, sec (T)	1.9

*For "a", select from the following: 0.25 for a canal motor boat
0.35 for a tug
0.80 for a barge

Blaauw, H.G., F.C.M. van der Knapp, M.T. de Groot and K.W. Pilarczyk (1984) "Design of Bank Protection of Inland Navigation Fairways." *Proceedings of the International Conference on Flexible Armoured Revetments Incorporating Geotextiles*, London, England, 29-30 March 1984.

Attachment E
Habitant Bench – Bellingham, Washington

Port of Bellingham
Habitat Bench
Typical Storm Stable Cap Armor

Existing Conditions:

Offshore/Deepwater Wave Height	H_o	ft	3.2
Offshore/Deepwater wave period	T	sec	2.9
Offshore/Deepwater wave length	Lo	ft	43
Wave steepness	H_o/gT^2	-	0.0118

Distance from shoreline	x	ft	3,000	2,000	1,000	800	600	400	200	100	50	30	20	18	10
Water depth	d	ft	26	20	18	15	12	10	8	7	6	6	6	6	3
Cotangent of bottom angle	cotθ	-	250	200	150	100	70	70	70	70	70	70	70	3	3
Bottom slope	m	-	0.004	0.005	0.007	0.010	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.333	0.333
Wave length	L	ft	39	37	36	33	31	28	26	24	22	22	22	22	16
Breaker height index (SPM Fig. 7-3)	H_b/H_o	–	0.95	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	1.08	1.08
Breaker height	H_b	ft	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5
Breaker steepness	H_b/gT^2	-	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.013	0.013
Upper breaker depth curve (SPM Fig. 7-2)	α	-	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58
Lower breaker depth curve (SPM Fig. 7-2)	β	-	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.29	1.29
Depth at breaking	d_{bmax}	ft	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	5.5	5.5
Depth at breaking	d_{bmin}	ft	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	4.5	4.5
Wave height at x	H	ft	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.5	3.5
Maximum horizontal velocity at bottom	u_{max}	ft/sec	0.1	0.3	0.4	0.5	0.8	1.1	1.6	2.0	2.4	2.4	2.4	2.6	5.7
Median stable stone size at bottom	D_{50}	ft	0.0001	0.0005	0.0008	0.0019	0.0047	0.0088	0.0177	0.0260	0.0393	0.0393	0.0393	0.0459	0.2198
Median stable stone size at bottom	D_{50}	mm	0.03	0.15	0.26	0.59	1.42	2.69	5.41	7.93	11.99	11.99	11.99	13.99	67.00

Capping Conditions:

Offshore/Deepwater Wave Height	H_o	ft	3.2
Offshore/Deepwater wave period	T	sec	2.9
Offshore/Deepwater wave length	Lo	ft	43
Wave steepness	H_o/gT^2	-	0.0118

Distance from shoreline	x	ft	3,000	2,000	1,000	800	600	400	200	100	50	30	20	18	10
Water depth	d	ft	26	20	18	15	9	7	5	4	3	3	3	3	0
Cotangent of bottom angle	cotθ	-	250	200	150	100	70	70	70	70	70	70	70	3	3
Bottom slope	m	-	0.004	0.005	0.007	0.010	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.333	0.333
Wave length	L	ft	39	37	36	33	27	24	21	18	16	16	16	16	0
Breaker height index (SPM Fig. 7-3)	H_b/H_o	--	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	1.08	1.08
Breaker height	H_b	ft	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5
Breaker steepness	H_b/gT^2	-	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.013	0.013
Upper breaker depth curve (SPM Fig. 7-2)	α	-	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58
Lower breaker depth curve (SPM Fig. 7-2)	β	-	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.29	1.29
Depth at breaking	d_{bmax}	ft	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	5.5	5.5
Depth at breaking	d_{bmin}	ft	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	4.5	4.5
Wave height at x	H	ft	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.5	3.5
Maximum horizontal velocity at bottom	u_{max}	ft/sec	0.1	0.3	0.4	0.5	1.3	2.0	3.0	3.9	5.3	5.3	5.3	5.7	#DIV/0!
Median stable stone size at bottom	D_{50}	ft	0.000	0.000	0.001	0.002	0.012	0.026	0.062	0.104	0.188	0.188	0.188	0.220	#DIV/0!
Median stable stone size at bottom	D_{50}	mm	0.03	0.15	0.26	0.59	3.78	7.93	18.90	31.56	57.44	57.44	57.44	67.00	#DIV/0!

Port of Bellingham
Habitat Bench
Extreme Storm Stable Cap Armor

Existing Conditions:

Offshore/Deepwater Wave Height	Ho	ft	6.1
Offshore/Deepwater wave period	T	sec	3.6
Offshore/Deepwater wave length	Lo	ft	66
Wave steepness	H_o/gT^2	-	0.0146

Distance from shoreline	x	ft	3,000	2,000	1,000	800	600	400	200	100	50	30	20	18	10
Water depth	d	ft	26	20	18	15	12	10	8	7	6	6	6	6	3
Cotangent of bottom angle	cotθ	-	250	200	150	100	70	70	70	70	70	70	70	3	3
Bottom slope	m	-	0.004	0.005	0.007	0.010	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.333	0.333
Wave length	L	ft	54	49	47	43	39	36	32	30	28	28	28	28	20
Breaker height index (SPM Fig. 7-3)	H_b/H_o	–	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	1.10	1.10
Breaker height	H_b	ft	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	6.7	6.7
Breaker steepness	H_b/gT^2	-	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.016	0.016
Upper breaker depth curve (SPM Fig. 7-2)	α	-	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.69	1.69
Lower breaker depth curve (SPM Fig. 7-2)	β	-	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.22	1.22
Depth at breaking	d_{bmax}	ft	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	11.3	11.3
Depth at breaking	d_{bmin}	ft	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	8.2	8.2
Wave height at x	H	ft	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.7	6.7
Maximum horizontal velocity at bottom	u_{max}	ft/sec	0.6	1.1	1.3	1.8	2.6	3.3	4.4	5.2	6.2	6.2	6.2	6.8	13.2
Median stable stone size at bottom	D_{50}	ft	0.003	0.008	0.012	0.023	0.045	0.075	0.134	0.183	0.259	0.259	0.259	0.313	1.185
Median stable stone size at bottom	D_{50}	mm	0.82	2.50	3.70	6.93	13.80	22.99	40.70	55.88	78.95	78.95	78.95	95.53	361.22

Capping Conditions:

Offshore/Deepwater Wave Height	Ho	ft	6.1
Offshore/Deepwater wave period	T	sec	3.6
Offshore/Deepwater wave length	Lo	ft	66
Wave steepness	H_o/gT^2	-	0.0146

Distance from shoreline	x	ft	3,000	2,000	1,000	800	600	400	200	100	50	30	20	18	10
Water depth	d	ft	26	20	18	15	9	7	5	4	3	3	3	3	0
Cotangent of bottom angle	cotθ	-	250	200	150	100	70	70	70	70	70	70	70	3	3
Bottom slope	m	-	0.004	0.005	0.007	0.010	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.333	0.333
Wave length	L	ft	54	49	47	43	34	30	26	23	20	20	20	20	0
Breaker height index (SPM Fig. 7-3)	H_b/H_o	--	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	1.10	1.10
Breaker height	H_b	ft	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	6.7	6.7
Breaker steepness	H_b/gT^2	-	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.016	0.016
Upper breaker depth curve (SPM Fig. 7-2)	α	-	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.69	1.69
Lower breaker depth curve (SPM Fig. 7-2)	β	-	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.22	1.22
Depth at breaking	d_{bmax}	ft	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	11.3	11.3
Depth at breaking	d_{bmin}	ft	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	8.2	8.2
Wave height at x	H	ft	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.7	6.7
Maximum horizontal velocity at bottom	u_{max}	ft/sec	0.6	1.1	1.3	1.8	3.8	5.2	7.5	9.3	12.0	12.0	12.0	13.2	#DIV/0!
Median stable stone size at bottom	D_{50}	ft	0.003	0.008	0.012	0.023	0.099	0.183	0.380	0.587	0.979	0.979	0.979	1.185	#DIV/0!
Median stable stone size at bottom	D_{50}	mm	0.82	2.50	3.70	6.93	30.31	55.88	115.79	178.85	298.53	298.53	298.53	361.22	#DIV/0!