60% Remedial Design Basis of Design Report

Appendix I
Engineered Protection Design Analysis for Engineered Caps and Area-Specific Technology

BLUE COAST
ENGINEERING

Preliminary (60%) Remedial Design
Basis of Design Report for
Lower Duwamish Waterway Middle Reach

Appendix I: Engineering Protection Analysis for Engineered Caps and Area-Specific Technology Areas

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1 Introduction

This appendix describes site data and engineering analyses used to inform the Intermediate 60% remedial design (RD) of erosion protection for engineered caps at proposed remedial action areas (RAAs) in the middle reach of the Lower Duwamish Waterway (LDW) between river miles (RM) 1.6 and 3.0 (Figure 2-2 of the Intermediate (60%) RD *Basis of Design Report* [BODR]). The middle reach includes all in-water areas of the LDW, including the federal navigation channel (FNC) and adjacent intertidal and shoreline/riverbank areas up to the mean higher high water (MHHW) elevation. The reach also includes four side-channel areas identified as the inlet at RM 2.2W and Slips 2, 3, and 4. The FNC within the middle reach has variable authorized depths, ranging downstream to upstream from -30 to -15 feet mean lower low water (MLLW; Figures 2-4a through 2-4e in the Intermediate [60%] RD BODR).

Within the middle reach, engineered capping is a technology that can be utilized in identified areas with deep contamination and appropriate final surface elevations, in accordance with the LDW Record of Decision (ROD; EPA 2014). Engineered caps have a dual function: stabilizing the underlying contaminated sediments and making the cap itself resistant to erosion (Palermo et al. 1988). Design methods for stabilizing the underlying contaminated sediments are described in Appendix H of the BODR, entitled *Engineered Cap Chemical Isolation Design Analysis*.

This appendix focuses on data and methods for design of the cap erosion protection layer (armor) that will protect the underlying contaminated sediments and chemical isolation layer from erosion due to hydrodynamic forces in the middle reach. Hydrodynamic processes that may act on the sediment cap within the middle reach of the LDW include the following:

- Localized propeller wash (propwash) from vessels
- Waves generated by transiting vessels (wakes)
- Wind-generated waves due to storm events (waves)
- River currents in the LDW due to variable tides, river flows, and other upstream sources of freshwater input (currents)
- Sea level rise (SLR) impacts on each of these processes

Each of these potential erosion processes was evaluated to determine the associated stable particle size for general cap erosion protection components in the FNC and representative off-channel capping areas (see Figure 5-2 in the BODR). Changes to existing capping areas or additional capping areas may be considered in 90% RD and will be evaluated in those phases of design.

The requirements for the cap erosion protection layer were then determined from these results to withstand erosion under the range of anticipated conditions. General methods for these analyses were taken from Appendix A of Palermo et al. (1998), entitled *Guidance for In-Situ Subaqueous*

Capping of Contaminated Sediments. Assessment and Remediation of Contaminated Sediments (ARCS) Program. This appendix also presents the results of this analysis.

2 Site Data Used in Analysis

Available site data that were used to complete the engineering design analysis for the cap erosion protection layer are summarized in this section and include bathymetry (i.e., water depths); water levels, including SLR estimates; and river currents for the middle reach of the LDW.

2.1 Bathymetry

Bathymetry and topography data for existing conditions within the middle reach and adjacent shoreline areas were developed from multiple datasets as described in Section 2.5.1 in the BODR. The FNC runs down the center of the middle reach and dictates the bed elevations in this area. The FNC has variable authorized bed elevations, increasing in elevation upstream from RM 1.6 to RM 3.0 as summarized as follows and shown in Figures 2-4a through 2-4e of the BODR:

- RM 1.6 to 2.0, -30 feet MLLW
- RM 2.0 to 2.8, -20 feet MLLW
- RM 2.8 to 3.0, -15 feet MLLW

Maximum bed elevations in Slips 2 (RM 1.7), 3 (RM 2.0), and 4 (RM 2.8), which generally follow the authorized navigation depth in the channel adjacent, are approximately -30, -20, and -15 feet MLLW, respectively.

Bed elevations in areas outside the FNC within the middle reach generally range from -20 feet to +4 feet MLLW, with shoreline areas sloping up to MHHW and above at the landward boundaries of the waterway.

Post-project elevations, which include bed elevations associated with remedial design (i.e., dredging and capping) were taken from the Intermediate 60% RD Drawings developed by Anchor QEA and provided in the BODR as Volume III, Part I.

2.2 Water Levels and Base Flood Elevation

The middle reach of the LDW is an estuary where freshwater flows from the Green River and other upstream sources mix with incoming salt water from Puget Sound. The upstream boundary of salt water inundation, referred to as the saltwater wedge, is generally located within the middle reach near RM 2.8 but can extend upstream to RM 10.2 during low river flow conditions (WRIA 9 2021).

Water surface elevations in the middle reach are tidally dominated and not significantly influenced by river flows (QEA 2008; FEMA 2020a). Tidal datums for the middle reach were taken from the National Oceanic and Atmospheric Administration (NOAA) Tidal Station at Seattle (in Elliott Bay) and are provided in Table I-1.

The 100-year base flood elevation defined by the Federal Emergency Management Agency (FEMA) for the middle reach (FEMA 2020b) is based on flooding due to coastal processes (high tides) and is the same elevation throughout the middle reach and further downstream to Elliott Bay. Therefore, water surface elevations within the middle reach are tidally dominated and are not significantly influenced by river flows.

The FEMA base flood elevation is 12.0 feet relative to the North American Vertical Datum 1988 (NAVD88), which is 14.3 feet relative to MLLW datum. This water level is also equivalent to the highest observed tide at the NOAA Tidal Station at Seattle (Table I-1).

Table I-1.
Tidal Datums at Seattle, Washington (NOAA Tidal Station #9447130)

Tidal Datum	Elevation (feet relative to MLLW)	Elevation (feet relative to NAVD88)
Highest Observed Tide (HOT) (1/27/1983)	14.4	12.1
Highest Astronomical Tide (HAT)	13.3	11.0
Mean Higher High Water (MHHW)	11.3	9.1
Mean High Water (MHW)	10.5	8.2
Mean Sea Level (MSL)	6.6	4.3
Mean Low Water (MLW)	2.8	0.5
North American Vertical Datum (NAVD88)	2.3	0
Mean Lower Low Water (MLLW)	0	-2.3

2.3 Hydrodynamic Forces due to River Currents

Current velocities in the middle reach due to river flows and variable tidal conditions have the potential to erode material on the channel bed, intertidal, and shoreline areas. Estimates of current velocities and excess shear stress due to a combination of the 100-year flow in the LDW and peak ebb tide conditions were developed by QEA using a three-dimensional hydrodynamic and sediment transport model documented in the *Lower Duwamish Waterway Sediment Transport Modeling Report* (QEA 2008).

Additional hydrodynamic modeling was not completed as part of 60% design to reflect proposed dredge depths within the middle reach. This is because the middle reach is tidally dominated, and increased water depths are not expected to significantly change near bed (e.g., bottom) current velocities because cross-sectional area would not be reduced. In addition, as highlighted in the following sub-sections, river current velocities are smaller than those from propeller wash and vessel wakes and therefore do not determine the design rock size for RAAs in the middle reach.

Shear stress is a measure of the force exerted laterally on the river bed due to hydrodynamic forces, including river currents (Ippen 1966). The critical shear stress is the value at which the sediment on the bed will begin to erode, and excess shear stress is a measure of shear stress above the critical shear stress for the sediment bed as shown in Equation I-1:

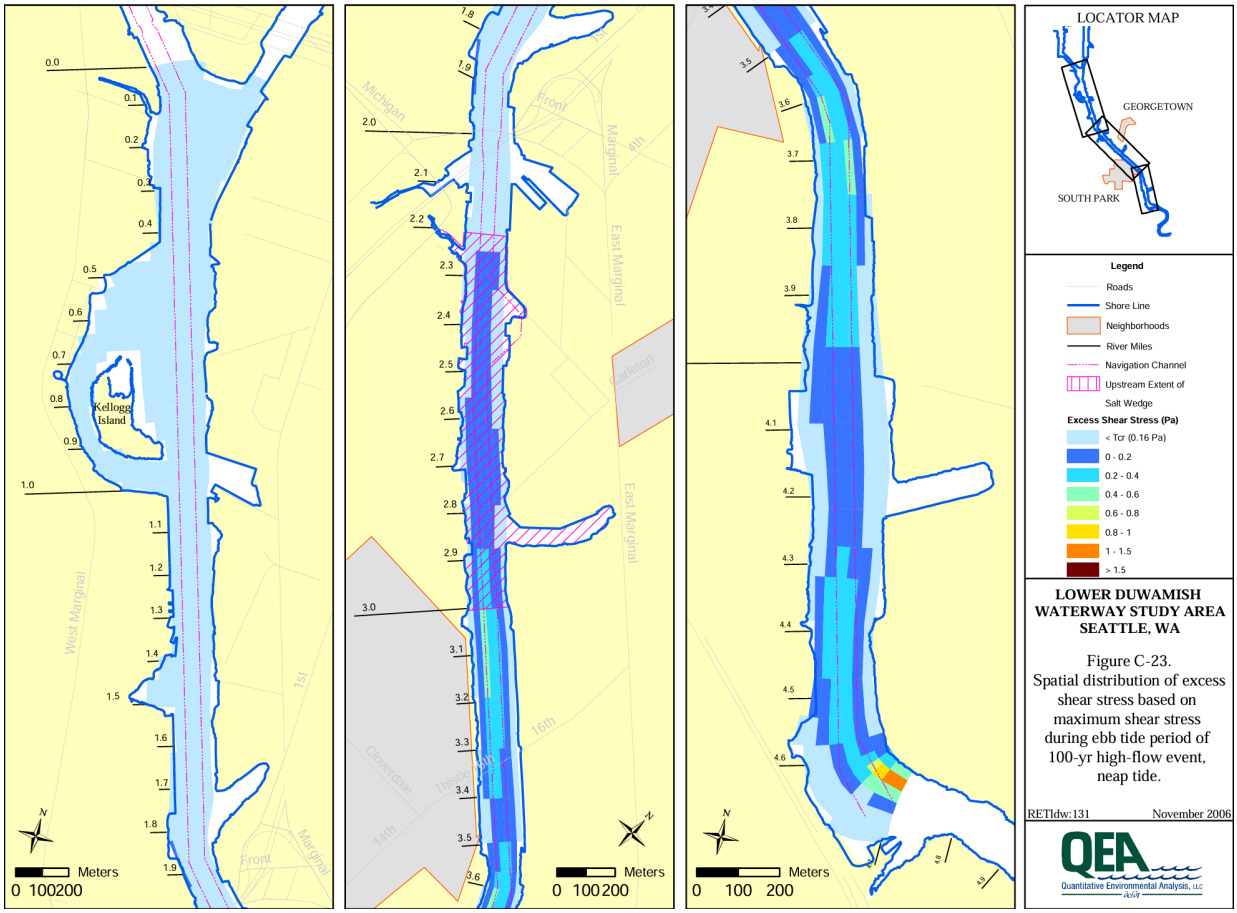
$$\boldsymbol{\tau_{ex} = \tau - \tau_{cr}} \qquad \textbf{Equation I-1}$$

Where:
τ_{ex} is the excess shear stress;
τ is the shear stress exerted on the sediment bed by river and tidal currents; and
τ_{cr} is the critical shear stress of the sediment bed.

The excess shear stress was estimated from sediment transport modeling completed for the LDW for the 100-year flow at peak flood and peak ebb tide, with higher values of excess shear stress occurring during peak ebb tide (QEA 2008). Figure I-1 (taken from Figure 3-16, QEA [2008]) shows model predicted excess shear stress values for the 100-year flow at peak ebb tide with the middle reach shown in the center panel of the figure.

Critical bed shear stress (τ_{cr}) for the LDW was estimated from Sedflume core data to be 1.6 pascal (QEA 2008). Therefore, the shear stress exerted on the sediment bed (τ) during the 100-year/peak ebb tide event can be determined by adding this critical shear stress value to the value of excess shear stress (τ_{ex}) shown in Figure I-1 (see Equation I-1). Predicted excess shear stress in the middle reach for the 100-year/peak ebb tide event ranges from approximately 0.2 to 0.6 pascal. This corresponds to shear stress values ranging from 1.8 to 2.2 pascals. This shear stress information can be used to estimate the size of sediment particles that would be stable during the 100-year/peak ebb tide scenario. This is discussed in Section 3.53 of this report.

Figure I-1.
Excess Shear Stress in LDW River (Middle Reach from RM 1.6 to 3.0) for the 100yr flow/peak Ebb Tide Scenario



Source: Figure C-23 of QEA (2008)

2.4 Sea Level Rise Predictions

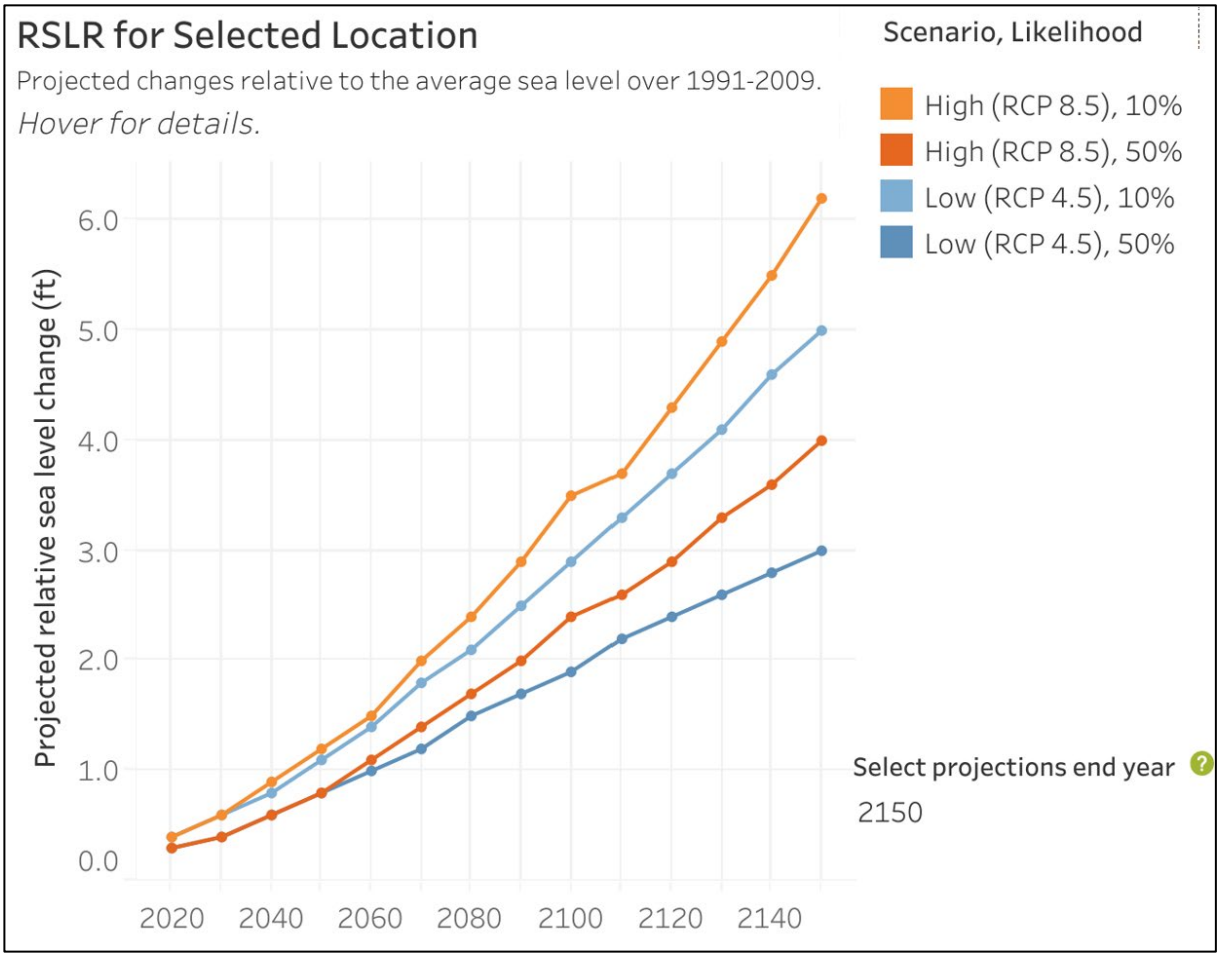
SLR estimates for the middle reach were taken from *Projected Sea Level Rise for Washington State – A 2018 Assessment* (Miller et al. 2018), published by the Washington Coastal Resilience Project. The SLR predictions provided in this study have been compiled into an online visualization tool available at: https://cig.uw.edu/projects/interactive-sea-level-rise-data-visualizations/. SLR predictions are available based on future year of interest through 2150, probability of occurrence, and for two Representative Concentration Pathways (RCPs), which are a measure of emissions that drive global changes in temperature and subsequent SLR. RCP 4.5 represents a moderate emissions scenario with future reductions, and RCP 8.5 represents a scenario where emissions continue to rise into the future.

Guidance on selection of SLR scenarios for use in risk evaluation and design for remediation projects is available in the U.S. Environmental Protection Agency (EPA) Engineering Forum Issue Paper titled *Conducting Climate Vulnerability Assessments at Superfund Sites* (EPA 2023). This reference suggests that a scenario-based evaluation should be completed (including a range of SLR values in the analysis) with the range for SLR defined as the RCP 4.5, 50% likelihood of occurrence value as the low bound, and RCP 8.5, 10% probability of occurrence as an upper bound.

SLR predictions for the middle reach for RCPs 4.5 and 8.5 for the 50% and 10% exceedance probabilities between years 2020 and 2150 are provided in Figure I-2, which is taken from the visualization tool developed from Miller et al. (2018) and available at the hyperlink above. Using the scenario selection guidance in EPA (2023), estimated values of SLR for the year 2100 used for this evaluation range from 1.9 feet (RCP 4.5, 50% likelihood of occurrence) to 3.5 feet (RCP 8.5, 10% likelihood of occurrence).

Because the middle reach is tidally dominated and dam-controlled, water surface elevations and near-bed river currents in the middle reach are not significantly influenced by river flows (QEA 2008; FEMA 2020a). Caps are not impacted by this aspect of climate change because as water levels increase due to SLR, predicted propwash velocities and stable rock size for the cap will decrease. In addition, where caps are placed in shoreline areas, the cap will extend to the top of slope and will be protective for both extreme high tide events and SLR.

Figure I-2.
Sea Level Rise Estimates for Middle Reach



Developed from the visualization tool from Miller et al. (2018), available at: https://cig.uw.edu/projects/interactive-sea-level-rise-data-visualizations/.

3 Erosion Protection Design for Engineered Cap Areas

The following subsections present the methodologies used in the design of the erosion protection layer (i.e., armor layer) for the proposed sediment caps within each of the applicable RAAs as described in the BODR. Each potential source of erosion, as well as how these sources of erosion could be affected by climate change, was evaluated with applicable guidance from the USEPA *Guidance for In-Situ Subaqueous Capping of Contaminated Sediments: Appendix A: Armor Layer Design* (Maynord 1998). The stable armor layer granular material size (median particle size [D50]) was computed based on each of the following erosive forces:

- Propeller wash
- Vessel wakes
- River currents
- Wind-waves

The design methodology and results for each evaluation are described in the following sections.

3.1 Stable Particle Size Due to Propeller Wash

The LDW is a very active waterway with frequent tug and barge combinations operating at the many dock and berth locations on both the left and right banks throughout the middle reach. Localized scour caused by propwash, as well as the severity of vessel-generated wake (Section 3.2), is dependent on these operations and the characteristics of the vessels being used. Vessel physical characteristics include the vessel size, draft, engine power, propeller size, and clearance above the bed sediments. Vessel-operations characteristics include operating locations, vessel orientation, applied engine power, frequency, and vessel speed. Both the physical and operational vessel parameters were compiled and used to estimate propwash and the corresponding design stable particle size for a cap armor layer at each RAA based on EPA cap armor layer design criteria (Maynord 1998).

3.1.1 Design Vessels

The vessels selected for this analysis were determined initially through publicly available vessel automatic information system (AIS) data and then verified through conversations with tugboat operators on the LDW. The AIS vessel track data were used to determine the large vessel types that have historically entered the LDW middle reach project site boundary. The AIS data also provided vessel characteristics (length, draft, and beam), speed, course, and location, and were obtained from Marine Cadastre (available at: https://marinecadastre.gov) from 2019 through 2024. These 5 years of data were analyzed to identify vessels that are expected to produce the highest propwash velocities and produce the largest wakes in the middle reach based on vessel properties and documented speed of travel. The focus of the AIS data evaluation was on larger tugboat vessels transiting the main navigation channel that would be expected to produce the largest propwash velocities on the

sediment bed in the middle reach. Based on this AIS data evaluation, the following two vessels were selected due to their type, size, or frequency of travel within the middle reach:

- *Garth Foss* (tractor tug): Selected because it was the largest tug, although not the most frequent, that traveled through the middle reach in the 5-year period of record
- *Clayton Arthur* (tug): Selected because it was the third-most-frequent tug that traveled through the middle reach in the 5-year period of record and was significantly larger than the first- and second-most-frequently operated tugs in the middle reach

The extent of travel within the middle reach for both tugs was also examined using the AIS data over the same time period. The larger tug, the *Garth Foss*, did not travel south of RM 2.6, while the *Clayton Arthur* traveled the entire length of the middle reach. For this reason, the *Garth Foss* is the design vessel between RM 3.0 and RM 2.6, and south of that location, the *Clayton Arthur* is the design vessel for the stability calculations due to propwash in the FNC and due to wake in specific capping areas outside the FNC. While these vessels were found to travel within the FNC throughout the middle reach project boundary, conversations with tug operators (described in detail in Section 3.1.4) revealed that these vessels are ocean-going tugs and thus not likely to be maneuvering or transporting barges within the middle reach. These low-speed maneuvering operations require tugs to turn barges and have the potential to direct propwash toward the off-channel RAAs located throughout the middle reach.

Therefore, two additional tugs, the *Alaska Mariner* and *Gretchen H*, were included as design vessels to evaluate propwash that could impact off-channel RAAs. Both of these tugboats were confirmed by operators to be actively used to facilitate barge movements throughout the middle reach and could potentially be used at any location in the middle reach in the future. The *Alaska Mariner* represents one of the largest tugs that would be used to maneuver barges within the middle reach, while the *Gretchen H* represents a lower-powered tug that is smaller and can operate in shallower depths and closer to off-channel RAAs.

Specific vessel physical characteristics were determined from publicly available vessel databases and is provided for the four design tugboats in Table I-2.

Table I-2.
Design Vessel Information

Characteristic	*Garth Foss*	*Clayton Arthur*	*Alaska Mariner*	*Gretchen H*
Applicable RAA Locations	FNC (Channel RAAs)		Off-Channel RAAs	
Vessel Type	Enhanced Tractor Tugboat	Tugboat	Tugboat	Tugboat
Length Overall, feet	155	124	109	85
Maximum Breadth, feet	48	32	32	30
Maximum Draft, feet[1]	20	15	15	9
Propeller Type (number of propellers)	5-Blade Voith Cycloidal (2)	Fixed Pitch Propeller (2)	Nautican Nozzle, Azimuth Stern Drive (2)	Kort Nozzle (3)
Ducted Propeller[2]	non-ducted	non-ducted	ducted	ducted
Propeller Diameter, feet	9.8	7.7	8.7	5.3
Total Engine Power, hp	8,000	3,900	4,000	2,250

hp - horsepower; FNC - federal navigation channel
Notes:

1. Maximum draft is defined as the distance between water surface elevation and the lowest point along keel under fully loaded conditions.
2. Ducted propeller refers to the propeller being enclosed or shrouded.

Complete and/or reliable information on frequency and speed of travel for recreational and fishing vessels is not available in the AIS data record. It is possible these vessels occasionally travel at faster speeds than commercial vessels (on average) in the middle reach and therefore could produce a larger wake than the design tugs selected for this analysis. However, these events are expected to be infrequent compared to continuous commercial operations in the middle reach used for cap design.

3.1.2 Propeller Wash Calculations

As a vessel moves through the water, the propeller produces an underwater high-velocity jet that can resuspend and/or erode adjacent riverbed sediments. The velocity distributions in the propwash jet are turbulent and complex, and the velocity plume can extend several boat lengths behind and to the sides of the vessel, depending on vessel operations. The magnitude and spatial extent of the velocity plume can depend on the water depth, propeller draft (distance from the water line to the propeller shaft), size and type of propeller, rotational speed of the propeller (e.g., horsepower [hp] applied to the engine), and type of movement of the vessel (i.e., transiting through a channel or berthing).

Potential effects on the design of the erosion protection for proposed cap areas were evaluated in accordance with Appendix A of Palermo et al. (1998) cap armor layer design guidance.

The propwash velocity was calculated using an empirical method developed by Blaauw and van de Kaa (1978). The stable particle size under these velocities was calculated based on an empirical method by Blaauw et al. (1984) and additional research by Maynord (1988); both methods are presented in Appendix A (Armor Layer Design) of Palermo et al. (1998). These methods consider physical vessel characteristics (e.g., propeller diameter and propeller draft) and operational and site conditions (e.g., applied horsepower and water depth) to estimate the maximum propeller-induced bottom velocity due to vessels transiting the FNC. As part of the 30% design, maximum propeller-induced velocities on the bed ($V_{b(max)}$) and stable particle sizes (D_{50}) in line with the direction of vessel travel were calculated using Equations I-2 and I-3 from Blaauw and van de Kaa (1978) and Equation I-4 from Blaauw and van de Kaa (1984). Equation I-5 (Maynord 1998) was used to predict the 2D propwash velocity field behind the propeller. The equations used in the propwash analysis are presented below.

Maximum Bed-Level Propwash Velocity (Channel RAAs)

$$V_{b(max)} = \frac{C_1 U_o D_p}{H_p}$$ **Equation I-2**

Where:
$V_{b(max)}$ is maximum bed velocity (Equation H-2);
C_1 is a coefficient set to 0.22 for non-ducted propellers, 0.30 for ducted propellers;
U_o is the jet velocity exiting the propeller;
D_p is the propeller diameter; and
H_p is propeller clearance above the bed.

Propwash Efflux Velocity

$$U_o = C_2 \left(\frac{P_d}{D_p^2}\right)^{\frac{1}{3}}$$ **Equation I-3**

Where:
C_2 is a coefficient set to 9.72 for non-ducted propellers, 7.62 for non-ducted propellers;
P_d is the applied engine power in horsepower (hp); and
D_p is the propeller diameter.

Stable Median Particle Size (D_{50})

$$V_b(max) = C_3(g * Ä * D_{50})^{\frac{1}{2}}$$ **Equation I-4**

Where:
C_3 is a coefficient set to 0.7 for navigation channel protection based on infrequent impact and set to 0.55 for off channel protection calculations based on frequent impact;

g is acceleration due to gravity; and
Ä is the proportionality constant for the unit weight of stone and seawater, respectively.

The $V_{b(max)}$ and corresponding D_{50} calculations (Equations I-2 and I-4) were used to evaluate the bottom bed velocity and stable D_{50} sizes at RAAs within the FNC and center of the channel. For evaluating the off-channel RAAs, propwash jet spatial distributions were evaluated to determine how the propwash jet could interact with the LDW side slopes and areas not directly beneath where the tugboats area operating. The propwash jet velocity behind the propeller decays in relation to the x (lateral) and z (vertical) distances away from the propeller shaft (axis). This jet velocity decay is predicted with Equation I-5 below.

Propwash Velocity Jet Field (2D):

$$\frac{V_x}{U_0} = 2.78 * \frac{D_0}{x} * exp[-15.43 \left(\frac{z}{x}\right)^2] \qquad \textbf{Equation I-5}$$

Where:
V_x is the propwash velocity within the 2D velocity field;
U_0 is the jet velocity exiting the propeller (Equation I-3);
D_0 is equivalent to the propeller diameter for a ducted propeller, or 0.71 times the propeller diameter if non-ducted;
x is the horizontal distance from the propeller; and
z is the radial distance from the axis of the propeller.

By plotting every computed propwash jet velocity for a range of x and z dimensions, a 2D propwash jet velocity field can be plotted and compared to the bathymetry to see which areas of the bathymetry might experience the highest propwash velocities (Section 3.1.4).

3.1.3 Channel RAAs

Equations I-2 through I-4 were used to predict maximum bed velocities and corresponding stable particle sizes on the riverbed within the FNC when subjected to steady state propwash (i.e., the vessel is essentially stationary or maneuvering at a very low speed) from the *Garth Foss* and *Clayton Arthur* tugboats (Table I-2). Compared to the *Clayton Arthur*, the *Garth Foss* tugboat created higher propwash velocities on the bed due to its larger vessel size and smaller propeller clearance above the bed. Therefore, the *Garth Foss* propwash velocities were used to design the stable sediment sizes resistant to propwash within the middle reach where it was shown to operate in AIS data and based on minimum required keel clearances discussed below. In areas where the *Garth Foss* is not likely to operate (i.e., upstream of RM 2.6), the *Clayton Arthur* was the design vessel used for the propwash calculations.

To evaluate propwash velocities on the riverbed and associated stable particle sizes, operational assumptions for the design vessel within the middle reach were established. There are no specific requirements for engine operation and under-keel draft[1] for tug vessels operating within the LDW, so available guidance documents were used to develop operational assumptions used in the evaluation as described in the following:

- Applied hp while transiting the middle reach:
  - PIANC (2015) suggests using 5% to 15% of the installed power for the main propellers for transiting vessels. Therefore, for this analysis, 15% applied vessel power was conservatively used to calculate the propwash velocities.
- Under-keel clearance:
  - General guidelines for vessel operations developed by the Puget Sound Pilots (2025) require all vessels greater than 400 feet in length to maintain a minimum under-keel clearance of 3 feet or 10% of draft, whichever is greater. While both design vessels for the middle reach are smaller than 400 feet in length, this standard was used as a reasonable assumption for the *Garth Foss* and *Clayton Arthur* tugs in the middle reach. Design vessel drafts are significantly less than 30 feet, so 3 feet minimum was assumed.
  - The ROD (EPA 2014) requires any engineered cap within the FNC to be at least 4 feet below the authorized depth. For the propwash evaluation, the minimum under-keel clearance estimated from the Puget Sound Pilots (2025) general guidelines presented in the preceding bullet was increased by 4 feet.
  - Based on these two criteria, the minimum required vessel under-keel clearance is 7 ft.

The maximum draft of the *Garth Foss* tug (Table I-2) is 20 feet and the propellers on the *Garth Foss* tug are 9.8 feet in diameter. Therefore, the propeller draft (i.e., distance between the water line and the shaft of the propeller[2]) is assumed to be 15.1 feet. For the *Clayton Arthur*, the propeller draft is 11.2 feet. The minimum water depth under the propeller for the calculations was set to 7 feet based on the under-keel clearance requirements discussed above. A similar analysis was completed for the *Clayton Arthur* for the middle reach upstream of RM 2.6 (where the *Garth Foss* has not been documented to operate).

The calculation scenarios were developed for a range of tidal water levels. The design water levels are based on the range of tidal elevations in the middle reach extending down to the Lowest Observed Tide (from the NOAA Tidal Station #9447130) and the allowed minimum water depth under the propeller for both tugs (7 feet minimum). The clearance of the propeller shaft for each of the design

[1] Draft is defined as the distance between the water line (e.g., water surface elevation) and the lowest part of the keel. For the purposes of propwash velocity calculations, the maximum draft is also assumed to be the distance between the water line and the bottom of the propeller, which is typical for most vessel with traditional propulsion.

[2] The propeller shaft is the assumed centerline axis of rotation elevation for the propeller and propwash calculations.

water level conditions is presented in Table I-3 and results of the evaluation (maximum bottom velocity and design stable particle size calculations) for each scenario are provided in Table I-4, along with the applicable RAAs within the channel that each result applies to.

Table I-3.
Propwash Scenario in the Federal Navigation Channel

Propwash Scenario	Design Vessel	Applied Vessel Power[1] (hp)	FNC-Authorized Elevation[2] (feet, MLLW)	Water Level[3] (feet, MLLW)	Propeller Clearance Above Bed[4] (feet)
1	*Garth Foss*	1,200 (15% of total vessel power)	-30 (RM 1.6 to 2)	MHHW (11.3)	30.2
2				MSL (6.6)	25.5
3				MLLW (0)	18.9
4				Lowest Observed Tide (-3)	15.9
5			-20 (RM 2 to 2.6)	MHHW (11.3)	20.2
6				MSL (6.6)	15.5
7				Lowest allowable (3)	11.9
8	*Clayton Arthur*	585 (15% of total vessel power)	-20 (RM 2.6 to 2.8)	MHHW (11.3)	24.1
9				MSL (6.6)	19.4
10				Lowest allowable (-2)	10.8
11			-15 (RM 2.8 to 3)	MHHW (11.3)	19.1
12				Lowest allowable (3)	10.8

Notes:

1. Based on suggested guidance in PIANC (2015). Available total power on *Garth Foss* tug is 8,000 hp and on *Clayton Arthur* is 3,900 hp. For propwash calculations, applied vessel power was divided by the number of propellers for each vessel (Table I-2).
2. For propwash calculations, these water depths were increased by an additional 4 feet due to ROD (EPA 2014) requirements in capped areas within the FNC. Combined with the required 3-foot under keel clearance, the lowest allowable water surface elevation is based on minimum 7 feet of water depth under the propeller.
3. Tidal datums are provided in Table I-1.
4. Clearance refers to the distance between the propeller axis and the bed sediments per the FNC-authorized Elevation, clearance requirements, and the water level.

Table I-4.
Maximum Bottom Velocities and Stable Particle Sizes due to Propeller Wash in the Federal Navigation Channel

Propwash Scenario	FNC-Authorized Elevation[1] (feet, MLLW)	Applicable RAAs	Maximum Bottom Velocity[1] (ft/s)	Stable Particle Size[2] (inches)
1	-30 (RM 1.6 to 2)	30C, 30D, 30E, 30F, 30G, 30H	1.3	0.8
2			1.5	1.1
3			2.0	1.9
4			2.4	2.7
5	-20 (RM 2 to 2.6)	14A, 22, 30B	1.9	1.7
6			2.5	2.9
7			3.2	4.9
8	-20 (RM 2.6 to 2.8)	9J, 9K[3]	1.2	0.6
9			1.4	1.0
10			2.6	3.1
11	-15 (RM 2.8 to 3)	1B	1.5	1.0
12			2.6	3.1

Notes:
ft/s: foot per second
1. See Equation H-2; maximum riverbed velocities in line with vessel travel direction within the FNC
2. See Equation H-4; associated with maximum riverbed velocity
3. RAA 9K is designated as AST D, which is a utility crossing cover (refer to BODR Section 9.6.3)

The largest predicted stable sediment D_{50} for the FNC between RM 2.0 to 3.0 is 4.9 inches (Unified Soil Classification System [USCS] cobble-size material) based on lowest allowable (Table I-3) water level for tugboat operations. It was assumed that during water levels lower than the lowest allowable water levels evaluated as part of this design, these vessels will likely not operate within the middle reach.

3.1.4 Off-Channel RAAs

Stable sediment sizes due to propwash were also evaluated for eight off-channel RAA capping areas shown in Figure 5-2 of the Preliminary (60%) RD BODR. These RAAs are located on the submerged banks of the LDW and generally have steeper slopes and a larger elevation range than the channel RAAs within the FNC. These RAAs are more affected by tugboat barge operations than the channel RAAs due to the higher elevations of these RAAs being more directly in line with the propwash jets from the maneuvering tugboats. Some off-channel RAAs are more sheltered from direct propwash Equation I-5 was used to compute the propwash jet and how it may impact the bathymetry of these off-channel RAAs on the LDW side slopes for each of the smaller design tugboats (the Alaska

Mariner and Gretchen H). Direct conversations with tugboat operators were used to gather information related to vessel operating characteristics and develop vessel operations scenarios.

3.1.4.1 Vessel Operations Scenarios

Conversations with the port engineer at Deforge Towing (phone conversation with Port Engineer Brad Petefish at Deforge Towing, May 19, 2026) revealed that the *Clayton Arthur* (a Deforge-owned tugboat) is not generally used in the Duwamish Waterway as it is an open-ocean capable vessel. It is often berthed within the middle reach project area just north of RAA 31, which explains why this vessel was frequently seen in the AIS data within middle reach. The Garth Foss, being even larger than the Clayton Arthur, was also assumed to generally not be used for barge maneuvering in the middle reach due to size constraints, except for travel within the FNC.

In conversations with Boyer Towing (phone conversation with Reagan Cloudy at Boyer Towing, May 20, 2026), a towing company that frequently operates barges within the Middle Reach, it was understood that the largest tugboat that they would use for operations near RAA8 and 9 would be the *Gretchen H* at 2250 total horsepower, while most of the push tugs that normally operate there are even small at around 850 horsepower. In conversations with Western Towboat (phone conversation with Ross Shrewsbury at Western Towboat, May 21, 2026), it was revealed that the highest power towboat they would operate in the Middle Reach would be the *Alaska Mariner* which has 4,000 horsepower. This information drove the decision to evaluate both the *Gretchen H* and *Alaska Mariner* as design vessels for the off-channel propwash analysis, as it includes the largest known class of tugboat that could operate with barges in the middle reach (according to Western Towboat), as well as a lower powered vessel that is able to operate in shallower depths and closer proximity to some off-channel RAAs.

Conversations with Boyer Towing (phone conversation with Reagan Cloudy at Boyer Towing, May 20, 2026) also revealed key insights into how barges arrive at and depart from berths in the LDW. Specifically, barges seen in satellite imagery berthed perpendicular to the shoreline near RAA 8 are brought up the waterway with one tugboat pulling at the bow and one tugboat pushing at the stern. Once they approach a berth, the tugboat at the bow comes around the side of the barge and begins rotating the barge and pushing it into berth (potential for high propwash velocities). During departures, the tugboats will pull either the bow and stern of the barge out into the channel, which catches the current, and helps guide the barge into the FNC. The initial pulling of the barge into the channel is another source of potential high propwash velocities. It was determined that while these tugboats could use up to 100% applied vessel horsepower in rare emergency scenarios, the typical upper limit of applied power during barge operations is 50%. Therefore, 50% power was selected for this erosion protection scenario as a reasonable high estimate of applied power. Also, according to Boyer Towing, the barge seen in satellite imagery berthed near RAA 26 has been there for several years without being maneuvered (i.e., operations are infrequent in this location).

Western Towboat utilizes Azimuth Stern Drive tugs, commonly referred to as Z-drive tugboats, which have steerable propellers that can rotate a full 360 degrees. As a result, many of their tug operations involve one tug at the bow and one at the stern facing each other, maneuvering a barge in various directions without having to reposition unless they are obstructed. The propwash can be directed in any direction necessary for maneuvering.

The calculations of propwash velocity are steady state calculations, meaning they are representative of one representative vessel in a fixed location (vessel speed close to zero) with one set of operating conditions (vessel orientation, water level, and applied power). To represent the typical tug operations that could create propwash affecting the riverbed sediments during barge operations, a series of individual steady-state propwash scenarios were developed. Each scenario is defined in Table I-5 and describes the tug operating conditions, water level, and transect used in each steady state calculation. Transects (i.e., x-distance and corresponding bathymetric elevation) were modified if necessary to approximate the post-remedy elevations of the 60% design. The transects used to compute bottom bed velocity and stable D_{50} are shown in Figures I-3a, I-3b, and I-3c.

Table I-5.
Off-Channel RAA Vessel Operations Summary

Propwash Scenario	Propwash Transect (Figure Number)	RAA[1]	Description of Vessel Operations[2]	Design Vessel[3]	Water Level[4] (ft MLLW)
1	1 (Figure I-3a)	8B	Satellite imagery shows a floating dock over the RAA. Scenario assumes a 50-ft barge berthed parallel to the floating dock being pulled out into the channel by a tug at its side and directing propwash perpendicular to the riverbank. *Gretchen H* was selected due to draft limitations.	*Gretchen H*	6.0
2	2 (Figure I-3a)	9A 9B 9C 9D	Satellite imagery shows multiple barges berthed in a shore-perpendicular manner on the opposing side of the LDW. This scenario represents a tug at the bow of the barge, pushing at the barge's port side with its bow, maneuvering it into its berthed position, directing propwash toward RAA 9 on the opposing side of the LDW.	*Gretchen H*	0.4
3			This scenario represents a tug at the bow of the barge, with its starboard side aligned with the barges' port side, pushing it into its berthed position and directing propwash toward RAA 9 on the opposing side of the LDW.	*Alaska Mariner*	5.7
4	3 (Figure I-3a)	9I	Satellite imagery shows barges are often berthed against each other in a side-by-side manner that extends out into the LDW, parallel to the shoreline. This scenario represents a barge being towed and pushed into place against another barge, with the tugboat pushing the side of the barge with its bow and directing propwash toward RAA 9I on the opposing side of the waterway.	*Alaska Mariner*	4.2

Propwash Scenario	Propwash Transect (Figure Number)	RAA[1]	Description of Vessel Operations[2]	Design Vessel[3]	Water Level[4] (ft MLLW)
5			This scenario represents a barge being towed and pushed into place against another barge, with the tugboat pushing the side of the barge with its port side, directing propwash toward RAA 9I on the opposing side of the waterway.	*Alaska Mariner*	0.4
6			This scenario represents a barge being towed and pushed into place against another barge, with the tugboat pushing the side of the barge with its bow and directing propwash toward RAA 9I on the opposing side of the waterway.	*Gretchen H*	0
7	5 (Figure I-3b)	20B	This scenario represents a tug pushing the stern of the barge to the north of the RAA with its bow, directing propwash at an angle towards the RAA as it pushes the barge out into the waterway.	*Alaska Mariner*	4.9
8	4 (Figure I-3b)		These scenarios represent a tug pulling the barge that is to the south of the RAA out into the waterway and directing propwash towards the RAA.	*Alaska Mariner*	4.5
9				*Gretchen H*	0
10	6 (Figure I-3b)	23A	Satellite imagery shows barges berthed within this RAA. This scenario represents a tug at the side of a barge directing propwash at an angle over the RAA as it pushes the barge out into the waterway.	*Alaska Mariner*	0
11	7 (Figure I-3b)	24I	These scenarios represent a tug on the side of a barge, directing propwash towards the RAA as the tug pulls the barge into the waterway.	*Alaska Mariner*	10.9
12				*Gretchen H*	4.8
13	8 (Figure I-3c)	26	Satellite imagery shows a barge in the berth near RAA 26. Operations are rare here according to Boyer Towing. A hypothetical scenario was created in which there is a tug pulling the barge out into the slip at the bow/stern end closest to the RAA. The *Gretchen H* was used as it does not seem feasible that a large 4,000 Hp ship would be used in a confined area.	*Gretchen H*	0

Propwash Scenario	Propwash Transect (Figure Number)	RAA[1]	Description of Vessel Operations[2]	Design Vessel[3]	Water Level[4] (ft MLLW)
14	9 (Figure I-3c)	31B 31C	Satellite imagery shows a barge just to the north of RAA 31 B-D. This scenario is for a tugboat pushing the barge from behind at an angle to swing the barge into the waterway such that propwash is directed across the RAA.	*Alaska Mariner*	0

Notes:

1. Remedial Action Area, excluding RAAs within the navigation channel. See Section 3.1.3 for results within RAAs in the navigation channel.
2. An applied power of 50% was assumed to represent typical maximum operating power. Applied power up to 100% applied power is possible for short durations and is not expected to develop a fully formed propwash field under these limited uses of power higher than 50% applied power.
3. Design vessel was selected based on the size and draft limitations of each particular RAA (see Note 4). The larger vessel (*Alaska Mariner*) known to operate with barges at the RAAs was used wherever physically possible because the larger vessel is more conservative for armor layer design.
4. A minimum clearance of 4 ft between the bottom of the tug and bottom of channel was assumed to represent the shallowest potential depth allowable for tug operations. This conforms to ROD (EPA 2014) requirements in capped areas within the FNC as described in Appendix I of the 30% Sediment Stability Report. A still water level of 0 (MLLW) was assumed for a baseline low water level; however, water levels for various scenarios were increased to meet this 2-foot clearance criteria when required based on the elevations of the proposed remedy in each RAA.

Figure I-3a.
Off-Channel Propwash Transects (RAAs: 8B, 9A, 9B, 9C)

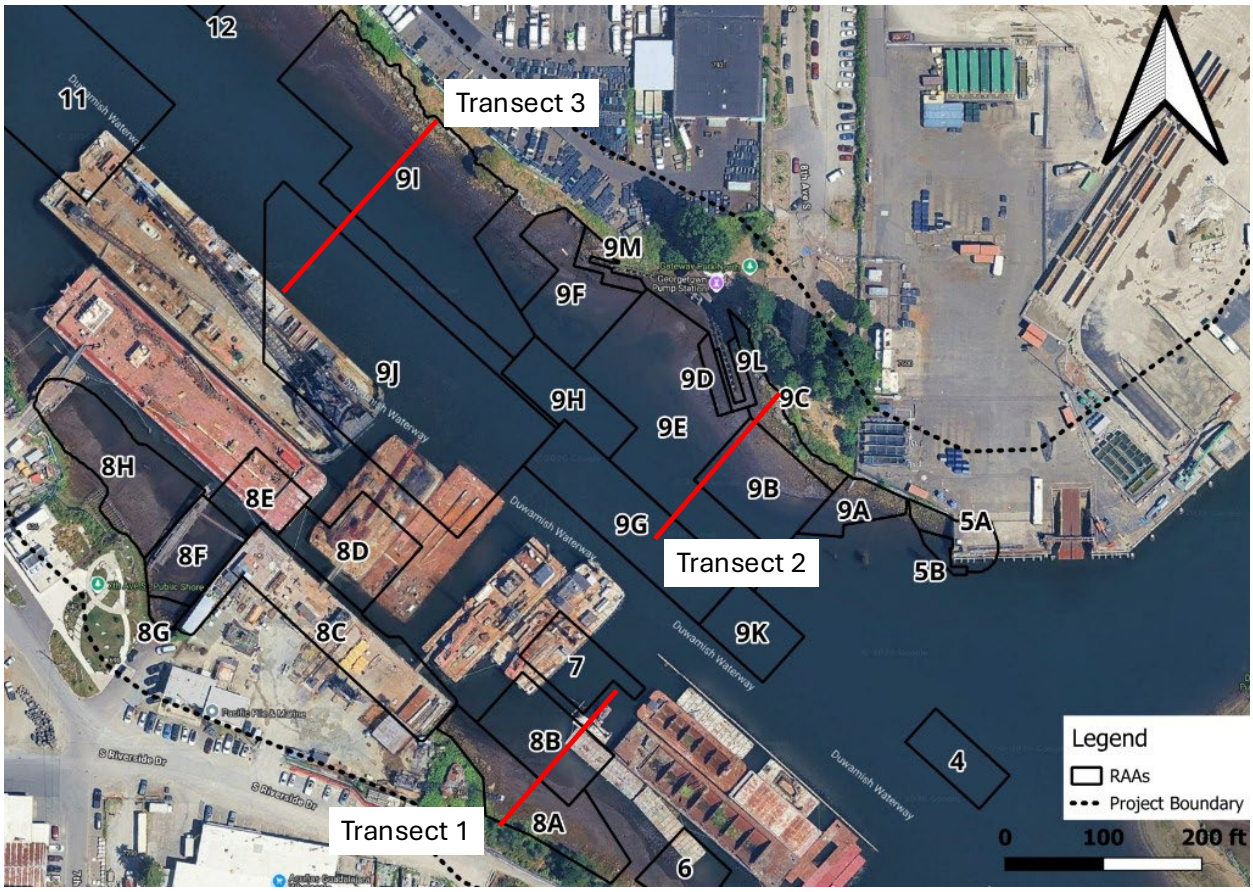


Figure I-3b.
Off-Channel Propwash Transects (RAAs: 20B, 23A, 24I)

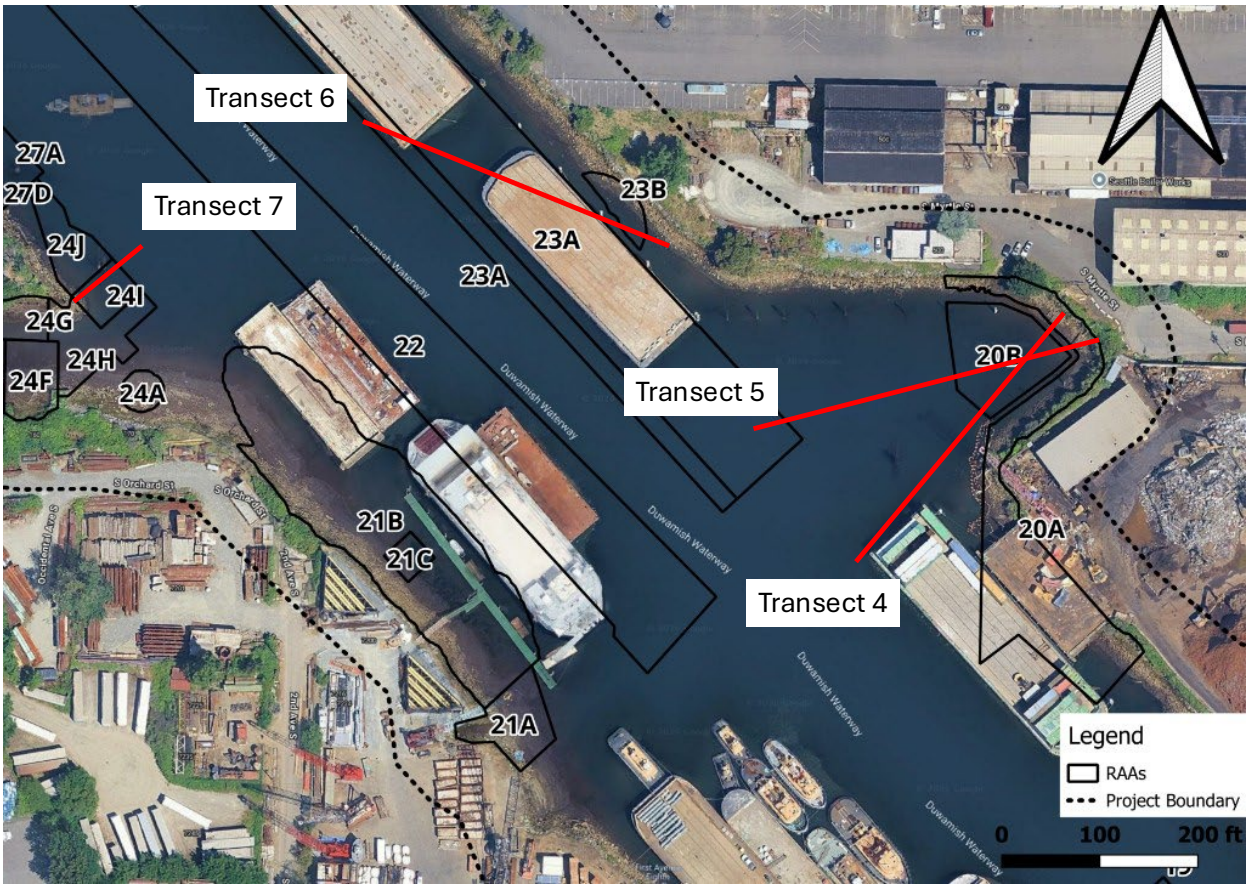
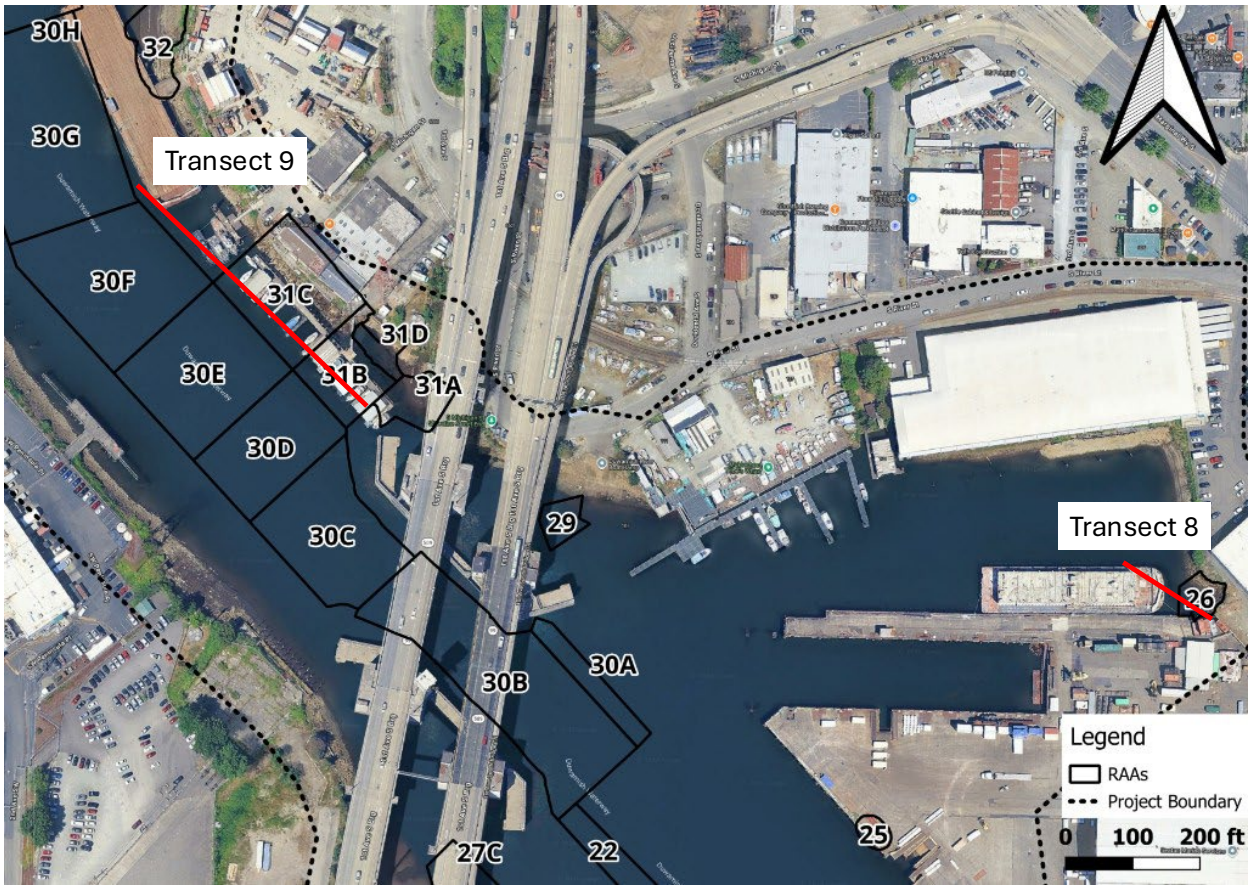


Figure I-3c.
Off-Channel Propwash Transects (RAAs: 26, 31B, 31C)



3.1.4.2 Results by RAA

Table I-6 below details the design propwash scenario and the maximum bed velocity and median stable D_{50} size for each RAA. Figure I-4 contains two plots showing the transect used and spatially varying propeller wash velocities for RAA 20A, 20B, and 20C, as well as the computed bottom bed velocities across the transect.

The Maynord method for estimating the two-dimensional spread simply calculates the propwash velocity at a specified horizontal and radial distance from the propeller. By overlaying the channel bed bathymetry, it is possible to extract the calculated velocities along the transect. However, the equation is conservative as it does not account for reduction in predicted stable particle size due to bottom boundary layer effects or propeller jet deflection. In shallow depths or when the propeller is close to the channel bottom, these effects are expected to be greater and thus the level of

conservatism of this methodology (e.g., larger rock sizes predicted) is expected to be significantly higher in such situations.

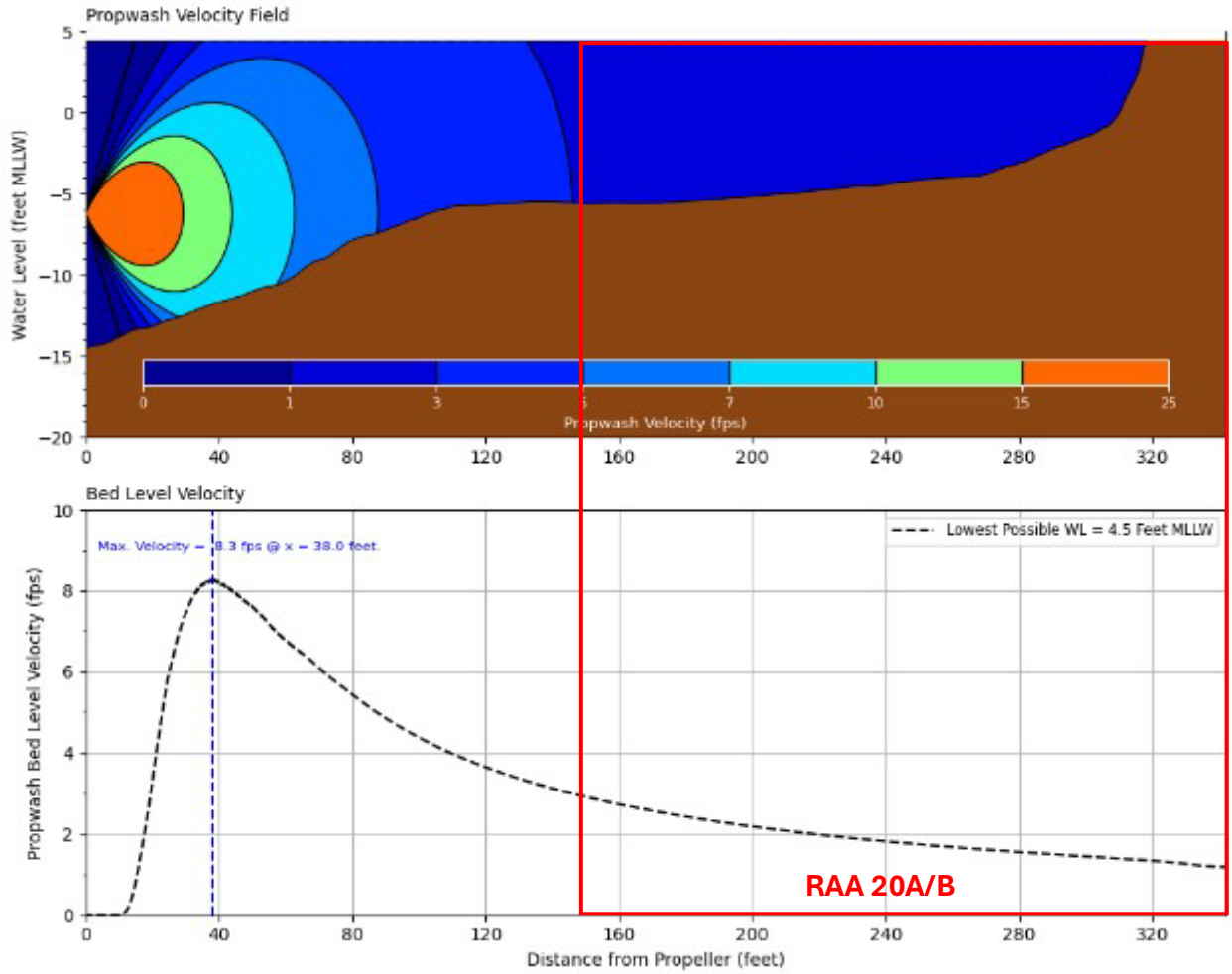
Based on conversations with operators completed as part of 60% design, many off-channel RAAs were found to have tug and barge operations occurring at high engine power in shallow water conditions. For these types of operations, the Maynord method preferred by EPA for sizing cap material due to propeller wash is overly conservative for reasons discussed above. For these RAA areas, estimated stable particle sizes have a very wide range of possible particle sizes based on these empirical calculations. If capping is the selected remedy for these RAAs, refinement of vessel operations at these locations and more complex evaluation methods may be required to determine stable particle size in these areas.

Table I-6.
Off-Channel RAA Maximum Bed Velocity and Median Stable Armor Size (D_{50}) Results

RAA	Design Propwash Scenario[1]	Maximum Predicted Bed Velocity[2] (ft/s)	Median Stable Particle D_{50} Size[3] (inches)
8B	1	9.6	Varies, additional analysis needed[3]
9A, 9B, 9C, 9D	3	10.1	Varies, additional analysis needed[3]
9I	4	10.5	Varies, additional analysis needed[3]
20B	8	3.0	6.9
23A	10	7.5	Varies, additional analysis needed[3]
24I	11	7.2	Varies, additional analysis needed[3]
26	13	3.1	7.3
31B, 31C	14	2.4	4.4

Notes:
1. The design scenario is the propwash scenario from Table I-5 that resulted in the largest predicted median armor particle size within the RAA.
2. The maximum predicted bed velocity is based on one transect scenario and may only occur at one particular region of the RAA. Additional refinement to understanding of vessel operations may be required (based on preferred remedy at each RAA) to determine if this maximum predicted velocity is applicable to the entirety or just a portion of the RAA.
3. "Varies, additional analysis needed" indicates that predicted stable particle sizes have a very wide range of possible particle sizes based on the empirical calculations. If capping is the selected remedy for these RAAs, refinement of vessel operations at these locations and more complex evaluation methods may be required to determine stable particle size in these areas.

Figure I-4.
RAA B – Propeller Wash Velocity Field Results and Bed-Level Velocities



Note:

3.2 Stable Particle Size Due to Vessel Wakes

Vessels transiting north and south along the LDW have the potential to create wakes with enough energy to mobilize sediments within intertidal, subtidal, and shoreline (riverbank) areas of the middle reach. The size of the wake depends on many factors, including proximity of vessel line of travel to area of interest, vessel dimensions, vessel speed, and water depth. The design vessels identified for the middle reach are both tugs that are expected to transit the middle reach most frequently and are expected to produce a large wake based on vessel specifications (Table I-2) and speed of travel identified from the AIS data (see Section 3.1).

Wake characteristics were estimated using an empirical method developed by Kriebel and Seelig (2005), which improves upon the original methodology developed by Sorensen and Weggel (1984).

Vessel operations and shoreline slopes that represent the range of potential scenarios within the middle reach were used in the calculations to provide a range of potential stable particle sizes under predicted wake conditions. Measured information from the AIS data (i.e., travel distance from shore and speed of travel over ground) and site bathymetry/topography were used to define the typical vessel operations and shoreline slope conditions within the middle reach:

- Design vessels: *Garth Foss* and *Clayton Arthur* (Table 2)
- Speed of travel: 4 to 9 knots (from AIS data)
- Distance between vessel line of travel and shoreline: 100 to 450 feet (from AIS data)
- Shoreline slope: 1H:1V to 5H:1V (horizontal to vertical)

The stable particle size was calculated using the estimated wake parameters using a stability formula developed by Van der Meer (Van der Meer 1987 and USACE 2008). This formula allows for the use of a damage parameter, which can increase or decrease the size of the stable armor rock based on a safety factor. For this calculation, a conservative value of the damage parameter was selected to provide a conservatively large estimate for stable particle size. Estimated stable particle (rock) sizes along the entire middle reach shoreline (not just within identified RAA/caping areas) based on vessel wakes for representative scenarios are shown in Table I-7.

In addition to the general evaluation presented in Table I-1, stable particle sizes due to vessel wake were evaluated for the off-channel capping areas considered in the propwash analysis (see Section 3.1) The range of wake parameters and stable particle sizes developed for the middle reach as a whole (see Table I-7) were used as a lookup table to estimate stable particle sizes in each of the RAA areas; this information is provided in Table I-8. Additional analysis may be completed as part of 90% design to refine predictions of stable particle size, if needed.

Table I-7.

Range of Wake Parameters and Associated Stable Particle Size

Design Vessel[1]	Distance from Shore[1]	Speed of Travel Over Ground (knots)[2]	Shoreline Slope (H:V)[3]	Wake Height[4] (ft)	Wake Period[4] (s)	Stable Particle Size[5], D_{50} (inches)
Clayton Arthur	100	9	1:1	0.8	2.4	5
			5:1			2.5
	450		1:1	0.5	2.3	3
			5:1			2
Garth Foss	100		1:1	1.25	2.4	8
			5:1			3.5
	350		1:1	0.8	2.3	5
			5:1			2.5

Notes:
1. Distance from line of travel of vessel to shoreline; bookend values selected based on AIS data see Section 3.1). Results for *Garth Foss* only apply to RMs 3.0 to 2.6.
2. Approximate maximum recorded speed over ground in AIS data (over period of record).
3. Variation in shoreline slope (bookend values) based on review of bathymetry/topography data.
4. Kriebel and Seelig (2005)
5. Van der Meer (1987)

Table I-8.

Off-Channel RAA Stable Particle Size (D_{50}) due to Wakes

RAA	Design Vessel[3]	Distance from Shore[1] (feet)	Approximate Shoreline Slope[2] (H:V)	Median Stable Particle D_{50} Size[4] (inches)
8B	*Clayton Arthur*	120	5:1	2.5
9A, 9B, 9C, 9D	*Clayton Arthur*	75	7:1	2.5
9I	*Clayton Arthur*	85	7:1	2.5
20B[5]	*Garth Foss*	n/a	n/a	n/a
23A[5]	*Garth Foss*	n/a	n/a	n/a
24I	*Garth Foss*	220	3:1	8
26	*Garth Foss*	1000	2:1	5
31B, 31C	*Garth Foss*	150	4:1	8

Notes:
1. Distance from line of travel of vessel to shoreline based on review of AIS data (see Section 3.1)
2. Shoreline slope represents the steepest existing slope within the RAA area based on review of bathymetry/topography data
3. The *Garth Foss* operates in the navigation channel adjacent to this area but not at lower tides compared to the *Clayton Arthur*.
4. Taken from most closely related representative scenario provided in Table I-7
5. Subtidal area. RAA is below MLLW water line.

3.3 Stable Particle Size Due to River Currents

Stable particle sizes to resist hydrodynamic flows (i.e., river currents) were generally assessed for the middle reach using LDW shear stress model results from QEA (2008), summarized in Section 2.3. Although the hydrodynamic model used to provide the shear stress predictions was developed in 2008, it is considered valid and conservative for the purpose of design for the cap erosion protection design. The bathymetry used in the hydrodynamic model represents a shallower condition than the proposed dredged and cap surface, resulting in the velocities being more conservative. Similarly, although SLR was not modeled, it is expected that any SLR added to the simulation would result in lower velocities than currently used in the protection layer analysis. Additionally, simulations with higher flows due to potential climate change were not performed because the flows are controlled by the Howard Hanson Dam. Therefore, the hydrodynamic model results are considered conservative for the cap protection design.

Predicted bed shear stress within the middle reach ranges from 1.8 to 2.2 pascal for the 100-year flow in the LDW at peak ebb tide conditions (see Figure I-1). The U.S. Geological Survey (USGS) developed a summary table of critical bed shear stress and corresponding particle (rock) size (USGS 2008), provided as Figure I-5. For the modeled range of bed shear stress, the corresponding stable particle (rock) size ranges from 2 to 4 millimeters (roughly 0.1 to 0.2 inches; very fine gravel).

The results predict bed shear stress in the middle reach exceeds the critical shear stress of fine sediments and sand, which are the predominant particle sizes present in bed sediments in the LDW (QEA 2008). This is consistent with prior identification of most of the middle reach as net erosional.

Figure I-5.
Critical Bed Shear Stress Versus Stable Particle Size

Particle classification name	Ranges of particle diameters		Shields parameter (dimensionless)	Critical bed shear stress (τ_c) (N/m^2)
	φ	mm		
Coarse cobble	-7 – -8	128 – 256	0.054 – 0.054	112 – 223
Fine cobble	-6 – -7	64 – 128	0.052 – 0.054	53.8 – 112
Very coarse gravel	-5 – -6	32 – 64	0.05 – 0.052	25.9 – 53.8
Coarse gravel	-4 – -5	16 – 32	0.047 – 0.05	12.2 – 25.9
Medium gravel	-3 – -4	8 – 16	0.044 – 0.047	5.7 – 12.2
Fine gravel	-2 – -3	4 – 8	0.042 – 0.044	2.7 – 5.7
Very fine gravel	-1 – -2	2 – 4	0.039 – 0.042	1.3 – 2.7
Very coarse sand	0 – -1	1 – 2	0.029 – 0.039	0.47 – 1.3
Coarse sand	1 – 0	0.5 – 1	0.033 – 0.029	0.27 – 0.47
Medium sand	2 – 1	0.25 – 0.5	0.048 – 0.033	0.194 – 0.27
Fine sand	3 – 2	0.125 – 0.25	0.072 – 0.048	0.145 – 0.194
Very fine sand	4 – 3	0.0625 – 0.125	0.109 – 0.072	0.110 – 0.145
Coarse silt	5 – 4	0.0310 – 0.0625	0.165 – 0.109	0.0826 – 0.110
Medium silt	6 – 5	0.0156 – 0.0310	0.25 – 0.165	0.0630 – 0.0826
Fine silt	7 – 6	0.0078 – 0.0156	0.3 – 0.25	0.0378 – 0.0630

Source: Table 7 in USGS (2008)

3.4 Impacts of Wind-Waves

Wind-generated wave parameters are generally a function of sustained wind speed and fetch. Fetch is the open-water distance over which wind can blow without obstruction. The LDW is a narrow waterway with minimal fetch distance in directions that would create wind-waves that would impact shoreline (riverbank) areas. In addition, the waterway has a low length-to-width ratio, meaning wind-waves produced along a stretch of the LDW will be smaller than waves produced over the same length in an open sea for the same fetch distance. Therefore, wind-waves are not expected to be the dominant force for defining stable particle size in the middle reach compared to propwash and vessel wake.

A wind-wave evaluation was completed for Final 100% RD for the upper reach of the LDW (Anchor QEA 2022). Since wind exposure and fetch distances (both across and along the middle reach channel) are the same as for the upper reach, no additional analysis was done to estimate wind waves for the middle reach. Therefore, wind waves estimated for the upper reach were used for the

middle reach. Calculated 100-year wave heights were approximately 0.5 foot. These are similar in size to the maximum vessel wakes calculated for the middle reach described in Section 3.3 and provided in Table I-7 (0.6 foot). Thus, as expected, wind-waves will not govern the stable particle size for the middle reach.

3.5 Impacts of Climate Change

Estimates for stable particle size in the middle reach under SLR conditions resulting from future climate change impacts were evaluated as part of this study (see Section 2.4).

Future SLR conditions are not expected to increase the required stable particle size in the middle reach based on propwash, vessel wakes, river currents, or wind-waves. The stable particle size due to these hydrodynamic forces is inversely proportional to water depth. Therefore, in the tidally dominated LDW, the stable particle size will decrease with increasing water depth resulting from SLR. Stable particle sizes calculated for existing water levels, as outlined in this report, will remain conservative for future conditions with SLR. Changes in freshwater flow rates in the LDW due to climate change will have minimal impact on water levels at the site due to tides.

Wind-waves due to extreme wind-wave events are not a significant factor (at present or in future) in the middle reach due to limited fetch distances. Therefore, increased water levels due to SLR, or a combination of SLR and extreme high-water events (e.g., storm surge), will increase water depths and decrease potential for erosion of bed sediments due to vessel operations. Increased water levels will not impact cap design in shoreline areas because those remedies will run to the top of existing slope.

4 Summary

This study presents preliminary estimates of stable particle sizes for cap layers placed within the FNC and off-channel areas over a range of typical hydrodynamic forces including propwash, vessel wakes, river/tidal currents, and wind-waves.

This study evaluated stable particle size based on a single erosive force occurring at a time. The forces considered are generally not additive because they each act on the sediment bed in different physical ways. In addition, for the LDW, the results of this analysis illustrate that the near-bed current velocities due to vessels are approximately ten times the forces associated with a 100-year flow event, which is not significant enough to change the calculated stable particle size (D_{50}) by more than 0.2 inches if those forces were superimposed.

In the FNC, stable particle sizes were determined based on moderately conservative propwash assumptions for transiting vessels (see Table I-4). Calculated maximum stable particle sizes (D_{50}) throughout the middle reach (regardless of authorized navigation depth) is 4.9 inches. No additional analysis or data collection is required for material sizing in the FNC.

In off-channel RAA areas where engineered caps are proposed, stable particle size was a function of either propwash or vessel wakes, depending on the bed elevation and specific vessel operations within and adjacent to each area. The evaluation of stable particle size in these areas was based on vessel operation information obtained through targeted outreach to operators during 60% design. Stable particle sizes in each RAA area are summarized in Tables I-6 and I-8 for propwash forces and wake impacts, respectively.

For most off-channel RAA areas, the model used to estimate stable particle size was overly conservative due to the shallow water depths (Palermo et al. 1988). Once the results of the Phase III investigation are completed and cap boundaries are finalized, more sophisticated models will be used to evaluate the final stable particle sizes and associated armoring design during 90% design. Additional outreach to operators and field data collection (e.g., in-situ propeller wash velocities) may be completed during 90% design to further refine vessel operation assumptions.

The materials and geometry of the proposed cap layers will depend on site-specific conditions, including underlying sediment characteristics. In general, erosion control will consist of a 1-foot layer of armor rock based on the stable particle sizes calculated for the area and an additional 0.5-foot layer of filter rock based on both the armor rock size and underlying sediment size (Van der Meer 1987). The filter rock layer is required to prevent winnowing of underlying sediments through the armor rock. Specifics of erosion protection in each proposed cap area will be completed at 90% design.

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