



Prepared for:
City of Cambridge

City of Cambridge Municipal Marina- Wave Analysis and Remediation Recommendations



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1. INTRODUCTION

The Cambridge Municipal Yacht Basin (Yacht Basin) is located along the Choptank River in Cambridge, Maryland. The Yacht Basin includes the 245-slip Cambridge Municipal Marina, the 130-slip Cambridge Yacht Club and the Choptank River Lighthouse. The basin is protected by concrete floating breakwaters and a timber wave fence along a perimeter pier, both constructed as part of the marina expansion in 2006. A Vicinity Map showing the location of the Yacht Basin is presented in Figure 1.

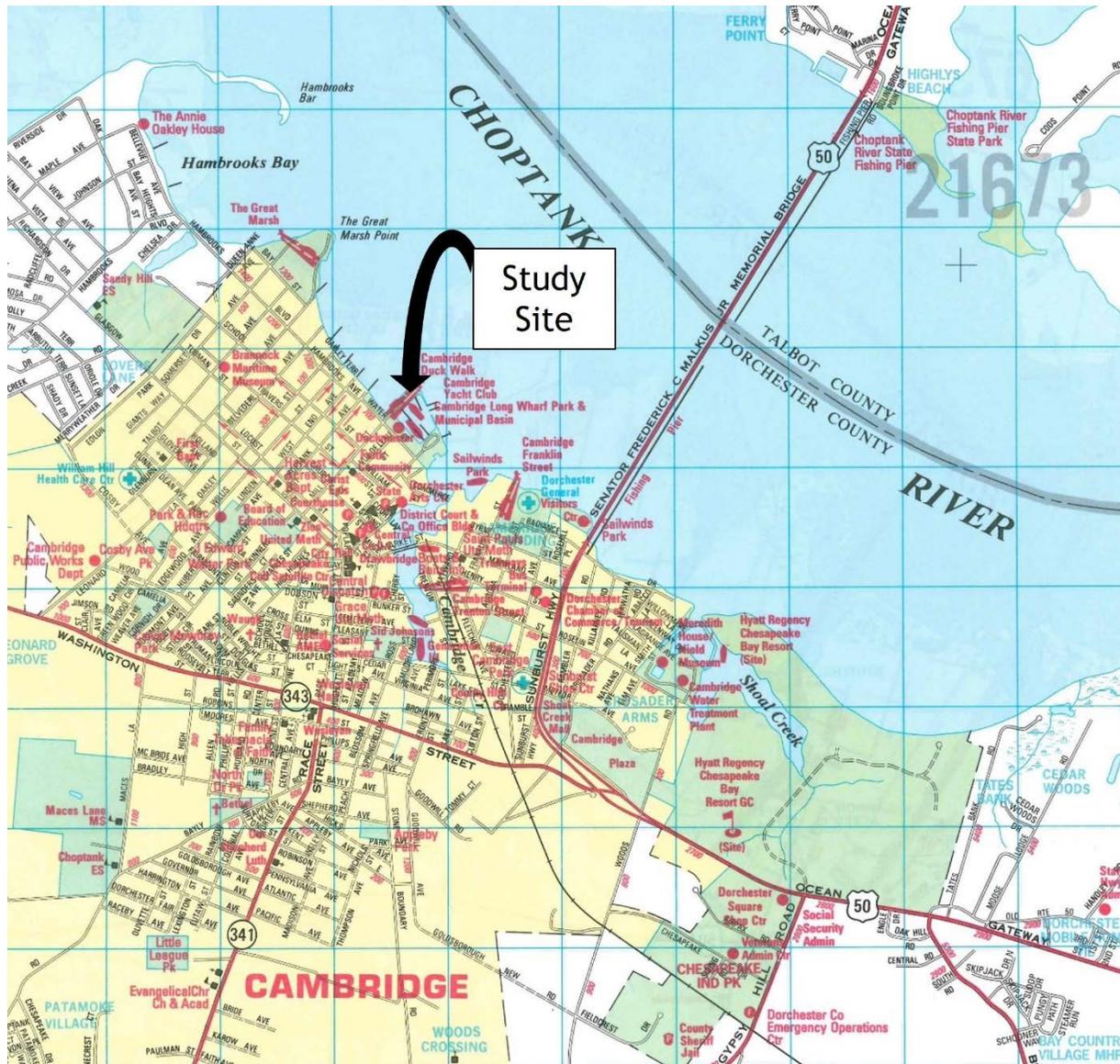


Figure 1 - Vicinity Map

1.1. Background

The original construction of the Yacht Basin occurred in the 1960s and was expanded in 2006. As part of the expansion, concrete floating breakwaters and a timber wave fence

were constructed to reduce the wave action within the Yacht Basin. Observations have indicated that, while the floating breakwaters and wave fence have been effective in protecting the marina against wind driven waves, boat wakes continue to result in excessive wave action within the Yacht Basin.

1.2. Purpose

The purpose of this study is to examine the performance of the floating breakwaters against boat wakes from passing vessels and propose solutions for reducing the waves within the Yacht Basin.

2. EXISTING CONDITIONS

The following subsections summarize the available data on existing marina conditions.

2.1. Marina Features

The Yacht Basin, shown in Figure 2, encompasses approximately 18 acres along the southern bank of the Choptank River. The Municipal Marina contains 245 slips along seven fixed timber piers with slip sizes ranging from 35 to 60 feet long. The Yacht Club comprises of an additional 130 slips along five fixed timber piers. Water depths within the Yacht Basin range between -5 and -8 feet below Mean Low Water (MLW). Landmasses extend out into the Choptank River on both the upriver and downriver side of the Yacht Basin. Along these landmasses and the shoreline, a timber bulkhead surrounds approximately 45% of the marina area.

Along the northwestern-most pier, Pier N, owned by the Yacht Club, a timber wave fence was constructed during the marina expansion to protect the Yacht Basin from waves propagating from the Northwest. Based on the 100% Construction Documents developed by Andrews, Miller & Assoc., Inc. dated August 2005, the first 245 feet of the timber wave fence extending from the bulkhead consists of solid sheeting while the last 120 feet of sheeting contains one-inch gaps between sheets. For both reaches, the sheeting extends into the existing subgrade. The drawings indicate that the wave fence does not extend along the portion of Pier N along slip N15 that runs parallel with the river channel, but discussions with marina management have indicated that a wave fence is present along this area, as shown in Figure 2.

2.2. Floating Breakwaters

Two sections of concrete floating breakwaters produced by SF Marina out of Goteborg, Sweden make up the wave attenuators for the marina, designated as the Northwest (NW) breakwater and the Southeast (SE) breakwater and shown in Figure 2. Based on the report provided by the Virginia Institute of Marine Science (VIMS) to Coastal Design and Construction Inc (CDCI), the two breakwaters are constructed using different

floating units¹. The breakwater along the Northwestern end of the Yacht Basin, herein referred to as the NW Breakwater, was anticipated to experience the most wave action and, therefore, constructed using the T400 floating wave attenuators. The SE Breakwater, located along the Southeastern length of the Yacht Basin, was constructed using multiple floating attenuator modules, namely, the T400, T300 and T1040. The location of each breakwater module provided in the VIMS report is shown in Figure 2.



Figure 2 – Marina Layout and Features

Dimensions for the T400 and T300 docks were obtained from the *Floating Breakwater Submittal* document developed by Vanasse Hangen Brustlin (VHB) and CDCI². However, dimension for the T1040 are not available in this document. The final design appears to differ from the design provided in the VIMS documents, therefore the dimensions of the floating docks were approximated based on data provided and observations. These dimensions are provided in Table 1.

Table 1 – Approximate Dimensions of Floating Breakwaters		
Dimension	Value (m)	Value (ft)
Width	4.0	13.1
Height	1.8	5.9
Freeboard	0.6	2.0
Draft	1.2	3.9

¹ Maa, Jerome P.Y. Virginia Institute of Marine Science, *Selection of Floating Breakwaters for the Cambridge Municipal Marina*. Prepared for Coastal Design and Construction, Inc. May 2006.

² Vanasse Hangen Brustlin, Inc. *Floating Breakwater Submittal for City of Cambridge Municipal Marina Expansion/Reconstruction*, March 26, 2016.

Typical water depth in the vicinity of the breakwaters is approximately 8 feet deep. The breakwaters are anchored using approximate 90-foot long mooring chains designed to withstand forces from wind, waves and currents for the 100-year return period storm (VHB 2016). The anchoring of the system is assumed to be functioning properly and is not evaluated as part of this study.

2.3. Wave Analysis

The Yacht Basin is exposed to wind-waves traveling across the Choptank River from the Northwest to the Southeast directions. The longest fetch, or distance that wind can travel across open water and produce waves, is approximately 3.5 miles to the North-Northwest. Additionally, the Choptank River channel is located an average of 3,015 feet from the marina. Water depths in the channel can exceed 40 feet with 10 feet of water depth in close proximity to the Yacht Basin. Wind-generated waves as well as boat wakes from vessels traveling within and outside of the channel will impact the marina infrastructure and are discussed in subsequent sections.

2.3.1. Wind waves

Wind-generated waves impacting the Yacht Basin were evaluated during the design of the floating breakwaters (VIMS 2006). The following design wave conditions were used to evaluate the performance of the breakwaters.

Wave Direction	Wave Height (ft)	Wave Period (s)	Wave Length (ft)
NNW	5.29	3.30	52.2
N	4.42	3.00	44.3
NNE	3.65	2.72	-
NE	3.44	2.64	-
E	3.63	2.76	36.7

The report states that the SF Marina floating breakwaters meet the design criteria of reducing the wave heights to approximately 25% of the incident wave. To confirm this assertion, the same wave conditions with the final structures were input into the US Army Corps of Engineers Coastal Modeling System (CMS) Wave model. CMS, developed by the Coastal Inlets Research Program (CIRP) division of the United States Army Corps of Engineers - Engineering Research and Development Center (USACE-ERDC), Coastal and Hydraulics Laboratory (CHL) is an integrated 2-D numerical model that simulates waves, currents, water levels, sediment transport and morphology change along shorelines and in coastal inlets.

The wave conditions were input into the model and simulated assuming the floating breakwater dimensions presented in Table 1. Additionally, wave reflection along the

³ Maa, Jerome P.Y. Virginia Institute of Marine Science, *Selection of Floating Breakwaters for the Cambridge Municipal Marina*. Prepared for Coastal Design and Construction, Inc. May 2006.

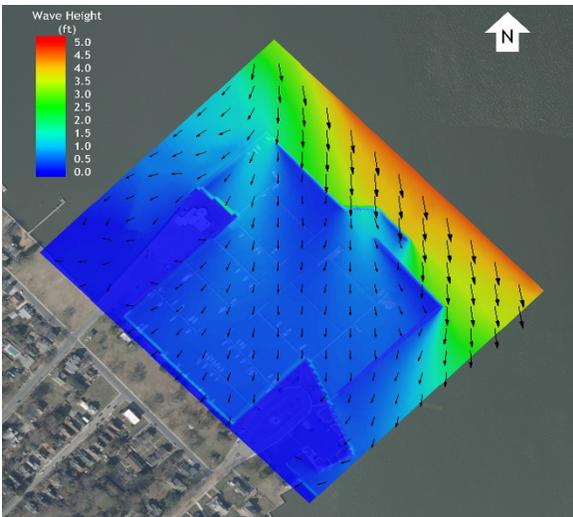


Figure 3 - Design Wave from NNW

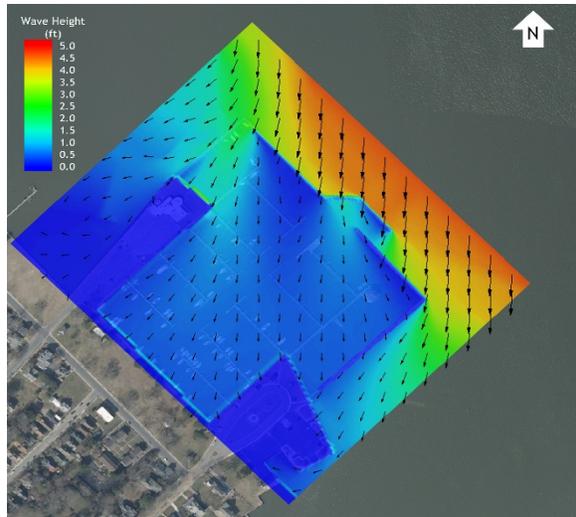


Figure 4 - Design Wave from North

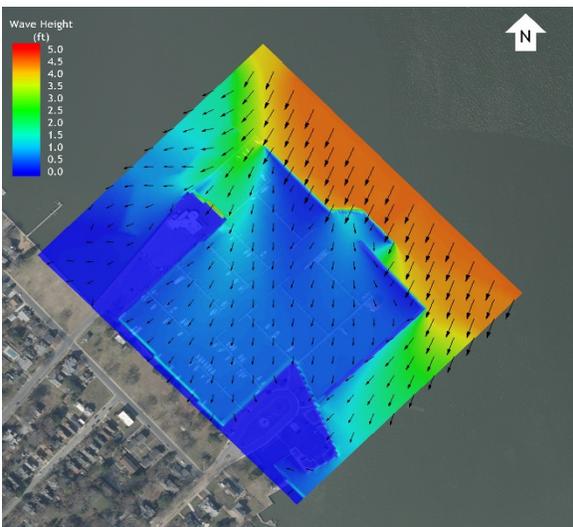


Figure 5 - Design Wave from NNE

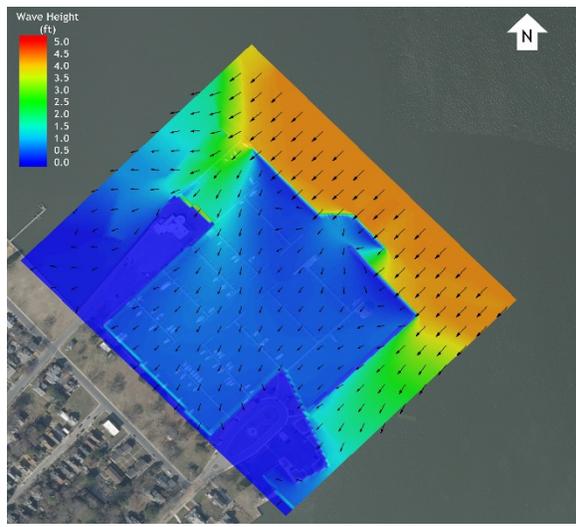


Figure 6 - Design Wave from NE

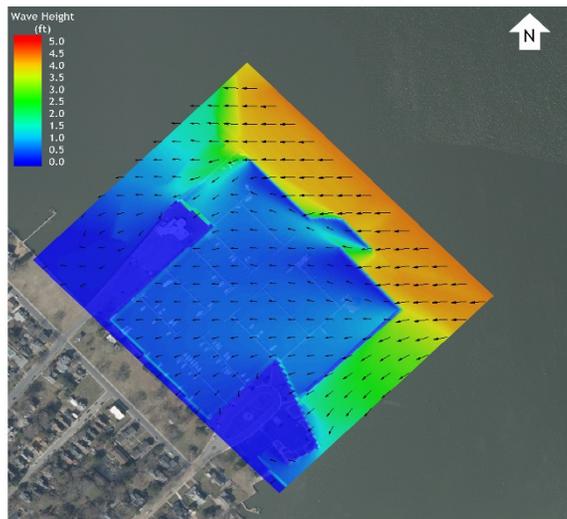


Figure 7 - Design Wave from East

timber bulkhead located on three sides of the marina was also input so that 100% of the wave energy reaching the bulkhead is reflected back into the Yacht Basin. The results of the design wave simulations are presented in Figure 3 through Figure 7.

The results of the analysis show that, for the design wave conditions, the reduction of wave height to 25% of the incoming wave criteria is met, as shown in Table 3.

Table 3 – Design Wind-wave Model Results			
Wave Direction	Design Wave Height (ft)	Average Wave Height in Yacht Basin	Percent of Design Wave Height
NNW	5.29	0.45	8%
N	4.42	0.50	11%
NNE	3.65	0.48	13%
NE	3.44	0.44	13%
E	3.63	0.41	11%

2.3.2. Boat Wakes

Given the close proximity of the Yacht Basin to the main channel in the Choptank River, waves generated from passing vessels, or boat wakes, will also impact the marina infrastructure. Boat wakes are caused by the displacement of the water as the boat’s hull moves through water. Figure 8 shows an approximation of the wave patterns caused by a moving vessel and Figure 9 shows the angle of approach of the boat wakes caused by vessels traveling up and down the Choptank River channel.

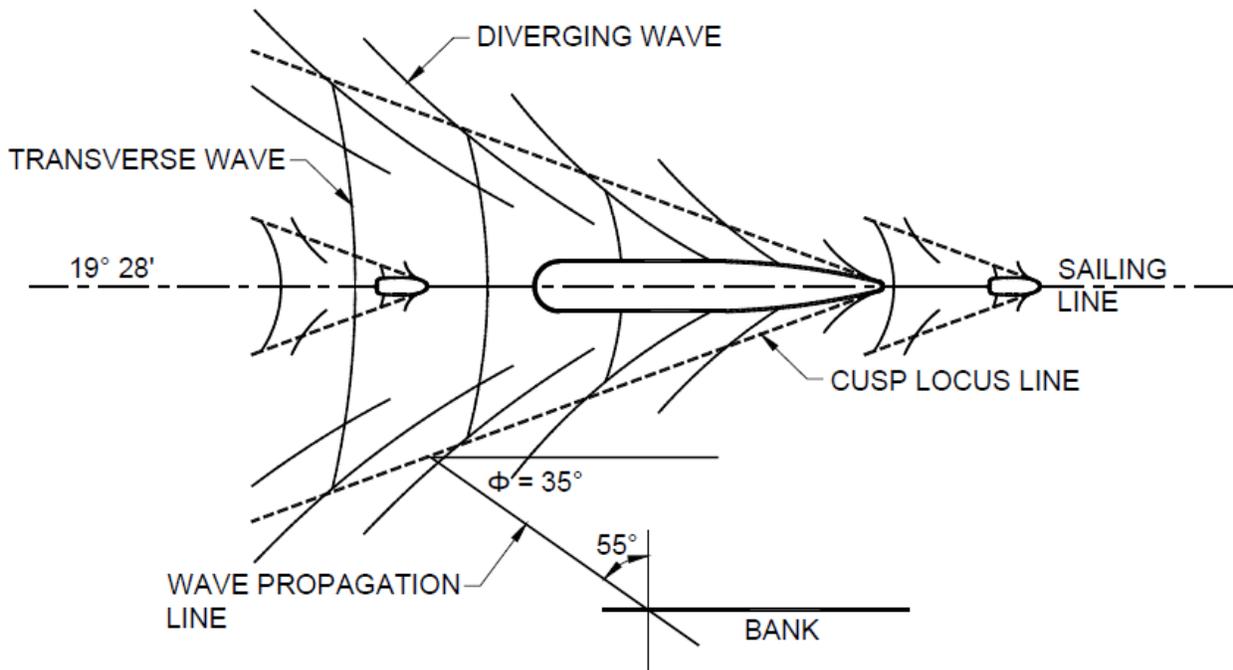


Figure 8 - Boat Wake Wave Pattern (Source: Schierech, 2001)



Figure 9 - Directions of Boat Wake Propagation

Methodology presented by Verhey and Bogaerts (1989)⁴ was used to estimate boat wakes based on sailing speed, sailing distance to site and water depth. Faster moving large vessels, which are not yet planing (skimming the water surface due to lift caused by hydrodynamic forces), will displace the most water and result in the highest waves with the longest wave periods. For this reason, a fully loaded pleasure yacht traveling 15 knots sailing in the approximate middle of the channel was used to estimate the resulting wake, presented in Table 4.

Table 4 – Vessel and Wake Wave Characteristics					
Sailing Direction	Wake Angle (degrees N)	Vessel Speed (knots)	Distance to Marina (ft)	Wake Wave Height (ft)	Wake Wave Period (seconds)
Downriver	281°	15	3,015	2.7	4.1
Upriver	171°	15	3,015	2.7	4.1

⁴ Verhey, H.J., and Bogaerts, M.P.(1989). "Ship Waves and the Stability of Armour Layers Protecting Slopes." Proceedings for the 9th International Harbour Congress, Antwerp, Belgium.

Inputting these parameters into the wave model with the floating breakwater dimensions presented in Table 1 yielded the following results that are depicted in Figure 10 and Figure 11.

Table 5 – Existing Wake Wave Model Results			
Sailing Direction	Design Wake Wave Height (ft)	Average Wave Height in Yacht Basin	Percent Height of Design Wave Height
Downriver	2.7	1.0	37%
Upriver	2.7	0.9	33%

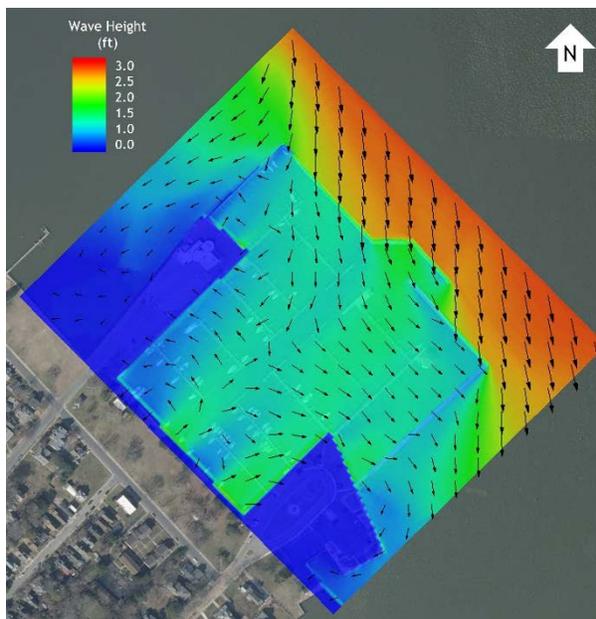


Figure 10 - Boat Wake Sailing Upriver

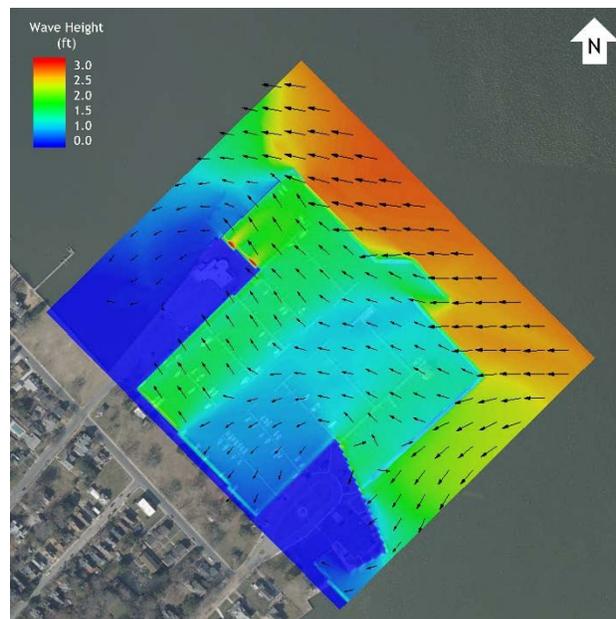


Figure 11 - Boat Wake Sailing Downriver

The analysis shows that the floating breakwaters are less effective against the boat wakes, even though the wave height outside of the Yacht Basin is smaller than the design wind-waves. This is likely due to the longer wave periods associated with boat wakes. In fact, a physical model study⁵ of floating breakwater options for Oyster Point Marina in the San Francisco Bay found that floating breakwaters attenuate wave heights for longer period waves (Period >3 seconds) half as well as they do for shorter period waves (Period < 3 seconds). This is also consistent with observations at the Cambridge Municipal Marina.

3. ALTERNATIVES ANALYSIS

After assessing the existing conditions, options for reducing the wave climate within the Yacht Basin were investigated. Various alternatives were modeled given the same wave conditions and evaluated per criteria developed by the American Society of Civil

⁵ Canadian Hydraulics Centre (CHC) 2011. Physical Model Studies of Floating Breakwaters for Oyster Point Marina – Controlled Technical Report (CHC-CTR-121).

Engineers (ASCE). These criteria, as well as the performance of each alternative, is discussed in the following paragraphs.

3.1. Marina Performance Guidelines

The ASCE Planning and Design Guidelines for Small Craft Harbors provides the following criteria for characterization of a marina based on wave climate:

Table 6 – Criteria for a “Good” Wave Climate in Small Craft Harbors ⁶			
Direction and peak period of significant wave	Significant Wave Height (Hs) Exceedance		
	50-year	1-year	Weekly
Head seas with $2 < T_p < 6$ s	Hs < 2-ft wave	Hs < 1-ft wave	Hs < 0.5-ft wave
Oblique Seas	Hs < $(2 - 1.25\sin\theta)$	Hs < $(1 - 0.5\sin\theta)$	Hs < $(0.5 - 0.25\sin\theta)$
Beam seas with $2 < T_p < 6$ s	Hs < 0.75-ft wave	Hs < 0.5-ft wave	Hs < 0.25-ft wave

Note: Criteria for an “excellent” wave climate - multiply recommended allowable wave height by 0.75, and for a “moderate” wave climate - multiply allowable wave height by 1.25.

As shown in the previous study and checked by this wave modeling effort, the existing breakwaters appear to provide sufficient wave attenuation for the return period wind-waves evaluated as part of the previous study. For the boat wakes presented in Table 4, the slips within the Yacht Basin have wave heights as shown in Table 7 and Table 8. A wave climate characterization of excellent, good, moderate or none was assigned to slips based on how well they met the criteria presented in Table 6 for wakes generated by boats sailing downriver and upriver.

Table 7 – Wave Climate Analysis for Vessel Sailing Downriver (Existing Conditions)				
Slips	Average Wave Direction (degrees N)	Limit of Allowable Wave Height (ft) for ‘Good’ Marina	Modeled Wave Height (ft)	Wave Climate Characterization
A1 – A17	306°	0.28	0.68	None
B1 – B10	293°	0.34	0.69	None
B11 – B22	291°	0.34	0.70	None
C1 – C13	286°	0.37	0.69	None
C14 – C25	285°	0.38	0.68	None
D1 – D13	277°	0.40	0.63	None
D14 – D27	241°	0.45	0.60	None
E1 – E20	226°	0.51	0.52	Moderate
E21 – E40	218°	0.53	0.50	Moderate
F1 – F20	210°	0.57	0.47	Moderate
F21 – F40	208°	0.59	0.44	Moderate
G1 – G13	290°	0.26	1.50	None

⁶ ASCE Planning and Design Guidelines for Small Craft Harbors, ASCE Manuals and Reports on Engineering Practice No. 50, Third Edition.

G13 – G41	216°	0.54	0.49	Moderate
H1 – H16	324°	0.25	1.30	None
H17 – H32	325°	0.25	1.23	None
I1 – I11	325°	0.25	1.22	None
112 – 124	323°	0.25	1.21	None
J1 – J13	323°	0.25	1.18	None
J14 – J29	322°	0.25	1.20	None
K1 – K18	317°	0.25	1.14	None
K19 – K28	312°	0.25	1.19	None
L1 – L12	310°	0.25	1.22	None
L13 – L23	310°	0.26	1.25	None
M1 – M11	325°	0.38	1.17	None
N1 – N15	319°	0.32	1.63	None

Table 8 - Wave Climate Analysis for Vessel Sailing Upriver (Existing Conditions)

Slips	Average Wave Direction (degrees N)	Limit of Allowable Wave Height (ft) for 'Good' Marina	Modeled Wave Height (ft)	Wave Climate Characterization
A1 – A17	140°	0.31	0.92	None
B1 – B10	141°	0.28	1.08	None
B11 – B22	141°	0.30	1.05	None
C1 – C13	136°	0.31	1.02	None
C14 – C25	130°	0.31	1.02	None
D1 – D13	118°	0.32	0.98	None
D14 – D27	116°	0.32	0.98	None
E1 – E20	176°	0.33	0.95	None
E21 – E40	264°	0.34	0.95	None
F1 – F20	302°	0.33	0.95	None
F21 – F40	294°	0.34	0.89	None
G1 – G13	279°	0.25	0.72	None
G13 – G41	318°	0.37	1.05	None
H1 – H16	291°	0.38	0.56	Moderate
H17 – H32	299°	0.39	0.62	Moderate
I1 – I11	311°	0.25	0.69	None
112 – 124	313°	0.25	0.72	None
J1 – J13	300°	0.27	0.75	None
J14 – J29	282°	0.41	0.79	None
K1 – K18	233°	0.29	0.85	None
K19 – K28	217°	0.27	0.85	None
L1 – L12	184°	0.26	0.92	None
L13 – L23	172°	0.26	0.95	None
M1 – M11	244°	0.43	0.89	None

N1 – N15	309°	0.25	0.49	None
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The analysis depicts the following conclusions:

- For vessels sailing downriver at 15 knots and generating wakes – some slips within the City-owned marina experience a ‘moderate’ wave climate with others experiencing wave heights too high for wave climate characterization. Similarly, slips within the Yacht Club-owned marina experience a wave climate that exceeds the recommended wave heights per ASCE guidelines.
- For vessels sailing upriver at 15 knots and generating wakes – All slips within the Yacht Club and City-owned marina, except the most sheltered area (Pier H), experience a wave climate that exceeds the recommended wave heights per ASCE guidelines.

The following paragraphs describe alternatives to reduce the wave heights within the Yacht Basin.

3.2. Alternative 1 – Extend Breakwater Draft

Previous studies have shown that increasing the breakwater draft can have a significant impact on wave attenuation. For the purposes of this study, the model was run for a 2-foot increase in breakwater draft. This would increase the breakwater draft from approximately 4 feet to 6 feet. Given that the water depth in the vicinity of the breakwaters is between 7 and 8 feet below MLW, increasing the draft more than 6 feet would result in the breakwaters resting on the bottom during periods of unusually low tides.

Implementation of this alternative would require retrofitting the existing structures. This could be done by adding ‘skirts’ to the front and back side of the floating breakwater to effectively increase the draft. However, installation of the skirts would also require a redesign of the breakwater anchoring system as the weight of the structure and loads impacting the larger surface area would change.

The results of the model runs for this alternative are presented in Table 9 and shown in Figure 12 and Figure 13.

Table 9 – Alternative 1 Wake Wave Model Results					
Sailing Direction	Design Wave Height (ft)	Modeled Wave Height in Yacht Basin	% of Design Wave Height- Yacht Basin	Modeled Wave Height in Marina*	% Design Wave Height – Marina*
Downriver	2.7	1.00	37%	0.90	33%
Upriver	2.7	0.49	18%	0.49	18%

*City-owned marina area

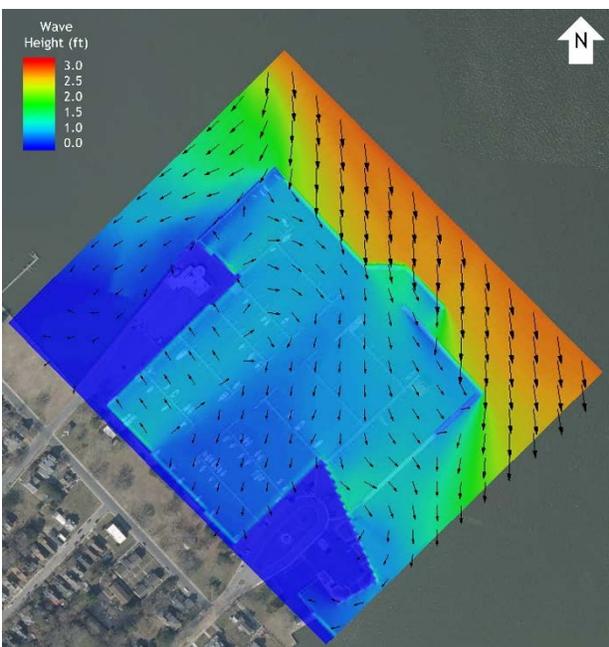


Figure 12 - Alternative 1 Wake Wave Sailing Upriver

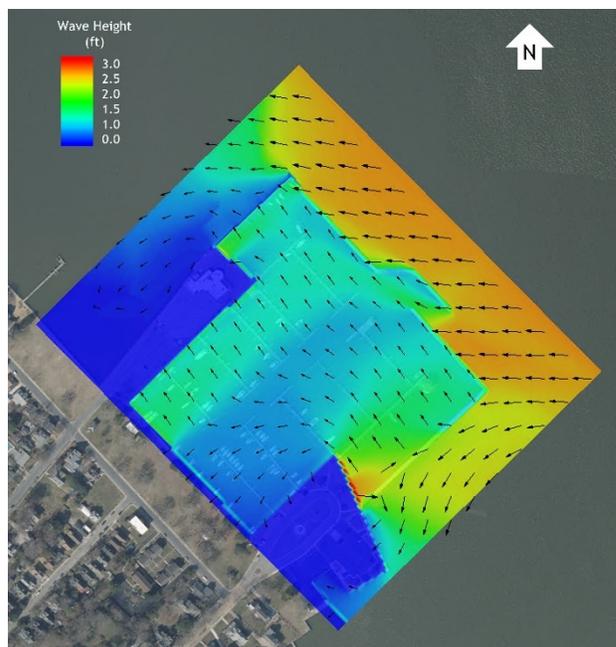


Figure 13 - Alternative 1 Wake Wave Sailing Downriver

The analysis shows that wave heights within the Yacht Basin is decreased below 0.5 feet for wakes produced by vessels sailing upriver. However, for wakes from vessels sailing downriver, the impact of the increase draft is minimal. The City-owned area of the Yacht Basin appears to perform better, but does not have reduced wave heights below the selected criteria. Additionally, the complications associated with retrofitting the existing structure would make this alternative difficult to implement.

3.3. Alternative 2 – Wave Attenuators at Piers E and H

During the development of this analysis, the City of Cambridge is simultaneously developing the design of the replacement of fixed piers with floating docks. Of the three piers proposed for replacement (Piers E, F and H), Alternative 2 proposes to utilize wave attenuators for Piers E and H. The wave attenuators would reduce both the incoming wave heights as well as the reflected waves along the bulkhead. This alternative would provide protection to the smaller boats located within the most sheltered part of the Yacht Basin.

The results of the model runs for this alternative are presented in Table 10 and shown in Figure 14 and Figure 15.

Table 10 – Alternative 2 Wake Wave Model Results					
Sailing Direction	Design Wave Height (ft)	Modeled Wave Height in Yacht Basin	% of Design Wave Height- Yacht Basin	Modeled Wave Height in Marina*	% Design Wave Height – Marina*
Downriver	2.7	1.00	37%	0.90	33%
Upriver	2.7	0.78	29%	0.80	30%

*City-owned marina area

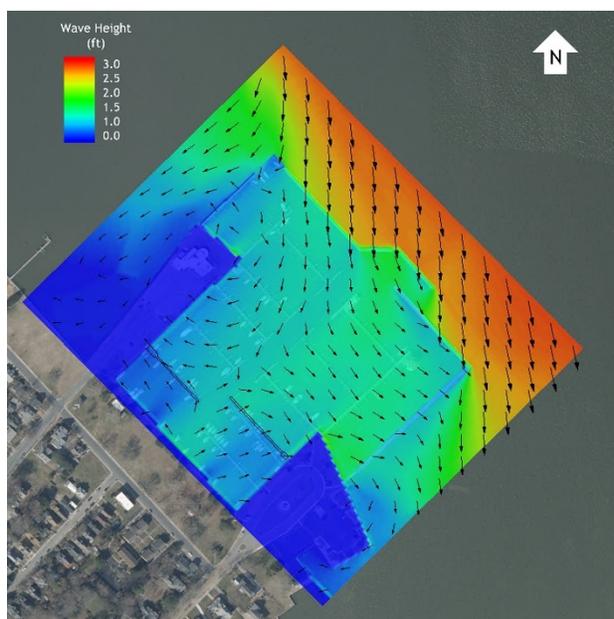


Figure 14 - Alternative 2 Wake Wave Sailing Upriver

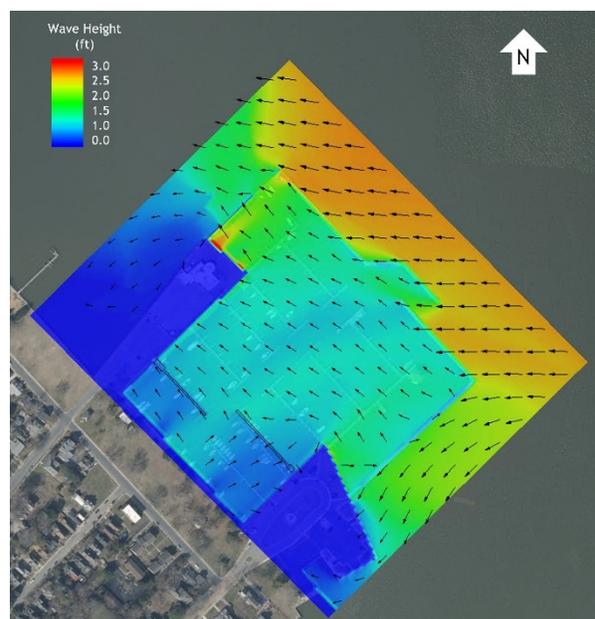


Figure 15 - Alternative 2 Wake Wave Sailing Downriver

The average wave height within the Yacht Basin is decreased to approximately 30% – 40% of the incoming wave. However, the majority of the reduction occurs immediately adjacent to the Pier E and H wave attenuators. Boat slips located along other piers experience minimal reduction in wave height.

3.4. Alternative 3 – Wave Fences

Alternative 3 examines constructing wave fences along the outermost fixed piers to further reduce the wave heights that pass the floating breakwaters. In addition to the Pier N wave fence, an ad-hoc wave screen exists along the four end slips on Pier B. Alternative 3 proposes to replace and extend the wave fence for the length of Piers A and B as well as construct an additional wave fence along Pier L belonging to the Yacht Club. The wave fences are proposed to be built along the seaward edges of the pier structure. Gaps would be placed for approximately 10% of the wave fence length to allow flow through the structure. The sheeting of the wave fence would extend into the bottom subgrade, similar to the existing Pier N wave fence structure.

The results of the model runs are presented in Table 11 and shown in Figure 16 and Figure 17.

Table 11 – Alternative 3 Wake Wave Model Results					
Sailing Direction	Design Wave Height (ft)	Modeled Wave Height in Yacht Basin	% of Design Wave Height- Yacht Basin	Modeled Wave Height in Marina*	% Design Wave Height – Marina*
Downriver	2.7	0.66	24%	0.54	20%
Upriver	2.7	0.52	19%	0.50	19%

*City-owned marina area

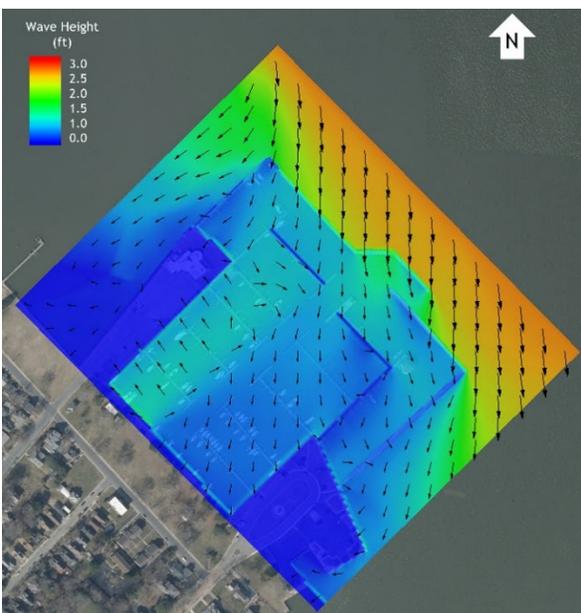


Figure 16 - Alternative 3 Wake Wave Sailing Upriver

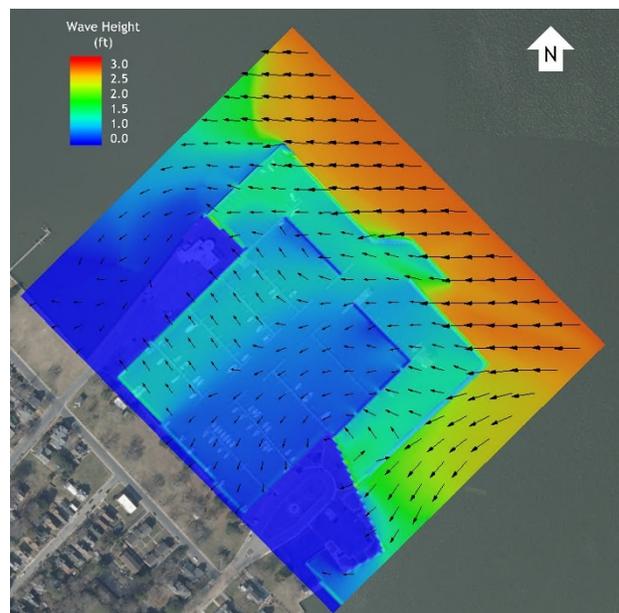


Figure 17 - Alternative 3 Wake Wave Sailing Downriver

Alternative 3 provides greater protection to a larger area within the Yacht Basin, decreasing the incoming wave height to 25% or less of its original height for vessels traveling downriver. The City-owned marina slips experience even more reduction in wave height for this direction. For vessels traveling upriver, this alternative provides an 80% or more decrease in wake wave heights in the Yacht Basin.

3.5. Alternative 4 – Wave Fences and Wave Attenuators

Alternative 4 examines implementing both Alternative 2 and 3. The wave fence would be placed along piers A and B as well as the Yacht Club's Pier L. Pier E and H would be constructed as wave attenuators with a draft of 5 feet. The result of the model runs for Alternative 4 are presented in Table 12 and shown in Figure 18 and Figure 19.

Table 12 – Alternative 4 Wake Wave Model Results					
Sailing Direction	Design Wave Height (ft)	Modeled Wave Height in Yacht Basin	% of Design Wave Height- Yacht Basin	Modeled Wave Height in Marina*	% Design Wave Height – Marina*
Downriver	2.7	0.42	16%	0.35	13%
Upriver	2.7	0.38	14%	0.34	13%

*City-owned marina area

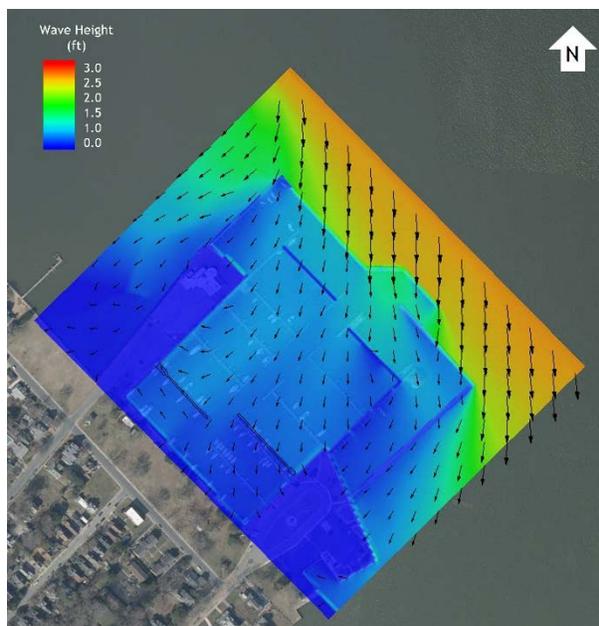


Figure 18 - Alternative 4 Wake Wave Sailing Upriver

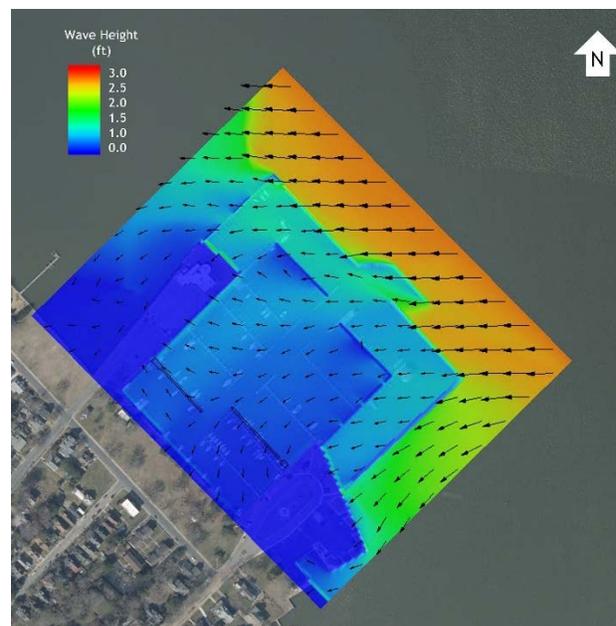


Figure 19 - Alternative 4 Wake Wave Sailing Downriver

Alternative 4 successfully reduces the average wave heights in the Yacht Basin to less than 0.5 feet for the design wake wave conditions. Wave heights impacting the City-owned marina are further decreased to approximately 0.35 feet, on average.

3.6. Alternative 5 – Wave Fences and Wave Attenuators at City- owned Marina Only

In the event that wave fences are not constructed at the Yacht Club Pier L, the fifth and final alternative examines installing the wave fences at Piers A and B only and the wave attenuators at Piers E and H. This alternative evaluates the wave heights within the Yacht Basin if only improvements are added to the City-owned Marina area.

The Alternative 5 model results are presented in Table 13 and shown in Figure 20 and Figure 21.

Table 13 – Alternative 5 Wake Wave Model Results					
Sailing Direction	Design Wave Height (ft)	Modeled Wave Height in Yacht Basin	% of Design Wave Height- Yacht Basin	Modeled Wave Height in Marina*	% Design Wave Height – Marina*
Downriver	2.7	0.64	24%	0.49	18%
Upriver	2.7	0.52	19%	0.45	17%

*City-owned marina area

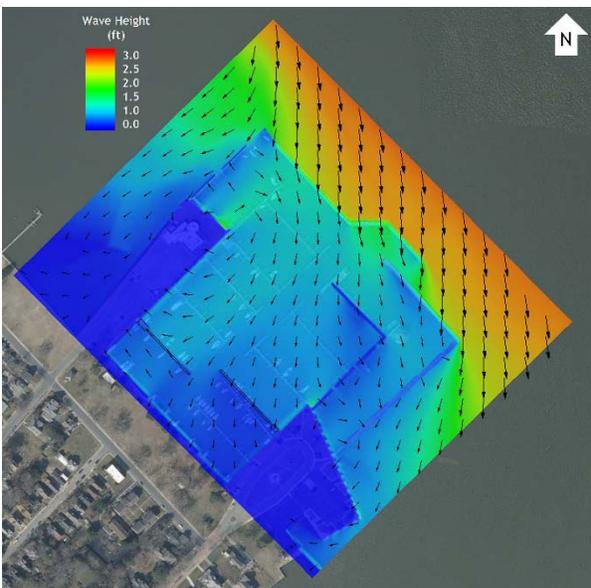


Figure 20 - Alternative 5 Wake Wave Sailing Upriver

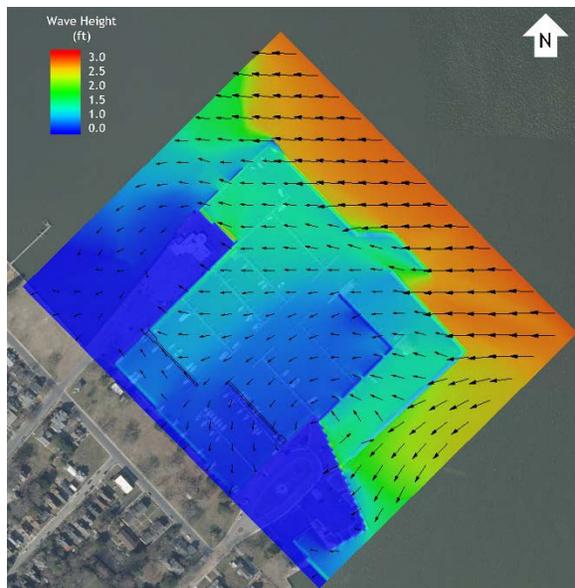


Figure 21 - Alternative 5 Wake Wave Sailing Downriver

The results of the Alternative 5 analysis show that this alternative does provide a larger decrease in wave heights within the Yacht Basin than each alternative except Alternative 4.

4. PREFERRED ALTERNATIVE

The preferred alternative for reducing the wave height within the Yacht Basin is Alternative 4 – installation of wave fences along Piers A, B, and L as well as constructing Piers E and H as wave attenuators. This alternative offers the greatest level of protection for the City-owned Marina as well as the entire Yacht Basin.

With the preferred alternative selected, the final step of the assessment is to determine the wave climate characterization for each pier as described in Table 6. To determine which areas of the Yacht Basin meet this criteria, it was assumed that the boat wakes used to evaluate the performance of the existing configuration and proposed alternatives, namely a loaded conventional vessel such as a pleasure yacht traveling at 15 knots through the center of the Choptank River channel, occurs weekly. The wave climate characterization criteria were then compared to the modeled wave heights at the slips to estimate the preferred alternatives performance.

For vessels traveling upriver and resulting in a 2.7-foot wake traveling from the North – Northwest direction, the results of the analysis are presented in Table 14 and shown in Exhibit 1.

Table 14 – Wave Climate Criteria for Vessel Sailing Upriver (Alternative 4)				
Slips	Average Wave Direction°	Recommended Wave Height (ft)	Modeled Wave Height (ft)	Wave Climate Characterization
A1 – A17	223°	0.25	0.23	Good
B1 – B10	180°	0.32	0.67	None
B11 – B22	183°	0.33	0.36	Moderate
C1 – C13	177°	0.31	0.40	None
C14 – C25	180°	0.32	0.42	None
D1 – D13	182°	0.32	0.41	None
D14 – D27	185°	0.33	0.41	Moderate
E1 – E20	189°	0.30	0.38	None
E21 – E40	202°	0.39	0.18	Excellent
F1 – F20	213°	0.44	0.20	Excellent
F21 – F40	210°	0.43	0.20	Excellent
G1 – G13	243°	0.43	0.10	Excellent
G13 – G41	212°	0.44	0.19	Excellent
H1 – H16	243°	0.43	0.10	Excellent
H17 – H32	239°	0.45	0.25	Excellent
I1 – I11	239°	0.45	0.26	Excellent
I12 – I24	237°	0.46	0.30	Excellent
J1 – J13	237°	0.46	0.31	Excellent
J14 – J29	232°	0.48	0.32	Excellent
K1 – K18	218°	0.46	0.37	Good
K19 – K28	209°	0.42	0.40	Good
L1 – L12	197°	0.38	0.42	Moderate
L13 – L23	191°	0.35	0.61	None
M1 – M11	200°	0.27	0.53	None
N1 – N15	213°	0.25	0.49	None

Because some slips along Pier B, L, M and N are outside of the shadow area of the wave screens, it is anticipated that they will experience less protection from installation of the preferred alternative. However, only slips along Piers B and L will experience wave heights exceeding 0.5 feet for this wake wave condition. The incoming waves impacting Pier C, D and E will be primarily beam seas, which require a smaller wave height to achieve a moderate, good or excellent wave climate characterization. However, even the slips with a wave climate characterization of 'None' will experience significantly improved wave attenuation, some as high as half of the pre-project condition.

For vessels sailing downriver and creating a 2.7-foot wake traveling from the Northeast, the resulting wave climate for the Yacht Basin is presented in Table 15 and shown in Exhibit 2.

Table 15 – Wave Climate Criteria for Vessel Sailing Downriver (Alternative 4)				
Slips	Average Wave Direction	Recommended Wave Height (ft)	Modeled Wave Height (ft)	Wave Climate Characterization
A1 – A17	269°	0.32	0.74	None
B1 – B10	265°	0.35	0.56	None
B11 – B22	281°	0.30	0.32	Moderate
C1 – C13	261°	0.36	0.33	Good
C14 – C25	250°	0.40	0.31	Good
D1 – D13	242°	0.44	0.3	Excellent
D14 – D27	216°	0.45	0.26	Excellent
E1 – E20	206°	0.41	0.26	Excellent
E21 – E40	310°	0.25	0.13	Excellent
F1 – F20	295°	0.27	0.13	Excellent
F21 – F40	293°	0.27	0.15	Excellent
G1 – G13	292°	0.27	0.18	Excellent
G13 – G41	276°	0.31	0.15	Excellent
H1 – H16	304°	0.26	0.15	Excellent
H17 – H32	285°	0.29	0.31	Moderate
I1 – I11	285°	0.29	0.36	None
I12 – I24	284°	0.29	0.39	None
J1 – J13	282°	0.30	0.42	None
J14 – J29	282°	0.30	0.46	None
K1 – K18	285°	0.29	0.48	None
K19 – K28	284°	0.29	0.49	None
L1 – L12	303°	0.26	0.37	None
L13 – L23	269°	0.33	0.84	None
M1 – M11	258°	0.36	0.82	None
N1 – N15	310°	0.25	1.41	None

For vessels sailing downriver, the preferred alternative offers the recommended level of protection for all slips within the City-owned marina except for Pier A and the outside slips on Pier B. However, for this sailing direction, the wake wave will result in beam seas along the Yacht Club-owned slips, requiring smaller wave heights that will not be achieved in order to reach an ‘excellent’, ‘good’, or ‘moderate’ wave climate characterization with the preferred alternative. However, all slips within the Yacht Club-owned marina will experience an average reduction of approximately 53% in wave height over existing conditions for this sailing direction. Therefore, Alternative 4 is still the recommended alternative for implementation.

4.1. Implementation Costs

A planning level implementation cost was developed for Alternative 4. The estimate assumes that Piers E and H are already planned to be replaced as floating docks, therefore the cost presented is only the incremental difference between installation of a

standard floating dock and a wave attenuator. For the wave fences, the implementation costs assume a timber fence with 10% gaps extending into the subgrade and supported by the outer pier piles. During Engineering and Design, an evaluation of the existing piers should be conducted to determine if cross-bracing or other structure fortification will be required.

The implementation cost estimate is presented in Table 16.

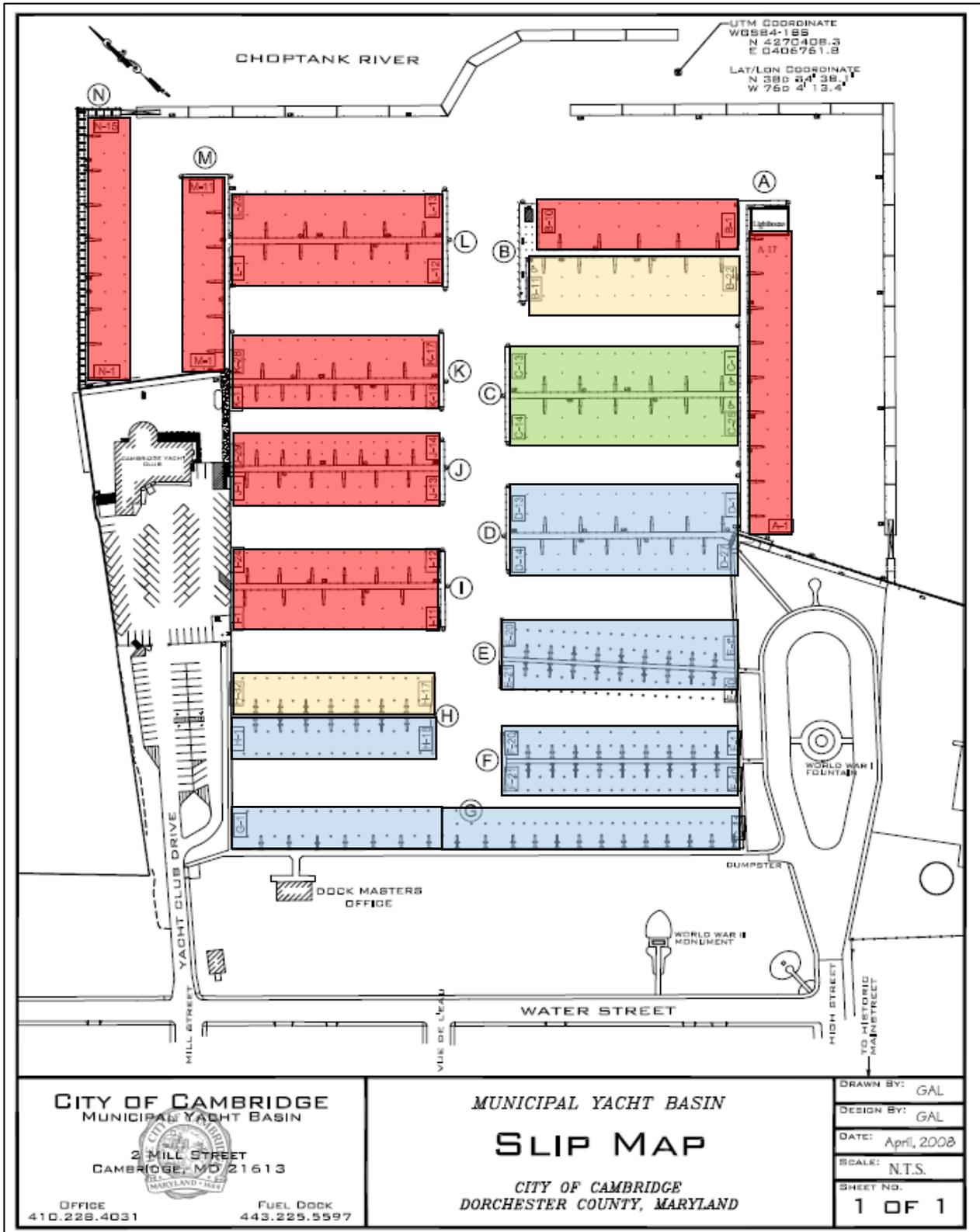
Table 16 – Implementation Cost Estimate				
Description	Unit	Unit Quantity	Cost/Unit	Total
Pier A – Wave Fence	LF	425	\$250	\$106,250
Pier B – Wave Fence	LF	280	\$250	\$70,000
Pier E – Wave Attenuator	SF	2025	\$45*	\$91,125
Pier H – Wave Attenuator	SF	2050	\$45*	\$92,250
Pier L – Wave Fence**	LF	270	\$250	\$67,500
Construction Total:				\$427,125
Contingency (15%):				\$64,069
Engineering, Permitting and Construction Management (25%):				\$106,781
Total Implementation Cost:				\$597,975

*incremental cost increase to install wave attenuator in lieu of floating dock

**Located within the Cambridge Yacht Club



EXHIBIT 1 – Alternative 4 Wave Climate Characterization for Wake from Vessel Sailing Upriver



Excellent
 Good
 Moderate
 None

EXHIBIT 2 – Alternative 4 Wave Climate Characterization for Wake from Vessel Sailing Downriver