Appendix H

Engineered Cap Erosion Design Analysis

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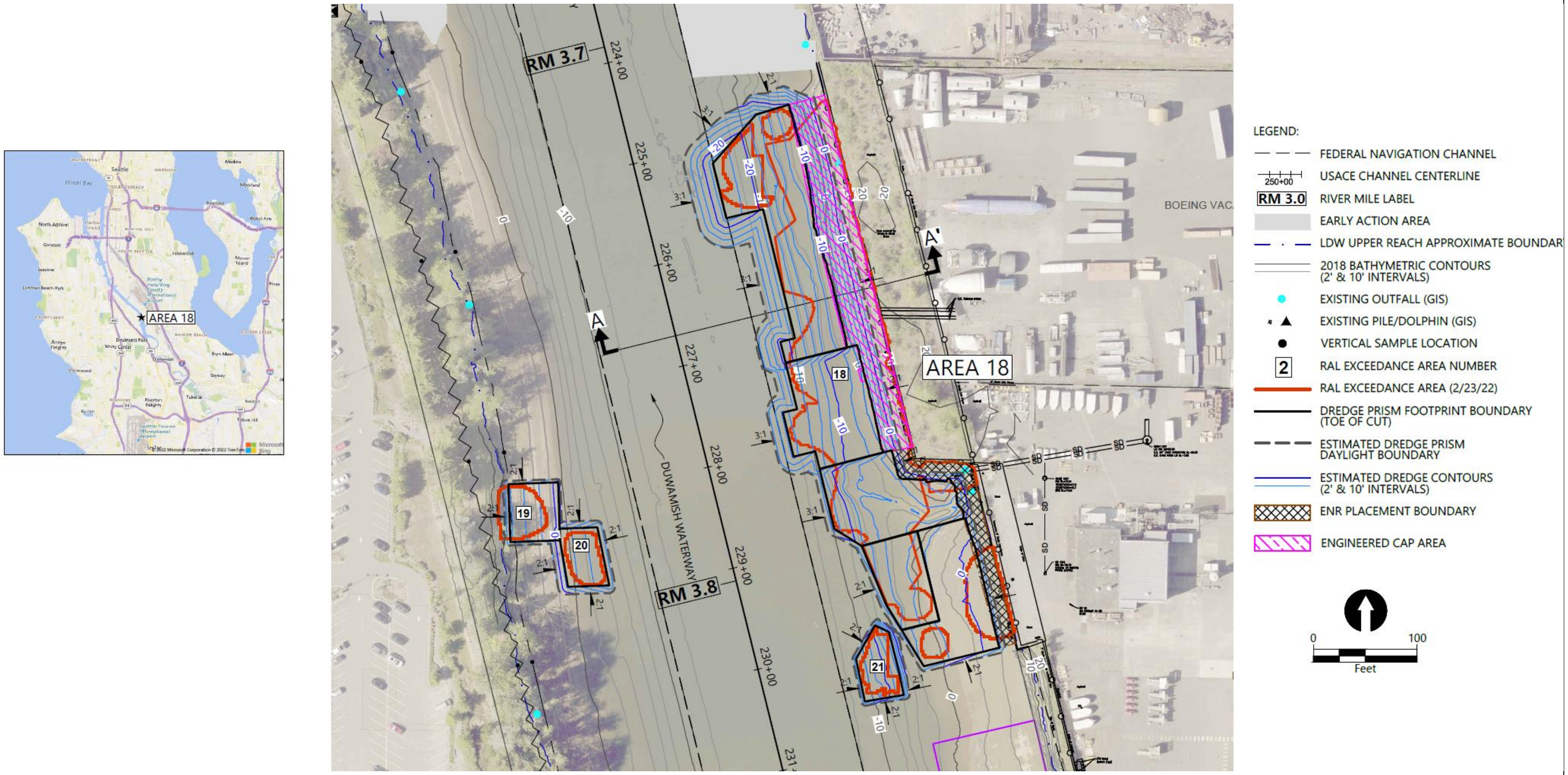
1 Introduction

This appendix describes the design of the erosion protection layer for caps in the upper reach of the Lower Duwamish Waterway (LDW). Cap contaminant mobility assessments and design are described in Appendix G and summarized in Section 10.3.1 of the Basis of Design Report (BODR) for the Preliminary (30%) remedial design (RD).

Within the upper reach, partial dredging and capping is a technology that can be assigned in certain areas with deep contamination and compatible final surface elevations, in accordance with the Record of Decision (ROD). For Preliminary (30%) RD, the selected technology assignment for a portion of Area 18 is partial dredge and cap as discussed in the BODR, returning the finished grade to approximate pre-construction elevations. Area 18 is located between river miles 3.7 and 3.8, between the federal navigation channel (FNC) and the bulkhead along the eastern bank of the LDW (Figure H-1).

Figure H-1
Vicinity Map: Area 18



Note: Cross Section A-A' is presented in Figure H-4

The primary objective of the erosion protection layer is to prevent exposure and erosion of the chemical isolation layer. The potential for erosion of the sediment cap depends on the erosive processes that are likely to occur in the LDW, as well as the materials comprising the cap layers. Potential erosive processes that may act on the sediment cap within the upper reach of the LDW include the following:

- Localized propeller wash from vessels
- Waves generated by passing vessels (wakes)
- Hydrodynamic flows in the LDW resulting from discharge of tributaries and other discharges, as well as from typical river circulation conditions
- Wind-generated waves due to storm events

Each of these potential erosion processes was evaluated independently to determine the design requirements for the cap erosion protection component. The cap erosion protection layer was then designed to withstand erosion under the range of anticipated conditions for each process. This appendix presents the results of this design analysis.

While the analysis in this appendix focuses on Area 18, the methodology for the erosion protection layer design is appropriate for other areas of the upper reach where capping may be the technology applied.

As described in Palermo et al. (1998):

> "The cap component for stabilization/erosion protection has a dual function. On the one hand, this component of the cap is intended to stabilize the contaminated sediments being capped and prevent them from being resuspended and transported offsite. The other function of this component is to make the cap itself resistant to erosion. These functions may be accomplished by a single component, or may require two separate components in an in-situ cap."

Methods for designing cap erosion protection (i.e., armor layer) are presented in Appendix A of Palermo et al. (1998). The cap armor material gradation and thickness must also be designed to stabilize and protect the underlying physical and chemical isolation layers from erosion (based on an evaluation of each potential erosional source). The erosion resistance design must account for the forces along the edge of the cap as well as on the surface of the cap to prevent scour for both typical flows and anticipated flood events.

The armor layer of the cap has been designed to provide stabilization of underlying finer grained cap materials (as well as sediment) to prevent the vertical migration of those materials through the armor layer, termed piping (Palermo et al. 1998). As described in the RD Work Plan, the cap design considers the physical, chemical, hydrodynamic, and hydrogeological properties (LDWG 2019).

Climate change is expected to affect the greater Puget Sound region and, relevant to the LDW, includes sea level rise (SLR); changes in precipitation patterns; and overall hydrological changes. Climate change adaptation generally focuses on evaluating a system's vulnerability to climate change and implementing adaptation measures, when warranted, to ensure the remedy continues to remain effective at meeting the ROD objectives. As such, an evaluation of the long-term effects of SLR and climate change on cap integrity is also discussed in this appendix.

2 Erosion Protection Design

This section presents an evaluation of the following as related to erosive forces in the vicinity of Area 18:

- Selection of design vessels
- Review of bathymetry, water levels, and potential changes due to SLR
- Predictive modeling to estimate stable particle size for propwash forces, wake forces, hydrodynamic forces, and wind-generated waves

2.1 Selection of Design Vessels

A propwash and vessel wake analysis was conducted to evaluate the stable particle sizes to resist propwash from vessels in the upper reach. Propwash and wake forces are related to specific characteristics of the vessel being considered, including vessel size, vessel power, vessel propeller size, operational speeds, and depth of the propeller beneath the water line. As such, a "design" vessel or vessels must be selected so that propwash and wake forces can be estimated. Vessel traffic data were obtained through the Automatic Identification System (AIS). The AIS vessel data are collected by the U.S. Coast Guard through onboard navigation safety devices that transmit and monitor vessel locations and characteristics of large vessels. These data were downloaded via MarineCadastre.gov (BOEM and NOAA 2021).

The design vessel selection consisted of the following components:

- Vessel activity was evaluated to establish the types and sizes of vessels that utilize the upper reach.
- Vessel characteristics (e.g., draft, propeller type, dimensions) were obtained for representative vessels; outlined below.
- Vessel operating information and assumptions (e.g., operating horsepower and vessel location and orientation) were selected to correspond with each representative vessel.

The available AIS data for 2020 were plotted. A portion of the data, from October 2020, is presented in Figures H-2 and H-3, showing AIS designated vessel types and vessel speeds, respectively. A total of 87 unique vessels were identified that transited near Area 18 during the year. Of those unique vessels, three representative design vessels were selected for analysis:

- Capt. Cae Tug
  - The largest tug to transit the area in 2020 (92 ft long)
- Westrac II Tug
  - An average sized tug (74 ft long), selected to represent the more typical tugs that frequent the area; the average length for tugs that transited the area in 2020 was 72 ft

- Arctic Pride Yacht
  - One of the largest pleasure vessels to transit the area in 2020 at 126 ft long; there were three larger vessels (up to 150 ft long), but Arctic Pride transited more frequently

Table H-1 outlines the specifications of the three design vessels used in the erosion protection basis of design.

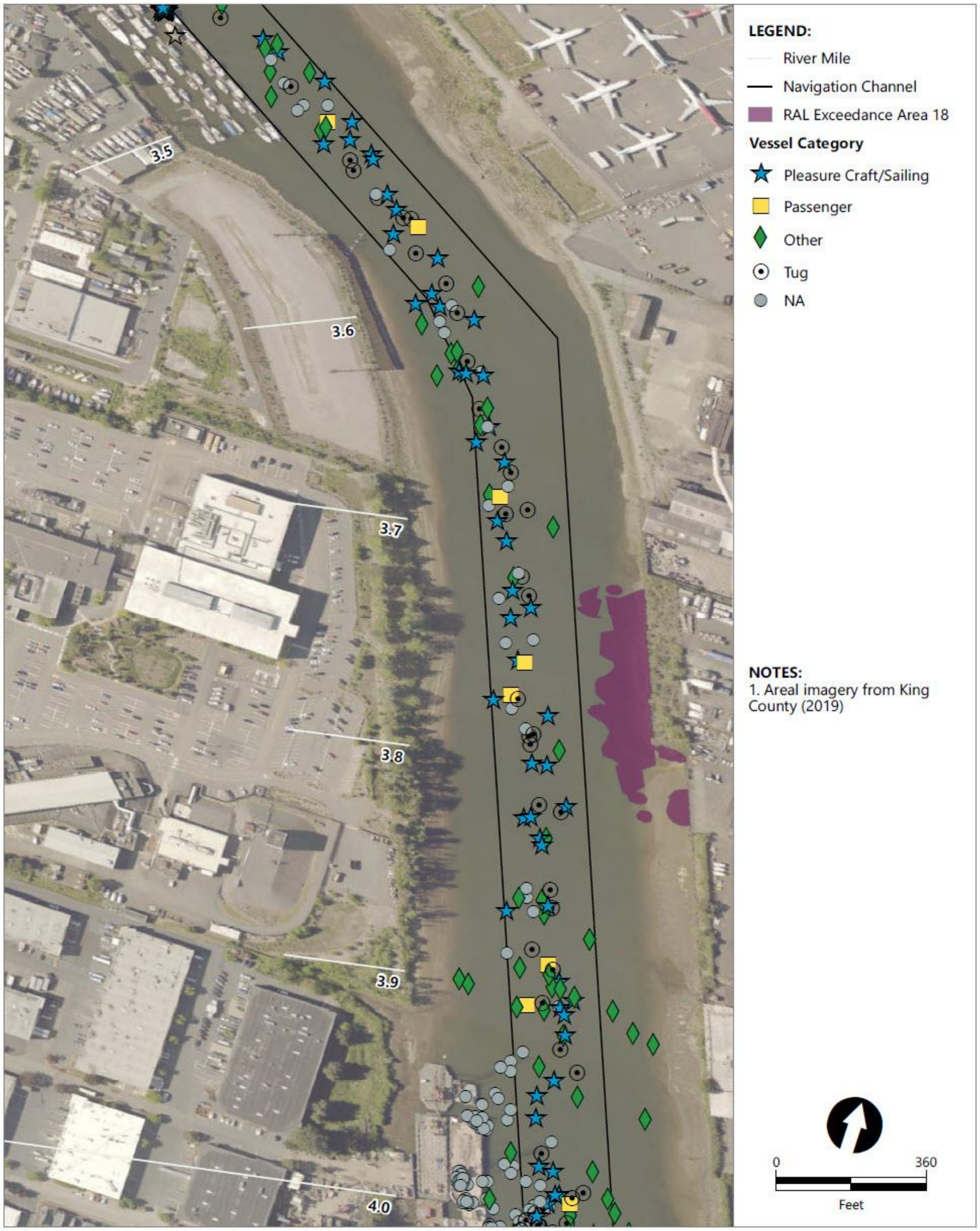
Table H-1
Design Vessel Specifications

Vessel Characteristic	Capt. Cae Tug	Westrac II Tug	Arctic Pride Yacht
Owner/Operator	DeForge Maritime Towing	Western Towboat Company	Private Recreational Vessel
Length	92 ft	74 ft	126 ft
Draft	11 ft	14 ft	6 ft
Propeller Diameter	7.25 ft	6.3 ft	4 ft
Horsepower per Propeller*	1400 hp	1250 hp	1250 hp
Operational Speed	4 to 8 knots	4 to 8 knots	4 to 8 knots

Note:
*Horsepower per Propeller is used because the propwash analysis utilizes a single propeller.

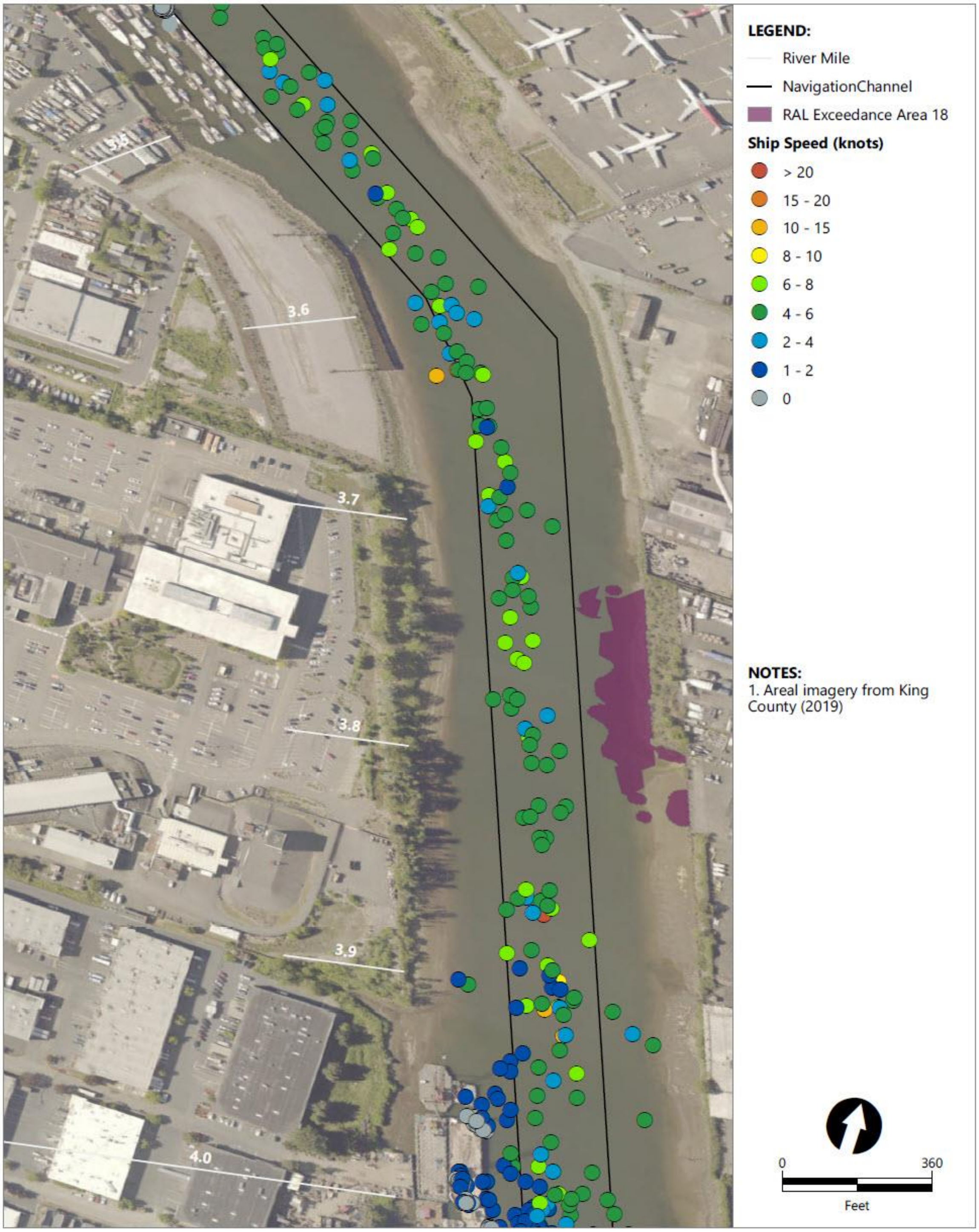
The FS propeller-induced riverbed scour analysis (Appendix C, Part 7 of the FS), utilized the J. T. Quigg tug, with a length of 100 feet, for the evaluation near Area 18. This vessel is similar to the Capt. Cae Tug, with similar specifications. Because the FS analysis was performed in 2009, the design vessels were updated to reflect more recent usage data.

Figure H-2
AIS Vessel Categories: October 2020



Note: Categories based on AIS Ship Types

Figure H-3
Vessel Speeds: October 2020



NOTES:
1. Areal imagery from King County (2019)

2.2 Bathymetry, Water Levels, and Sea Level Rise Impact

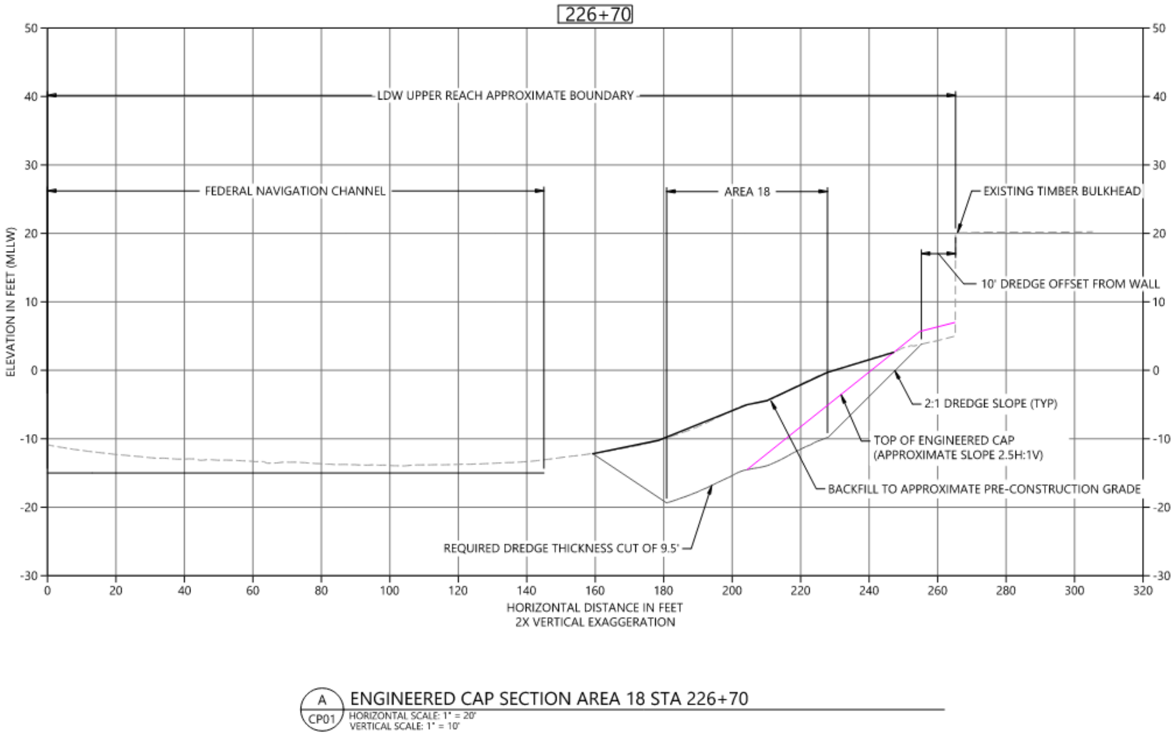
Erosion protection layer stability under vessel propwash and wakes is dependent on the configuration of the navigation channel and the water depths in which the vessels are operating. The upper reach is tidally influenced and experiences a large range of water levels. Table H-2 outlines the tidal datums for the Seattle, Washington, NOAA Tidal Station (944130).

Table H-2
Seattle Tidal Datums

Datum	Water Level (ft, MLLW)
Highest Astronomical Tide (HAT)	13.3
Mean Higher High Water (MHHW)	11.3
Mean Sea Level (MSL)	6.6
North American Vertical Datum of 1988 (NAVD88)	2.3
Mean Lower Low Water (MLLW)	0
Lowest Astronomical Tide (LAT)	-4.3

Survey data were used to develop a cross section perpendicular to the FNC, through the middle of Area 18 (Figure H-4). The authorized elevation for the FNC is -15 ft MLLW. The eastern channel boundary is approximately 60 ft from the edge of the proposed Area 18 capping area.

Figure H-4
Cross Section A-A′ Through Area 18



Notes:
Bathymetric survey by Northwest Hydro performed between April 18, 2019, and May 15, 2019. Additional bathymetric survey by Northwest Hydro performed June 2020 to fill data gaps. Composite data updated December 23, 2020.
The location of cross section A-'A' is shown in Figure H-1.

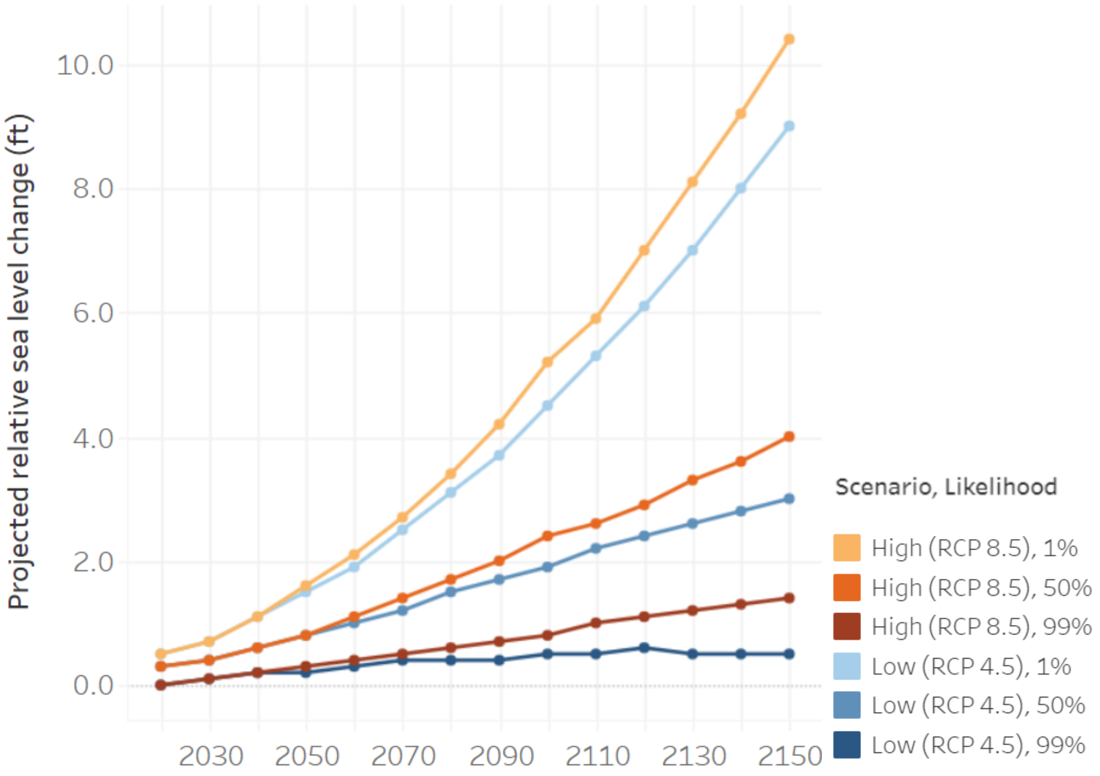
As described in Section 11.4.1 of the BODR, climate change is expected to increase sea levels over the next few hundred years. An increase in mean sea level will correspond to an increase in design water levels at the site. In the future, SLR will increase the water depths within the upper reach. The projected changes in sea level have been assessed in accordance with Washington State Department of Ecology (Ecology) guidance.

Figure H-5 shows the projected SLR for various potential scenarios for the upper reach. The figure presents the projected SLR under the low and high predictions for greenhouse gas scenarios (Representative Concentration Pathway [RCP] 4.5 and RCP 8.5) for the 1%, 50%, and 99% likelihood of occurrence. While there is no industry standard for the application of SLR projections, other projects in Puget Sound have incorporated the 50% central estimate for the design of site elevations.

Based on the projections and using the 50% central estimate, the relative sea level is predicted to rise between 1.9 and 2.4 ft by 2100 (Miller et al. 2018).

SLR will have different effects on the erosive forces acting on the cap, as discussed in Sections 2.3 through 2.6. Propwash forces are expected to be lower with SLR due to the larger propeller clearance as water depths increase. Wake forces are not expected to change with SLR because wake heights are not expected to change. Hydrodynamic forces are expected to be lower with SLR due to the larger flow area under the same flow volumes because flow is controlled by the upstream restriction at the Interstate 5 crossing of the Green River as described in 11.4.2 of the BODR. Wind-generated waves are not expected to be affected by SLR because they are limited by fetch lengths and the narrow shape of the waterway, which would not materially change under SLR.

Figure H-5
Sea Level Rise Projections for the LDW



Source: https://wacoastalnetwork.com/research-and-tools/slr-visualization/

2.3 Predictive Modeling to Estimate Stable Particle Size for Propwash Forces

As a vessel or boat moves through the water, the propeller produces an underwater jet. This turbulent jet is known as propwash. Where the jet reaches the mudline, it can contribute to resuspension or movement of bottom particles. Potential propwash effects of representative vessels that operate near and around Area 18 were evaluated in accordance with Appendix A of EPA's *Guidance for In-Situ Subaqueous Capping of Contaminated Sediment* (Palermo et al. 1998) cap armor layer design guidance.

The propwash velocity was calculated using the method developed by Blaauw and van De Kaa (1978). The stable particle size under these velocities was calculated based on a method by Blaauw et al. (1984) and additional research by Maynord (1984); both methods are presented in Appendix A of EPA's *Guidance for In-Situ Subaqueous Capping of Contaminated Sediment* (Palermo et al. 1998): *Armor Layer Design*. The model considers physical vessel characteristics (e.g., propeller diameter, depth of propeller shaft, and total engine horsepower) and operational and site conditions (e.g., applied horsepower and water depth) to estimate propeller-induced bottom velocities at various distances behind the propeller. The model is used to predict the particle size that would be stable when subjected to the steady-state propwash (i.e., the vessel is essentially stationary or maneuvering at a very low speed) from the modeled vessel.

Equation 6 from Appendix A of Palermo et al. (1998) predicts the propeller velocity at any location below (z distance) and aft of (x distance) the vessel propeller:

$$V_x = 2.78 \times U_0 \times \frac{D_0}{x} \exp\left(-15.43\left(\frac{z}{x}\right)^2\right)$$

where:

V_x = propeller wash velocity at location x and z (fps)

D_0 = adjusted propeller diameter (function of propeller type and diameter)

x = horizontal distance aft of propeller (feet)

z = distance from axis of propeller (feet)

U_0 = propeller wash jet velocity (fps) at the propeller (Equation 4 from Appendix A of Palermo et al. [1998])

The above equation was used to compute propwash velocities for the selected design vessels based on their specifications and operating conditions. For each scenario, bathymetric data were compiled to apply water depths and shoreline orientations (distances and slopes) such that realistic scenarios were analyzed. Propwash velocities at the sediment bed surface were calculated by applying jet velocities to the water depths and local bathymetry data and determining the velocity of the jet where it would meet the sediment bed mudline.

Area 18 is located east of the FNC (Figure H-1), and as Figures H-2 and H-3 show, the design vessels are not expected to transit directly over Area 18. A plan view analysis of the bottom velocities and stable sediments was conducted to estimate how a transiting vessel could affect the proposed cap (see Attachment H-1). The scenarios evaluated and results are outlined in Table H-3. All scenarios conservatively assume the design vessels are operating with the propeller located at the eastern boundary of the FNC (mudline elevation of -15 ft MLLW), which is approximately 60 ft from the edge of Area 18 (elevation of -4 ft MLLW). PIANC (2015) suggests using 5% to 15 % of the installed power for the main propellers for transiting vessels. For this analysis, 20% and 30% applied power were used to calculate the propwash velocities as an extra measure of conservatism above the PIANC guidelines and to more closely compare to the FS assumptions, which were based in part on interviews with local vessel captains. Although vessels typically operate at some sailing speed, which acts to significantly reduce the duration and magnitude of the propwash acting on the waterway bottom, for purposes of this analysis, static vessel conditions (stationary vessel) were used for evaluating potential propwash forces, which is another conservative factor.

In addition, sailing scenarios for larger vessels at low tidal elevations (e.g., MLLW) were not modeled because the large vessel drafts (drafting greater than 11 ft) would make navigation unsafe due to small propeller clearances. The modeled scenarios are considered to be conservative because of the additive conservative assumptions used to develop the modeled scenarios.

As shown in Table H-3, because Area 18 is 60 ft, or more, farther east of the FNC (Figure H-1), the predicted bottom velocities and required stable sediment D_{50} are relatively small (0.5 ft/s and <0.25 inch).

Future SLR conditions are not expected to increase the stable particle size required based on propwash. The stable particle size due to propwash forces increases as propeller jet induced bottom velocities increase. With SLR the water depths will increase, therefore increasing the propeller clearance and reducing the bottom velocities, ultimately requiring a smaller particle size to be stable.

Table H-3
Bottom Velocities and Stable Sediment Size

Attachment H-1 Figure No.	Design Vessel	Water Level (ft, MLLW)	Applied Power Percent	Max. Bottom Velocity in Area 18 (ft/s)	Max. Stable D_{50} in Area 18 (in)
1a	Capt. Cae Tug	MHHW (11.3)	20%	0.5	0.25
1b	Capt. Cae Tug	MSL* (6.6)	20%	0.5	0.25
2a	Westrac II Tug	MHHW (11.3)	20%	<0.5	<0.25
2b	Westrac II Tug	MSL* (6.6)	20%	<0.5	<0.25
3a	Arctic Pride Yacht	MHHW (11.3)	20%	<0.5	<0.25
3b	Arctic Pride Yacht	MLLW (0)	20%	<0.5	<0.25
4a	Capt. Cae Tug	MHHW (11.3)	30%	0.5	0.25
4b	Capt. Cae Tug	MSL* (6.6)	30%	0.5	0.25
5a	Westrac II Tug	MHHW (11.3)	30%	0.5	0.25
5b	Westrac II Tug	MSL* (6.6)	30%	0.5	0.25
6a	Arctic Pride Yacht	MHHW (11.3)	30%	<0.5	<0.25
6b	Arctic Pride Yacht	MLLW (0)	30%	<0.5	<0.25

Notes: All scenarios assume the design vessel is operating with the propeller on the edge of the FNC (elevation of -15 ft MLLW), which is approximately 60 ft from the edge of Area 18 (elevation of -4 ft MLLW).
*Capt. Cae Tug and Westrac II Tug were not analyzed at MLLW; given their larger drafts, it is unlikely they would operate with such small propeller clearances.
MLLW = Mean Lower Low Water
MHHW = Mean Higher High Water
MSL = Mean Sea Level
D_{50} = median particle size
ft/s = feet per second
in = inches

2.4 Predictive Modeling to Estimate Stable Particle Size for Wake Forces

Estimates of vessel-induced wake heights were completed through an evaluation of ship traffic patterns within the FNC adjacent to Area 18 and calculations of vessel wakes based on type of vessel, operational speed, and water depths.

Based on the vessel speed and locations shown in Figure H-3, the design vessels were assumed to be operating at speeds between 4 and 8 knots (4.6 and 9.2 mph) within the FNC[1], as close as 60 ft to the edge of the cap from the potential sailing line along the eastern edge of the FNC. The analysis used the Weggel and Sorensen (1986) methodology to predict vessel wakes. The Weggel-Sorensen method is an empirical model (developed from available laboratory and field data on vessel-

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[1] The Duwamish River has a 7-knot speed limit; AIS data indicate that some vessels exceed this limit

generated wakes) to predict maximum wake height as a function of vessel speed, vessel geometry, water depth, and distance from the sailing line. This model is applicable for various vessel types (ranging from tugboats to large tankers), vessel speeds, and water depths. The method calculates the wake height generated at the bow of a vessel as a function of the vessel speed, distance from the sailing line, water depth, vessel displacement volume, and vessel hull geometry (i.e., vessel length, beam, and draft). The method has been widely tested on different vessels and is recommended for use with conditions having a Froude number between 0.2 and 0.8; which was met. The non-dimensional Froude number used in this method is defined as follows:

$$\mathrm{Fr} = \frac{v}{\sqrt{g \times l_w}}$$

where:

Fr = Froude number
v = Vessel velocity (ft/sec)
g = Acceleration due to gravity (ft/sec^2)
l_w = Water depth (ft)

Design vessel wake heights were estimated to be between 0 and 1.2 ft with a period up to 2.2 seconds (see Table H-4).

Waves (or wakes) break in shallow water when the ratio of wave height to water depth surpasses 0.78 (Dean and Dalrymple 1991). The wide tidal range means Area 18 is sometimes fully inundated, and at lower tidal levels, parts of Area 18 are above the water surface. At a MLLW tidal elevation, the maximum water depth along the edge of Area 18 is approximately 4 ft. At the lowest astronomical tide (-4.3 ft MLLW) the entire Area 18 cap area would be above the water surface. As the water surface rises and falls over Area 18, every portion of the proposed cap area will fall within the wave breaking zone. For waves breaking on the cap, the rubble-mound revetment module (USACE 2004) from the Automated Coastal Engineering System (ACES) developed by the U.S. Army Corps of Engineers (USACE) (1992) was used to compute the median particle size (D_{50}) that is stable for the predicted wake height based on the proposed placement slope.

A bracketing analysis that considered flatter and steeper restored slopes was conducted; Figure H-4 depicts conditions where the cap would be placed at a 2.5 Horizontal to 1 Vertical (2.5H:1V) slope, with a backfill placed over with a finished grade slope of approximately 6H:1V, and the cap placed on existing grade near the bulkhead wall with a slope of 6H:1V. This area was considered to represent the range of typical slope conditions that are anticipated for backfill in the upper reach. If different cap slope angles are determined necessary during 60% design, this bracketing analysis will be revisited and updated as appropriate.

Based on these analyses, a stable median particle size diameter (D_{50}) of 3 inches would withstand vessel wakes that break on top of a 6H:1V backfill layer, and, assuming the backfill was eroded away, a 2.5H:1V erosion protection layer would require a D_{50} of 5 inches to withstand the breaking vessel wakes (summarized in Table H-4).

Table H-4
Vessel Wakes and Stable Sediment Sizes

Vessel	Vessel Speed (mph)	Distance from Sailing Line (feet)	Wake Height (feet)	Wake Period (seconds)	Slope	Stable Armor Stone Size, D_{50} (inches)
Captain Cae Tug (MLLW at edge of FNC)	9.2	60	1.2	2.2	Backfill: 6H:1V	2.8
					Erosion Protection Layer: 2.5H:1V	4.8
Westrac II Tug (MLLW at edge of FNC)	9.2	60	1.2	2.2	Backfill: 6H:1V	2.8
					Erosion Protection Layer: 2.5H:1V	4.7
Arctic Pride Yacht (MLLW at edge of FNC)	9.2	60	1.0	2.2	Backfill: 6H:1V	2.4
					Erosion Protection Layer: 2.5H:1V	4.0

The wake heights are not expected to increase or decrease with the addition of SLR to the waterway. Therefore, required stable sediment sizes for future SLR conditions are not expected to change. Additionally, SLR will reduce the size of the intertidal zone, as the water level range moves farther up the existing bulkhead wall on the shoreline and to the east of Area 18 (see Figure H-4). Therefore, SLR conditions are not expected to modify the evaluation scenario or resulting stable particle size for the erosion protection layer at Area 18.

2.5 Predictive Modeling to Estimate Stable Particle Size for Hydrodynamic Forces

Stable particle sizes to resist hydrodynamic flows (i.e., river currents) were assessed for the cap at Area 18. The 100-year flow event was modeled for the *Lower Duwamish Waterway Sediment Transport Modeling Report* in 2008 (QEA), and the velocity results from the hydrodynamic model cell that includes Area 18 were used to estimate the stable particle size.

The stable particle size was estimated using a method developed by Maynord (1988) *for Stable Riprap Size for Open Channel Flows*, which is presented in Appendix A of EPA's *Guidance for In-Situ Subaqueous Capping of Contaminated Sediment* (Palermo et al. 1998) .

The stable particle size is estimated utilizing the following equation:

$$D_{50} = S_f C_S C_V C_T C_G d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5}$$

where:
D_{50} = characteristic riprap size of which 50% is finer by weight
S_f = safety factor (1.5)
C_S = stability coefficient for incipient failure (0.3 for angular rock)
C_V = velocity distribution coefficient (1.0 for straight channels)
C_T = blanket thickness coefficient (1.0 for flood flows)
C_G = gradation coefficient = $(D_{85}/D_{15})^{1/3}$ (typically 1.2 to 1.5)
d = local depth
γ_w = unit weight of water
γ_s = unit weight of stone
V = local depth averaged velocity
K_1 = side slope correction factor = 0.97 (defined below)
g = gravitational constant

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \Phi}}$$

where:
K_1 = side slope correction factor
θ = angle of side slope with horizontal (2.5H:1V = 21.8 degrees)
Φ = angle of repose of riprap material (typically 40 degrees)

The modeled 100-year velocity over Area 18 was 1.5 ft/s, which results in an estimated 0.1-inch stable particle size. Note that the resulting stable particle size is smaller than that required for propwash, even though the 100-year velocity was larger than the propwash velocity. This is due to the propwash velocity being a turbulent jet, which results in a larger stable grain size for the 0.5 ft/s velocity as compared to the 0.1 inch stable particle size for river flow at 1.5 ft/s.

As described in section 11.4.2 of the BODR, hydrodynamic forces are expected to be lower with SLR due to the larger flow area under the same flow volumes. A larger flow area will reduce the velocities, therefore reducing the required stable sediment size.

2.6 Predictive Modeling to Estimate Stable Particle Size for Wind-Generated Waves

Wind-generated waves are a result of wind blowing over the water surface. Such waves become larger due to continuous wind in an unobstructed single direction, over long distances (fetch[2]). To estimate the wind-generated wave height, the ACES Wave Prediction module was used, which utilizes wind speed, water depth, and effective fetch distance (Leenknecht et al. 1992).

Measured wind direction and intensity data from King County International Airport, approximately 1.5 miles north of Area 18, are shown in the wind rose in Figure H-6.

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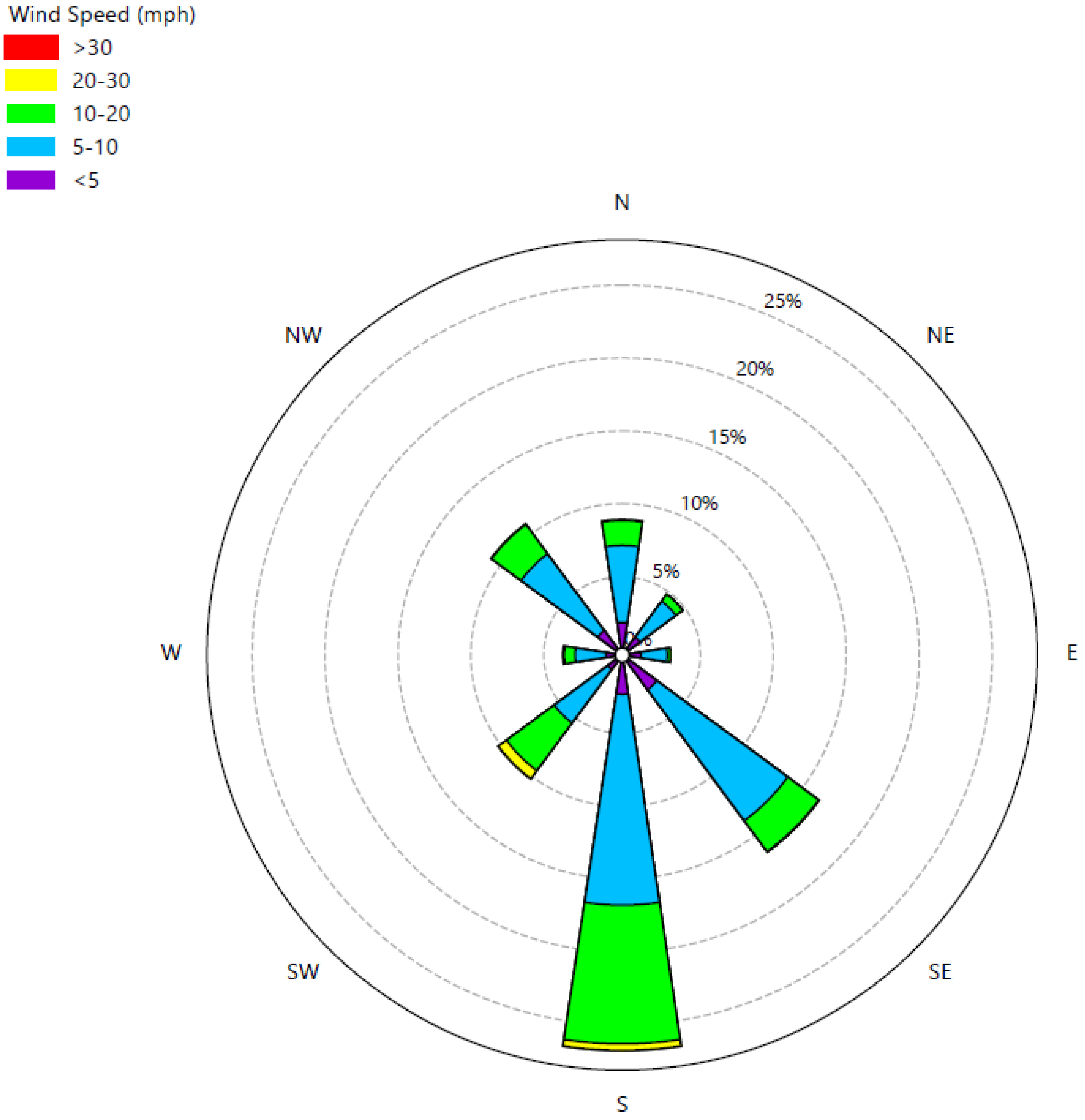
[2] Fetch refers to the unobstructed over-water distance in the wind direction of interest. Fetch distance can be very long in large open-water locations (e.g., oceans) and is very short where land masses and other wind obstructions (e.g., buildings, bridges) limit the ability of wind shear stress to act for sustained distance on the water surface.

Figure H-6
Wind Rose: King County International Airport (1943 through 2022)



Notes:

1. Maximum recorded wind speed: 62 mph
2. Wind data are presented as the "blowing from" direction

An extreme analysis was conducted for the 79 years of wind data to find the 100-year wind speeds at various directions. Area 18 is near a bend in the LDW that has two fetches, one from the northwest and one from the south. The 100-year wind speeds are 43 mph from the northwest and 62 mph from the south. The fetch from the northwest is approximately 1.7 miles and the fetch from the south is approximately 0.9 mile. However, given the waterway is narrow, with a low width to length ratio, effective fetch factors were included to reduce the fetch lengths to 0.2 and 0.3 mile, respectively (Ippen 1966). Utilizing the FNC depth of 26.3 ft at MHHW, maximum wave heights for the 100-year wind speeds are 0.3 ft from the northwest and 0.6 ft from the south. SLR, discussed in the Section 2.2, would not materially increase the width of the river, and therefore would not change the predicted future wave heights

Wind-generated wave heights are smaller than the predicted possible wake heights caused by transiting vessels (Section 2.4). Thus, wind-generated waves will not govern the size of the erosion protection layer aggregate.

2.7 Recommended Armor Material Size, Layer Thickness, and Filter Material Size

The cap at Area 18 is expected to be made up of a chemical isolation layer protected by an overlying erosion protection (armor) layer for cap stability on a 2.5H:1V slope, with habitat compatible sand backfill placed on top to return the area to existing grade, at approximately 6H:1V. Because the habitat-compatible layer will be the topmost layer, the armor material is not expected to be directly exposed to erosive forces. However, the armor layer is designed to resist erosive forces as a "backstop" in case the habitat-compatible layer is displaced. Habitat-compatible material is within a size range that can be moved by design-level erosive forces whereas armor material will be stable when subjected to the same forces.

The armor layer material size is driven by the largest particle size that is stable against a range of erosive forces in the upper reach, including hydrodynamic forces, wind-generated waves, vessel-generated propwash, and wakes. The primary design criterion for erosion protection is breaking wakes caused by vessel transit past Areas 18 (Section 2.4) and requires a median stable particle size (i.e., D_{50}) of 3 inches when placed on typical flatter slopes (6H:1V) and 5 inches when placed on steeper slopes (2.5H:1V).

Guidance from Appendix A of Palermo et al. (1998) was used to determine the minimum thickness of the armor layer of the cap. Based on the above stable particle size estimates, the armor size is dictated by the wake forces (Section 2.4) and requires a D_{50} of 3 to 5 inches. From the guidance, the armor layer thickness should be two times the D_{50} size, therefore, an armor material with a D_{50} of 3 inches would need to be a minimum of 6 inches thick and an armor material with a D_{50} of 5 inches would need to be a minimum of 10 inches thick. The armor design will be refined, if appropriate, during 60% RD if it is determined that armor layers are needed for capping areas that are subject to different erosion forces.

Development of gradations of cap materials will consider the design D_{50} values and criteria from the USACE Engineering Manual 1110-2-2300 - *General Design and Construction Considerations for Earth and Rock-Fill Dams* (USACE 2004). In addition, the potential for vertical migration of one granular material through another (often referred to as "piping") will also be considered, as recommended by the *Guidance for In-Situ Subaqueous Capping of Contaminated Sediment* (Palermo et al. 1998). The potential for piping can be minimized through the use of well-graded materials for the armor and chemical isolation layers. The compatibility of the two materials in combination is verified below in accordance with geotechnical filter criteria (Terzaghi and Peck 1967) and Palermo et at. (1998).

Standard geotechnical filter criteria presented by Terzaghi and Peck (1967) provide recommended particle size ratios between base and overlying materials (e.g., sand chemical isolation and overlying erosion protection materials). The primary filter criterion particle size relationship primarily applicable to subaqueous capping materials is the ratio of the D_{15} of the armor stone to the D_{85} of the base layer. This relationship relates to the ability of the base layer material (e.g., sand) to pass through the void spaces in the overlying larger material (e.g., erosion protection armor stone). Compliance with the recommended filter criteria minimizes the potential for wash out of the base material by the creation of internal filters in the armor stone voids.

The Terzaghi filter criteria recommend the following relationship to prevent material loss through the armor layer:

$$d_{15(Armor)} < 5d_{85(Base)}$$

where:

d_x = particle diameter, such that x percent of the sediment particles are smaller, by weight

The cap armor and chemical isolation material specifications will be developed so that a separate filter layer will not be required.

The specific armor and filter material gradations will be selected during Intermediate (60%) and Pre-Final 90% RD. A number of factors will be considered in developing the complete material specifications, including the following:

- Local availability of materials

- Material processing effort required to meet specifications
- Cap material placement equipment and limitations
- Required quantities
- Fines content relative to water quality (turbidity)
- Well-graded materials

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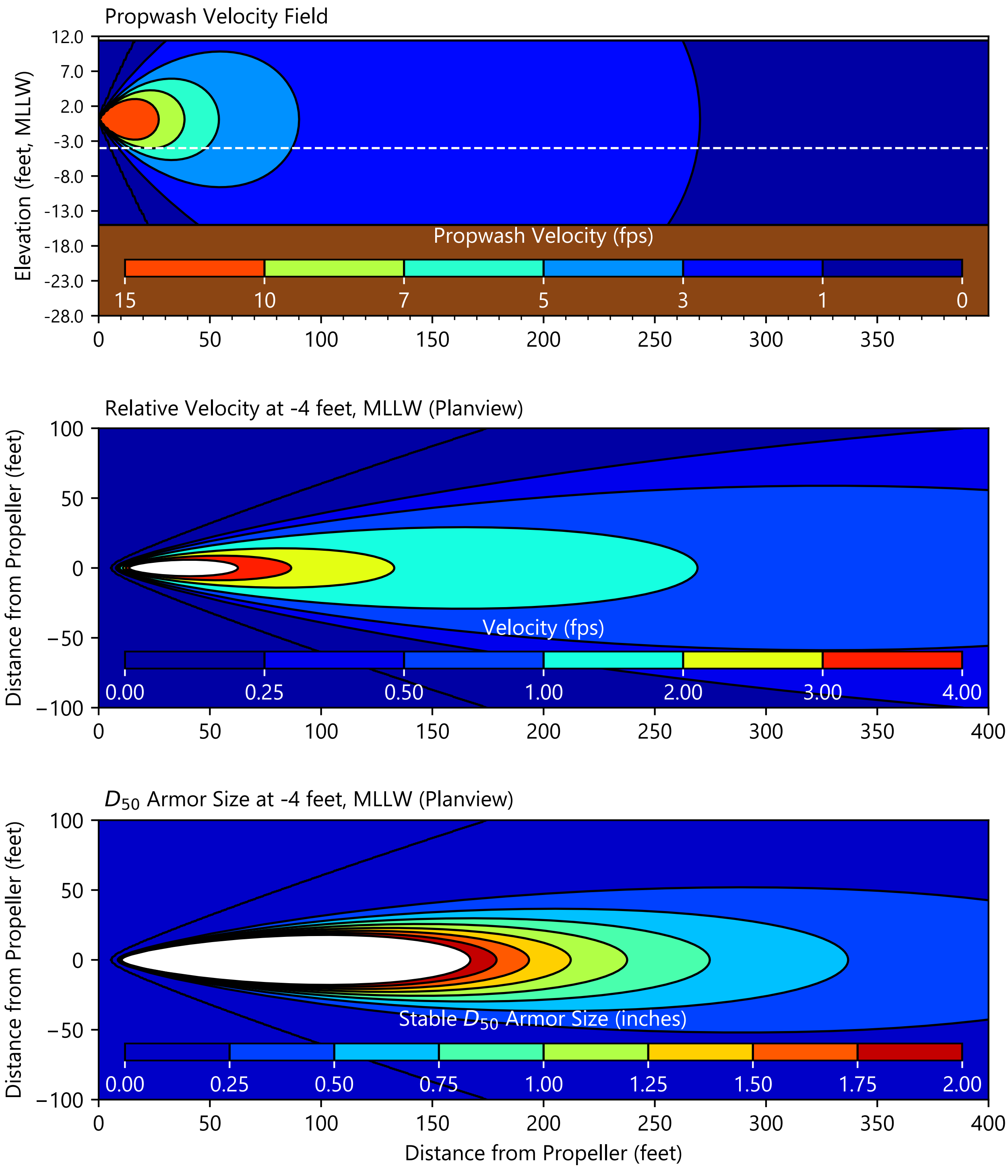
Attachment H-1

Bottom Velocity and Sediment Figures



Notes:
The white dashed line at -4 ft MLLW shows the location of the planview plane.
The -4 ft MLLW elevation is approximately 60 feet perpendicular to the sail line.
The propwash analysis is based on the Maynord 1998 capping methodology.
The C_3 coefficient = 0.55 for no sediment movement.

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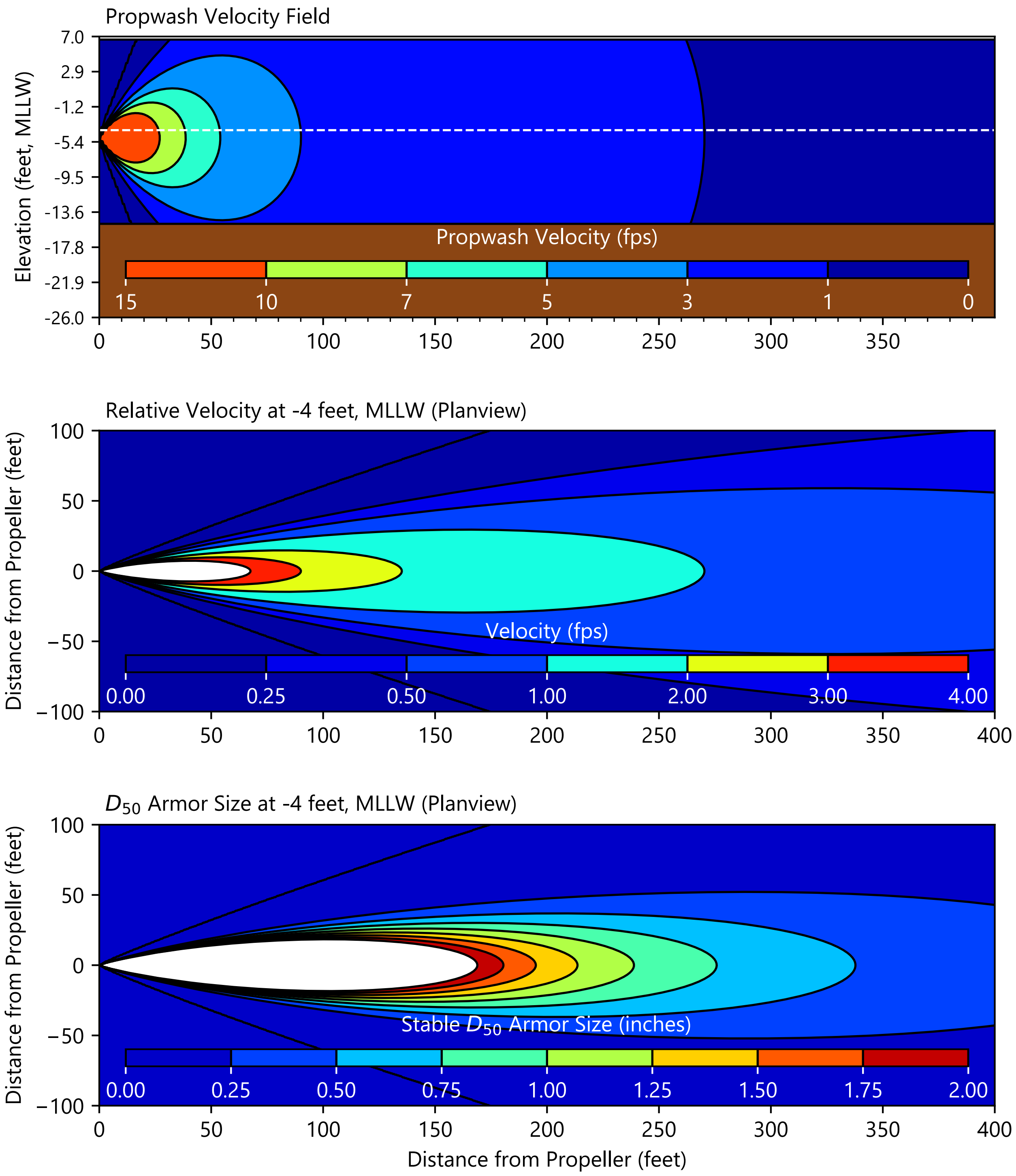
File Path: C:\Users\acannon\OneDrive - ANCHOR QEA\LDW Propwash\Python\LDW-Blaaw_and_Kaa_Propwash_Field_Analysis_v7_0 - 30pct.py

Figure 1a
Capt Cae Tug at 0 knots, using 20% Applied Power
Transect: Nav Channel at MHHW



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ANCHOR QEA

Figure 1b
Capt Cae Tug at 0 knots, using 20% Applied Power
Transect: Nav Channel at MSL

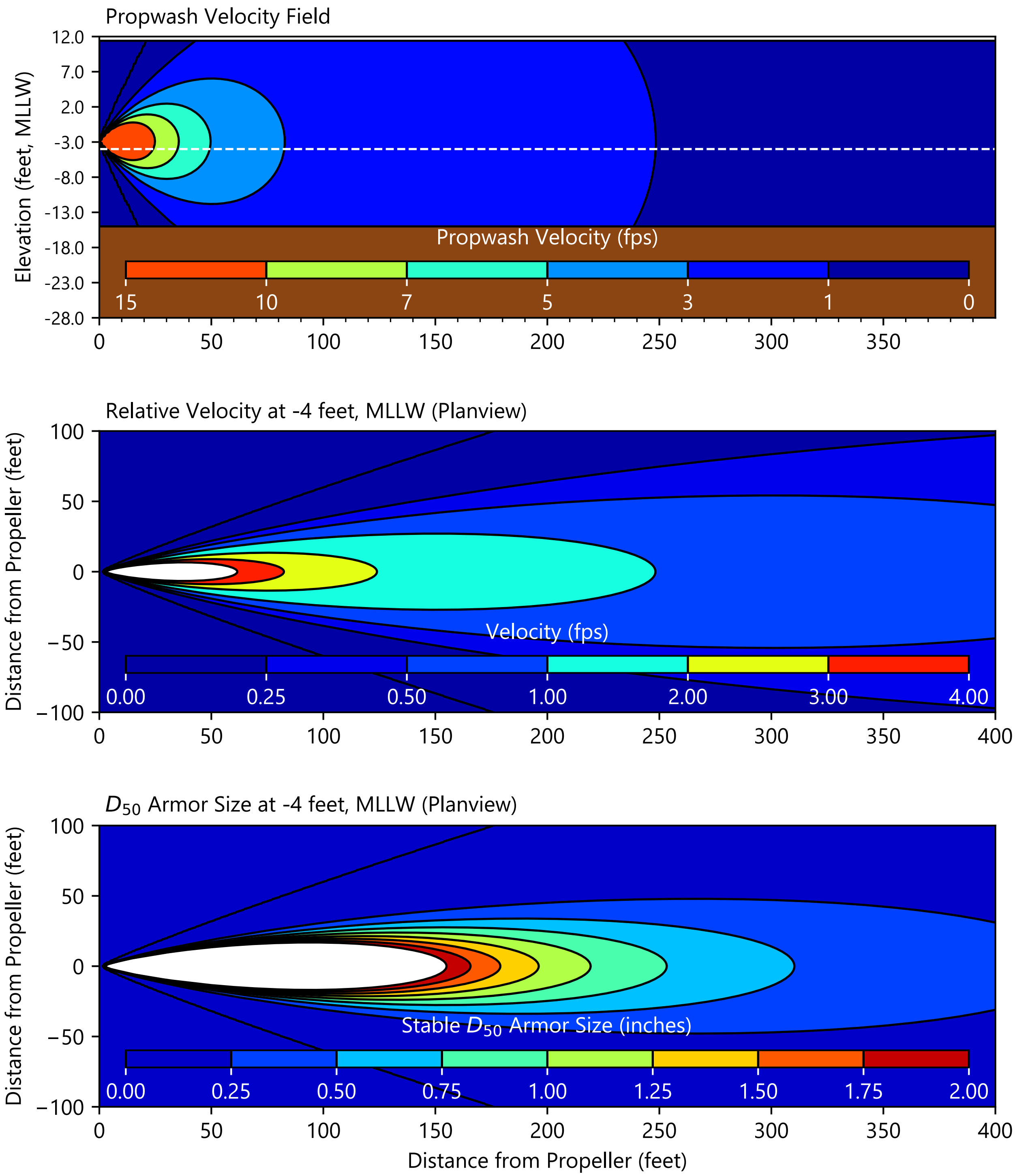

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Figure 2a
Westrac II Tug at 0 knots, using 20% Applied Power
Transect: Nav Channel at MHHW

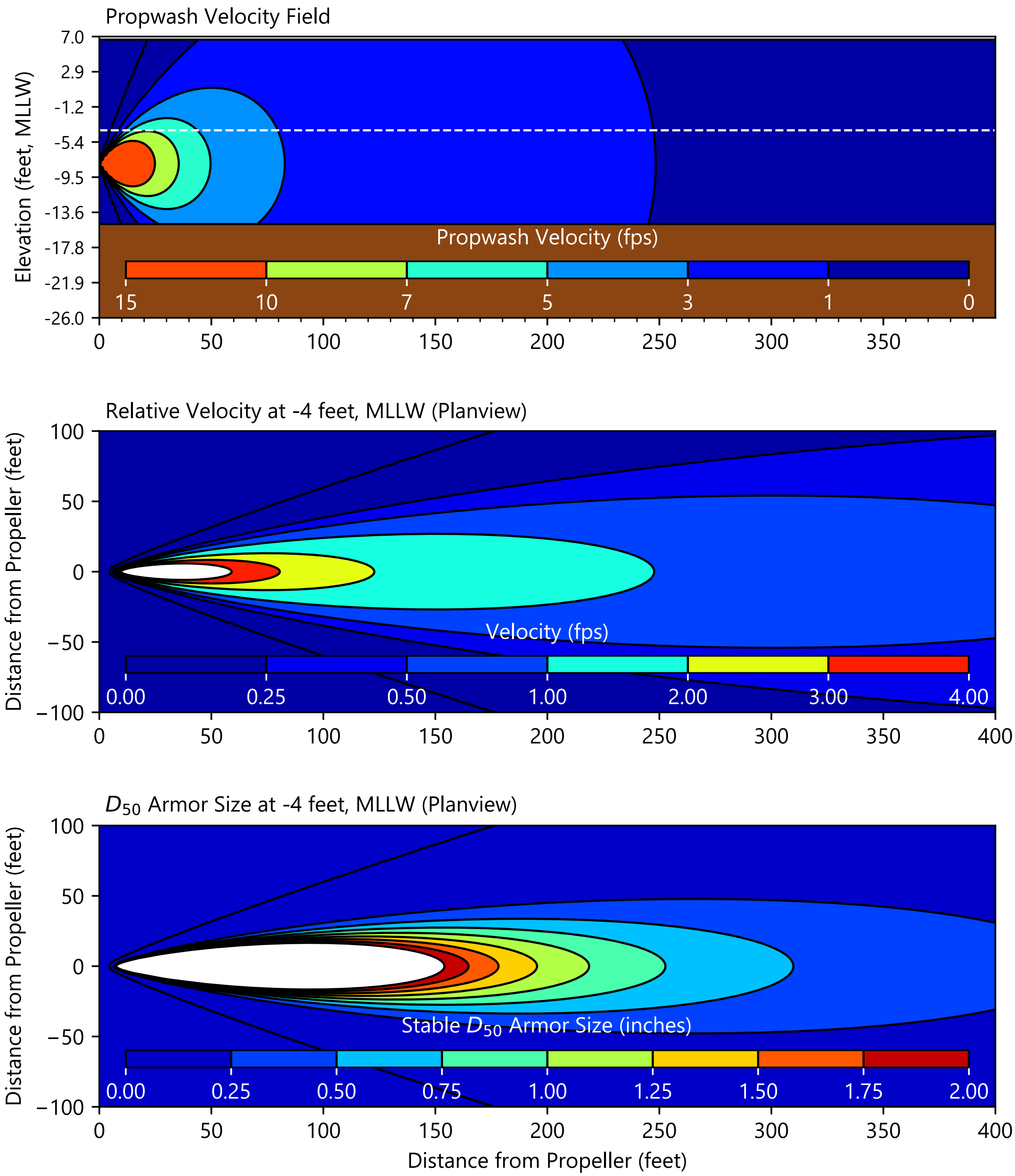

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Figure 2b
Westrac II Tug at 0 knots, using 20% Applied Power
Transect: Nav Channel at MSL

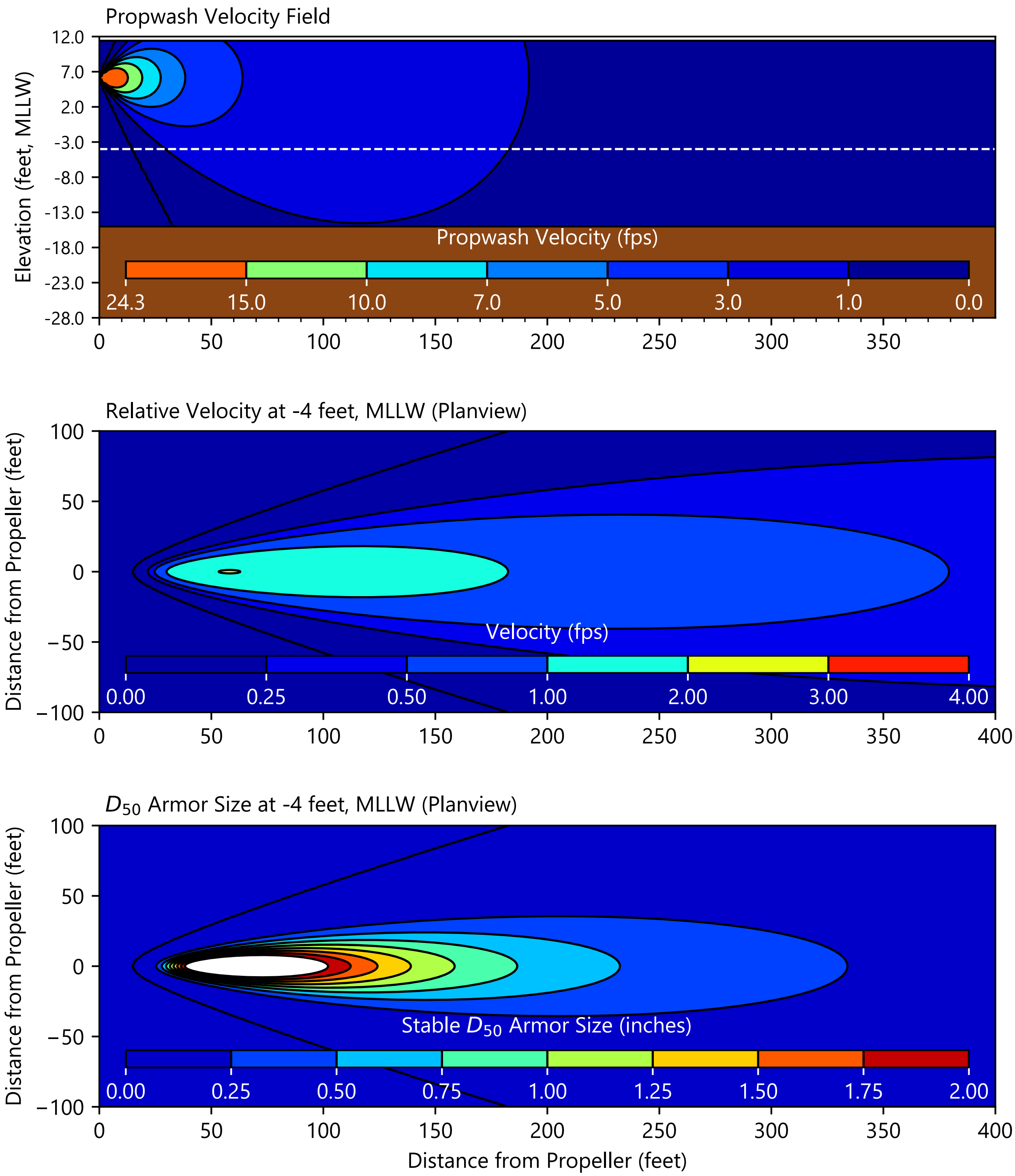

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Figure 3a
Arctic Pride Yacht at 0 knots, using 20% Applied Power
Transect: Nav Channel at MHHW

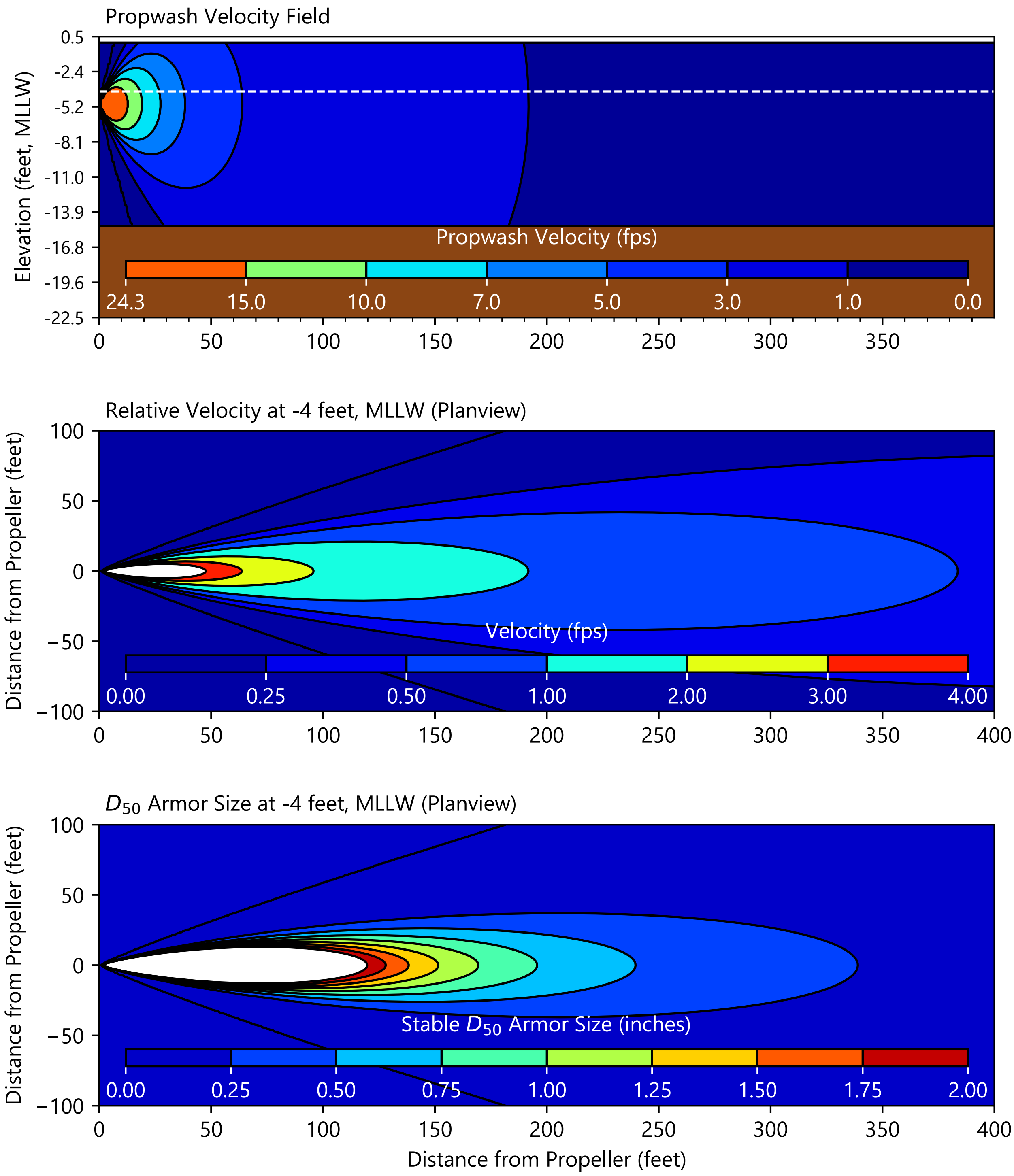

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Figure 3b
Arctic Pride Yacht at 0 knots, using 20% Applied Power
Transect: Nav Channel at MLLW

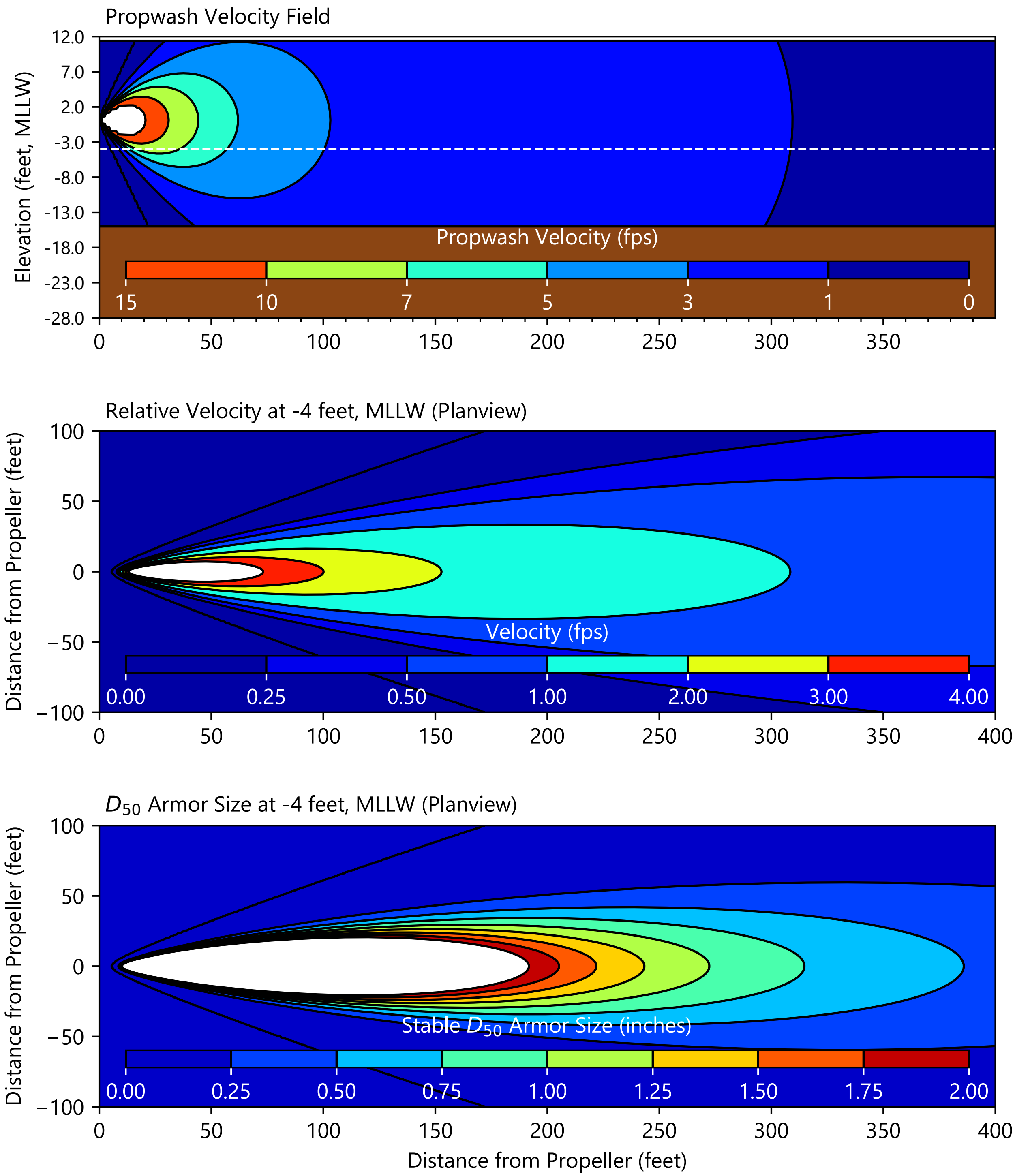

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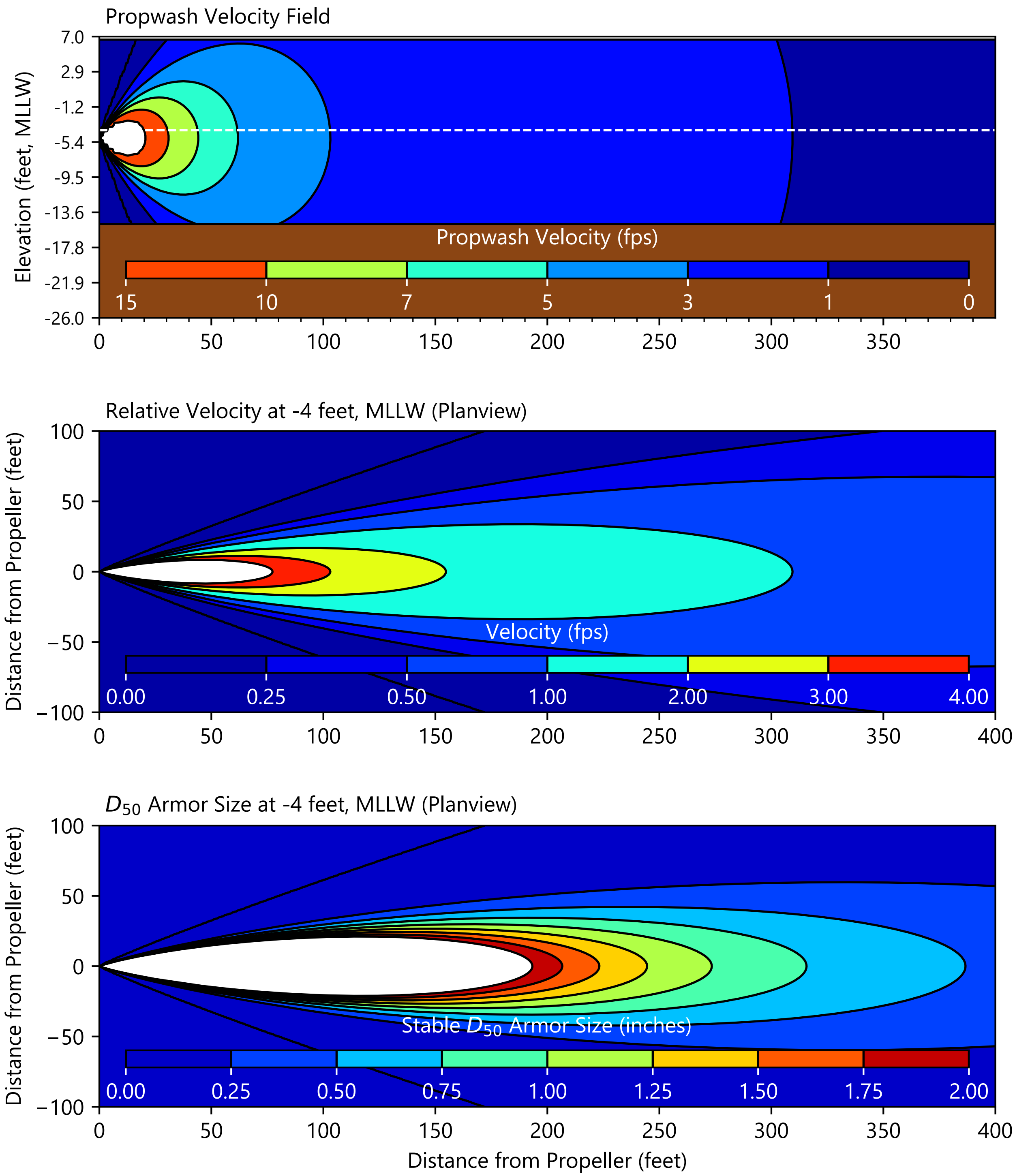
Figure 4a
Capt Cae Tug at 0 knots, using 30% Applied Power
Transect: Nav Channel at MHHW



Notes:
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The C_3 coefficient = 0.55 for no sediment movement.

Figure 4b
Capt Cae Tug at 0 knots, using 30% Applied Power
Transect: Nav Channel at MSL

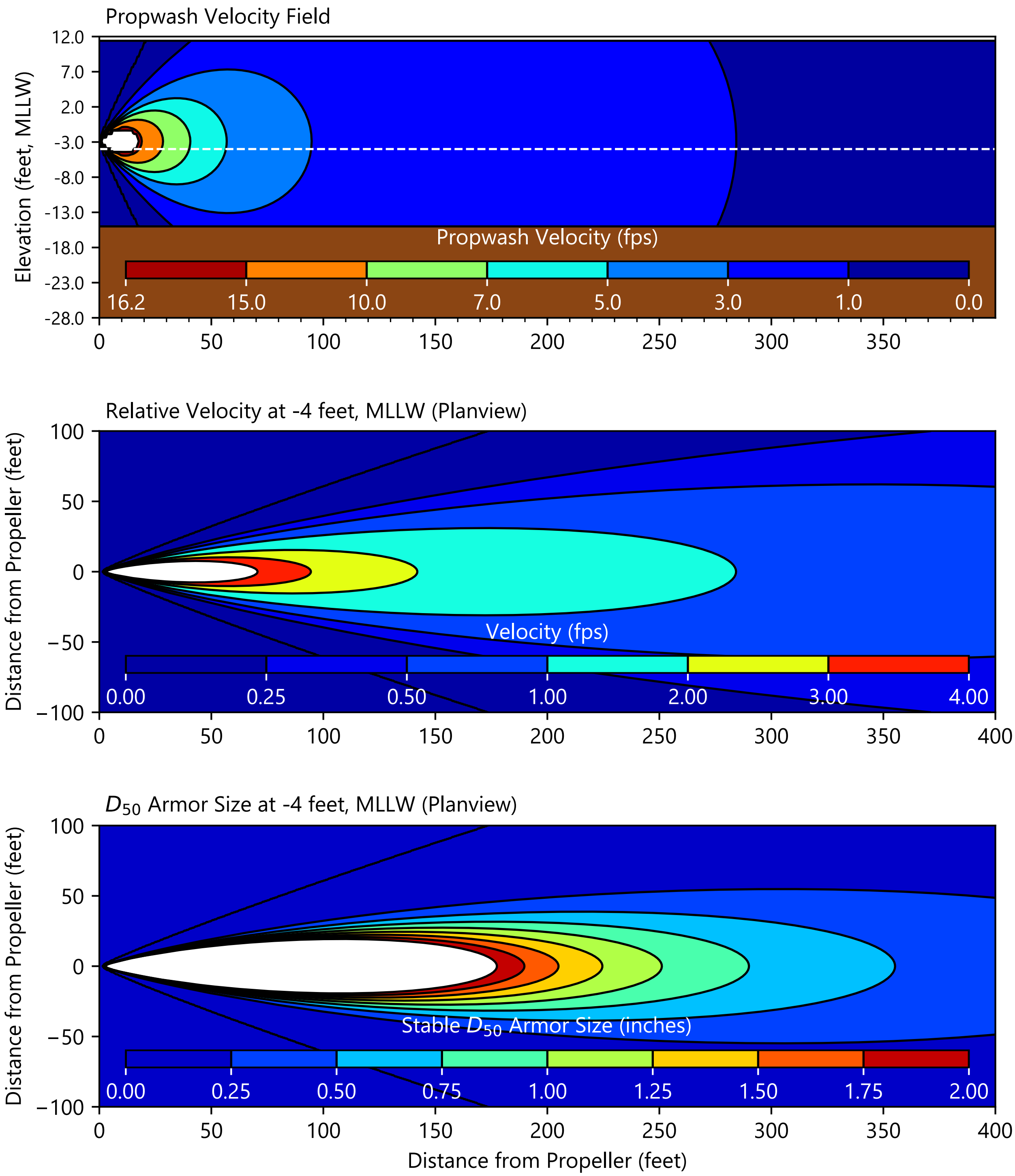

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Figure 5a

Westrac II Tug at 0 knots, using 30% Applied Power

Transect: Nav Channel at MHHW

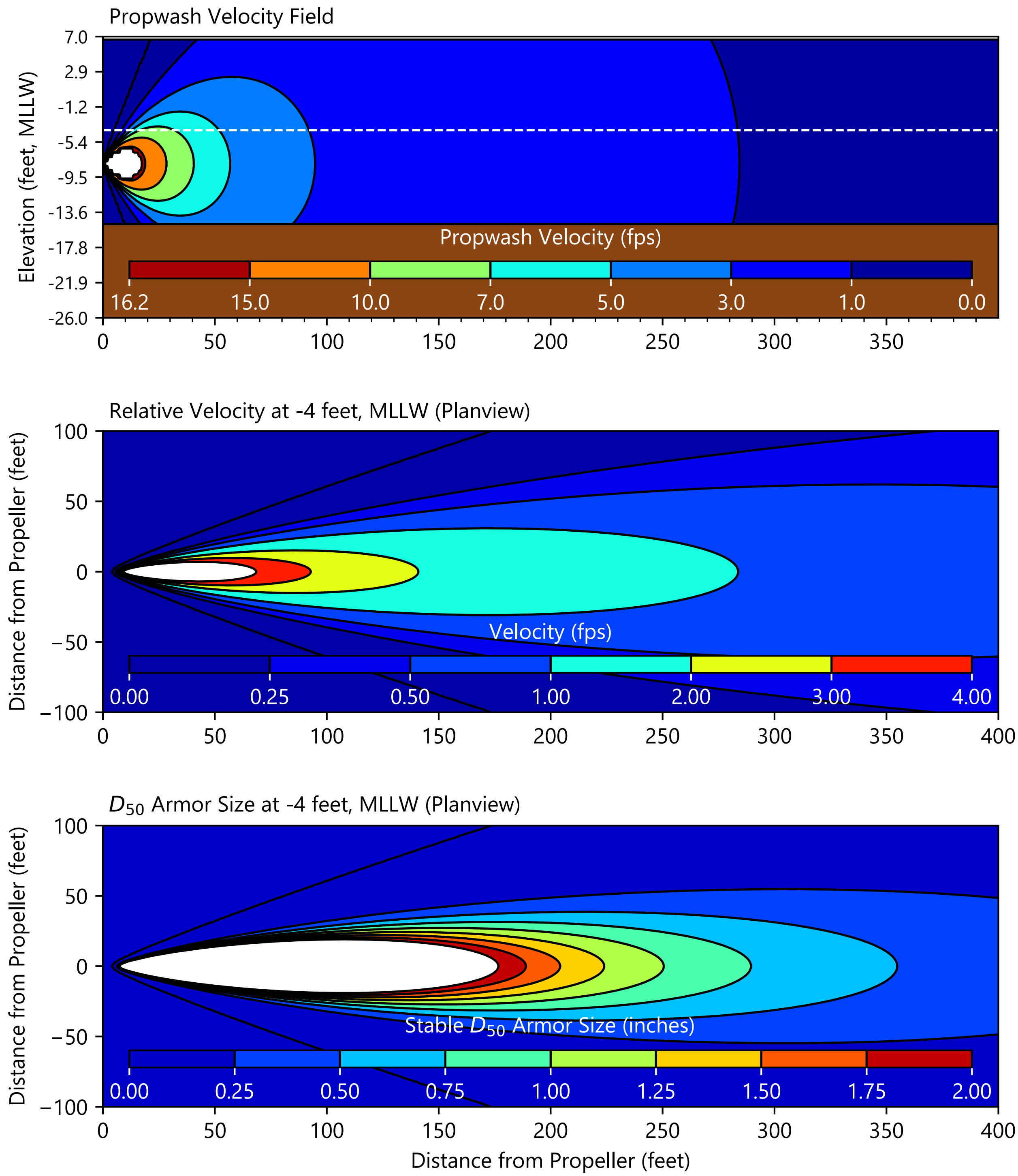

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Figure 5b
Westrac II Tug at 0 knots, using 30% Applied Power
Transect: Nav Channel at MSL
30% Remedial Design Basis of Design Report

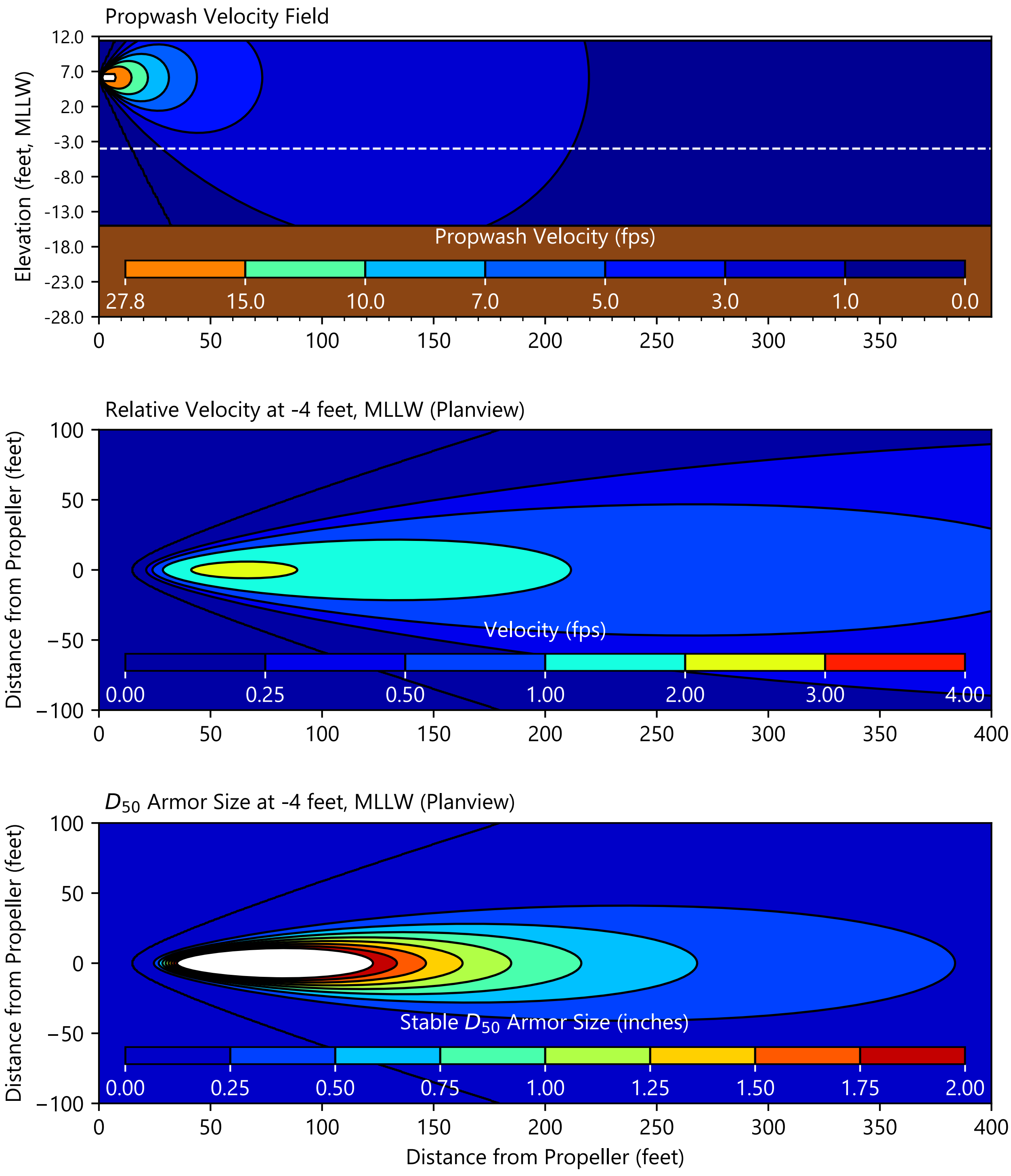

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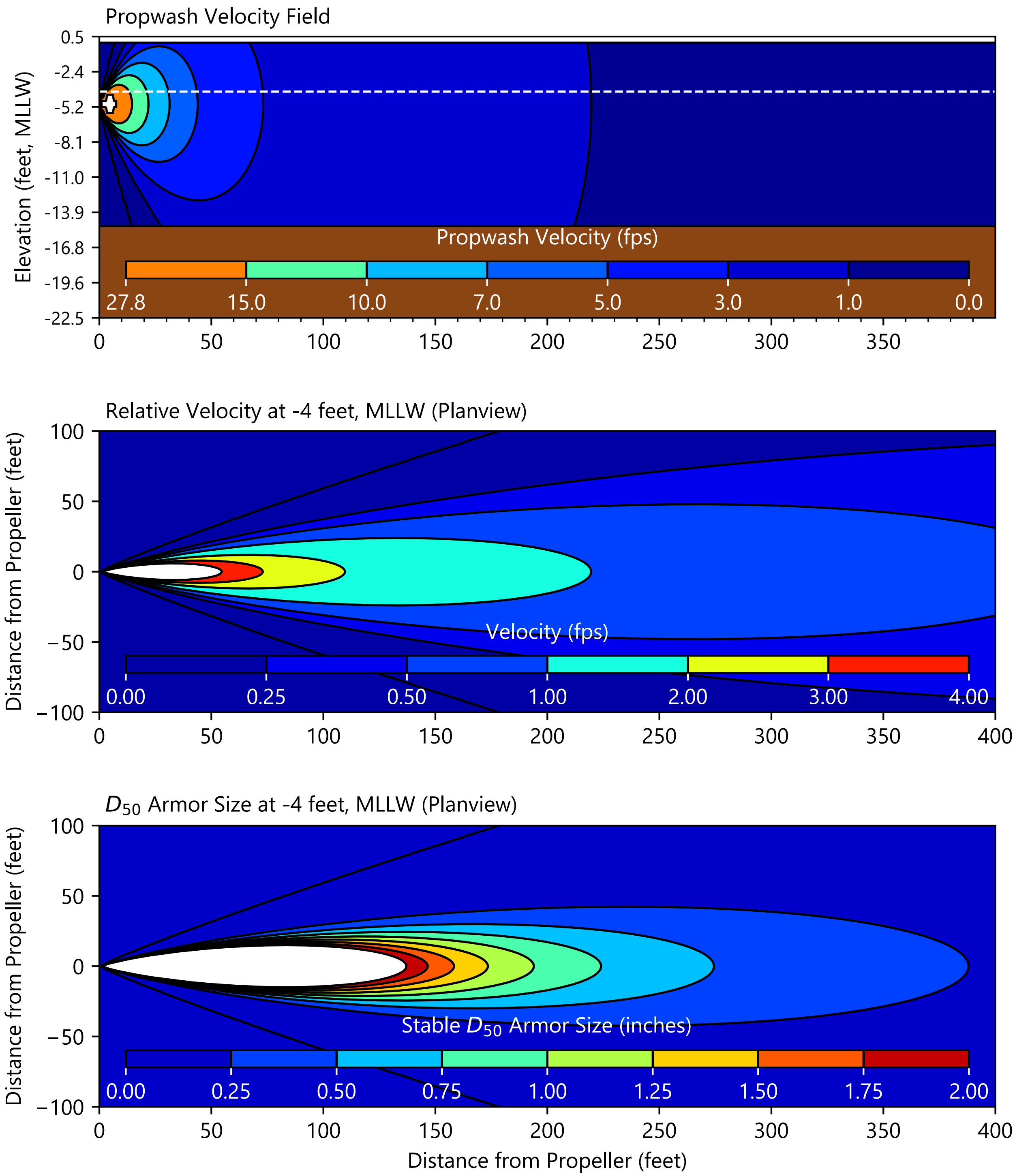
Figure 6a
Arctic Pride Yacht at 0 knots, using 30% Applied Power
Transect: Nav Channel at MHHW



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ANCHOR QEA

Figure 6b
Arctic Pride Yacht at 0 knots, using 30% Applied Power
Transect: Nav Channel at MLLW