ENGINEERING APPENDIX

NORFOLK HARBOR NAVIGATION IMPROVEMENTS GENERAL REEVALUATION REPORT/ ENVIRONMENTAL ASSESSMENT

VIRGINIA

APPENDIX A

May 2018

U.S. Army Corps of Engineers
Norfolk District

THE PORT OF VIRGINIA®

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1. Summary and Background

The U.S. Army Corps of Engineers (USACE) Norfolk District (CENAO), in partnership with the Virginia Port Authority (VPA), is evaluating measures which would improve the operational efficiency of commercial vessels currently using the federal navigation channels at the Norfolk Harbor and commercial vessels projected to use the federal navigation channels at the Norfolk Harbor in the future. The General Reevaluation Report (GRR) and integrated Environmental Assessment (GRR/EA) will examine whether authorized improvements remain in the federal interest and allow for reformulation of the authorized plan to develop a new alternative for implementation.

This Engineering Appendix details the methodology, assumptions and analyses completed to determine sufficient details to prepare costs of alternatives for plan formulation leading to a NED plan.

2. Existing Channels, Study Segments and Reaches

The Norfolk Harbor Project (shown in Figure 1 and additional detail in Appendix A) is a deep draft navigation project serving the port facilities in the cities of Norfolk, Newport News, Portsmouth, Chesapeake, and Hampton in southeastern Virginia. The authorized project (1986) includes a system of two-way, full-width channels to a depth of 55 feet MLLW in the Norfolk Harbor and Thimble Shoal Channels and 57 feet MLLW in the Atlantic Ocean Channel.

The authorized project is grouped into two planning segments. Segment 1 includes the 10-mile Atlantic Ocean Channel (AOC), the 13-mile Thimble Shoal Channel and Meeting Areas #1 and #2, the 2-mile Norfolk Harbor Entrance Reach, the 4-mile Norfolk Harbor Reach, the 3-mile Craney Island Reach and Anchorage F. This first planning segment, identified as “AOC to Lamberts Point,” provides access to the Norfolk International Terminal, the Virginia Gateway Terminal, and the Norfolk Southern coal terminal at Lamberts Point. Segment 2 is the 5.4-mile Newport News Channel that runs from the Norfolk Harbor Entrance Reach to Newport News, which is the entirety of the Newport News Channel and provides access to the Dominion Coal Terminal, the Kinder Morgan Coal Terminal (aka Pier 9), and other facilities in Newport News. In total, the two segments are approximately 37.4 miles in length.

Within these 37.4 miles, there are two authorized project depths: (1) the AOC has an authorized 57-foot project depth and (2) the remainder of the planning reaches have an authorized 55-foot MLLW project depth, as shown in Table 1. Within these separable elements, the federal channels have varying authorized widths as shown in Table 1.

Figure 1: Norfolk Harbor Navigation Improvements (in blue) – Channel Reaches

Table 1: Planning Reaches

Planning Reach	Channel Reaches	Channel Depth (feet) Authorized/ Constructed (MLLW)	Channel Width (feet) Authorized/ Constructed	Length (miles)
Atlantic Ocean Channel to Lamberts Point (Segment 1)	Atlantic Ocean Channel	57/52	1,300/1,300	10.0
	Thimble Shoal Channel	55/50	1,000/1,000	13.0
	Norfolk Harbor Entrance Reach	55/50	1,500/1,000-1,400	2.0
	Norfolk Harbor Reach	55/50	850-1,200/850-1,200	4.0
	Craney Island Reach	55/50	800/800	3.0
Newport News (Segment 2)	Newport News Channel	55/50	800/800	5.4

3. Geotechnical Evaluation of Dredged Material

3.1. Summary

This section provides an overview of existing sediment data within and adjacent to the project area, providing available data to evaluate alternatives and identify a Tentatively Selected Plan (TSP). Attached as Appendix B is the "Geotechnical Evaluation" for the project, characterizing the sediments to be dredged based on a literature search that included available historic subsurface and bathymetric data. The existing data also inform assumptions regarding the material placement plans for each reach of the project and are sufficient to inform the TSP. Additional sampling is proposed to finalize material placement decisions, but the necessary additional sampling would not discriminate among the alternatives being evaluated and the Project Delivery Team (PDT) determined sampling should be deferred to PED.

3.2. Geologic Considerations

The project area is described as a low-lying Coastal Plain characterized by deposits typical of deltaic alluvial plains. The bedrock of the Coastal Plain is situated at a depth of about 13,000 feet beneath these sediment deposits. Because of this, no rock blasting is necessary on this project.

The project site is an area of low recorded seismicity. There are no known active or inactive faults in the project's vicinity. Although low recorded seismicity, the design team is aware of potential seismic hazards. For the design of the Craney Island Eastward Expansion (CIEE) (immediately adjacent to the project area), seismicity was included in the design, and shown not to be a driver of

stability of proposed dikes. Because of this, the PDT determined that seismicity will not inform a different alternative selection. For reference, on the CIEE study (Fugro, 2009) a Peak Ground Acceleration (PGA), Maximum Considered Earthquake of 0.12g and a Design Level Event (DLE) of 0.08g was used. This was based on the IBC Design Spectrum. The equivalent return period for the DLE is higher than 475 years.

Another potential geologic hazard that was vetted was the proximity of shale deposits and possible future fracking. Use of hydraulic fracturing is limited to Southwest Virginia, over 300 miles from the project area (DMME, 2017). Because of the distance hydraulic fracturing has not been documented to influence seismicity in the coastal areas of Virginia, and was not a consideration in plan formulation.

The design team also considered the Chesapeake Bay Impact Crater (CBIC). Again, on the CIEE study the CBIC was considered in the general geology and there was a literature review of the meteor striking the lower Chesapeake Bay and its impact on the regional geological structures and features of the area. Although of great interest in defining major "global" geological features, the PDT relied on actual field collected data to inform the geology in terms of material to be dredged. Because of this, the PDT determined that the local geology (shallow/recently deposited materials) informs alternative selection. Sufficient data was available from collected vibracores and cone penetrometer tests along the channels to provide a detailed understanding of the material to be dredged. The crater impact on the geology of the area does not assist in differentiating the relatively shallow materials to be dredged as they are relatively recently deposits of marine sediments placed post crater. The crater may influence regional rates of subsidence and Sea Level Rise (SLR) (Boon, 2010); however, this did not inform, or differentiate, selection of alternatives for this project. Because of this, linking the reginal variability of SLR and Subsidence to the crater were beyond the information necessary to inform plan selection.

3.3. Segment 1

3.3.1. Atlantic Ocean Channel

As detailed in the attached Geotechnical Evaluation (Appendix B), the Atlantic Ocean Channel is described in three general zones, A1 (east), A2 (center) and A3 (west).

- Within Zone A1 the sediments are predominantly sands. Grain sizes are distributed between fine and coarse grained sandy materials (poorly graded sand to silty sand). Fines contents can vary from 13% to 25%.
- Within Zone A2 sediments up to El. -75 feet are predominantly sands with some silts and clays. Due to the relatively high fines content in some regions, the top strata was identified as silt using data from cone penetrometer test (CPT) soundings. There is an area of clay, which could be a paleochannel that was filled with fine grained sediments.
- Within Zone A3 the sediments (up to El. -70 feet) are predominantly clays.

AOC has been used multiple times as borrow for beach nourishment (City of Virginia Beach) as well as providing sand for dike construction for the Craney Island Eastward Expansion Project.

3.3.2. Thimble Shoal Channel and Meeting Areas

As detailed in the attached Geotechnical Evaluation (Appendix B), the Thimble Shoal Channel is described in six general zones, T1, T2 and T3 on the east side of the Chesapeake Bay Bridge Tunnel (CBBT) and T4, T5 and T6 on the west side of the CBBT.

- East side of the CBBT (Zone T1, T2 and T3) - The sediments (up to El. -70 feet) are predominantly clays with some sands on the eastern end of the TSC. Zone T3 consists of predominantly sands underlain with silts and clays. The thickness of the upper sand layer varies between 2 and 10 feet. This sandier Zone T3 area also likely describes the Meeting Areas. This area of TSC has been used multiple times as borrow for beach nourishment (City of Virginia Beach and Norfolk) as well as providing sand for dike construction for the Craney Island Eastward Expansion Project.
- West side of the CBBT (Zone T4, T5 and T6) – The sediments closest to the CBBT consist of predominantly sand, with some upper clay layers. Moving west from the CBBT the materials become predominantly clays and silts. Because of the fine grained material west of the CBBT, the placement has historically been in the offshore placement area, as opposed to beneficial use.

3.3.3. Norfolk Harbor Reaches and Anchorage F

The top 15 feet below the existing mudline within these reaches consist of predominantly clays and silts. The clays are predominantly classified as fat clay. In very limited areas explorations found some sands. These explorations could have been drilled through paleochannels that were filled with coarse grained material over time. The soils located above the authorized dredge line elevation are mostly classified as clayey and silty material.

3.4. Segment 2

3.4.1. Newport News Channel

Two different zones were identified within the Newport News Channel. Zone N1 is east of the Monitor–Merrimac Memorial Tunnel. The upper layer on the western side of this zone N1 consists of predominantly sandy materials. This layer starts to gradually dip from west to east below a predominantly clayey layer. Zone N2 consists of the western end of Newport News channel to approximately 2,000 feet west of the Monitor–Merrimac Memorial Tunnel. The layer that extends approximately 10 feet below the bathymetric line (2015) consists of predominantly fat clays.

4. New Work Quantities

4.1. Maintained Depth

The historically maintained depths provide the basis for determining the volume considered maintenance material and the volume for new work. Based on the District's maintenance records, Table 2 summarizes the historically maintained depths.

Table 2: Norfolk Harbor and Channel's Maintained Depth

Channel Segment	Channel Reach Names	Maintained Depth (feet, MLLW)
Segment 1	Atlantic Ocean Channel	-53
	Thimble Shoal Channel	-51
	Thimble Shoal Channel – Meeting Area #1	n/a
	Thimble Shoal Channel – Meeting Area #2	n/a
	Norfolk Harbor Entrance Reach	-51
	Norfolk Harbor Reach	-51
	Craney Island Reach	-51
	Anchorage F	-51
Segment 2	Newport News Channel	-51

It should be noted that both the Newport News Channel and Norfolk Harbor Reach have been maintained to -52 as well as part of an advanced maintenance dredging schedule. Both channels are regularly only dredged to -51, so that is what is used for this report.

4.2. Surveys

The basis for the quantity calculations are the most recent condition surveys available at the time of performing the calculations, started in July 2015. The following table summarizes the survey data, acquired by the Norfolk District, used for the quantities.

Table 3: Surveys used for quantity calculations

Channel Segment	Channel Reach Names	Date of Survey
Segment 1	Atlantic Ocean Channel	April 2014
	Thimble Shoal Channel	June 2014
	Thimble Shoal Channel – Meeting Areas #1 and #2	June 2014 supplemented with 2016 USACE survey outside of the current channel limits
	Norfolk Harbor Entrance Reach	July 2010, June 2014, and November 2014
	Norfolk Harbor Reach	"
	Craney Island Reach	"
	Anchorage F	June 2012 that was supplemented with data from two surveys; November 2014 and July 2010
Segment 2	Newport News Channel	March 2015

4.3. Quantity Calculations Methods

Quantities were developed based on the latest condition surveys provided by the USACE. Dates of the surveys are noted above. Quantities include 1 Vertical to 3 Horizontal side slopes, to match existing channel width. Volume calculations were completed for each channel reach at 1 foot increments to inform plan formulation. AutoCAD® Civil 3D® software is used to perform the volume calculation. Volumes are broken into "dredging zones", to clarify the calculated volumes, as described in the following section. Typical sections can be found in Appendix A.

4.4. Quantity Summary

The following tables summarize the volume to be dredged to determine project costs. We note that for evaluating environmental impacts the PDT requested volumes that included depth beyond pay depths to evaluate maximum impacts. The maximum volumes used for environmental impact analysis are presented in the relevant sections in the Environmental Assessment. In the tables below the following definitions apply based on Figure 2:

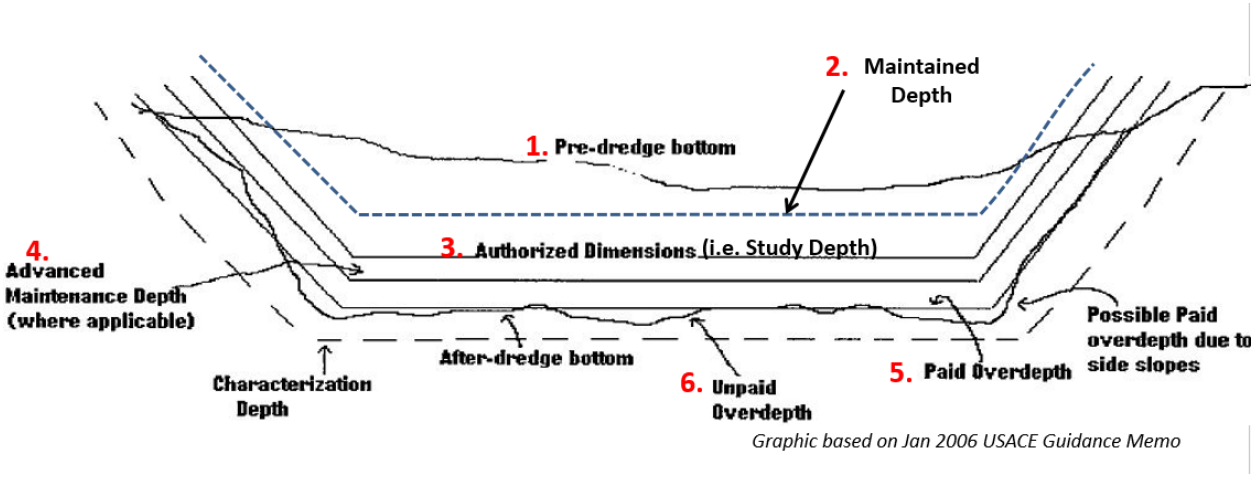

Figure 2: Typical Channel Cross Section with Dredging Zones and Channel Nomenclature, based on USACE Guidance Memo (USACE, 2006)

1. **Pre-Dredge/ Existing Grade/Mudline** – The mudline based on the latest condition survey of the channel.
2. **Maintained Depth** – Without-Project Condition - The maintenance quantity is the volume of dredging required to dredge from the existing condition (based on the latest condition survey of the channel) to the currently maintained channel dimensions. This volume to restore the channel to the District's historically maintained depth is included for inclusion in the Dredged Material Management Plan, but is not a new work dredging cost.
3. **Authorized Dimensions / Project Study Depth / Grade** – This is the Nominal Depth used for Plan Formulation Increments and includes consideration for Underkeel Clearance (UKC). UKC is further discussed below.
4. **Advanced Maintenance** – For cost estimates the inner harbor channels include 1' of advanced maintenance.
5. **Allowable (Paid) Overdepth** – To be consistent with historic dredging in these project reaches, 1' of paid overdepth is included.
6. **Over-dig (Non-Pay/Unpaid) Overdepth** – Non-pay volume is dredging beyond the new work quantity above due to inaccuracies in dredging, dredge type, dredge area, wind and wave conditions, etc. For cost estimates, the volume of non-pay dredged is based on the dredging area. For hydraulic (cutterhead) dredges, this equates to about ½ foot of non-pay depth, while the hopper dredges average less non-pay volume with about 3 inches. These non-pay volumes are based on assumptions developed in the Cost Engineering Dredge Estimating Program (CEDEP) worksheet that accounts for the efficiency of the dredges for each reach based upon the areas, volume, amount of pay, amount not dug on average, and the amount dug in excess of the allowable pay amount, and many other factors associated with dredging operations. CEDEP is the basis for the unit cost for dredging. For NEPA documentation non-pay volume is considered a contingency allowance to be included in the total for new work improvements. Note the inclusion of non-pay is in accordance with a USACE memorandum

(USACE, 2006) providing guidance on adequacy of describing the total volumes to be dredged (ex. Allowable overdepth and non-pay volumes).

For the economic alternatives Segment 1 and Segment 2 were analyzed individually and then combined, followed by evaluating the benefits of the Meeting Areas #1 (to provide 1,200 ft wide area) and #2 (to provide 1,300 ft wide area) and finally Anchorage F. Anchorage F is expanded, from the existing 3,000-foot diameter, to 3,620 feet to account for the larger vessels. The following tables summarize the dredge volumes used for the cost development for the new work dredging (volume above maintenance volume).

Table 4: Segment 1: Dredge Volumes, AOC, TSC, NH Ent Reach, NH Reach and Craney Island Reach

Economic Alternatives for Plan Formulation	**Nominal Depth (feet, MLLW)**	**Available Pay Volume, CY**
Nominal 52 feet Segment 1	52	6,478,538
Nominal 53 feet Segment 1	53	10,588,957
Nominal 54 feet Segment 1	54	15,410,479
Nominal 55 feet Segment 1	55	20,849,741
Nominal 56 feet Segment 1	56	26,931,614

Table 5: Segment 1: Dredge Volumes, Meeting Area #1 (Volume above TSC dredging to widen to 1,200 feet)

Economic Alternatives for Plan Formulation	**Nominal Depth (feet, MLLW)**	**Available Pay Volume, CY**
Nominal 52 feet Segment 1	52	2,491,326
Nominal 53 feet Segment 1	53	2,873,090
Nominal 54 feet Segment 1	54	3,270,760
Nominal 55 feet Segment 1	55	3,685,000
Nominal 56 feet Segment 1	56	4,116,500

Table 6: Segment 1: Dredge Volumes, Meeting Area #2 (Volume above TSC dredging to widen to 1,300 feet)

Economic Alternatives for Plan Formulation	**Nominal Depth (feet, MLLW)**	**Available Pay Volume, CY**
Nominal 52 feet Segment 1	52	1,017,519
Nominal 53 feet Segment 1	53	1,301,836
Nominal 54 feet Segment 1	54	1,598,000
Nominal 55 feet Segment 1	55	1,875,000
Nominal 56 feet Segment 1	56	2,161,000

Table 7: Segment 1: Dredge Volumes, Anchorage F, expanded to 3,620 ft diameter

Economic Alternatives for Plan Formulation	Nominal Depth (feet, MLLW)	Available Pay Volume, CY
Nominal 51 feet Segment 1	51	1,311,822
Nominal 52 feet Segment 1	52	1,452,427
Nominal 53 feet Segment 1	53	1,593,032
Nominal 54 feet Segment 1	54	1,786,612
Nominal 55 feet Segment 1	55	2,044,391
Nominal 56 feet Segment 1	56	2,376,122

Table 8: Segment 2: Dredge Volumes, Newport News Channel

Economic Alternatives for Plan Formulation	Nominal Depth (feet, MLLW)	Available Pay Volume, CY
Nominal 52 feet Segment 2	52	184,891
Nominal 53 feet Segment 2	53	502,822
Nominal 54 feet Segment 2	54	999,458
Nominal 55 feet Segment 2	55	1,651,747
Nominal 56 feet Segment 2	56	2,394,039

4.5. Underkeel Clearance

Underkeel Clearance (UKC) provides the safe maneuvering distance between the bottom of the vessel and the channel bottom. Determining UKC includes evaluation of the effect of fresh water, ship motions from waves, squat underway, and safety clearance or net underkeel clearance. For this study the UKC for the inner harbor reaches (all channel reaches once within the Hampton Roads Bridge Tunnel) is 4.3 feet based on slow operating speeds and the protected waters. For the ocean reaches, including Atlantic Ocean Channel, Thimble Shoal Channel and Meeting Areas, numeric modeling was completed on the design vessels for squat and ship motion due to waves to determine required UKC. The risk-based "Channel Analysis and Design Evaluation Tool" (CADET) software was used in this study (attached in Appendix C) to determine the days of availably a given vessel would have for a given channel depth. The model is based on probabilistic risk analysis techniques to evaluate the accessibility of a series of channel reaches for multiple vessel geometries, loading, and wave conditions.

Two design vessels are included in the CADET analysis including Gen III containership similar to the MSC Daniella and a Gen II bulk (coal) carrier. A summary of the two vessels are shown in the table below.

Table 9: CADET Model Ship Parameters

Parameter	Containership	Bulker Coal Carrier
Capacity	13,800 TEU	180,000 m^3
DWT (mt)	163,239	162,977
L_{oa} (ft)	1210.2	962.2
L_{pp} (ft)	1158.3	931.8
Beam *B* (ft)	168.0	147.6
Full Draft (ft)	45.8	51.1
SLL Draft (ft)	51.2	55.9

Notes:

1. *Full draft = design load*
2. *SLL = Summer load line draft, maximum draft based on structural limits*

Details of additional model inputs, including water levels, tides and waves can be found in the referenced report. The report includes model results in charts that show days of accessibility versus water depth. These charts are used by the design team (PDT) to determine the appropriate balance of accessibility with channel depth. CADET was run for the design bulker and container ships for speeds from 10 Knots (KTs) to 17KTs. The Virginia Pilots have advised that optimal speeds for AOC and TSC are 12 KTs (and below) for bulkers and 14 KTs for container ships based on ship operating characteristics, including center of gravity and maneuverability.

The PDT determined that using approximately 90% channel accessibility results would best inform the optimum project depth, and is consistent with use of CADET on other recent Feasibility Reports. Based on the above results, Plan Formulation and the selected plan includes the following UKC:

- Thimble Shoal Channel (and Meeting Areas): Inner Harbor UKC + 1 feet additional
- Atlantic Ocean Channel: Inner Harbor UKC + 4 feet additional

As an example a 55 feet nominal channel would be 55 feet in the inner harbor channels, the TSC and Meeting Areas would be 56 feet and AOC would be 59 feet.

4.6. Summary of NED Depths and Volumes

Below summarizes the current planned dredge depths (in feet, MLLW) and volumes.

- **Atlantic Ocean Channel**

Vessel draft	50’ (based on fled forecast and economic modeling)
+UKC	9’ (based on CADET modeling)
+Tide	-2’
+Safety	2’
+Advanced maint	0’
+Paid Overdepth	1’
+Non-pay Overdredge	1’
Project depth + Overdepth	**59’ MLLW + 2’ Overdepth**

- **Thimble Shoal Channel and Meeting Area**

Vessel draft	50’ (based on fled forecast and economic modeling)
+UKC	6’ (based on CADET report)
+Tide	-2’
+Safety	2’
+Advanced maint	0’
+Paid Overdepth	1’
+Non-pay Overdredge	1’
Project depth + Overdepth	**56’ MLLW + 2’ Overdepth**

- **Inner Harbor**

Vessel draft	50’ (based on fled forecast and economic modeling)
+UKC	4.3’ (based on Harborsym)
+Tide	-2’
+Safety	2’
+Advanced maint	1’
+Paid Overdepth	1’
+Non-pay Overdredge	1’
Project depth + Overdepth	**55’ MLLW + 1’ Adv Maint + 2’ Overdepth**

- **Channel to Newport News**

Vessel draft	50’ (based on fled forecast and economic modeling)
+UKC	4.3’ (based on Harborsym)
+Tide	-2’
+Safety	2’
+Advanced maint	0’
+Paid Overdepth	1’
+Non-pay Overdredge	1’
Project depth + Overdepth	**55’ MLLW + 2’ Overdepth**

Table 10: Summary of likely NED project volumes

Planning Reach	Channel Reaches	Likely NED Plan Channel Depth (feet, MLLW) Nominal/Maintained	Channel Width (feet)	Estimated Pay Volume (CY)	Length (miles)
Atlantic Ocean Channel to Lamberts Point (Segment 1)	Atlantic Ocean Channel	55/59	1,300	6.4 MCY	10.0
	Thimble Shoal Channel	55/56	1,000	8.2 MCY	13.0
	Thimble Shoal Channel MA #2	55/56	+300	1.9 MCY	4.3
	Inner Harbor	55/55	800-1,400	6.2 MCY	9.0
	Anchorage F	51/51	3,620 Dia.	1.3 MCY	n/a
Newport News (Segment 2)	Newport News Channel	55/55	800	1.6 MCY	5.4

5. Future Maintenance Quantities

As part of the impact assessments associated with the proposed deepening projects, an analysis was completed to estimate the maintenance dredging rate to be expected in the navigation channels following deepening. Attached, as Appendix D, is the report entitled "Desktop Assessment of Future Sedimentation Rates" (M&N, 2016). The report provides an overview of the approach for estimating the future sedimentation rate, the data used, and the results of this desktop analysis. As detailed in the sedimentation rate report, the analysis estimates current shoaling rates and shoaling rate increase based on anticipated channel dimensions and depths. To evaluate alternative dimensions and depths (from those in the study) the shoaling rate was scaled appropriately.

Historic maintenance dredging records were provided by the USACE for the period 1980 to 2014, and reviewed to inform this study (USACE 1994, USACE 2016). The available maintenance dredging records were used to develop an estimate of the annual sedimentation rate within the navigation channels in the study area. Historical (from 1980 onwards) and recent data were examined and used for developing the sedimentation report.

5.1. Projected Maintenance Dredge Volumes

Based on the above study, the following table summarizes the current annual sedimentation rate (based on historic volumes), and the estimated annual sedimentation rate (from the sedimentation study) based on the proposed channel improvements.

Table 11: Maintenance Volumes

Segment	Reach	Current Annual Sedimentation, CY/Year	Estimated Annual Sedimentation, CY/Year
1	Atlantic Ocean Channel	164,359	303,822
1	Thimble Shoal Channel	325,577	486,630
1	Thimble Shoal Channel – Meeting Area #1, 1,200 ft width	n/a	20,663
1	Thimble Shoal Channel – Meeting Area #2, 1,300 ft width	n/a	19,352
1	Norfolk Harbor Sewells Point to Lamberts Point	733,630	846,934
1	Anchorage F, expanded to 3,620 ft Dia.	137,036	137,177
2	Newport News Channel	109,624	133,526

6. Dredged Material Management Plan

This section will describe the areas proposed for placement of dredged material for the new work dredging, as well as future maintenance needs. The project's Dredged Material Management Plan (DMMP) is included as Appendix E to this Engineering Appendix. The DMMP describes existing conditions as well as the anticipated future 20 years of dredged material placement.

6.1. Summary of Existing Management Plan

6.1.1. Craney Island Dredged Material Management Area (CIDMMA)

The Craney Island Dredged Material Management Area (CIDMMA) is a 2,500-acre confined dredged material disposal site located near Norfolk, VA. Development of the CIDMMA was recommended and approved by Congress under the River and Harbor Act of 1946. Actual construction of CIDMMA was completed in 1957. Since that time, this site has received new work, maintenance, private, and permit dredged material from numerous dredging projects in the Hampton Roads area. The site provides a disposal area for material dredged from the channels and ports in the Hampton Roads area. Hampton Roads, including the ports of Norfolk, Portsmouth, Chesapeake, Newport News, and Hampton, comprises Virginia's greatest port complex (USACE, 2016). The attached Plate 1, Appendix A shows the location relative to the project area.

CIDMMA receives dredged material which is pumped hydraulically into the cells. Dredged material is typically pumped in over the east dike. This is evidenced by the large sand mounds observed at the influent points where these heavier sand particles quickly settle out of the dredge slurry.

CIDMMA is currently operated using the guidance from the existing DMMP prepared in 1981. The 1981 DMMP has been credited with allowing CIDMMA to accept over 250 MCY of dredged material (since it began operation in 1957), a significant increase over the original capacity estimate of 96 MCY.

The existing DMMP is based on the current configuration of CIDMMA, which is divided into three cells: South Cell (734 acres for storage), Center Cell (766 acres for storage) and North Cell (689 acres for storage). Currently Norfolk District rotates each of the three cells annually to allow two years of drying before dredged material is again pumped into the cell. The District also typically caps the volume of dredged material that can be pumped into an individual cell at no more than 5 MCY annually. Monthly inflows are typically limited to 650,000 CY.

Existing dikes are continually maintained to compensate for consolidation settlement of the marine clay foundation beneath the dikes, and the need to maintain adequate freeboard on the dikes.

Each cell has two spillboxes along the west dike. Spillboxes are operated by the dredging contractor pumping into the cell. The dredging contractor is responsible for ensuring effluent being released from CIDMMA is clarified water. The contractor verifies by sampling the effluent total suspended solids (TSS). The target, or goal, is to release only clarified water from the spillboxes, with the daily average effluent TSS concentration of 500 mg/l as an upper action limit. Typically measured effluent TSS values are 100 mg/L or less.

Remaining Capacity of CIDMMA. As part of the Craney Island Eastward Expansion's (CIEE) Final Feasibility Report (USACE, 2006) a detailed assessment of the remaining dredged material capacity was completed for the existing CIDMMA. An appendix to the 2006 report included a 2005 study by the U.S. Army Engineer Research and Development Center (ERDC) detailing the lifespan of CIDMMA. The study was based on assumptions of dredged material inflows into CIDMMA that was inclusive of all federal, local and private dredging work, in addition to consideration of historic inflows. The computer model Primary Consolidation, Secondary Compression and Desiccation of Dredged Fill (PSDDF) (Stark 1996) was used to model dredged material inflows and estimating the height of dredged material within the cells through the inflow assumptions. With that, PSDDF estimated the volume of fill that could be placed within CIDMMA and the resulting elevation of dredged material within the area.

For the Baseline condition (no Craney Island Eastward Expansion cells considered) the inflows modeled spanned the years 2000 to year 2055. The 2005 study estimated that, with the existing 3 disposal cells under present management conditions, CIDDMA will reach the limiting elevation of +47 feet MLLW in approximately the year 2025. The total dredged material volume (in channel volumes) capacity of CIDMMA, based on the estimated inflows, from 2000 to 2025 was calculated to be 117.5 MCY. The annual inflow volume assumptions are shown in Table 11 below.

To estimate the remaining CIDMMA capacity available for future dredged material placement, for this study, the total inflow volume estimated in the 2005 study was subtracted from the actual

inflows based on USACE records of use of CIDMMA. Note that as assumed in the ERDC study, O&M will be available to continue to raise the dikes to meet inflows.

As shown in the table below with a capacity of 117.5 MCY and actual inflows of 68.8 MCY the remaining capacity in CIDMMA, based on the ERDC analysis, is 48.7 MCY (117.5 – 68.8 = 48.7).

Table 12: CIDMMA Baseline Inflow Assumptions versus Actual Inflows

Year	Inflow Assumptions for 2005 ERDC Study "Baseline CIDMMA", CY	Actual Inflows based on USACE Records, CY
2000	4,010,000	4,743,227
2001	3,110,000	2,548,028
2002	3,020,000	4,722,609
2003	3,050,000	6,244,604
2004	11,780,000	2,335,501
2005	11,680,000	10,184,962
2006	4,030,000	12,105,324
2007	5,150,000	2,687,955
2008	5,580,000	1,709,180
2009	7,400,000	2,883,972
2010	3,720,000	3,815,874
2011	4,300,000	6,218,781
2012	4,020,000	552,194
2013	3,900,000	2,692,878
2014	4,620,000	2,228,070
2015	3,950,000	3,155,374[1]
2016	4,600,000	
2017	4,700,000	
2018	2,500,000	
2019	2,650,000	
2020	4,100,000	
2021	2,500,000	
2022	2,650,000	
2023	3,500,000	
2024	3,500,000	
2025	3,500,000	
Sum	**117,520,000**	**68,828,533**

[1] Note that the District's data for actual inflows did not have the 2011 Navy deepening, this number includes 2.9MCY for the Navy deepening, which was the bid volume.

Based on the ERDC report (Pranger et al, 2004) the CIDMMA (Baseline conditions) would reach the fill elevation of 47' in 2025, based on assumed inflows, from 2000 to 2025, totaling 117.5 MCY. Actual inflows from 2000 to 2015 have been 68.8MCY. Therefore, with a capacity of 117.5 MCY and actual inflows of 68.8 MCY the remaining capacity in CIDMMA is 48.7 MCY (117.5 – 68.8 = 48.7).

6.1.2. Craney Island Eastward Expansion

The Craney Island Eastward Expansion's (CIEE) Southeast Cell is currently under construction, with its completion dependent on Federal funding. If available at the time of the proposed deepening the cells could be considered as a placement area. CIEE will effectively provide an additional cell to CIDMMA. After the cell dikes are completed (confined) filling with material from both the proposed deepening and maintenance dredging can occur. The CIEE project expands existing CIDMMA to the east by constructing a new approximate 522-acre placement area. The cell will be subdivided with a cross dike to form the Southeast Cell and the Northeast Cell. With the proposed filling to elevation +18 feet MLLW the Southeast Cell and Northeast Cell have an initial neat volume capacity of 6.7 and 12.7 MCY respectively. This is the volume within the cell, and does not include bulking of the dredged material.

Beyond the initial capacity, to +18 feet MLLW, dredged material capacity within the eastward expansion will continue due to the volume created by consolidation settlement of placed dredged fill and soft foundation clays. As settlement occurs additional capacity is realized. In total with initial capacity and filling for settlement, the CIEE provides for an additional 43.5 MCY. The capacity is documented in the recent Limited Reevaluation Report (LRR, USACE, 2015).

6.1.3. Dam Neck Ocean Dredged Material Disposal Site (DNODS)

As shown in the attached DMMP (Appendix E to this document) the least cost dredging includes the use of the DNODS for placement of the dredged material from AOC and TSC.

The DNODS has an area of about 9-square nautical miles with a water depth averaging about 40 feet. The DNODS is currently designed and managed to hold approximately 50 MCY of dredged material. The Dam Neck SMMP states that future evaluation and management could increase this quantity.

No specific disposal method is required for this site. Disposal may be by hopper dredge, dump scow, or by pipeline discharge. There are no seasonal restrictions to the placement of dredged material within the DNODS. Approximately 1.2 MCY of material from the three federal navigation channels will be placed in the site every 2 years.

Material dredged for placement at DNODS will most likely be dredging via hopper dredge, although mechanical dredging with material transported to the site using bottom dump scows may be used. Placement will be performed and monitored in accordance with the Norfolk District's Site Management and Monitoring Plan.

6.1.4. Norfolk Ocean Dredged Material Disposal Site (NODS)

At such time when CIDMMA is no longer available, suitable dredged material can be disposed of at the U.S. Environmental Protection Agency (USEPA) designated ocean disposal site (Norfolk Ocean Dredged Material Disposal Site), located approximately 35 miles from CIDMMA and 17 miles east of the mouth of the Chesapeake Bay. From the Norfolk Ocean Disposal Site Management and Monitoring Plan (SMMP):

- The NODS is a 42,600-acre area.
- The site is delineated by a circle with a radius of 4 nautical miles centered at 36 degrees, 59 minutes north latitude, and 75 degrees, 39 minutes west longitude.
- Water depth at the site ranges from 43 to 85 feet.
- The Norfolk Ocean Disposal site is permitted to receive both coarse and fine grained materials that meet the USEPA requirements for ocean disposal
- The SMMP specifically accounts for the future condition when the CIDMMA is no longer available, allowing suitable material from channels that would have normally be placed in CIDMMA to go to the NODS.
- Estimated total capacity of 1,300 MCY.

Placement will be performed and monitored in accordance with the Norfolk District's Site Management and Monitoring Plan.

6.1.5. Upland Sites

Although not anticipated, should there be any material that is determined to be unsuitable for CIDMMA or in-water placement sites dredged material will need to be disposed of at an approved upland site(s). This section summarizes potential upland placement areas for dredged material that does not meet the acceptance criteria established for the CIDMMA and conclusions supporting which upland site(s) to use for plan formulation.

The following upland placement/disposal sites were identified and vetted during development of the GRR:

- Charles City County Landfill
- CFS, Tri-City Regional Landfill & Recycling Center
- John C. Holland Enterprises Landfill
- Southeastern Public Service Authority (SPSA) Regional Landfill
- Portsmouth City Craney Island Landfill
- Bethel Landfill
- King and Queen Sanitary Landfill

Additionally, the following soil processing services were identified:

- Port Tobacco/Weanack Land, LLC (also can accept some dredged material)

- Clearfield MMG, Inc. Soil Recycling

Additionally, acceptance criteria was evaluated, and is documented in Technical Letter 14, "Upland Placement Areas – Preliminary Findings" (M&N TL14, 2016).

TL14's recommendation was to assume material that was not suitable for CIDMMA to be mechanically dredged and transported by barge to Port Weanack (approximately 70 nautical miles via the James River). Once at Port Weanack the material would be processed and loaded onto 12 CY dump trucks for placement in one or both of the nearby landfills for permanent placement. The local landfills include the Charles City landfill and/or the CFS, Tri-City Regional Landfill & Recycling Center in Petersburg, with one-way truck haul distances of 13 and 17-mile respectively.

In discussing the project with the other facilities noted, some concern was expressed regarding the volume of dredge material. Initial indications provided by points of contact indicate that the SPSA, John C. Holland, and Portsmouth landfill facilities are unlikely to accept the material or place significant limits on it.

Bethel Landfill and the King and Queen Sanitary Landfill facilities are potential sites but would have higher transportation costs than other alternatives. Neither of the Clearfield MMG facility locations are strategically located where they could mitigate transportation costs.

Therefore, Port Tobacco/Weanack in conjunction with Charles City landfill and/or the CFS, Tri-City Regional Landfill & Recycling Center in Petersburg appears to be the most viable upland disposal sites depending on the contamination levels found in the dredge material. This recommendation is similar to completed projects in the Elizabeth River.

6.1.6. Beneficial Use

Dredged material removed from the Atlantic Ocean Channel and Thimble Shoal Channel (east of the Chesapeake Bay Bridge Tunnel, CBBT) may be suitable for beneficial use. Reasonably foreseeable beneficial use placement areas for this material include sites for which environmental analysis of the proposed activity that would use the dredged material has already been completed (i.e., NEPA is done) and the actions at the beneficial use sites are approved to accept appropriate material. Three USACE Erosion Control and Hurricane Protection projects (Sandbridge and Big Beach in Virginia Beach and Willoughby/Ocean View in Norfolk) and the USACE Craney Island Eastward Expansion project have completed NEPA documents and could accept dredged material for beneficial use. The maximum combined total amount of construction material that could be placed at these sites is approximately 11 MCY.

7. Construction Assumptions and Methodology

The following describes the construction assumptions for developing costs and quantifying impacts for the recommended navigation improvements.

7.1. Navigation Aids

Existing navigation buoys are anticipated to be relocated to accommodate the TSC Meeting Areas, with the USCG in charge of these changes. No new ranges are anticipated, only relocating of the markers along the TSC in the area of the proposed Meeting Areas.

7.2. CBBT Rock Cover

The Thimble Shoal tunnel of the Chesapeake Bay Bridge Tunnel (CBBT) was originally designed for a maintained channel depth of -50 feet MLLW and width of 1,000 feet, and included 3 feet of over-dredge/advanced maintenance allowance and 10 feet of sand cover over the tunnel tube. Based on existing record drawings, the shallowest point of the tunnel structure within the footprint of the Federal project, is the 'top of tunnel' flange/bulkhead elevation, which is at elevation -63 feet MLW within the footprint of the channel. The tunnel itself is approximately 1.5' below the flange/bulkhead (CBBT, 1960).

Several studies have been completed to determine concepts to allow for a deeper channel (USACE, 1986 and Transystems 2002). Both studies concluded the most economical method would be to provide a minimum 5 feet of protective cover, including a minimum of 3 feet of that protective cover be rock armor in place of the 10 feet of sand cover. Reduction of the protective cover to 5 feet would accommodate a maintained channel depth of 55 feet, which at that time, conservatively included 1 foot of advance maintenance and 2 feet of overdepth dredging (3 feet of over-dredge/advanced maintenance allowance).

The 2002 study recommended further investigation regarding the tunnel joints, feasibility of replacing the existing cover with rock armor, and determining its effectiveness to protect the tunnel from vessel or anchor impacts.

The CBBT Authority responded to a letter (dated 10/27/2016) sent by the VPA confirming their awareness and agreement with the various studies to deepen the channel and to alter the tunnel protective cover to accommodate a deeper channel and support conducting the detailed engineering work during the PED phase of the project.

Costs associated with re-armoring the tunnel with recommended armor protection cover are currently included in the construction costs generated as part of this Deepening study. The concept for the cover modification is shown in Appendix F.

The main elements of the work are projected to include:

- Dredging the existing sand fill cover over the tunnel to allow the rock blanket to be placed. Dredged sand is assumed to be placed beneficially on the CIEE dikes. Volume of dredged material is estimated to be 102,000 cubic yards (CYs).
- Placing the 3 feet thick rock blanket. The rock is assumed to be a nominal 10-inch diameter. Volume of rock is 20,300 CYs. Rock is assumed to come from existing and permitted upland quarries along the James River (near Richmond).
- Backfill excavated slopes on either side to the tunnel to elevation -59 feet with sand. This sand would be from upland sources, also from permitted borrow areas up the James River. Estimated volume of sand is 46,500 CYs.

The detailed design of the rock cover over the CBBT will be performed during PED

7.3. Dredging

Assumptions on materials to be dredged is describe above and in attached Appendix B. During PED additional sediment sampling will be performed to verify that materials are suitable for their proposed placement locations and the appropriate permits will be obtained.

All dredging will be performed within the voluntary environmental windows established by the USACE to protect sea turtles from hopper dredging during the fall migration period when there is a higher density of sea turtles in the Atlantic Ocean and Thimble Shoal channels. Therefore, no dredging is projected to occur in these channels from 01 September through 15 November. There are no time-of-year restrictions for the remaining channels in the Norfolk Harbor Channel project.

Overall, the dredging component of the Norfolk Harbor Channels improvement project may extend up to four years depending on the final channel depth and width selections (see attached proposed construction schedule in the Cost Appendix). Dredging will be performed by crews working 12-hour shifts 24 hours per day and seven days per week. Although dredging crews are projected to be on-site and working as described above, dredging production will likely be limited to 25 days per month due to necessary set up, break down, and maintenance operations. Please note that mention of dredging equipment types is for the purpose of preliminary discussion and is not meant to limit the types of dredges that may actually perform the work.

7.3.1. Segment 1

7.3.1.1. Ocean Channels: Atlantic Ocean Channel, Thimble Shoal Channel and Thimble Shoat Channel Meeting Areas

Dredging is anticipated to be performed by a 7,600 hopper dredge in the Atlantic Ocean Channel, Thimble Shoal Channel (east and west of the CBBT), and in the two meeting areas. Excess water will be decanted on-site. The dredged material will be hauled to the placement area at the Dam Neck Ocean Dredged Material Disposal Site (ODMDS) and dumped from the split-hull vessel. Average one-way haul distances include:

- Atlantic Ocean Channel: 9 miles;
- Thimble Shoal Channel:17 to 26 miles;
- Meeting Area 1 (west): 25 miles; and
- Meeting Area 2 (east): 17 miles.

7.3.1.2. Inner Harbor and Anchorage F

Dredging will be performed in the interior channels (Norfolk Harbor Entrance Reach, Channel to Newport News, Norfolk Harbor Reach, Craney Island Reach, and Anchorage F) by a 30-inch cutter head. Dredged material will be pumped to CIDMMA. Average pumping distances are approximately 30,000 feet, with the exception of the channel to Newport News, which has an average pumping distance of 43,000 feet and has the additional requirement of two booster pumps.

The pipelines would discharge upland of the main dikes on the east side of CIDMMA. Excess water is decanted through the manually operated spill boxes on the west side of CIDMMA. Excess water is sampled and tested based on USACE protocols prior to discharge through the spill boxes.

The crew on a large cutterhead dredge, where crew live aboard, is estimated to be 55 inclusive of required captains, engineers, leverman, tug captains, deckhands, maintenance engineers and support, and shore crews. The dredge operates 24/7, with personnel shifts assumed to be 8 hrs/day, 7 days a week.

The cutterhead dredge is assumed, with downtime, to effectively dredge 427 hrs/month.

7.3.2. Segment 2

7.3.2.1. Newport News Channel

Dredging will be performed in the Channel to Newport News by a 30-inch cutter head. Dredged material will be pumped to CIDMMA. Average pumping distance is approximately of 43,000 feet and includes the requirement of two booster pumps.

The pipelines would discharge upland of the main dikes on the east side of CIDMMA. Excess water is decanted through the manually operated spill boxes on the west side of CIDMMA. Excess water is sampled and tested based on USACE protocols prior to discharge through the spill boxes.

The crew on a large cutterhead dredge, where crew live aboard, is estimated to be 55 inclusive of required captains, engineers, leverman, tug captains, deckhands, maintenance engineers and support, and shore crews. The dredge operates 24/7, with personnel shifts assumed to be 8 hrs/day, 7 days a week.

8. Constraints

This section summarizes the tunnel, bridge, and utility infrastructure in close proximity to the project channels that may become constraints and/or drive additional improvements for the dredging alternatives under consideration. The data contained herein was collected from a variety of available references including USACE project drawings and reports, NOAA charts, and input from owners of the utilities.

8.1. Tunnels

Three bridge-tunnels cross the channels within the Norfolk Harbor and Channel Deepening Study area. A fourth crossing, the Patriot's Crossing, was in the planning process during initiation of the study, but has since been removed from the Virginia Department of Transportation's project list. It is noted below for completeness.

- Chesapeake Bay Bridge Tunnel / US Route 13 (CBBT)
- Hampton Roads Bridge Tunnel / Interstate 64 (HRBT)
- Monitor-Merrimac Memorial Bridge Tunnel / Interstate 664 (MMMBT)
- Patriot's Crossing (Planned)

Each of these structures consists of over-water bridges that transition to tunnels to pass under the major navigation channels they cross. Within the channels, the tunnels are designed to accommodate a maximum channel depth. The maximum channel depth refers to the maintained channel depth and includes allowances for over-dredge/advanced maintenance plus protective cover over the tunnel tube structure. At each side of the channel, the tunnel – bridge transitions may be an additional constraint when evaluating changes to channel geometry. See Table 9 for a summary of their characteristics.

8.1.1. Chesapeake Bay Bridge Tunnel

The tunnel was originally designed for a maintained channel depth of -50 feet MLLW and width of 1,000 feet, which includes a 3 feet over-dredge/advanced maintenance allowance and 10 feet of protective cover over the tunnel tube, which is at elevation -63 feet MLLW within the channel. A 2002 study identified that USACE guidance specifies a minimum 5 feet protective cover, but recommends a minimum of 3 feet of that protective cover be rock armor. Reduction of the protective cover to 5 feet would accommodate a maintained channel depth of 55 feet, but will require excavation and armoring efforts. The 2002 study recommends further investigation regarding the tunnel joints, feasibility of replacing the existing cover with rock armor, and its effectiveness at protecting the tunnel from vessel or anchor impacts. The cover modification is discussed above in the Constraints section. The intent of this study is to modify the cover to support a 55-foot nominal channel depth, with ability to maintain to 56-foot.

Planning has begun to construct a second tunnel across Thimble Shoal Channel and includes recommendations to base the design on a -65 feet maintained channel. For the channel to benefit, however, the existing tunnel would need to be removed and replaced at a deeper depth – currently not a planned project.

8.1.2. Hampton Roads Bridge Tunnel

The HRBT is located at the transition between the Thimble Shoal Channel and Norfolk Harbor Entrance Reach of Segment 1 of the project channel. The existing navigation channel intersects the tunnel at a location where the tunnel can accommodate a maximum channel depth of -60 feet MLLW (currently maintained at 1,000 feet wide). If the navigation channel were to be shifted approximately 1,000 feet to the north, it would be aligned with a deeper segment of the tunnel and could accommodate a maximum channel depth of approximately -65 feet MLLW. In 2017 the Virginia Department of Transportation began planning for the HRBT Expansion project to build another bridge-tunnel and widen the four-lane segments of I-64. Planning for this tunnel will include allowing for maximum future channel depths.

8.1.3. Monitor-Merrimac Memorial Bridge Tunnel

MMMBT is located on the Newport News Channel, which is Segment 2 of the study. It is designed to accommodate a -60 feet MLLW maximum channel depth across a portion of the channel that is approximately 967 feet wide (i.e. it crosses at a channel bend; the straight segments of the channel are maintained at 800 feet wide).

8.1.4. Patriot's Crossing (future project)

Patriot's Crossing (also referred to as the Third Crossing) is the planned construction of a bridge tunnel extending from Norfolk (between Norfolk International Terminals and Naval Station Norfolk) to the MMMBT just south of its tunnel. A tunnel would be used to cross the Norfolk Harbor Reach channel segment. Current concepts recommend the design be based on accommodating a 65 feet maximum channel depth.

8.1.5. Tunnel Summary

The following table summarized clearances of the tunnels in the project area.

Table 13: Summary of Bridge-Tunnel Vertical Constraints

Bridge-Tunnel	Top of Structure Elevation in Channel (feet, MLLW)	Protective Cover Thickness (feet)	Allowable Advanced Maint./Over-dredge (feet)	Maximum Maintained Channel Depth (feet, MLLW)	Channel Width (feet)
CBBT (Exist)	-63	10	3	-50	1,000
CBBT (Reduced Cover)	-63	5	2	-56	1,000
HRBT (Exist)	-68	5	3	-60	2,000[A]

HRBT (Relocated Channel)	-73	5	3	-65	1,000
MMMBT	-68	5	3	-60	967
Patriot's Crossing (future project)	N/A	N/A	N/A	-65[B]	

[A]Channel is maintained at 1,000 feet wide but could be shifted 1,000 feet to the north, thereby resulting in a width constraint of 2,000 feet total.
[B]Recommended by current concepts

8.2. Bridges

The study area of the Norfolk Harbor and Channel Deepening Study does not have any bridge crossings except those associated with the bridge-tunnels described above. The bridges associated with the bridge-tunnels are not configured to accommodate large vessels, leaving the tunnels as the sole crossing point for the channels.

8.3. Utilities

Nautical charts and previous USACE dredging project plans were reviewed to identify utilities within the study area that could be impacted by the project. Refer to the figures in Appendix A for locations and other information regarding the identified utilities. Available data indicates the shallowest utility crossing (City of Norfolk Raw Water) is at -60 feet MLW, which is 5 feet below the study dredge of -55 feet MLLW. The data indicates all other crossing utilities are located deeper.

Four sanitary sewer outfalls were also identified within the project area but are outside the limit of disturbance for the increased width of the channel at top of cut resulting from a deeper channel.

Lamberts Bend Deperming (Magnetic Silencing Facility) Station is within the Norfolk Harbor Entrance Channel reach. The Norfolk District has documented the need for the United States Navy (USN) to relocate the Degaussing Range at a deeper depth to accommodate the future channel deepening. 55-Foot Channel. During the 50-Foot Outbound Channel deepening during (1987-1989) the USN relocated the Degaussing Range to its present location in the Norfolk Harbor Entrance Reach, at Navy expense, for an amount of $3.2 million as reported by the USN at that time. The sensors were relocated to a depth to accommodate the deepened channel. The USN performed an upgrade (Navy, 2006) of the Degaussing Range placing the sensors at -57 feet with conditions that USN relocate at their expense as necessary for future deepening. Currently, the dimensions under consideration for the Norfolk Harbor Entrance Channel are a depth of -55 feet and a width of 1,000 feet. To provide these dimensions, only the areas currently shallower than -55 feet would need to be dredged. The contract required depth of dredging is expected to be -55 feet, and would include one foot of allowable overdepth for a total dredging depth of -56 feet. Immediately over the Degaussing Range, there are limited areas on the edge of the channel that are shallower than -55 feet. Based on available information, it appears the 55-Foot Channel can be constructed in the Norfolk Harbor Entrance Reach without adversely affecting the Navy Degaussing Range, with its sensors at -57 feet. If however the USN determines the Degaussing Range will be at risk either from

dredging operations, future deeply laden ships or anchor drag, under conditions of their Corps permit the USN would be required to relocate the sensors to deeper depths to accommodate the channel, at USN expense. There will be no requirements or cost included in the plan for relocating the Degaussing Range. The range of depths under consideration for the Norfolk Harbor Channel and Entrance Reach can be accommodated to a depth as deep as -55 feet, with one foot of allowable overdepth. During detailed surveys and channel design studies to be performed during the Preconstruction Engineering and Design phase, additional coordination among the project team and USN representatives will be conducted to validate project dredging requirements with respect to the Navy Degaussing Range.

9. Costs

This section discusses the methodology used in developing the costs for the array of alternatives, details are provided in the Cost Appendix. The costs to dredge the channels at their existing maintained depths, as well as 1 foot increments up to the elevations described above in Section 4.4 are calculated. Quantities were developed based on the latest condition surveys provided by the USACE. Quantities include the 1 Vertical:3 Horizontal side slope volume.

9.1. New Work

9.1.1. Dredging

Dredging costs are developed using the USACE Dredge Estimating Program (CEDEP) worksheet that accounts for the efficiency of the dredges for each reach based upon the areas, volume, amount of pay amount not dug on average, and the amount dug in excess of the allowable pay amount, any many other factors associated with dredging operations. CEDEP sheets can be found in the Cost Appendix. All costs associated for the contractor including overhead, profit, and bonds are included in the unit price calculated. The CEDEP spreadsheet also calculates costs for mobilization and demobilization, which are provided separately from the unit costs. It was assumed that the USACE would provide the post construction survey, so no cost was estimated with regards to surveys (note: the contractor is assumed to have a surveyor of their own, but no surveys were included for the owner). For the initial deepening scenarios, it is assumed that the initial mobilization is included in the maintenance dredging (where applicable).

9.1.2. Relocations/LERRS

Modifications to the CBBT tunnel cover are included under the lands, easements, rights-of-way, or relocations (LEERS) element of the project cost. The cost for the work is built up in MII with CEDEP supporting dredging elements. No other LERRS have been identified.

9.1.3. PED

Pre-construction, engineering and design (PED) are estimated for input into the total project costs. The estimate for PED is shown in Cost Appendix and includes a breakdown of field work including Cultural Resources, sediment sampling and testing, engineering and surveys to assemble bid documents, as well construction management and support through construction.

9.1.4. Local Service Facilities

As part of the total cost development, improvements to Local Service Facilities was estimated. Input from the major marine terminal facilities indicated that the wharfs and piers were adequate for deepening to the range of nominal depths studied, and the only cost would be to deepen the existing berths to the projects depth. These included 7 facilities listed below.

Segment 1

- Virginia International Gateway
- Norfolk International Terminal (NIT) South
- NIT North
- Norfolk Southern, Lamberts Pier 6

Segment 2 – Newport News Channel

- Pier IX, Kinder Morgan
- Dominion Terminals
- Newport News Marine Terminal

Knowledge of the existing conditions were known, and quantities were estimated based on volume required to obtain the target project dredge elevation. The volumes were calculated by multiplying the dredging area by the depth of dredging needed to equal the proposed adjacent channel depth. Dredged material is anticipated to go to CIDMMA.

9.1.5. Abbreviated Risk Analysis

To better develop contingences to evaluate alternatives and Plan Selection, the PDT evaluated uncertainties associated with each major construction cost item or feature in coordination with input with other members of the project development team. This was completed via Walla Walla's guidelines to develop an abbreviate risk analysis.

9.2. Maintenance Costs

Similar to New Work costs, dredging costs are developed using CEDEP worksheet that accounts for the efficiency of the dredges for each reach based upon the areas, volume, amount of pay amount not dug on average, and the amount dug in excess of the allowable pay amount, any many other factors associated with dredging operations. CEDEP sheets can be found in the Cost Appendix. For the initial deepening scenarios, it is assumed that the initial mobilization is included in the maintenance dredging (where applicable).

For inner harbor channels dredging costs are for placement in CIDMMA/CIEE. Beyond the timeframe of the existing DMMP, when current CIDMMA reaches capacity, dredged material will be disposed of at the Norfolk Ocean Dredged Material Disposal Site.

Offshore channel, TSC and AOC, have maintenance material continuing to be placed in the offshore sites, with opportunities for beneficial use as discussed above.

10. Cost Schedule Risk Analysis

A Cost Schedule Risk Analysis (CSRA) was completed on the Tentatively Selected Plan. The CSRA Report is included as a sub-appendix to the Cost Appendix.

11. References

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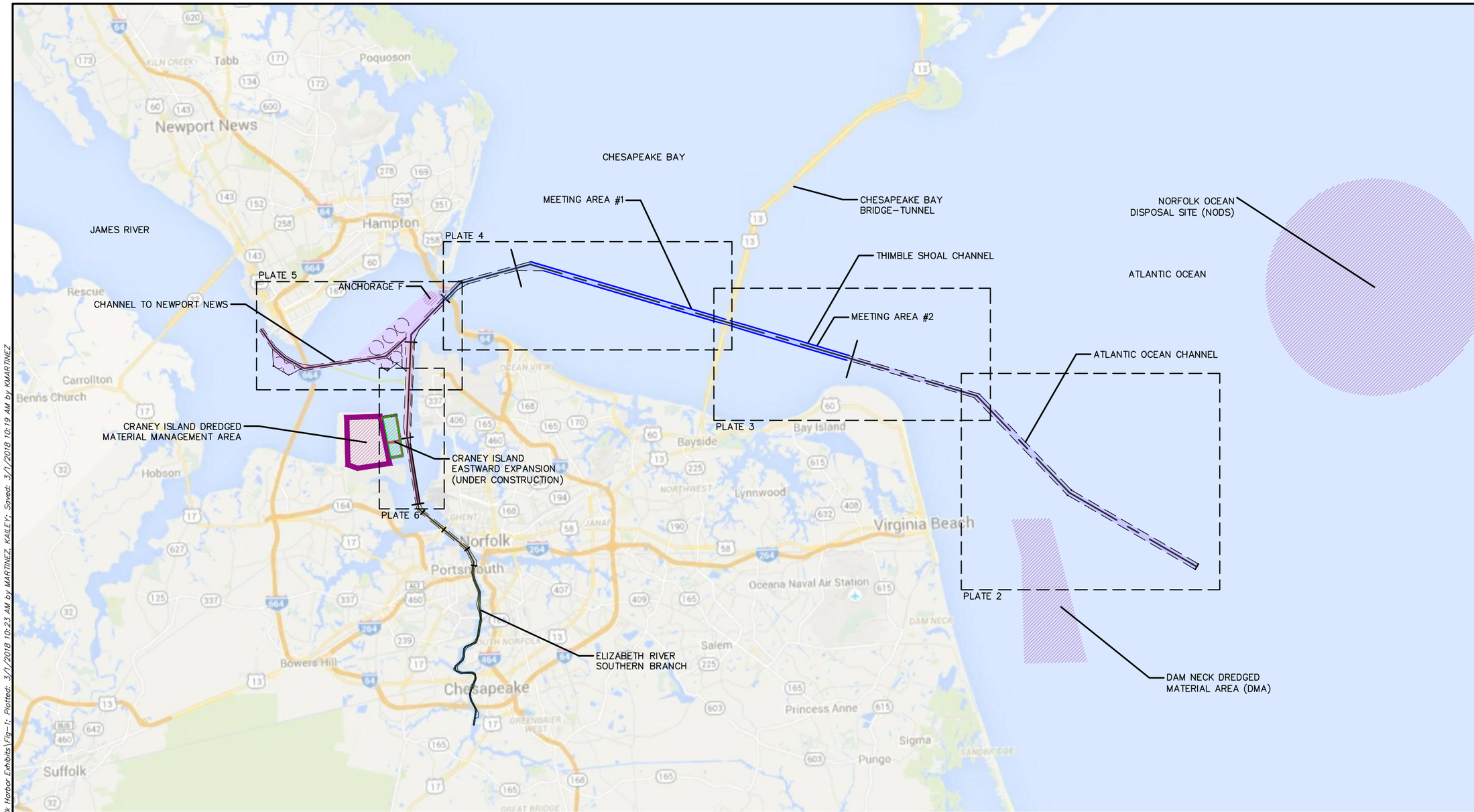
Engineering Appendix A: Figures



LEGEND:

EXISTING PLACEMENT AREAS

2 MILES 0' 2 MILES 4 MILES

SCALE: 1"=4 MILES

ELIZABETH RIVER SOUTHERN BRANCH NAVIGATION IMPROVEMENTS STUDY

PLATE 1 - OVERALL PLAN

moffatt & nichol

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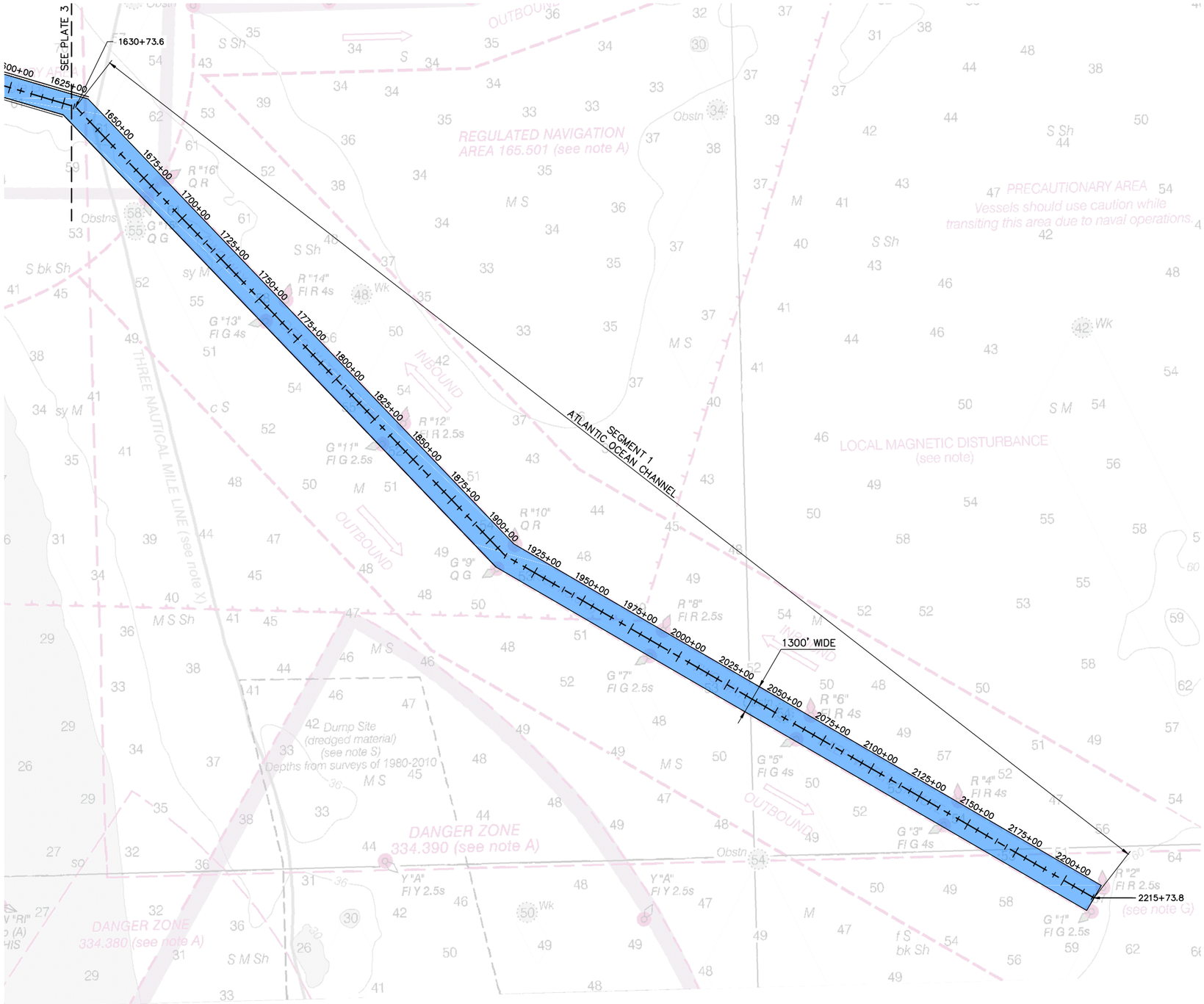


NOTES

1. BACKGROUND IS NAVIGATION CHART OF CHESAPEAKE BAY ENTRANCE DATED APRIL 2011.
2. STATIONING SHOWN IS BASED ON ARMY CORPS OF ENGINEERS PROJECT.

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 2 - ATLANTIC OCEAN CHANNEL

moffatt & nichol

File: G:\NOR\8885-01\500 CADD_Active_Norfolk Harbor Exhibits\Fig-2; Plotted: 10/2/2017 4:22 PM by AYTODA, BINA; Saved: 9/29/2017 1:08 PM by BAYTODA

NOTES

1. BACKGROUND IS NAVIGATION CHART OF CHESAPEAKE BAY ENTRANCE DATED APRIL 2011.
2. STATIONING SHOWN IS BASED ON ARMY CORPS OF ENGINEERS PROJECT.

2500' 0' 2500' 5000'

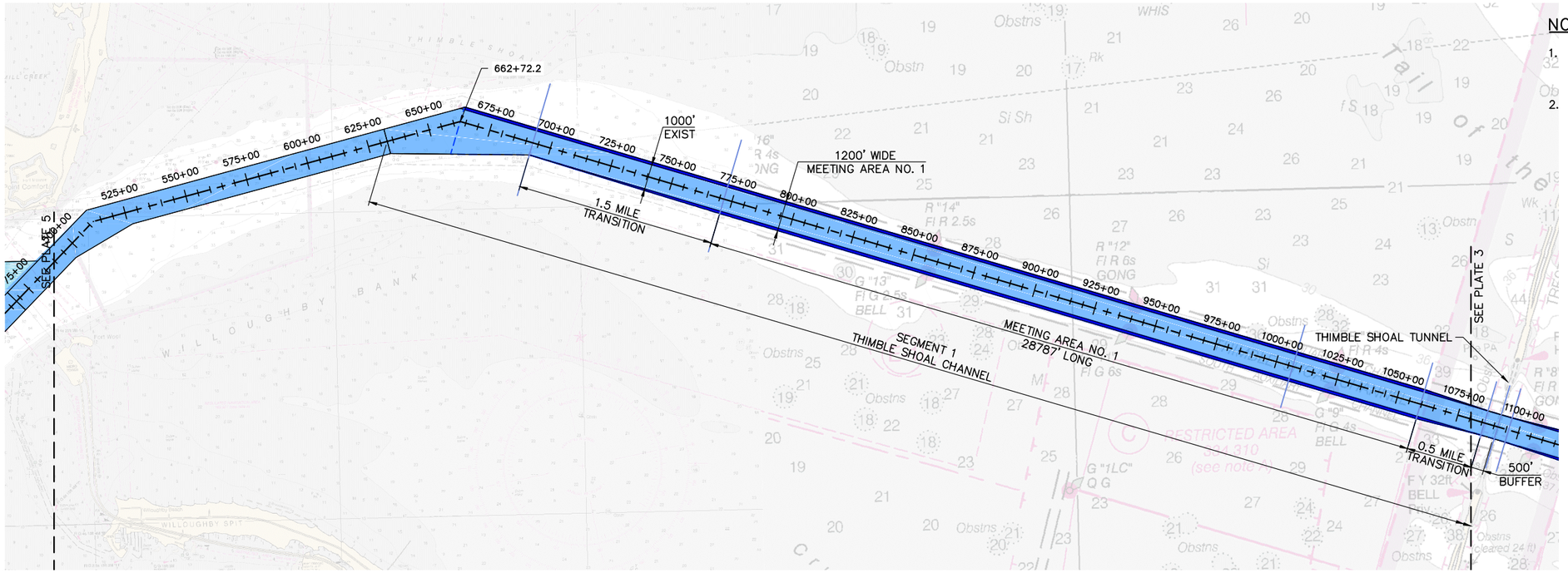
SCALE: 1"=5000'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 3 - EAST THIMBLE SHOAL CHANNEL

moffatt & nichol

File: Q:\WOR\8885-01\500 CADD_Active_Norfolk Harbor Exhibits\Fig-3; Plotted: 2/22/2018 1:51 PM by LIPKINS, TURI; Saved: 9/29/2017 3:15 PM by TLIPKINS



NOTES

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2. STATIONING SHOWN IS BASED ON ARMY CORPS OF ENGINEERS PROJECT.

2500' 0' 2500' 5000'

SCALE: 1"=5000'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 4 - WEST THIMBLE SHOAL CHANNEL

moffatt & nichol

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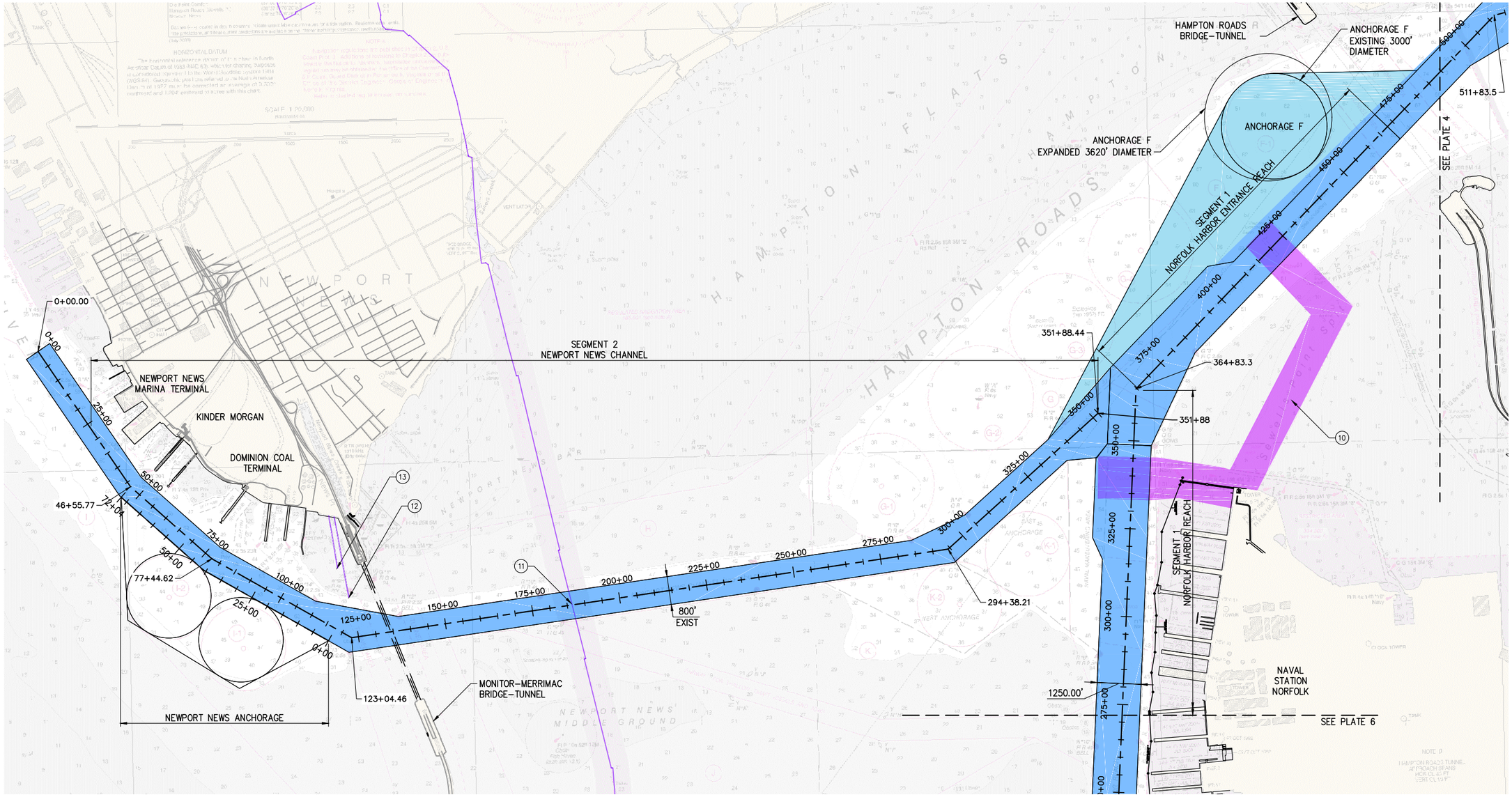

NOTES

1. BACKGROUND IS NAVIGATION CHART OF HAMPTON ROADS DATED AUGUST 2008.
2. STATIONING SHOWN IS BASED ON ARMY CORPS OF ENGINEERS PROJECT.

LEGEND:

SUBMERGED UTILITY

SUBMERGED UTILITY CROSSINGS				
NO.	DESCRIPTION	OWNER	DEPTH CONSTRAINT (FT. MLW)	NOTES
10	MAGNETIC SILENCING RANGE	U.S. NAVY	–57	
11	NATURAL GAS PIPELINE	VIRGINIA NATURAL GAS	–65	
12	SANITARY SEWER OUTFALL	HRSD	N/A	955'L OF ℄
13	SANITARY SEWER OUTFALL	HRSD	N/A	1520'L OF ℄

1500' 0' 1500' 3000'

SCALE: 1"=3000'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 5 - NORFOLK HARBOR ENTRANCE REACH AND NEWPORT NEWS CHANNEL

moffatt & nichol

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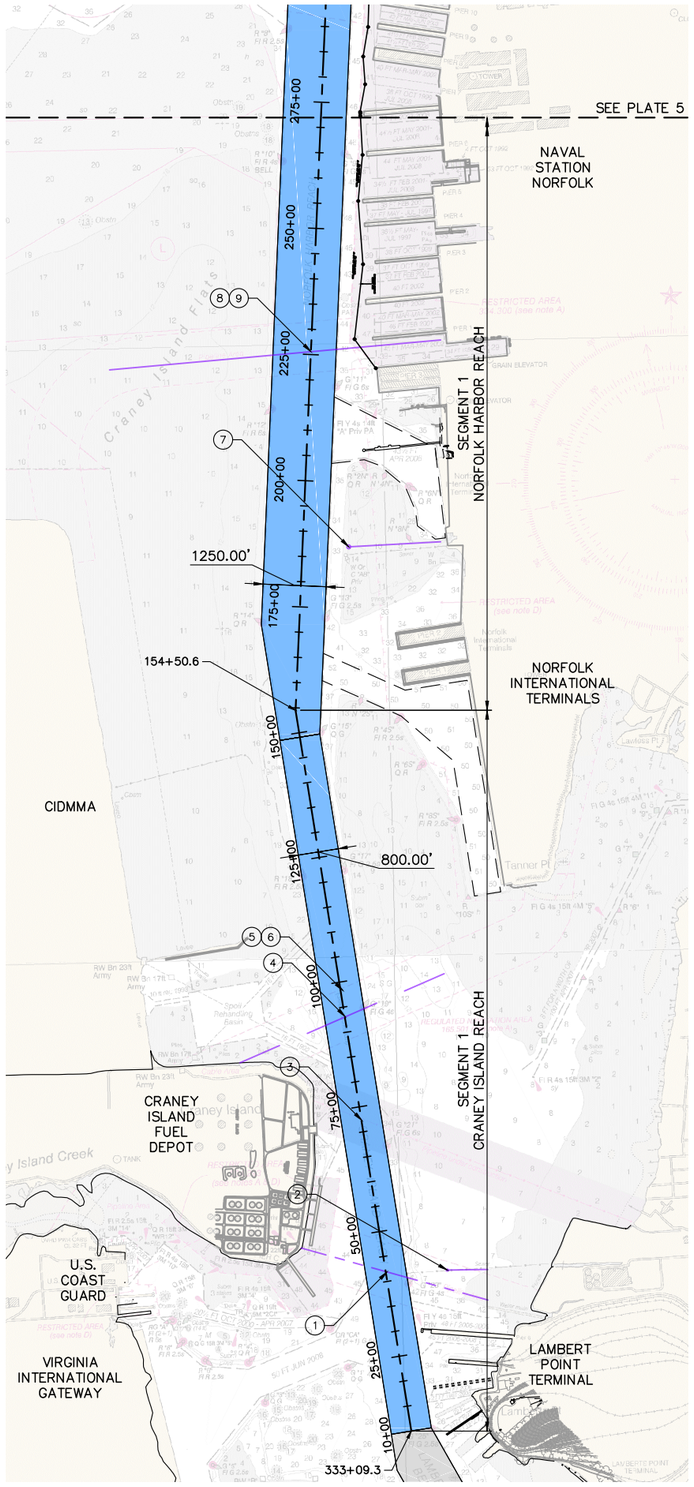

NOTES

1. BACKGROUND ARE NAVIGATION CHART OF HAMPTON ROADS DATED AUGUST 2008 AND NAVIGATION CHART OF NORFOLK HARBOR AND ELIZABETH RIVER DATED AUGUST 2008.
2. STATIONING SHOWN IS BASED ON ARMY CORPS OF ENGINEERS PROJECT.

LEGEND:

SUBMERGED UTILITY

SUBMERGED UTILITY CROSSINGS				
NO.	DESCRIPTION	OWNER	DEPTH CONSTRAINT (FT. MLW)	NOTES
1	36" WATER MAIN	CITY OF NORFOLK	−60	
2	54" SANITARY SEWER OUTFALL	HRSD	N/A	1210'R OF ℄
3	NATURAL GAS PIPELINE	VIRGINIA NATURAL GAS	−100	
4	230 KV TRANSMISSION LINE	VIRGINIA POWER	−75	
5	POWER TRANSMISSION LINE "B"	VIRGINIA POWER	−110	
6	POWER TRANSMISSION LINE "A"	VIRGINIA POWER	−90	
7	48" SANITARY SEWER OUTFALL	HRSD	N/A	905'R OF ℄
8	8" SLUDGE PIPE	U.S. NAVY	−74	
9	10" MULTI−USE PIPE	U.S. NAVY	−74	

1500' 0' 1500' 3000'

SCALE: 1"=3000'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 6 - NORFOLK HARBOR REACH AND CRANEY ISLAND REACH

moffatt & nichol

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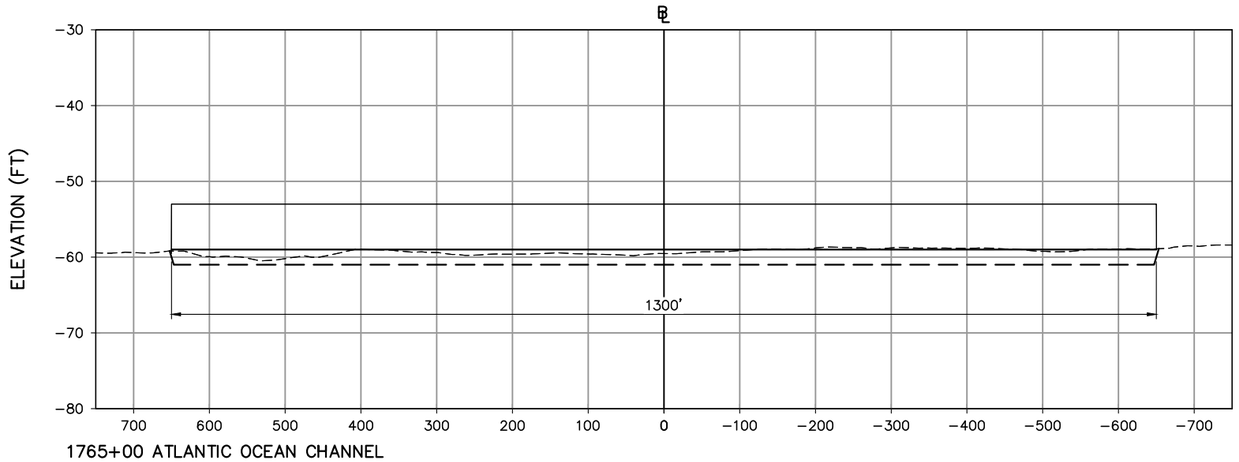
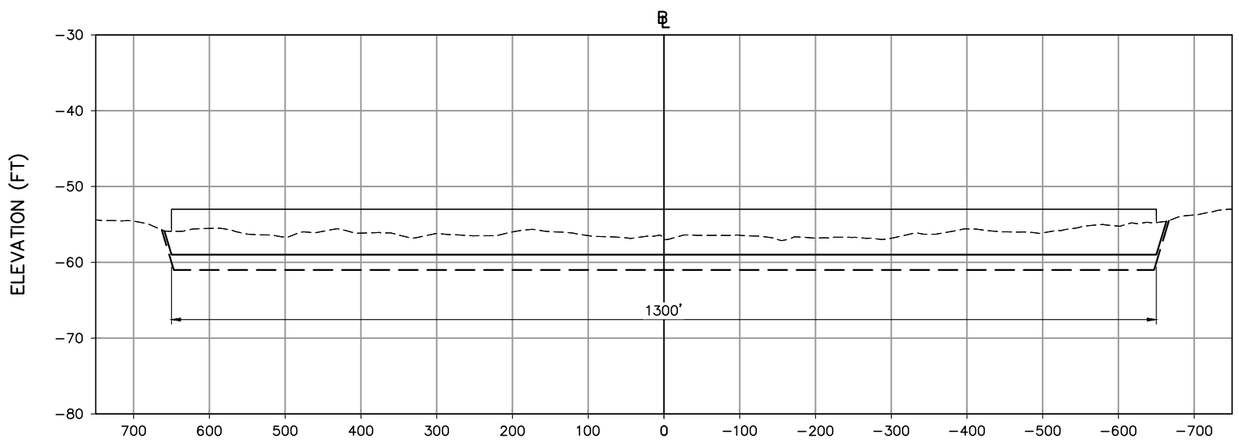


1765+00 ATLANTIC OCEAN CHANNEL



2025+00 ATLANTIC OCEAN CHANNEL

LEGEND:

- EXISTING SURFACE
- REQUIRED DEPTH EL −59
- PAID ALLOWABLE DEPTH EL −60 + 1' NON−PAY OVERDREDGE EL −61
- HISTORICALLY MAINTAINED DEPTH EL −53

10' 0' 10' 20'
VERTICAL SCALE: 1"=20'

100' 0' 100' 200'
HORIZONTAL SCALE: 1"=200'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 7 - SECTION - ATLANTIC OCEAN CHANNEL

moffatt & nichol

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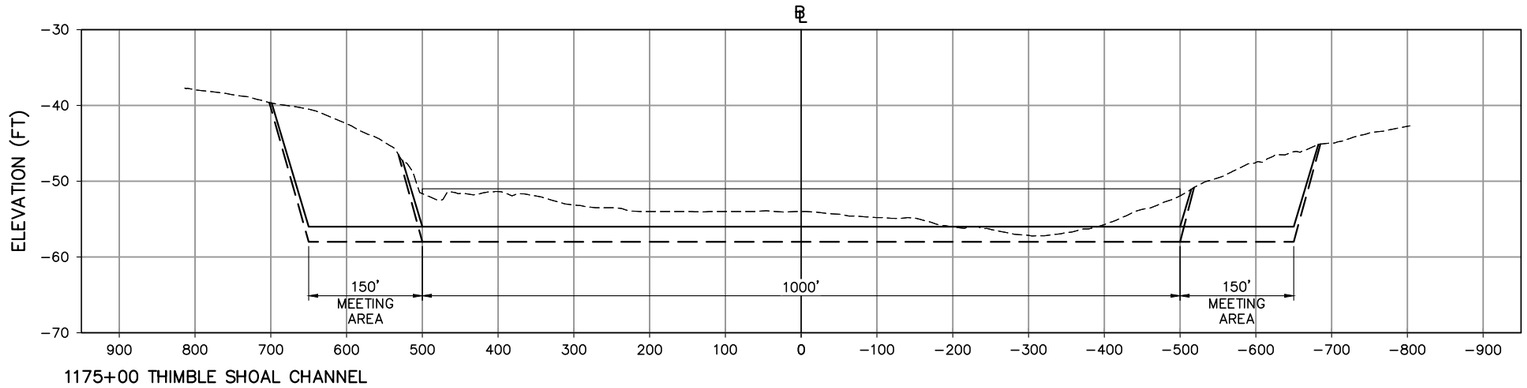
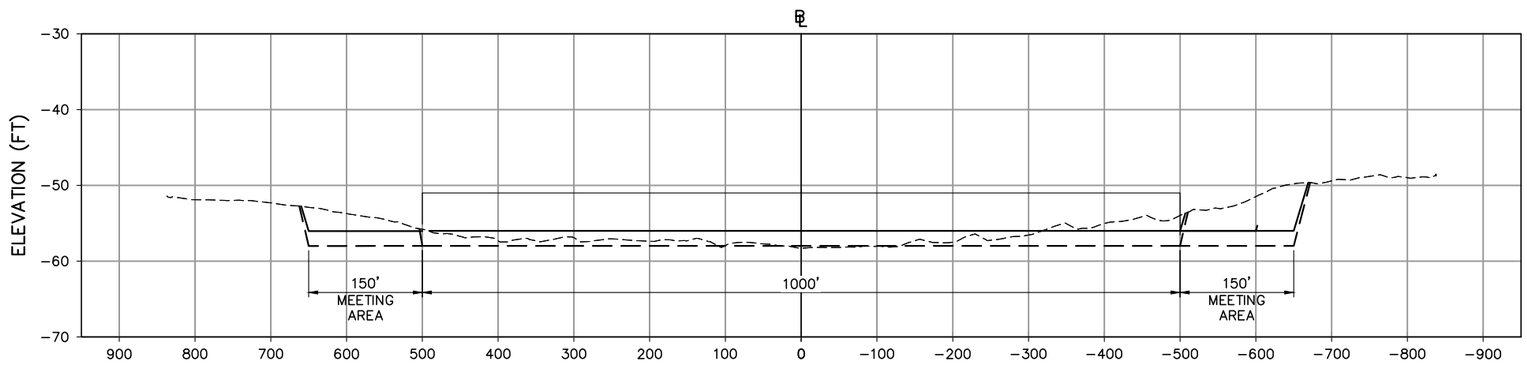


1175+00 THIMBLE SHOAL CHANNEL



1325+00 THIMBLE SHOAL CHANNEL

LEGEND:

- EXISTING SURFACE
- REQUIRED DEPTH EL -56
- PAID ALLOWABLE DEPTH EL -57 + 1' NON-PAY OVERDREDGE EL -58
- HISTORICALLY MAINTAINED DEPTH EL -51

10' 0' 10' 20'
VERTICAL SCALE: 1"=20'

100' 0' 100' 200'
HORIZONTAL SCALE: 1"=200'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 8 - SECTIONS - THIMBLE SHOAL CHANNEL

moffatt & nichol

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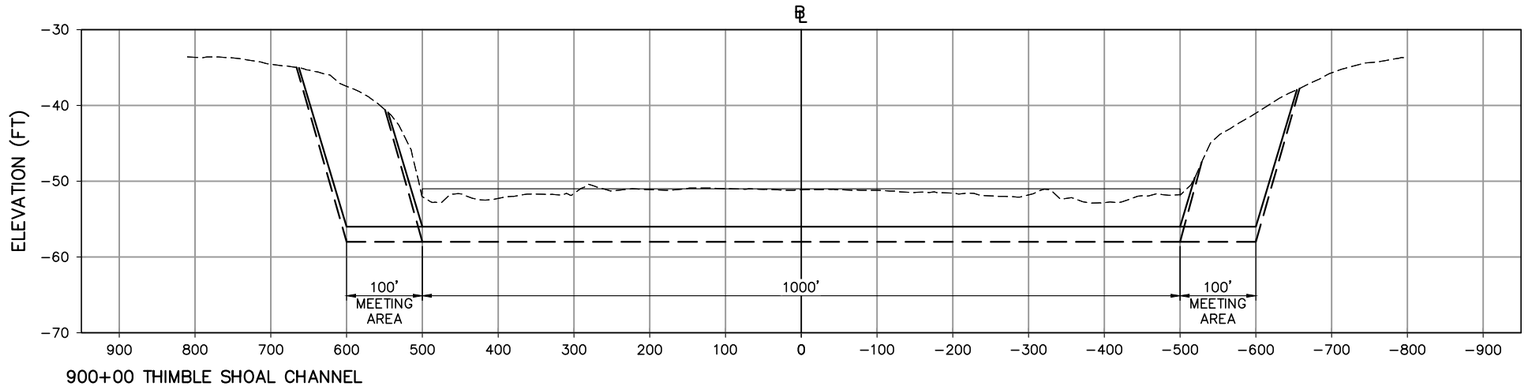
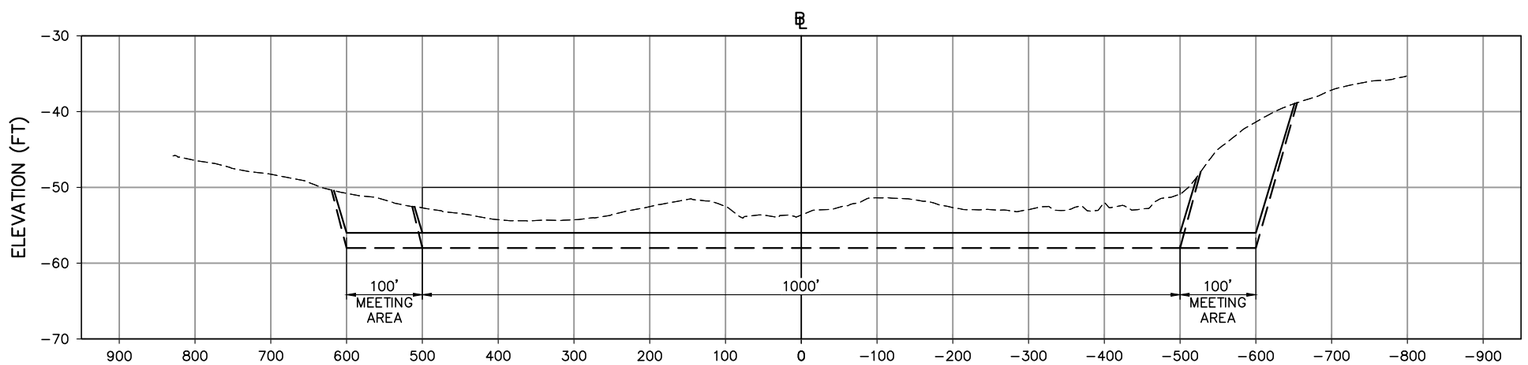


900+00 THIMBLE SHOAL CHANNEL



1025+00 THIMBLE SHOAL CHANNEL

LEGEND:

- - - - - - EXISTING SURFACE

——— REQUIRED DEPTH EL -56

— — — PAID ALLOWABLE DEPTH EL -57 + 1' NON-PAY OVERDREDGE EL -58

——— HISTORICALLY MAINTAINED DEPTH EL -51

10' 0' 10' 20'
VERTICAL SCALE: 1"=20'

100' 0' 100' 200'
HORIZONTAL SCALE: 1"=200'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 9 - SECTIONS - THIMBLE SHOAL CHANNEL

moffatt & nichol

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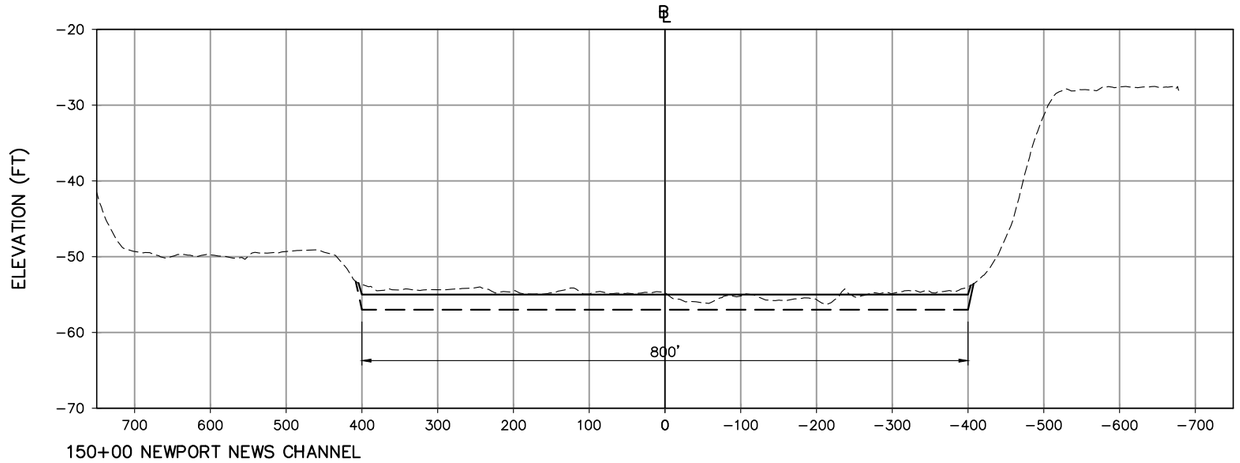
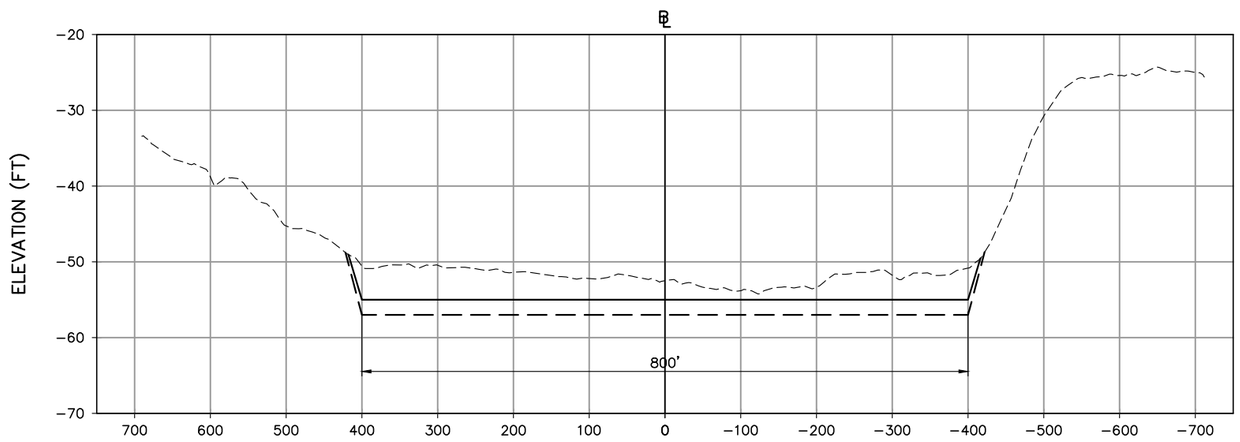


150+00 NEWPORT NEWS CHANNEL



250+00 NEWPORT NEWS CHANNEL

LEGEND:

- - - - - - EXISTING SURFACE

——— REQUIRED DEPTH EL −55

— — — PAID ALLOWABLE DEPTH EL −56 + 1' NON-PAY OVERDREDGE EL −57

10' 0' 10' 20'

VERTICAL SCALE: 1"=20'

100' 0' 100' 200'

HORIZONTAL SCALE: 1"=200'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 10 - SECTIONS - NEWPORT NEWS CHANNEL

moffatt & nichol

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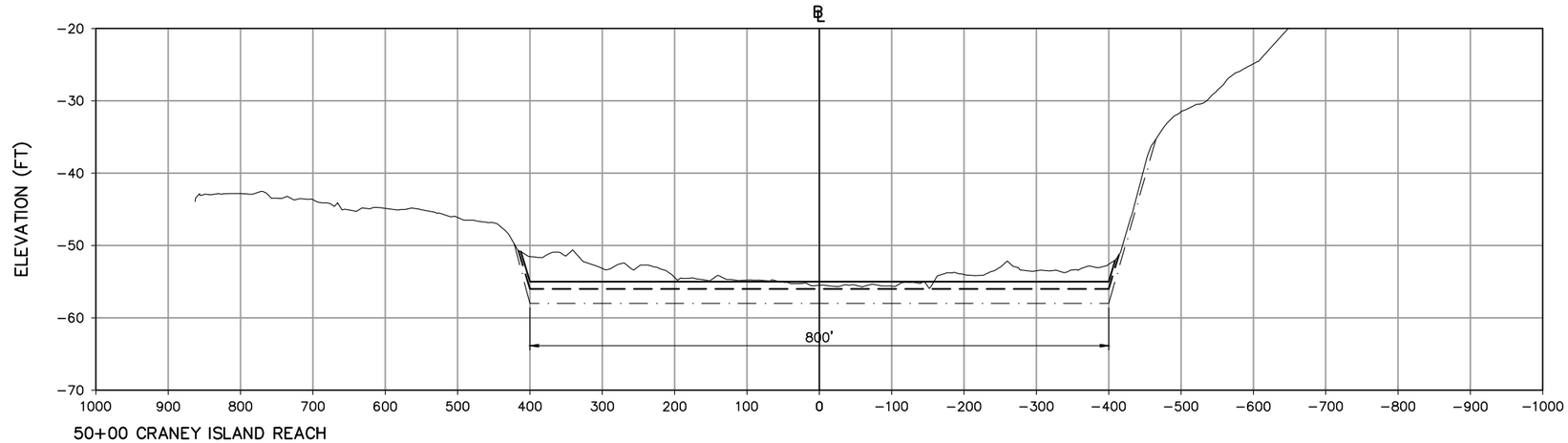
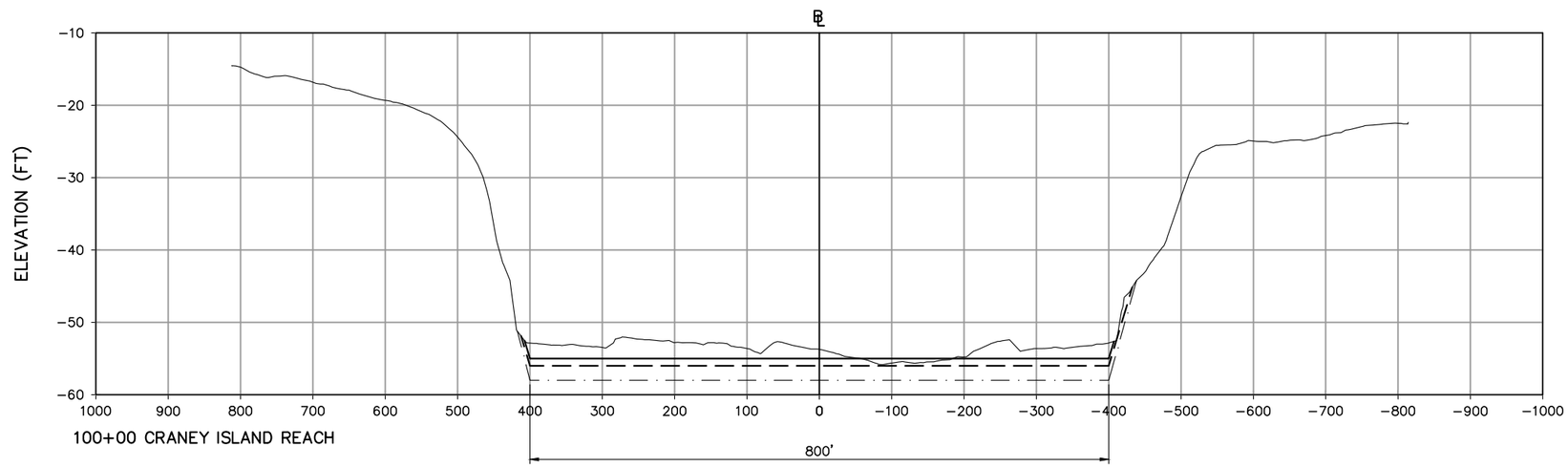


50+00 CRANEY ISLAND REACH



100+00 CRANEY ISLAND REACH

LEGEND:

- EXISTING SURFACE
- REQUIRED DEPTH EL -55
- REQUIRED ADVANCE MAINTENANCE DEPTH EL -56
- PAID ALLOWABLE DEPTH EL -57 + 1' NON-PAY OVERDREDGE EL -58

10' 0' 10' 20'
VERTICAL SCALE: 1"=20'

100' 0' 100' 200'
HORIZONTAL SCALE: 1"=200'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 11 - SECTIONS - CRANEY ISLAND REACH

moffatt & nichol

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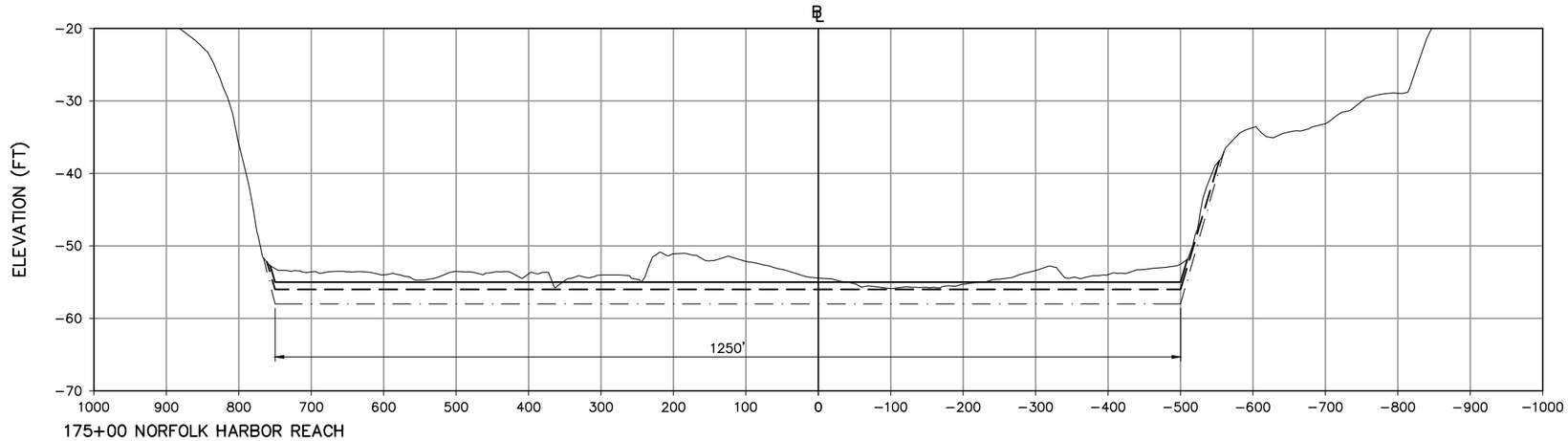

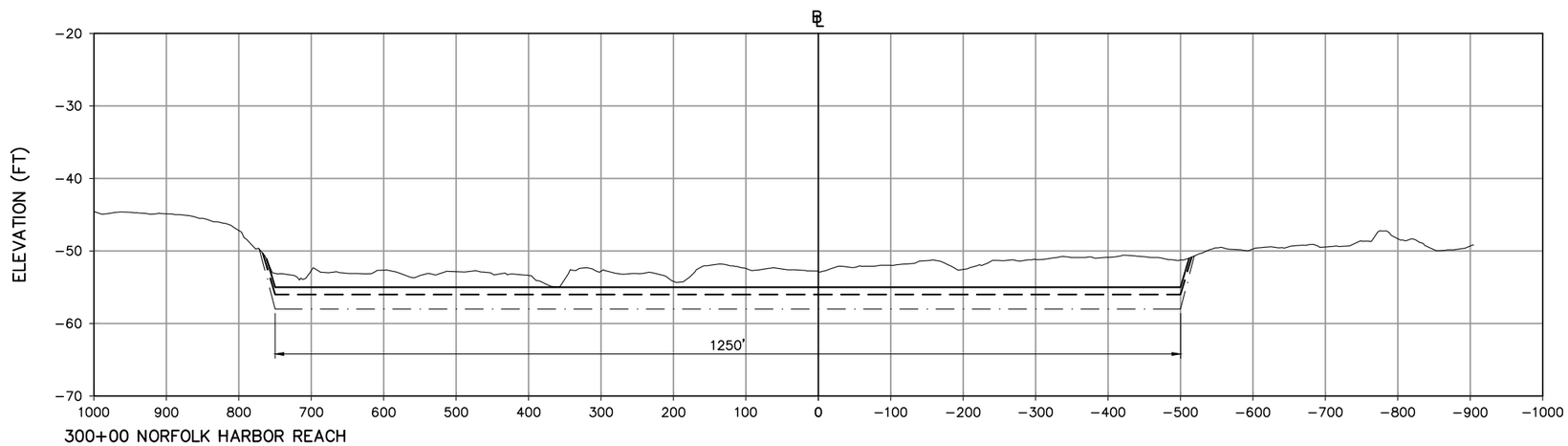

LEGEND:

- EXISTING SURFACE
- REQUIRED DEPTH EL -55
- REQUIRED ADVANCE MAINTENANCE DEPTH EL -56
- PAID ALLOWABLE DEPTH EL -57 + 1' NON-PAY OVERDREDGE EL -58

10' 0' 10' 20'
VERTICAL SCALE: 1"=20'

100' 0' 100' 200'
HORIZONTAL SCALE: 1"=200'

NAVIGATION HARBOR AND CHANNEL DEEPENING STUDY

PLATE 12 - SECTIONS - NORFOLK HARBOR REACH

moffatt & nichol

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Engineering Appendix B: Geotechnical Study

FUGRO CONSULTANTS, INC.

GEOTECHNICAL EVALUATION
NORFOLK HARBOR AND CHANNELS
DEEPENING STUDY
HAMPTON ROADS, VIRGINIA

Prepared for:
MOFFATT & NICHOL

May 2016

Fugro Project No. 04.81150012

May 3, 2016
Project No. 04.81150012

Moffatt & Nichol, Inc.
800 World Trade Center
Norfolk, Virginia 23510

Attention: Mr. Ira Brotman, P.E.

Subject: Geotechnical Evaluation, Norfolk Harbor and Channels Deepening Study, Hampton Roads, Virginia

Dear Mr. Brotman:

Fugro Consultants, Inc. (Fugro) is pleased to submit this geotechnical evaluation of subsurface conditions in the Norfolk Harbor and Channels. This report has been prepared by Fugro to summarize our geotechnical evaluation of sediments within Norfolk Harbor and Channels. Sediments are characterized in this study using available historical subsurface and bathymetric data. The objective of this study is to provide geotechnical characterization of materials that may be dredged as part of future navigation improvements in the Norfolk Harbor and Channels.

The work was performed in accordance with Moffatt & Nichol's Subconsultant Agreement, Moffatt & Nichol, Inc. (M&N) Project number 8885-01 dated November 10, 2015.

We appreciate the opportunity to support the Norfolk Harbor and Channels Deepening Study. Please let us know if you have any questions or if we may be of further assistance

Sincerely,
FUGRO CONSULTANTS, INC.

Kevin Smith
Associate Engineering Geologist

Haitham Dawood, Ph.D.
Staff Engineer

Bill Mack, P.E.
Senior Engineer

Copies Submitted: 1 electronic

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1.0 INTRODUCTION

This report presents the findings of a desktop study intended to provide geotechnical characterization of sediments anticipated to be encountered during dredging within the federal navigation channels of the Norfolk Harbor and associated channels. Figure 1 presents the location of the study area. This evaluation was conducted in support of the navigation improvements study being performed by the United States Army Corps of Engineers (USACE) and the Virginia Port Authority.

The objective of this study is to characterize the physical properties of the near surface sediments within Norfolk Harbor and Channels study area based on available historical data. Information presented in this report can be used by project partners to aid their assessment of the placement options for future dredged material. The navigation channels studied include (Figure 1):

- Atlantic Ocean Channel,
- Thimble Shoal Channel,
- Norfolk Harbor Entrance Reach,
- Norfolk Harbor Reach,
- Craney Island Reach, and
- Newport News Channel.

This report provides a description of the data compiled and reviewed in this study and presents a summary of our geotechnical evaluation of the subsurface material characteristics based on those data. Maps, cross sections, and graphs of geotechnical data used to aid our evaluation are included in this report.

1.1 AUTHORIZATION

This geotechnical study was authorized under Project No. 8885-01 dated November 10, 2015 between Moffatt & Nichol and Fugro. We performed our services in general accordance with the scope of work outlined in Fugro Proposal No. 04.81159023 dated July 8, 2015.

1.2 STUDY METHODOLOGY

We conducted a literature search to identify, collect and synthesize existing bathymetric and geotechnical data. We also utilized geotechnical and geological information from Fugro's in-house Hampton Roads Database to support this study. Relevant data were synthesized into a GIS database that was used to characterize existing water depths and subsurface conditions within potential future dredging envelopes.

We also used bathymetry data collected in channel conditions assessment surveys conducted in 2010, 2014 and 2015. Those data were provided to Fugro and Moffatt & Nichol by the USACE during the study.

Geotechnical data compiled during this study were collected by various companies between 1981 and 2009 using a variety of sampling and in-situ testing methods. Locations of the explorations are presented on Figure 2. Those exploration methods utilized vibracores, gravity cores, grab samplers, boreholes, cone penetration test (CPT) soundings to collect samples and perform in situ testing. Geotechnical data, including laboratory test results, related to those explorations were reviewed and assimilated into the project GIS database used in this study.

Subsurface sediments were characterized in each channel reach using the compiled geotechnical data. The extent of each channel reach is presented in Figure 1. Based on the reviewed data, generalized subsurface material type zones were defined as shown on Figure 3. Subsurface material type zones are also presented on a series of plan and profiles. Subsurface profile locations, key to symbology used on the profiles, and subsurface cross sections are presented on Figures 4 through 6.

Subsurface material type zone boundaries were selected based on approximate boundaries between generalized material types and channel reach boundaries shown in Figure 1. Physical characteristics of the sediments used to delineate the different zones include soil classification, fines content, and Atterberg limits. Section 6 of this report provides a description of material types in each zone. The sediment characterization is provided in terms of elevation to assist in choosing the optimum dredging elevation within each reach.

M&N provided Fugro with the authorized depths for the different reaches. The authorized depths are shown on the cross sections in Figures 5 and 6 and also summarized in Table 1.

2.0 BATHYMETRIC DATA

USACE Norfolk District provided bathymetric survey data from the recent condition surveys performed within the harbor and channels. Table 1 provides a summary of the survey dates for the respective channel reach bathymetries. The survey data were input into the Fugro GIS database and used to create three dimensional bathymetric surfaces and contours displayed on the cross sections and maps in this report. Channel bottom elevations within each reach and dates of surveys that the elevations are based upon are summarized in Table 1. Note that the channel bottom elevations listed in Table 1 do not include the channel slope and accretionary (shoal) areas that may be present along the toe of the channel slopes.

Table 1. Current Bathymetric Data Summary

Reach	Most Recent Reported Survey Date	Sub-Reach Figure	Average Channel Bottom Elevation[a] (ft)	Channel Bottom Elevation Range within Center of Channel[b] (ft)	Authorized Channel Bottom Elevation[a] (ft)
Atlantic Ocean Channel Reach	June 2014		-60	-54 to -65	-57
Thimble Shoal Channel Reach	June 2014	Figure 5d	-62	-61 to -66	-55
		Figure 5e	-65	-60 to -67	
		Figure 5f	-67	-65 to -70	
		Figure 5g	-60	-58 to -65	
		Figure 5h	-55	-51 to -60	
		Figure 5i	-51	-50 to -53	
		Figure 5j	-51	-50 to -52	
		Figure 5k	-58	-52 to -80	
		Figure 5l	-78	-60 to -95	
Norfolk Harbor Entrance Reach	November 2014 and July 2010		-58	-54 to -62	-55
Norfolk Harbor Reach	November 2014		-53	-52 to -62	-55
Craney Island Reach	November 2014		-55	-50 to -56	-55
Newport News Channel Reach	March 2015	Figure 5q	-55	-52 to -57	-55
		Figure 5r	-55	-55 to -60	
		Figure 5s	-62	-58 to -72	

[a] Elevations reference Mean Lower Low Water (MLLW)

[b] Elevation range does not include the channel side cut and localized areas where bathymetry is lower due to scour, utility trenches, or localized dredging

3.0 HISTORICAL GEOTECHNICAL DATABASE

Fugro's Hampton Roads geotechnical database was used to supplement this desktop study. Fugro maintains a GIS-based database that includes geotechnical, environmental, geophysical and bathymetric data within the Hampton Roads region. Readily available historical data collected from several investigations conducted within the studied area were also integrated into Fugro's existing GIS database. The geotechnical exploration types consist of grab samples, vibracore, soil borings and cone penetrometer tests. Prior to mapping, the data was reviewed for consistency between soil classification schemes, coordinate systems and datums, quality, and relevance.

The data was originally presented in the following reports:

- United States Army Corps of Engineers, Norfolk District (1986), "*Geology and Soils Subsurface Investigation, Norfolk Harbor Channel, Norfolk Harbor and Channels, Virginia,"* dated June 1986.
- Fugro (2008). "*Geotechnical Data Report, Seabed Testing and Marine Drilling Programs, Craney Island Eastward Expansion,*" prepared for Craney Island Design Partners, LLC, dated January 2008.
- S&ME, Inc (2009). "*Craney Island Eastward Expansion, Geotechnical Evaluation of Potential Offshore Borrow, Atlantic Ocean Channel, Thimble Shoals Channel, Newport News Channel and Anchorages: Appendix IV – NNCA Geophysical Report and Lab Data*," prepared for U.S. Army Corps of Engineers, dated July 2009.
- Virginia Institute of Marine Science, School of Marine Science, College of William and Mary (1981). "*Appendix E: Core Logs and Grain Size Analyses for Composite Sediment Samples*," prepared for the Coastal Erosion Abatement Commission, Commonwealth of Virginia.
- Exmar (1990). "Subsurface Investigation by Vibracoring, Atlantic Ocean Channel, Thimble Shoal Channel, and Off Sandbridge," prepared for U.S. Army Corps of Engineers.
- Fugro (2009) "Site Characterization Report, Atlantic Ocean Channel, Offshore Southeastern Virginia," prepared for Craney Island Design Partners, LLC, dated November 2009.

The following sections will briefly introduce the data presented in each report that are relevant to this study. Figure 2 shows the location of the different explorations used in this study.

3.1 USACE (1986; VIBRACORES)

The U.S. Army Corps of Engineers in support of a previous Norfolk Harbor and Channel Deepening Project performed multiple subsurface investigations within the Norfolk Harbor Channel located in the Elizabeth River and Hampton Roads Harbor, Virginia (May 1983, August 1984, and July 1985). The purpose of the study was to identify sediment type characteristics to a El.-58 feet (MLLW) and to assess the suitability of the dredge material within the project site for engineering construction. Exploration identification prefixes used in this study are CEA83V, CEC83V, CED83V, and CED85V.

Eighty-two (82) vibracore explorations were completed between May 4, 1983 and July 31, 1985. The vibracores were advanced to depths of 14.5 to 39.5 feet below mudline (most performed to a depth of 20 feet below mudline). The laboratory testing program consisted of grain size distribution, fines content from No. 200 wash sieves, Atterberg limits, dry unit weight, and specific gravity.

3.2 FUGRO (2008; CPT SOUNDINGS)

As part of the Craney Island Eastward Expansion project, Fugro performed 126 cone penetration test (CPT) soundings. The soundings were advanced to depths ranging from approximately 57 to 142 feet below the mudline, with an average completion depth of 108 feet. The CPT soundings were performed using the Roson seabed system. Exploration identification prefix used in this study is FA07C.

Two of these CPT soundings were performed within the limits of the channels. The two soundings were advanced between June 30, 2007 and July 20, 2007. These soundings were advanced to depths of 86.0 and 97.3 feet below mudline.

3.3 S&ME, INC (2009; MINI-CPT SOUNDINGS AND VIBRACORES)

S&ME conducted a site investigation to locate offshore zones with sediments that could be used in the construction of the Craney Island Eastward Expansion. A total of 68 vibracores and 30 CPT soundings were advanced as part of this study. Exploration identification prefixes used in this study are SA07BC and SA07BV.

The area of interest contained forty-one (41) mini-cone penetration test (mCPT) soundings and forty-six (46) vibracore explorations that were performed from October 29, 2007 to December 17, 2007. The mCPT soundings recorded depth, tip resistance and sleeve resistance however the system did not record pore pressure data. The soundings were advanced to depths of approximately 7 to 33 feet below mudline. The vibracore explorations were advanced to depths of approximately 4 to 20 feet below mudline. The laboratory testing program included grain size distribution and Atterberg limits.

3.4 VIRGINIA INSTITUTE OF MARINE SCIENCE (1981; VIBRACORES)

Ten (10) vibracore explorations were advanced between July 24, 1980 and February 1, 1982. The vibracores were advanced to depths of approximately 20 to 35 feet below mudline. Grain size distribution was the only laboratory test data reported for these vibracores. Exploration identification prefix used in this study is VIB81V.

3.5 EXMAR (1990; VIBRACORES)

Exmar under contract to the US Army Corps of Engineers, Norfolk District collected samples from a total of 162 vibracores within the Atlantic Ocean Channel, Thimble Shoal Channel, and within the waters near Sandbridge. The laboratory testing program consisted of grain size distribution, moisture content, specific gravity, dry unit weight, and moist unit weight. A total of 82 vibracores from the study referenced above are located within the area of interest of this project. These vibracore explorations were advanced to depths of approximately 10 to 20 feet below the mudline. Exploration identification prefix used in this study is CEA90V.

3.6 FUGRO (2009; MCPT SOUNDINGS AND VIBRACORES)

S&ME was contracted to the USACE to complete a total of 61 mCPT soundings and 25 vibracores. Alpine Ocean Seismic Survey, LLC conducted the vibracores and ConeTec, Inc. conducted the mCPT soundings. The study was conducted between October and December of 2008. The investigation included the Cape Henry Channel and Atlantic Ocean Channel. A total of 18 mCPT and 5 vibracores were completed within the area of interest of this project. The laboratory test results include moisture content, Atterberg limits, and grain size distribution. The data was presented and discussed in details in a report by Fugro Atlantic dated November 2009. These vibracore explorations were advanced to depths of approximately 4 to 32 feet below the mudline. Exploration identification prefixes used in this study are SA08BC and SA08BV.

3.7 SUMMARY OF THE AVAILABLE GEOTECHNICAL DATA

Two hundred eighty-six historical explorations from 6 historical site investigations were identified to be within the navigation channels or its vicinity and were used in this study. Those explorations consist of 225 vibracores and 61 cone penetrometer tests (CPT). The exploration locations are shown in Figure 2. Table 2 provides a summary of the explorations, year they were conducted, and exploration type.

Table 2. Summary of Exploration Data Sources

Report	Exploration Type	Quantity within or adjacent to the navigation channels
USACE (1986)	Vibracores	82
Fugro (2008)	CPT Soundings	2
S&ME (2009)	mCPT Soundings and Vibracores	41 mCPT and 46 vibracores
VIMS (1981)	Vibracores	10
Exmar (1990)	Vibracores	82
Fugro (2009)	mCPT Soundings and Vibracores	18 mCPT and 5 vibracores

4.0 INTERPRETATION OF CPT AND MCPT DATA

CPT and mCPT soundings provide a near-continuous record of sleeve friction and cone tip resistance. The friction ratio, expressed as a percent, is computed by dividing the sleeve friction measurement taken at the depth of the center of the sleeve by the average of the tip resistance measured over the length of the sleeve.

Empirical relationships between CPT measurements and soil classifications have been derived from thousands of measurements for varying classifications of soils. Robertson and

Campanella (1988) proposed a chart that divides the graph of tip resistance versus friction ratio into 12 soil classification zones. This chart is shown in Figure 4b. The CPT measurements can be associated with a specific soil classification zone. Hence, this chart was used to differentiate between primarily fine-grained and primarily coarse-grained soil layers. Moreover, procedure by Robertson and Wride (1998) was used to estimate the percentage of fine-grained materials within the different layers.

The methods referenced above were used to estimate the different engineering parameters using data from CPT and mCPT soundings. It should be noted that these procedures are typically developed based on data from full-size cones (e.g. 15 cm^2). Hence, caution should be exercised when using engineering properties empirically derived from field data collected by mini-CPT (mCPT).

5.0 CROSS SECTIONS

Centerline cross sections of the navigation channels are presented on Figures 5a through 5s. Transverse cross sections at selected locations along the navigation channels are presented on Figures 6a through 6f. The cross sections were developed using proprietary software and Environmental Systems Research Institute's (ESRI) ArcGIS program. ArcGIS is a software package used by Fugro for mapping spatial data. Logs of vibracores, boreholes, CPT, and mCPT soundings are set to the same vertical scale and projected onto the line of cross section. The sections also project the recent bathymetric survey data onto the line of the section at the same vertical scale of the other exploration.

The cross sections present several key pieces of information including:

- Soil type as logged and classified from vibracores and boreholes;
- CPT tip resistance, friction ratio, and soil behavior type;
- Standard penetration test blow counts;
- Fines content from laboratory tests;
- Authorized channel depth; and
- Bathymetry based on the most recent USACE condition survey (refer to Table 1 for a summary of the data).

The vertical and horizontal scales for the cross sections are 1 inch = 20 feet and 1 inch = 1,000 feet, respectively. The directional convention used in reading the cross sections is station advance in the western direction, thus the cross sections should be read from right to left in the direction of advancing station.

6.0 GEOLOGY AND GENERAL STRATIGRAPHIC CONDITIONS

6.1 GEOLOGIC SETTING

The study area is located in the Coastal Plain physiographic province. Flat-lying plains and terraces dominate the landscape. The Coastal Plain is underlain by a wedge of Cretaceous to Holocene age sediments that thicken to the east. Jurassic-Triassic age basement rocks lie

approximately 1,800 feet beneath the study area. The wedge of Cretaceous and younger sediments was deposited as a result of multiple marine transgressions and regressions. Sediments within the upper 100 feet beneath the site are Pliocene to Recent in age. The Pliocene age and younger sediments have been deposited and subsequently eroded in places during the rising and falling sea levels that resulted from glacial and interglacial periods.

The waterbodies in which the channels are located include the Elizabeth River, James River, Chesapeake Bay, and Atlantic Ocean. The Elizabeth River is a sub-estuary of the James River, the most southern tributary of the Chesapeake Bay. Surficial and shallow sediments in the Elizabeth and James Rivers and Chesapeake Bay are inferred to be Holocene age predominantly fine-grained sediments but may include large bodies of sand with variable amounts of silt and clay. In the Atlantic Ocean on the inner continental shelf, the surficial and shallow materials are predominantly silty sand marine deposits. Pleistocene aged deposits from the Tabb formation comprised of interbedded sand and fine-grained sediments or predominantly sand bodies typically underlie the Holocene deposits. Pliocene aged deposits from the Yorktown formation commonly underlie the Quaternary deposits. Locally, the Pleistocene and Yorktown formation deposits may be eroded completely away.

Two high tides and two low tides occur each day in the James and Elizabeth Rivers. Tidal range at NOAA's Sewell's Point Station No. 8638610 located on the Norfolk Harbor Reach is about 2.7 feet.

Human-related factors that could influence channel deepening activities are the presence of utilities that cross the river. The Monitor Merrimac, Hampton Roads, and Chesapeake Bay Bridge Tunnel systems have tunnel components that cross beneath channels included in this study (Figure 1). Channel deepening may require some utilities to be relocated to deeper depths in order to accommodate dredging. Inventorying and verifying vertical positions of utility crossings is not part of the current study.

6.2 SUBSURFACE CONDITIONS

Every channel/reach is divided into a single or multiple zone(s) based on the available geotechnical data. Each zone delineates an area where the physical characteristics of the marine sediments are similar. Physical characteristics used for delineating the different zones included soil classification, fines contents, median grain size and Atterberg limits. The sediments are characterized up to the maximum depth of available explorations within each zone. Most of the exploration depths range from about 5 to 20 feet below the most recent bathymetric survey data (Figures 5a through 5s).

Figure 3 shows the limits of the different zones identified within the study area. Figure 4a shows the locations of the different longitudinal and transverse cross section on the map. Longitudinal cross sections showing physical characteristics by zone are presented on Figures 5a through 5s and transverse cross sections showing physical characteristics by zone are presented on Figures 6a through 6f.

As shown in Figure 3, the name of each zone starts with a prefix letter(s) that denotes the name of the channel/reach (e.g., A = Atlantic Ocean Channel, T = Thimble Shoal Channel). This prefix is followed by the zone number. The zone number sequential beginning at the entrance of each channel/reach. The zone number is increased in the direction of ships entering from the Atlantic Ocean. It is worth mentioning that the subsequently reported zones are highly generalized material type zones that were delineated based on a limited amount of shallow explorations and laboratory tests.

Grain size characteristics are the primary factors in determining suitability and performance of dredge material for use in construction. Primary criteria considered in engineering evaluations in this study were fines content, particle size distribution, and median (D50) grain size. Grain size curve data was compiled and entered from the different historical reports. Figures 7a through 7f present the grain size curves in each reach. The fines content profiles derived from laboratory tests and mCPT soundings for the different reaches are presented on Figures 8a and 8f. Fines content was estimated from mCPT data using the procedure by Robertson and Wride (1998). As shown in Figures 8a through 8f, the fines content estimates from mCPT data using Robertson and Wride (1998) are generally in agreement with the laboratory test data. Median (D_{50}) grain size profiles are presented on Figures 9a through 9f. Atterberg limits and water content profiles are presented on Figures 10a through 10f. Each one of the aforementioned figures present data from a specific reach. The data presented in each figure is grouped by zones within each reach.

Soil characteristics are described in the region to a depth where data collection supports classification using a combination of field and available laboratory testing. There is the potential for variation of sediment over relatively short distances within the harbor and channels due to changes commonly seen in the subsurface as a result of sea and river bed morphology.

6.2.1 Atlantic Ocean Channel Reach

Figures 5a through 5d show the plan views and vertical cross sections along with the explorations available in this reach. Four different zones were identified within the Atlantic Ocean Channel as follows (the distances presented are approximate and are measured from the eastern (offshore) entrance of the channel):

- **Zone A1: Exploration CEA90V56A to CEA90V28A (Between approximately 0 and 24,000 feet).** The sediments in this zone are predominantly sands. Grain sizes are distributed between fine and coarse grained sandy materials (poorly graded sand to silty sand). Soil properties within this zone are similar above El. -63 feet. Fines contents are less than 25% from the existing mudline to El. -63 feet in this zone and less than 13% between El. -63 and El. -75 feet in this zone (Figures 5a, 5b, 7a, 8a, 9a and 10a). Above El. -63 feet, the sand particles are distributed between fine and coarse grained (Figure 9a). Below El. -63 feet the sand in this zone is mostly coarse grained (Figures 7a and 9a). The authorized dredge line elevation lies above the mudline elevation over most of this zone (Figures 5a and 5b).

- **Zone A2: Exploration CED83V109 to CED85V176 (Between approximately 24,000 and 48,000 feet).** Sediments up to El. -75 feet are predominantly sands with some silts and clays (Figures 5b through 5d, 6a, 7b, 8a, 9a, and 10a). Due to the relatively high fines content in some regions, the top strata was identified as silt using data from CPT soundings. An exception is the area between CED85V181 and CED85V180 which consists of fat clay (92 to 96% fines content) which adds scatter to the data shown in Figure 8a for Zone A2. This could possibly be a paleochannel that was filled with fine grained sediments. Sand properties are similar within the zone above El. -60 feet. Above El. -60, sand particle size ranges from fine to coarse. Below El. -60, the sand is predominantly coarse grained. The authorized dredge line elevation lies above the mudline elevation over most of this zone (Figures 5b through 5d).

- **Zone A3: Exploration CED83V101 to SA07BV003 (Between approximately 48,000 and 59,000 feet).** The sediments (up to El. -70 feet) are predominantly clays (Figures 5d, 7c, 8a, , 9a and 10a). The clays in this zone were predominantly classified as fat clays. The authorized dredge line elevation lies above the mudline elevation over most of this zone (Figure 5d).

6.2.2 Thimble Shoal Channel Reach

Six different zones were identified within the Thimble Shoal Channel as follows (the distances presented are approximate and are measured from the eastern edge of the Thimble Shoal Channel). Figures 5e through 5l show the plan views and vertical cross sections along with the explorations available in this reach.

- **Zone T1: Exploration eastern end of the Thimble Shoal Channel to SA07BV123 (Between approximately 0 and 26,000 feet).** No data is available within this reach (Figures 5e and 5f). The material properties could be similar to the material encountered within Zones A3 or T2.

- **Zone T2: Exploration SA07BV123 to SA07BV120 (Between approximately 26,000 and 30,000 feet).** The sediments below the existing mudline (up to El. -70 feet) are predominantly clays with some sands (Figures 5g, 7d, 8b, 9b and 10b). Sand particle size is fine grained (Figure 9b). The majority of clayey materials within this zone were classified as lean clays. The authorized dredge line elevation lies above the 2014 bathymetry (Figure 5g).

- **Zone T3: Exploration CEA90V32T to CEA90V02T (Between approximately 30,000 and 49,500 feet).** Figures 5g through 5h show the plan views and vertical cross sections along with the explorations available in this zone. The sediments consist of predominantly sands underlain with silts and clays (Figures 5g, 5h, 6b, 7e, 8b, 9b and 10b). The thickness of the upper sandlayer varies between 2 and 10 feet. The sand within this zone is predominantly coarse in size (Figure 9b). Along the majority of this zone, the authorized dredge line elevation lies above the 2014 bathymetry (Figure 5h). The limited amount of explorations available within the material that may be dredged

within this zone are highly heterogeneous (i.e., wide range of fines contents and material behavioral types; Figure 5h).

- **Zone T4: Exploration CEA90V02T to VIB81V024 (Between approximately 49,500 and 72,500 feet).** This zone consists of predominantly sand (Figures 5h, 5i and 5j). There were no laboratory tests conducted on the soils encountered within this zone. There may be soil variations within this zone that are not identified by the two field testing locations available in this reach.

- **Zone T5: Exploration VIB81V022 to VIB81V080 (Between approximately 72,500 and 99,000 feet).** The materials in this zone consisted predominantly of clays and silts (Figures 5j, 5k, 7f). The laboratory data for this zone consisted of only one sieve analysis (Figure 7f). Clays in this zone were predominantly classified as fat clays. There may be soil variations within this zone that are not identified by the limited field testing available in this reach.

- **Zone T6: Exploration VIB81V080 to CEC83V031 (Between approximately 99,000 and 115,500 feet).** There is no available geotechnical data within this portion of the Thimble Shoal Channel (Figure 5l).

6.2.3 Norfolk Harbor Entrance (E1), Norfolk Harbor (NH1), and Craney Island (C1) Channel Reaches

Figures 5m through 5p show the plan views and vertical cross sections along with the explorations available in these three reaches. Figures 6c through 6e show the transverse cross sections within these three reaches. The top 15 feet below the existing mudline within these zones consists of predominantly clays and silts (Figures 7g through 7i, 8c through 8e, 9c through 9e and 10c through 10e). The clays are predominantly classified as fat clay. Three explorations in this zone (SA07BV190, CEC83V072; and CEC83V021B; Figures 5o and 5p) consisted predominantly of sands. These explorations could have been drilled through paleochannels that were filled with coarse grained material over time. Two explorations (CSC83V022 and CE83V017; Figures 5n and 5o) showed some layered sands along with silts and clays. The soils located above the authorized dredge line elevation are mostly classified as clayey and silty material (Figures 5m through 5p).

6.2.4 Newport News Channel Reach

Two different zones were identified within the Newport News Channel. Figures 5q through 5s show the plan views and vertical cross sections along with the explorations available in this reach. The zones in this reach are as follows:

Zone N1: Exploration CEB83V006 to SA07BV128 (From the eastern end of Newport News channel to approximately 1,500 feet west of the Monitor–Merrimac Memorial Tunnel). The upper layer on the western side of this zone consists of predominantly sandy materials. This layer starts to gradually dip from west to east below a predominantly clayey layer (Figures 5q, 5r, 7k, 7k, 8f, 9f and 10f). The clayey soil strata start to appear at around

13,000 feet east of Monitor–Merrimac Memorial Tunnel (Figure 5q) and reaches a thickness of approximately 5 feet at about 15,500 feet east of the Monitor–Merrimac Memorial Tunnel. The clayey materials are mostly classified as fat clay and organics. The sand within this zone is mostly fine sand (Figure 9f). The soil located above the authorized dredge line elevation is mostly sandy material (Figures 5q through 5r). It is important to note that the explorations performed along the transverse cross section within this zone (Figure 6f) show significantly different material classifications and fines contents.

Zone N2: Exploration SA07BV128 to SA07BV154 (From the western end of Newport News channel to approximately 2,000 feet west of the Monitor–Merrimac Memorial Tunnel). The layer that extends approximately 10 feet below the bathymetric line surveyed in 2015 consists of predominantly fat clays (Figures 5r, 5s, 7k, 8f, 9f and 10f). The authorized dredge line elevation lies well above the mudline elevation over most of this zone (Figures 5r and 5s).

6.3 BENEFICIAL USE OF DREDGED MATERIALS

Disposal of dredged materials can be accomplished by placing them at designated disposal areas like the Craney Island Dredge Material Management Area (CIDMMA) or ocean disposal areas (e.g. Dam Neck Ocean Disposal Site or Norfolk Ocean Disposal sites). Use of ocean disposal sites can be costly to due long vessel transit times or can use up highly valued storage at CIDMMA, a facility that is approaching its storage capacity. An alternative to using CIDMMA or ocean disposal areas, is to use the dredged materials for beneficial use in various projects around the area. Evaluation of dredge materials for use in other projects is usually based on geotechnical properties including fines content and median particle size (e.g. d_{50}) and environmental characteristics. Evaluation of the potential use of dredge materials for some project types (e.g. beach renourishment) may also be based on material colors and shell content. Typical types of projects that derive benefit from dredging projects include:

- Land reclamation (high quality fills or lower quality fills for shading materials or surcharge),
- Beach renourishment and shoreline stabilization,
- Riverbed restoration projects,
- Sea grass, shallow water habitat creation, or environmental improvement projects, or
- Confined underwater disposal areas.

Land reclamation and beach nourishment projects typically have the strictest requirements for material specification and typically target materials with low fines content. Fines content requirements are typically less strict for riverbed restoration and environmental improvement projects. Confined underwater disposal areas may utilize fine-grained deposits with a low permeability for construction.

Table 3 provides a summary of where historical geotechnical data, when compared to recent bathymetric data, indicate that sandy deposits may be located at the existing channel bottom or within 5 feet of the channel bottom. Indication of the potential beneficial use is based solely on whether the material is predominantly sand and note suitability for use as fill in

projects with strict material specifications. Based on the information presented in the profiles in Figure 5 and Table 2, the data indicate that sandy deposits may be present at or near the channel bottom in some portions of the study area.

Table 3. Summary of the Potential for Beneficial Use

Reach	Figure	Material Type Zone	Potential for Beneficial Use	Comments Based on Evaluation of Historical Data
Atlantic Ocean Channel Reach	5a & 5b	A1	High(?) – channel may be deep enough to accommodate post-Panamax	Sand is very high quality
	5b & 5c	A2	High; but includes clay channel infills	Potential for beneficial use is based predominantly on if sand is present within 5 feet of existing channel bottom.
	5d	A3	Low	Thin layer of sand deposits overlie fine-grained deposits
Thimble Shoal Channel Reach	5d – 5f	T1	Unknown	No data
	5g	T2	Low	Thin layer of sand deposits overlie fine-grained deposits
	5g & 5h	T3	Moderate	High quality sand is present; may include fine grained deposits locally or beneath sand
	5i & 5j	T4	Low to Moderate	Limited amount of data
	5k	T5	Low(?)	Limited amount of data
	5l	T6	Low; Channel bottom naturally deep (>62 feet)	No data
Norfolk Harbor Entrance Reach	5m	E1	Low	Predominantly fine-grained
Norfolk Harbor Reach	5n & 5o	NH1	Low	Predominantly fine-grained; may contain sand locally with 15 to 45% fines
Craney Island Reach	5p	C1	Low to Moderate	Predominantly fine-grained; may contain sand locally with 2 to 25% fines
Newport News Channel Reach	5q & 5r	N1	Moderate	Channelized deposits; sand with 15 to 45% fines; anchorages may contain significant sand
	5s	N2	Low	Predominantly fine-grained

Potential for beneficial use is based predominantly on if sand is present within 5 feet of existing channel bottom.

7.0 REFERENCES

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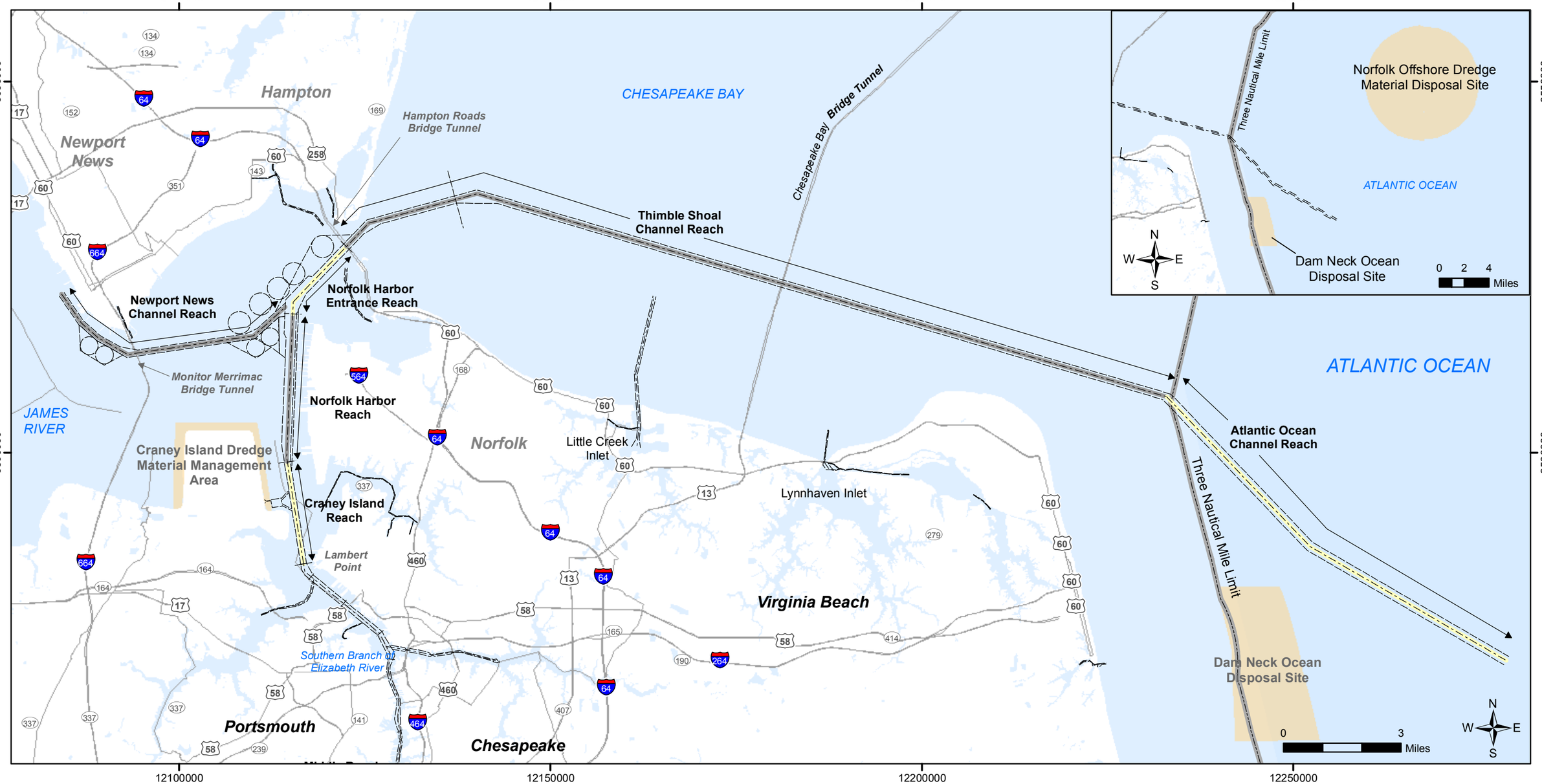
FIGURES



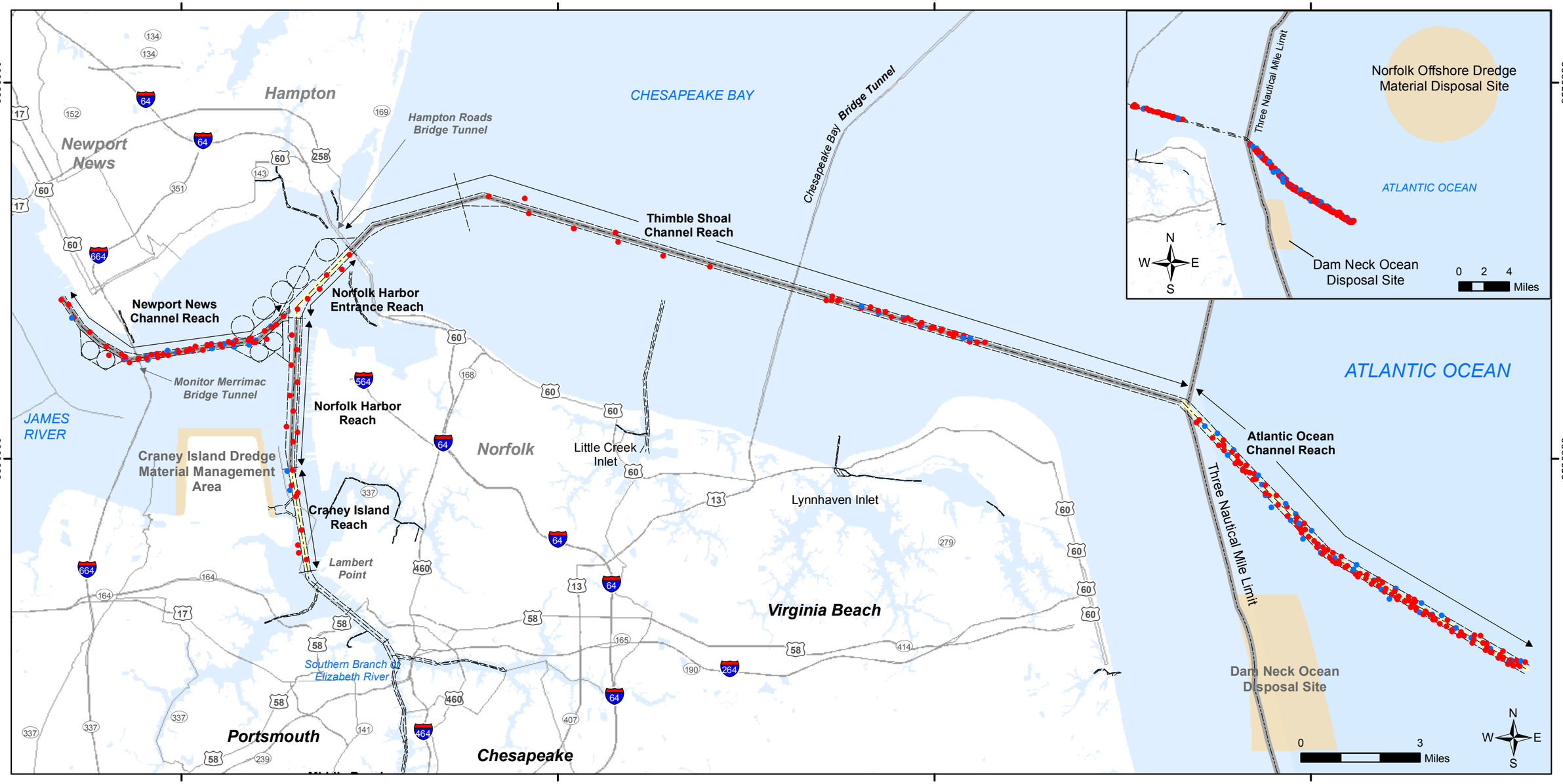
LEGEND

- Reach Boundary
- Channel Centerline
- Navigation Channel Boundary

STUDY AREA
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 1

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Figure1_Location_Map.mxd, 4/28/2016, wcupples



LEGEND

- Reach Boundary
- Channel Centerline
- Navigation Channel Boundary

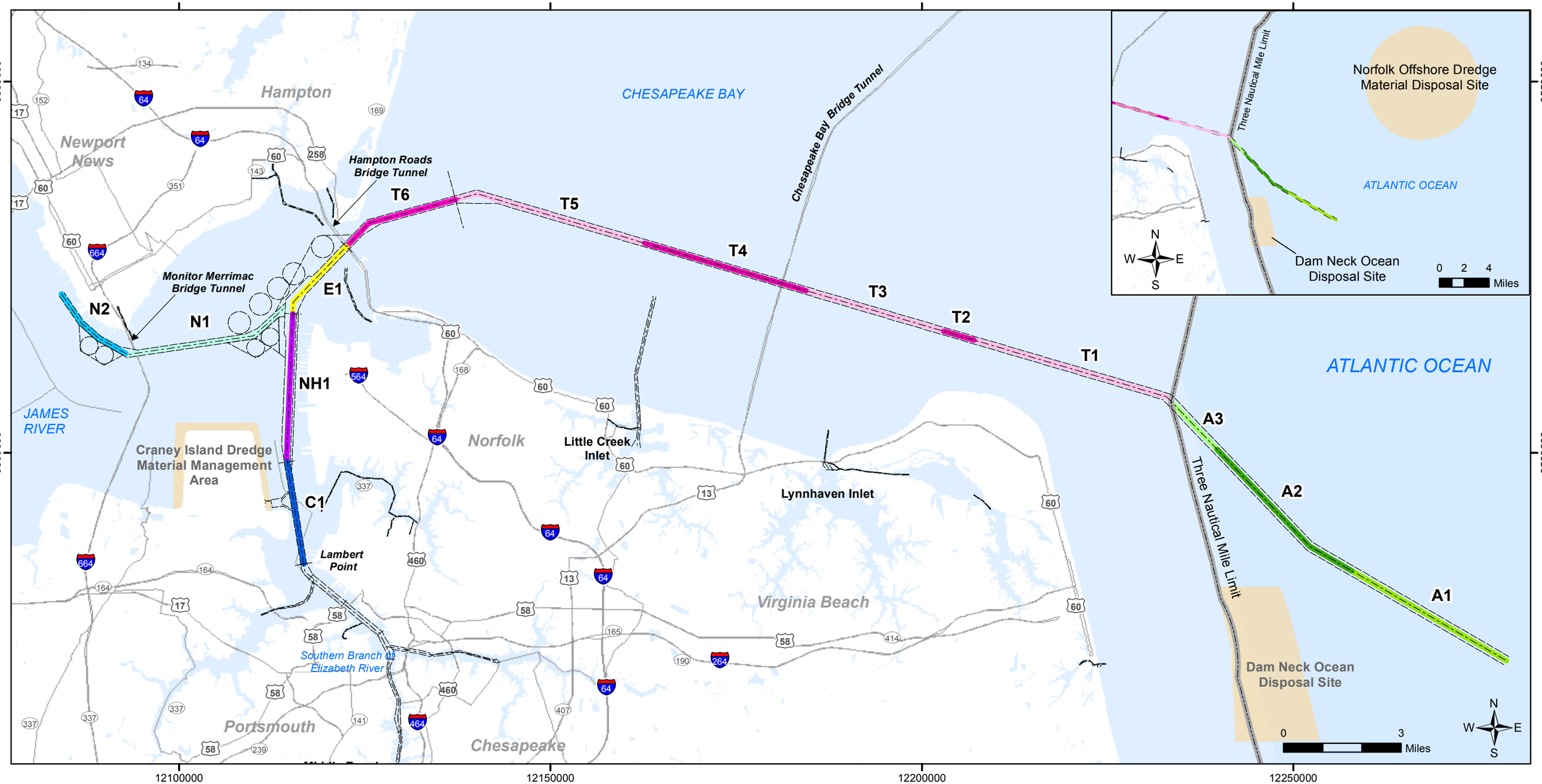
Historical Subsurface Explorations

- Existing Boring/Vibracores data used in this study
- Existing CPT data used in this study

EXPLORATION LOCATIONS
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 2

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Figure1_Location_Map.mxd, 4/28/2016, wcupples



Coordinate grid is in Virginia State Plane, South Zone, NAD83, Feet

Legend

A3 — Generalized Subsurface Material Type Zone
Zones interpreted to represent generalized material types that may be encountered during channel deepening. Interpretation based on review of historical subsurface data. Refer to report text for description of interpreted material types.

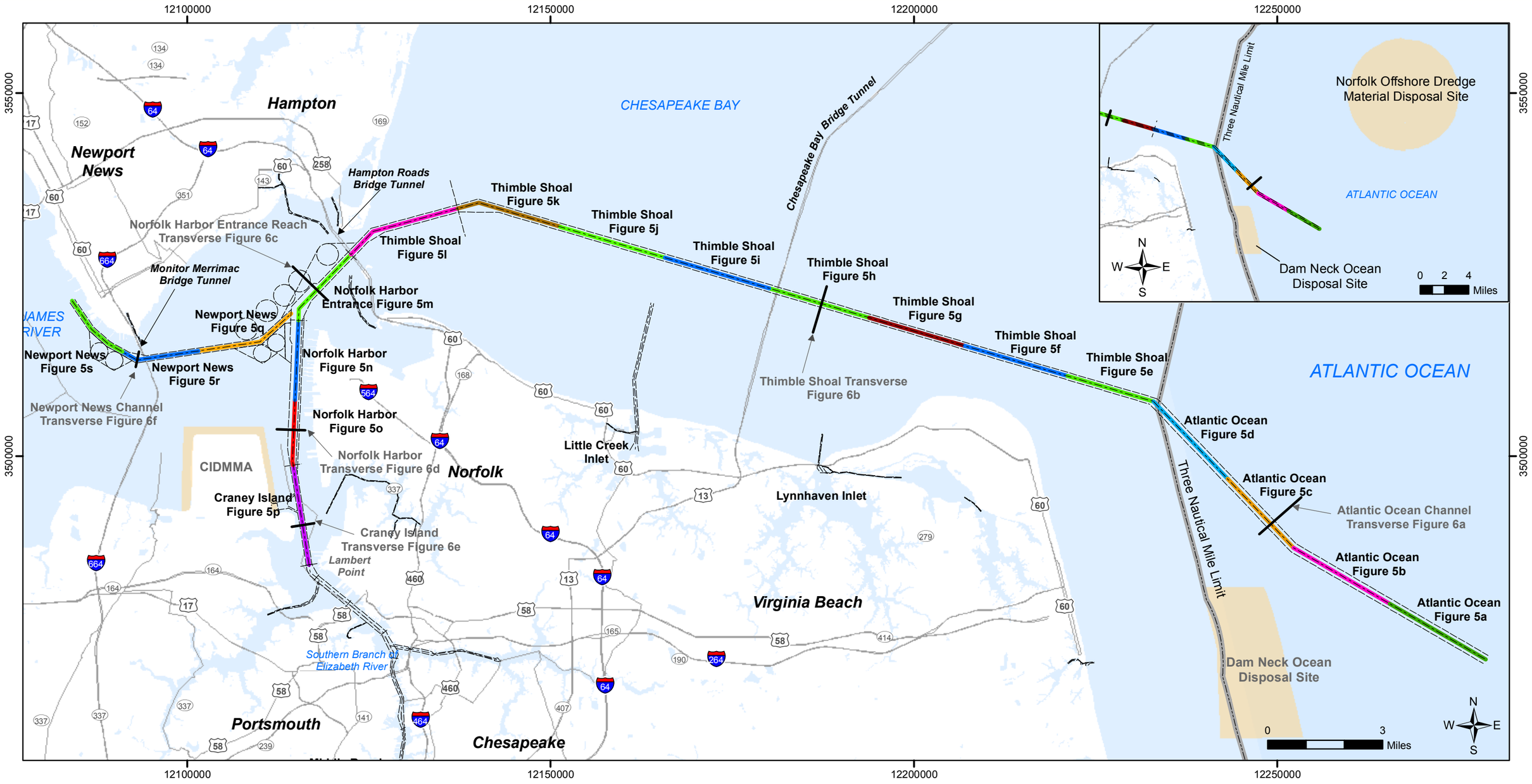
Navigation Channel Centerline

Navigation Channel Boundary

SUBSURFACE MATERIAL ZONATION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 3

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_3_Zonation_Map.mxd, 4/28/2016, wcupples



Legend

- Longitudinal Cross Section Locations (Colors)
- Transverse Cross Section Locations (Black)
- Channel Centerline
- Navigation Channel Boundary

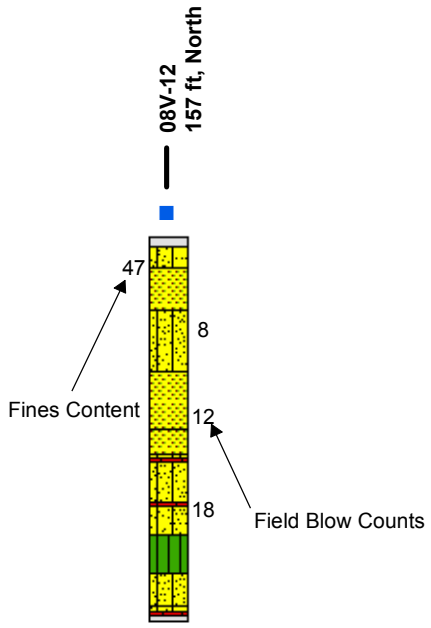
CROSS SECTION LOCATIONS
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 4a

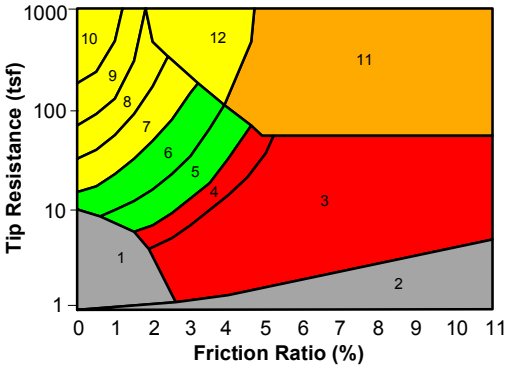
N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_4a_Cross_Section_Locations.mxd, 4/28/2016, wcupples

SOIL TYPES

- Lean CLAY (CL)
- Silty CLAY (CL-ML)
- Lean CLAY with Sand (CL)
- Sandy Lean Clay (CL)
- Lean to Fat CLAY (CL-CH)
- Fat CLAY (CH)
- Silt (ML)
- Clayey SILT (ML)
- Sandy SILT (ML)
- Elastic Silt (MH)
- Elastic Silt with Sand (MH)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Clay (SP-SC)
- Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND (SP)
- Well-Graded SAND (SW)
- Clayey SAND (SC)
- Silty SAND (SM)
- Poorly-Graded GRAVEL (GP)
- Low-Plasticity Organic (OL)
- High-Plasticity Organic (OH)
- PEAT
- Claystone
- ROCK Fragments
- Fill



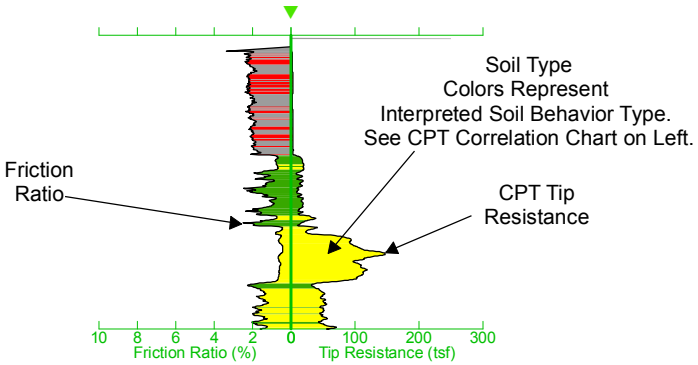
SOIL BORING LITHOLOGY WITH INDEX TESTS MEASURED IN LABORATORY AND FIELD BLOW COUNTS



Zone	Soil Behavior Type	U.S.C.S.
1	Sensitive Fine-grained	OL-CH
2	Organic Material	OL-OH
3	Clay	CH
4	Silty Clay to Clay	CL-CH
5	Clayey Silt to Silty Clay	MH-CL
6	Sandy Silt to Clayey Silt	ML-MH
7	Silty Sand to Sandy Silt	SM-ML
8	Sand to Silty Sand	SM-SP
9	Sand	SW-SP
10	Gravelly Sand to Sand	SW-GW
11	Very Stiff Fine-grained *	CH-CL
12	Sand to Clayey Sand *	SC-SM

*overconsolidated or cemented

CPT CORRELATION CHART
(Robertson and Campanella, 1988)

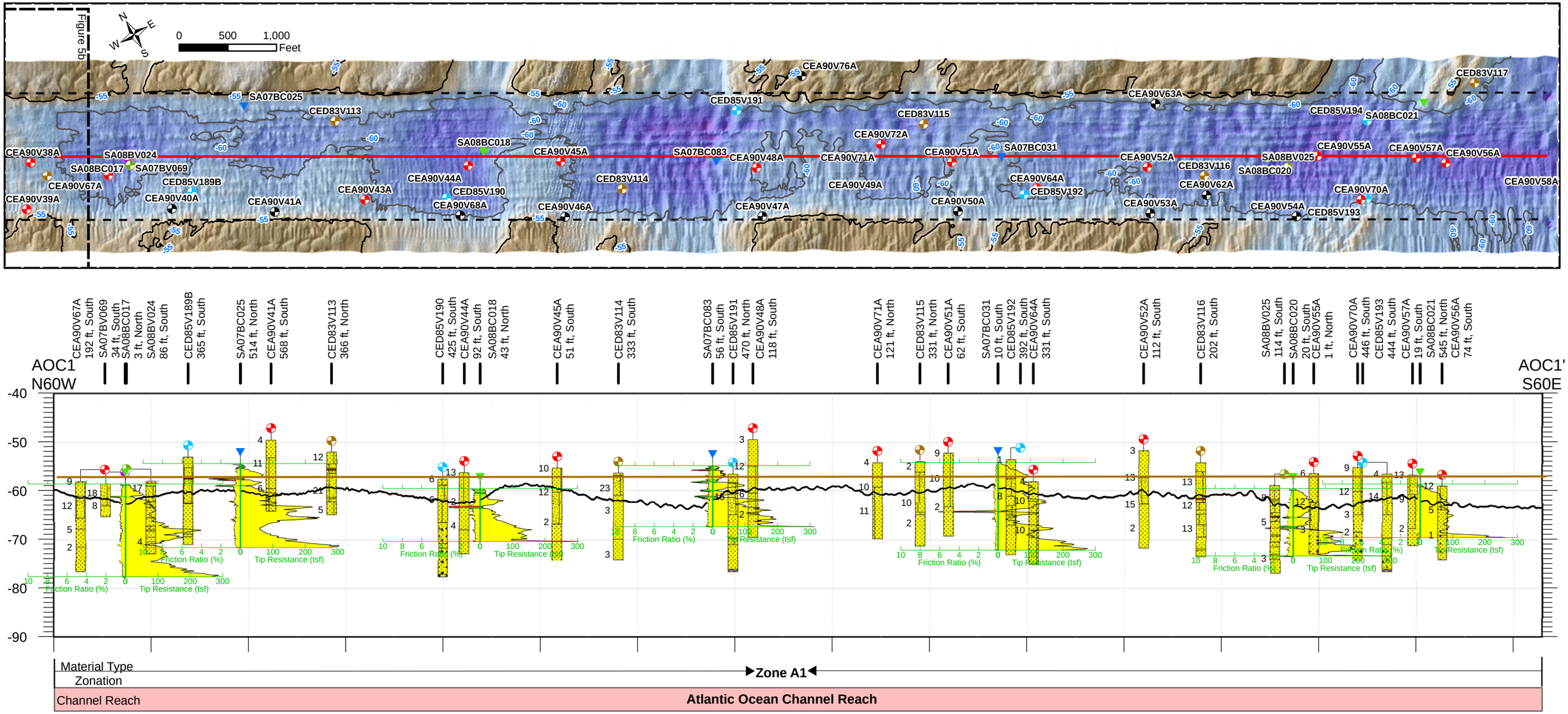


CPT SOUNDING WITH FRICTION RATIO AND TIP RESISTANCE

KEY TO SUBUSRFACE CROSS SECTIONS
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 4b

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_4b_Key_to_Subsurface_Cross_Sections.mxd, 4/28/2016, wcupples



PLAN VIEW LEGEND

- 2008 Vibracore
- 2007 Vibracore
- 1990 Vibracore
- 1985 Vibracore
- 1983 Vibracore
- Exploration (not shown on the cross section)
- 2008 CPT
- 2007 CPT
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

Fines Content (%) — Standard Penetration Test N-Value

Lithology Type

- Lean CLAY (CL)
- Fat CLAY (CH)
- Sandy Fat CLAY (CH)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND (SP)
- Well-Graded SAND (SW)
- Clayey SAND (SC)
- Silty SAND (SM)
- Gravelly Silty SAND (SM)
- Poorly-Graded GRAVEL (GP)
- PEAT

20 ft — 1000 ft

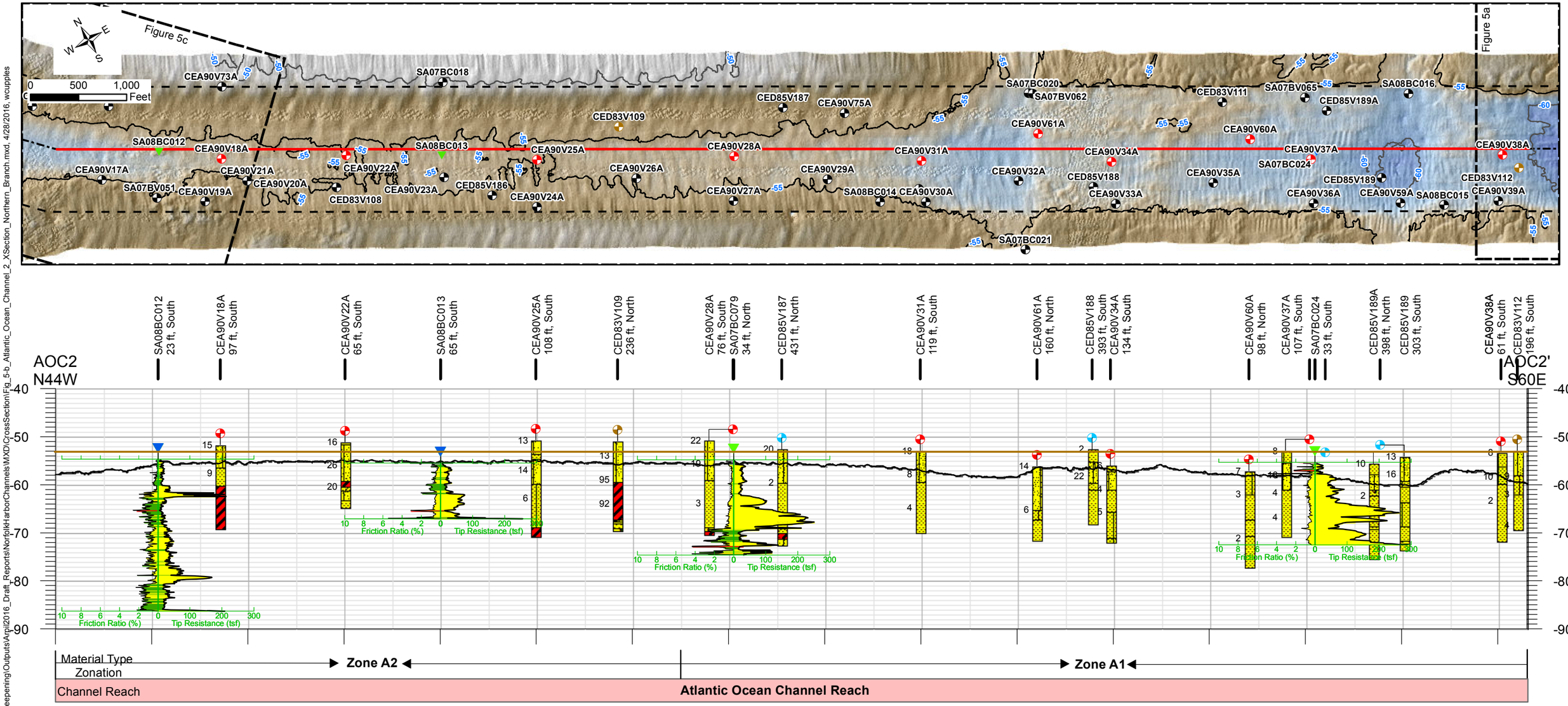
Vertical exaggeration is 50x.

Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

ATLANTIC OCEAN CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5a

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-a_Atlantic_Ocean_Channel_1_XSection_Northern_Branch.mxd, 4/28/2016, wcupples



PLAN VIEW LEGEND

- 1990 Vibracore
- 1983 Vibracore
- Exploration (not shown on the cross section)
- 2008 CPT
- 2007 CPT
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

- Fat CLAY (CH)
- Sandy Fat CLAY (CH)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND (SP)
- Well-Graded SAND (SW)
- Clayey SAND (SC)
- Clayey to Silty SAND (SC-SM)
- Silty SAND (SM)
- Poorly-Graded GRAVEL (GP)
- Clayey GRAVEL (GC)

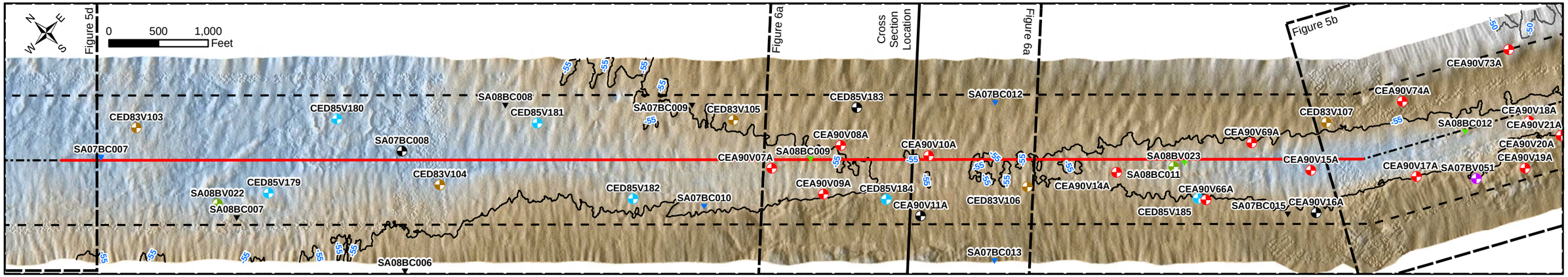
20 ft
1000 ft
Vertical exaggeration is 50x.

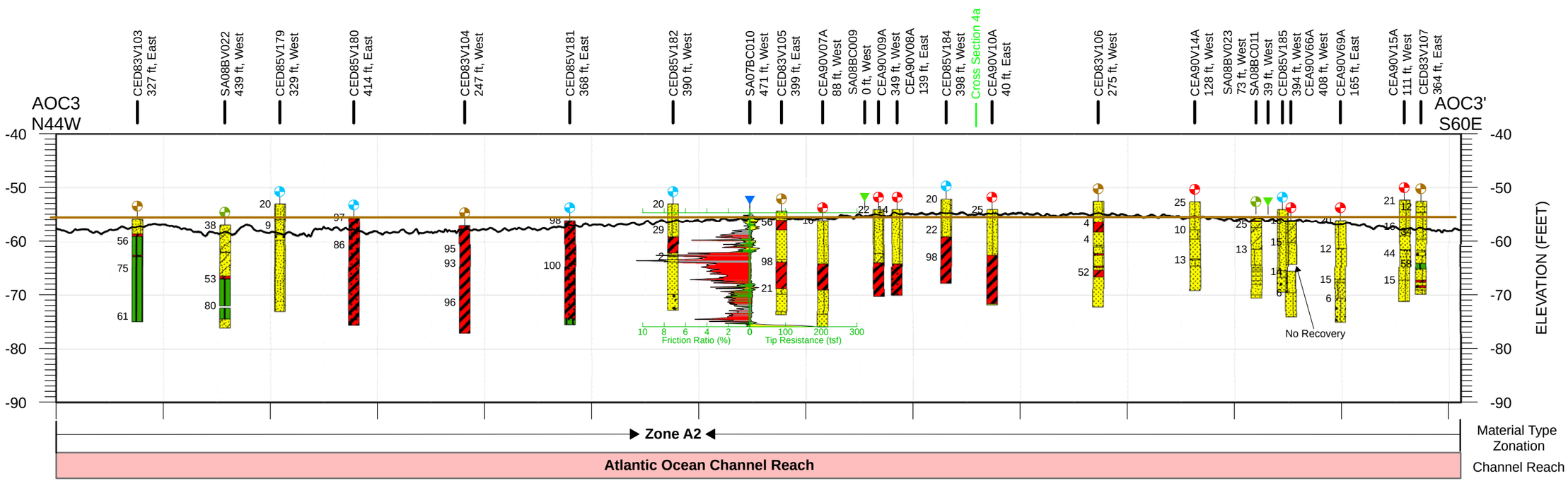
Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

ATLANTIC OCEAN CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5b

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\April2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-b_Atlantic_Ocean_Channel_2_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2008 Vibracore
- 1990 Vibracore
- 1985 Vibracore
- 1983 Vibracore
- Exploration (not shown on the cross section)
- 2008 CPT
- 2007 CPT
- Cross Section Location
- Transverse Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

WOR
WOR
96
3
1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

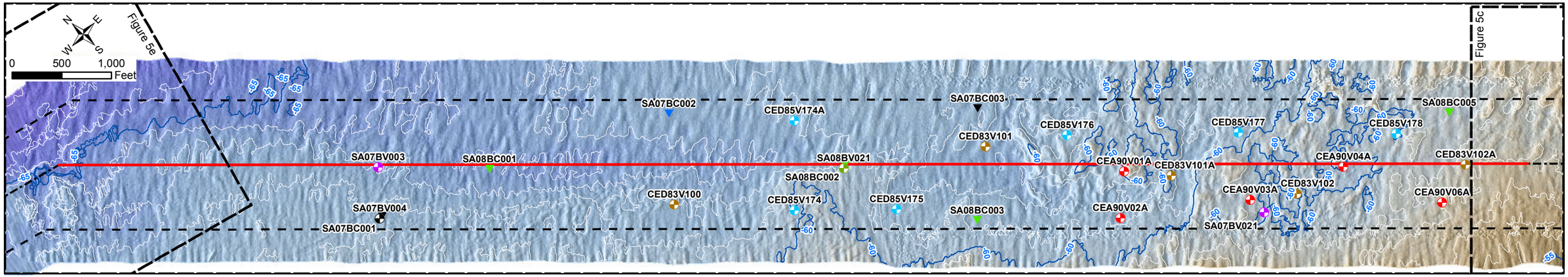
- Lean CLAY (CL)
- Silty CLAY (CL-ML)
- Fat CLAY (CH)
- Sandy Fat CLAY (CH)
- Silt (ML)
- Sandy SILT (ML)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND (SP)
- Well-Graded SAND (SW)
- Clayey SAND (SC)
- Clayey to Silty SAND (SC-SM)
- Silty SAND (SM)
- Poorly-Graded GRAVEL (GP)
- Silty Gravel (GM)

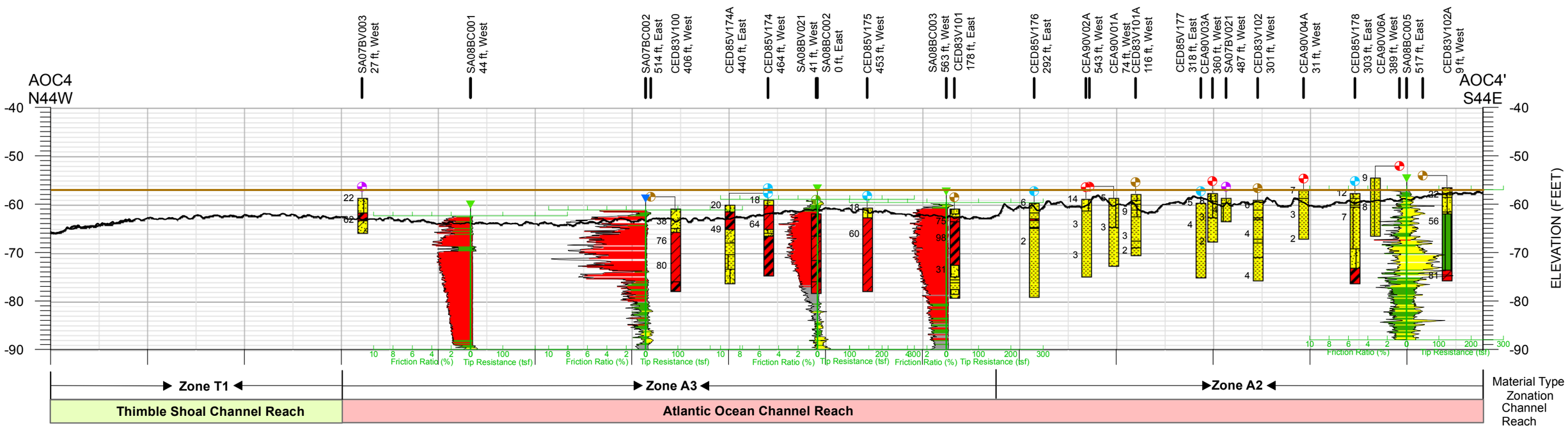
20 ft
1000 ft
Vertical exaggeration is 50x.

ATLANTIC OCEAN CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5c

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-c_Atlantic_Ocean_Channel_3_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2008 Vibracore
- 2007 Vibracore
- 1990 Vibracore
- 1985 Vibracore
- 1983 Vibracore
- Exploration (not shown on the cross section)
- 2008 CPT
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

High : -50

Low : -65

Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

- Lean CLAY (CL)
- Fat CLAY (CH)
- Silt (ML)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Clay (SP-SC)
- Poorly-Graded SAND with Silt (SP-SM)
- Well-Graded SAND (SW)
- Clayey SAND (SC)
- Silty SAND (SM)
- Poorly-Graded GRAVEL (GP)

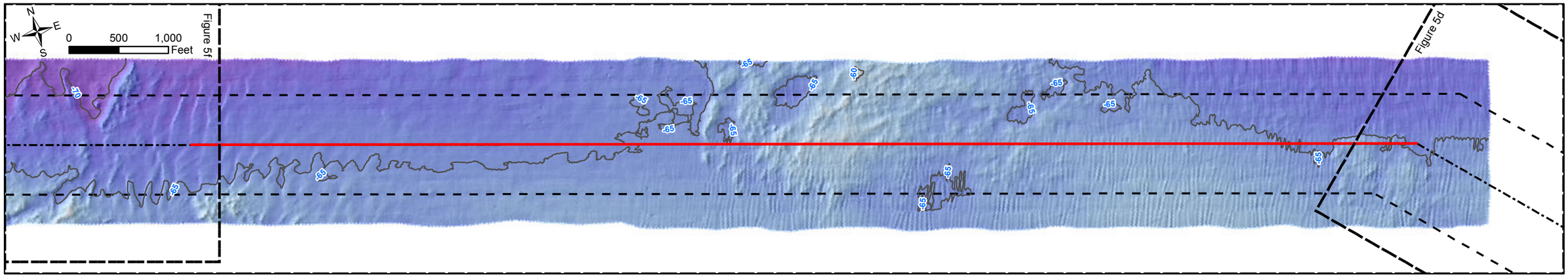
20 ft
1000 ft
Vertical exaggeration is 50x.

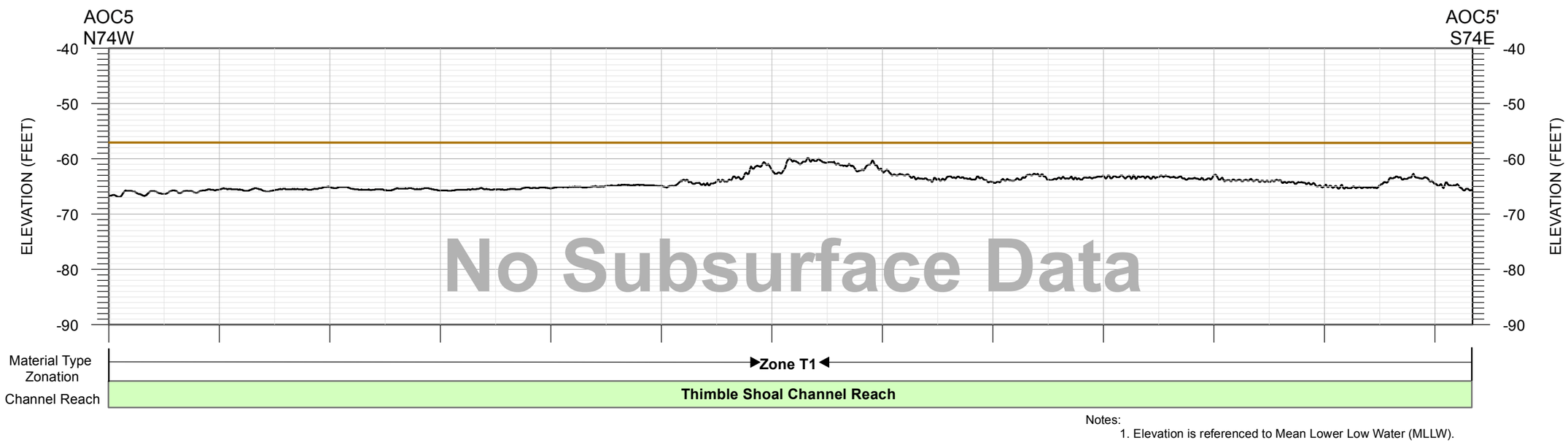
ATLANTIC OCEAN CHANNEL CROSS SECTION

Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5d

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-d_Atlantic_Ocean_Channel_4_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).

PLAN VIEW LEGEND

- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

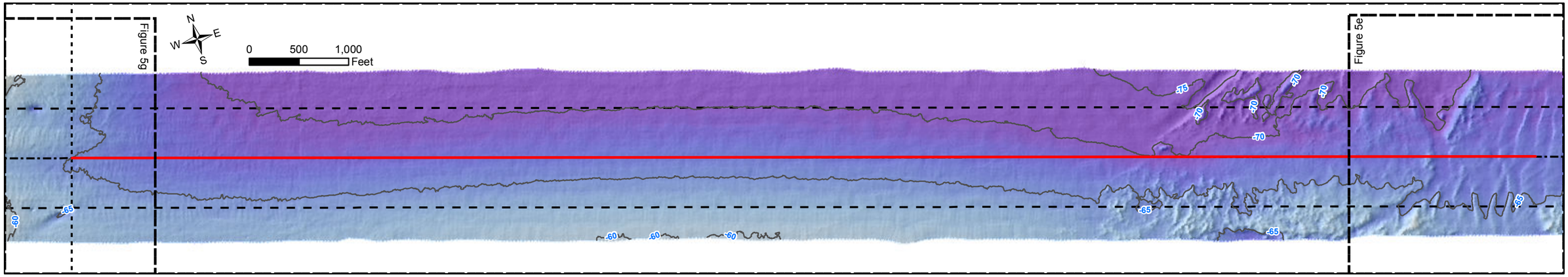
- 2014 Bathymetry
- Authorized Channel Depth

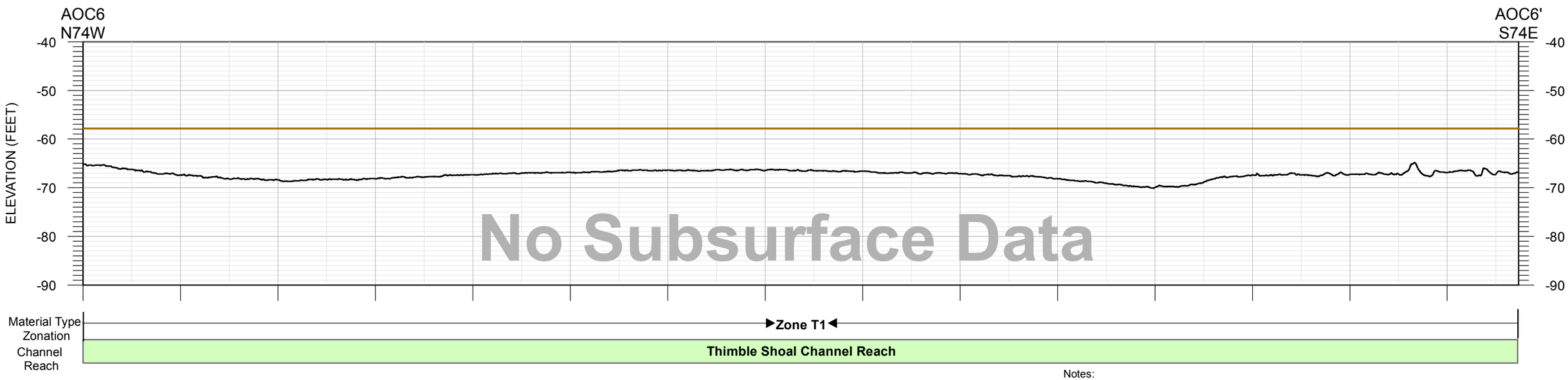
20 ft
1000 ft
Vertical exaggeration is 50x.

THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5e

N:\Projects\04_2015\04_8115_0012_Port_of_Virgnia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-e_Atlantic_Ocean_Channel_5_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).

PLAN VIEW LEGEND

- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

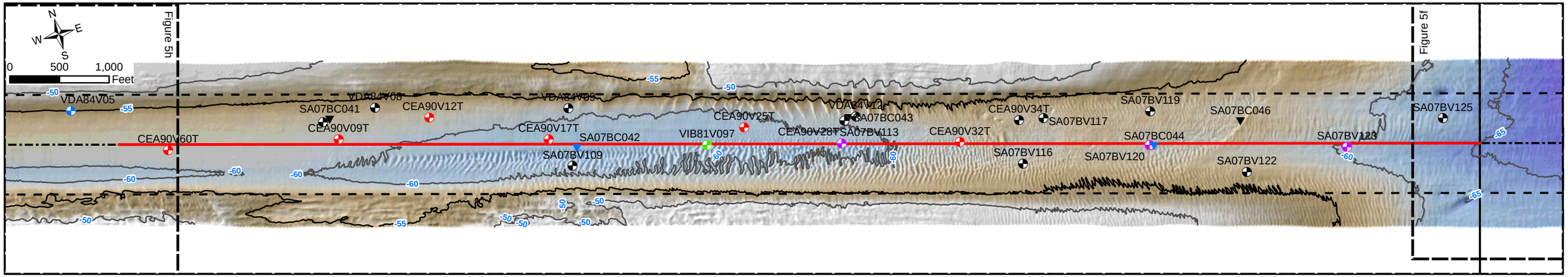
- 2014 Bathymetry
- Authorized Channel Depth

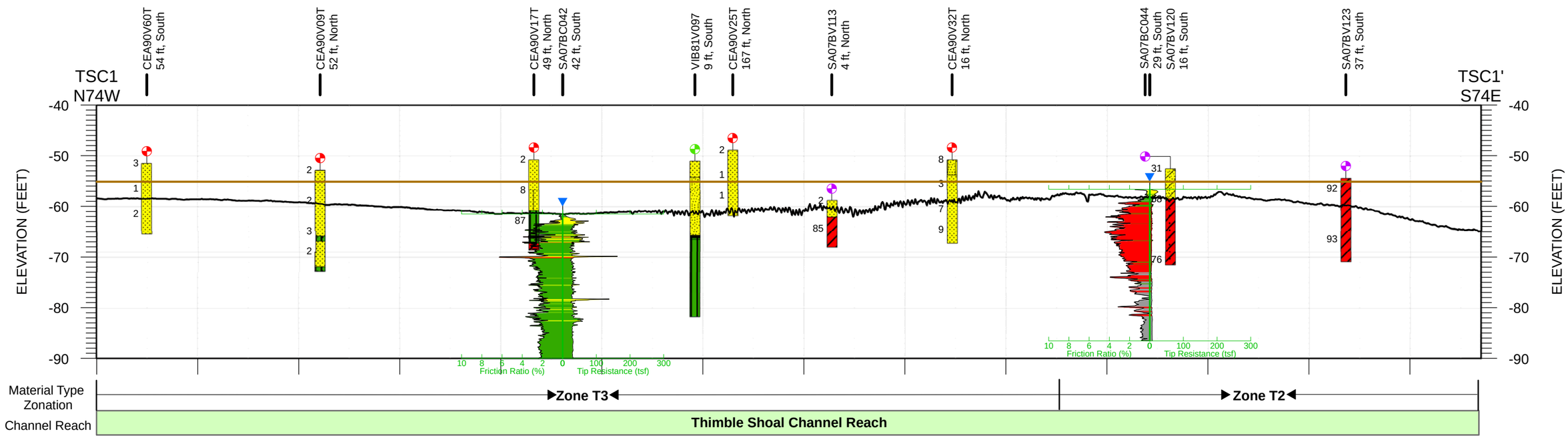
20 ft
1000 ft
Vertical exaggeration is 50x.

THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5f

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-f_Atlantic_Ocean_Channel_6_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





PLAN VIEW LEGEND

- 2007 Vibracore
- 2005 Vibracore
- 1990 Vibracore
- 2005 Vibracore
- Exploration (not shown on the cross section)
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

- Lean CLAY (CL)
- Sandy Lean Clay (CL)
- Silt (ML)
- Clayey SILT (ML)
- Sandy SILT (ML)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Well-Graded SAND (SW)
- Clayey SAND (SC)
- Silty SAND (SM)

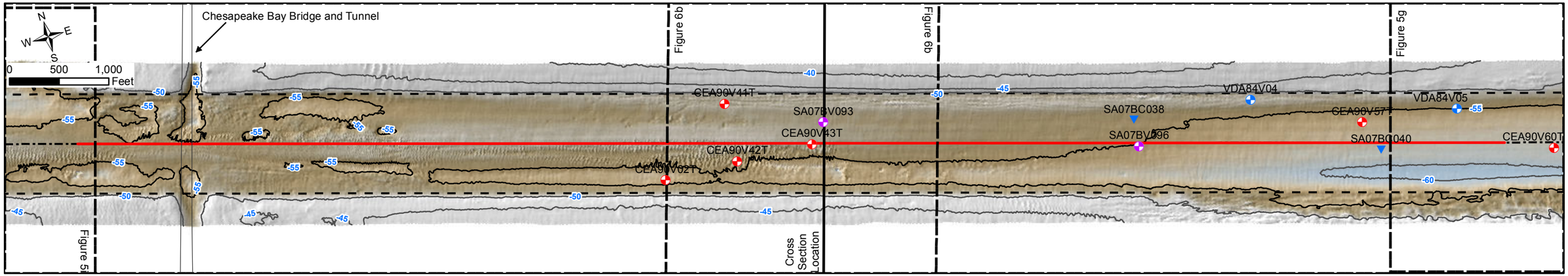
Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

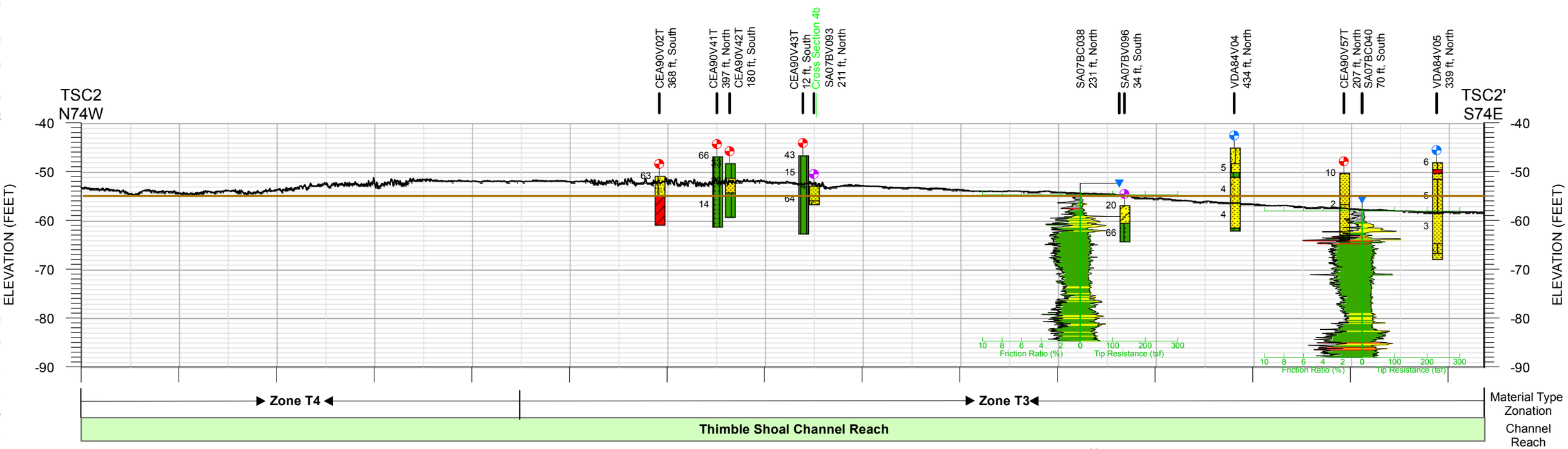
20 ft
1000 ft
Vertical exaggeration is 50x.

THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5g

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-g_Thimble_Shoal_Channel_1_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 2005 Vibracore
- 1990 Vibracore
- 2005 Vibracore
- Cross Section Location
- Transverse Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR WOR 3 1 5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

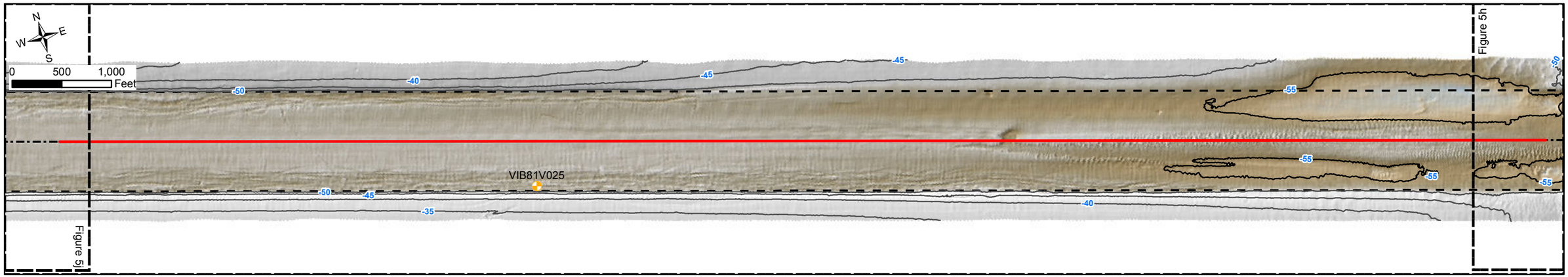
- Lean CLAY (CL)
- Silt (ML)
- Sandy SILT (ML)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND with Silt (SP-SM)
- Gravelly Poorly-Graded SAND (SP)
- Clayey SAND (SC)
- Silty SAND (SM)

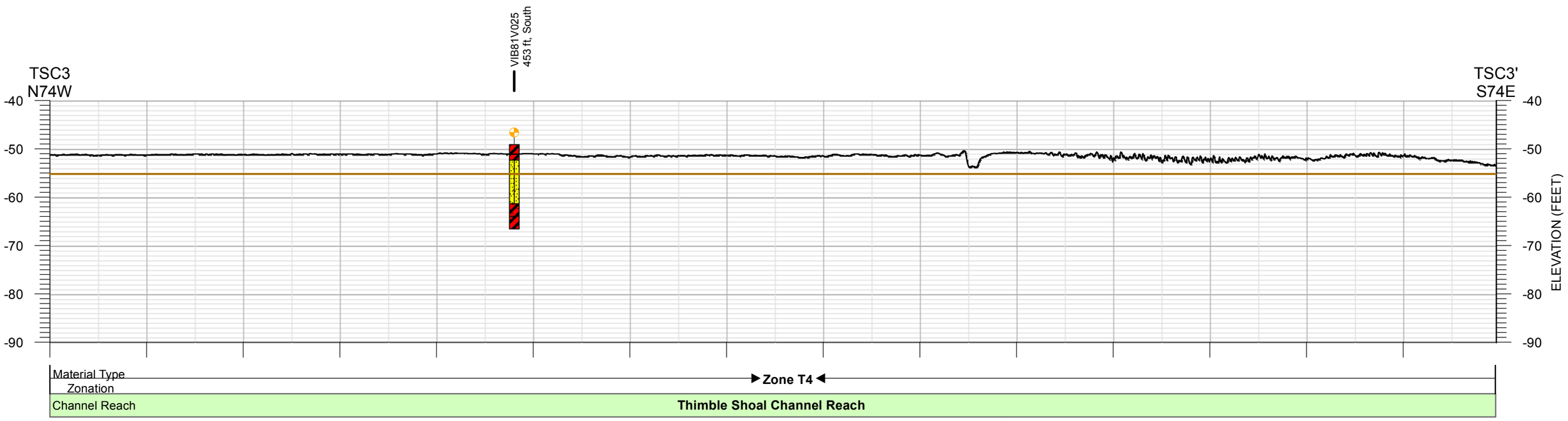
20 ft
1000 ft
Vertical exaggeration is 50x.

THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5h

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-h_Thimble_Shoal_Channel_2_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 1982 Vibracore
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

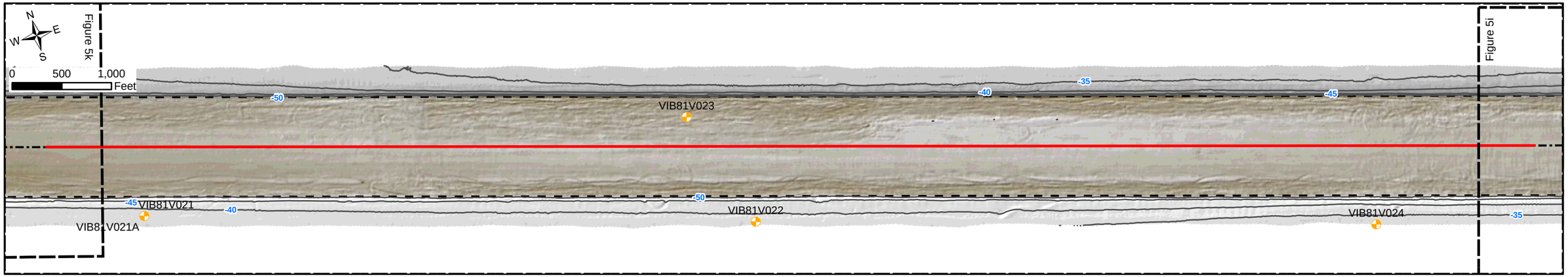
- Fat CLAY (CH)
- Sandy Fat CLAY (CH)
- Silty SAND (SM)

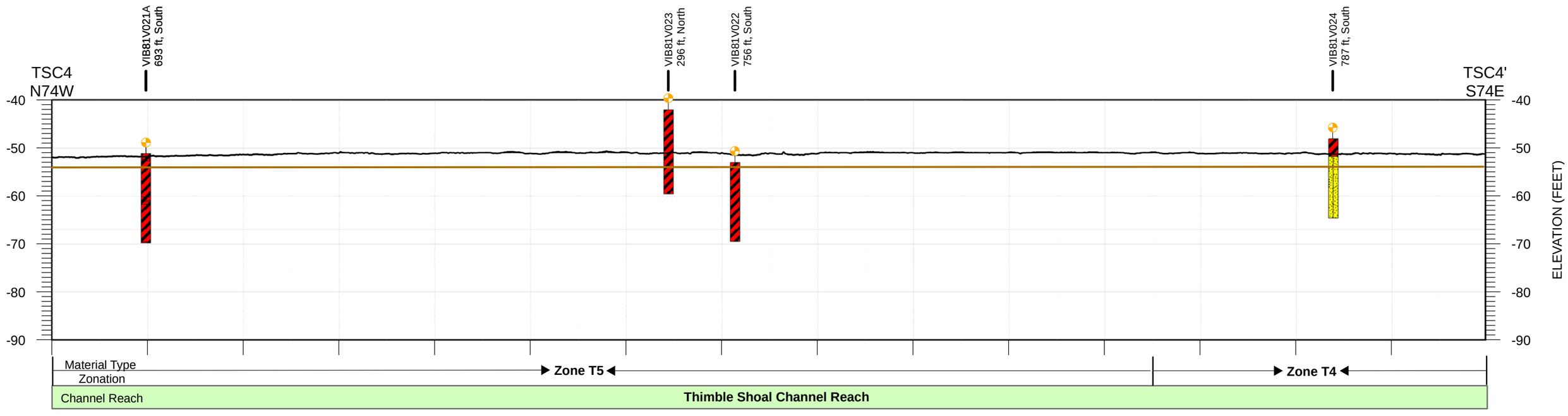
20 ft
1000 ft
Vertical exaggeration is 50x.

THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5i

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-i_Thimble_Shoal_Channel_3_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 1982 Vibracore
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3
1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

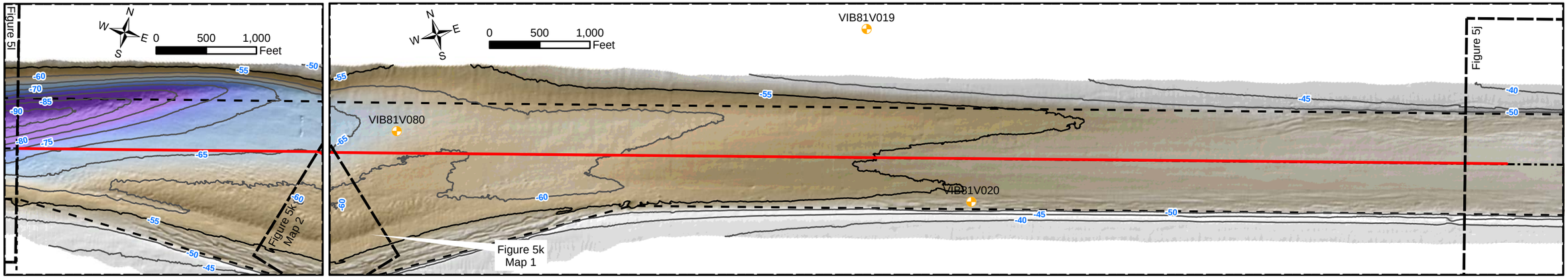
- Fat CLAY (CH)
- Silty SAND (SM)

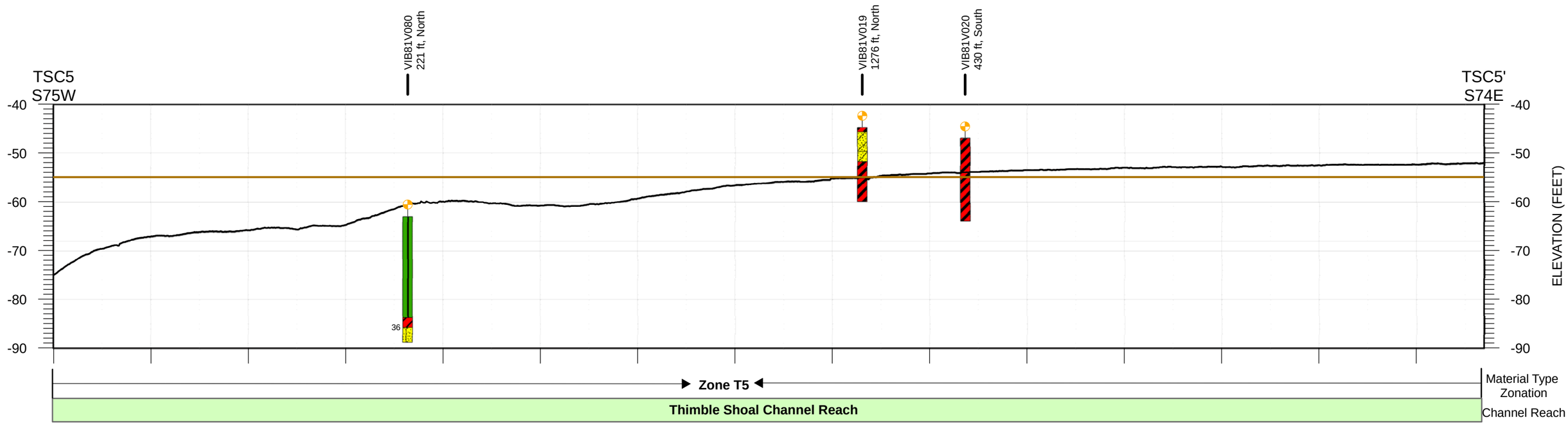
20 ft
1000 ft
Vertical exaggeration is 50x.

THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5j

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-j_Thimble_Shoal_Channel_4_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 1982 Vibracore
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -80
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3
1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

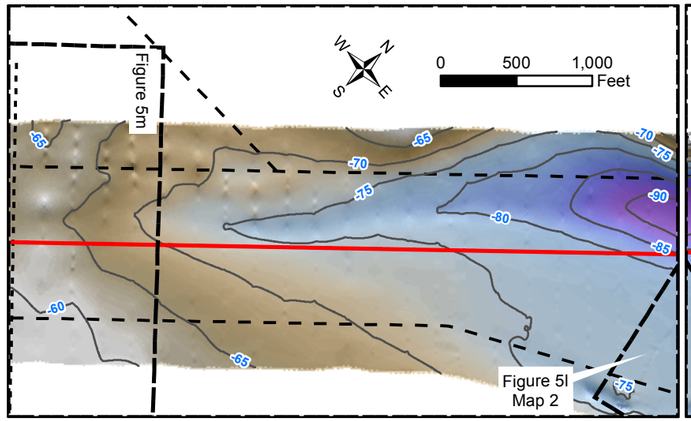
- Lean CLAY (CL)
- Fat CLAY (CH)
- Silt (ML)
- Clayey SAND (SC)
- Silty SAND (SM)

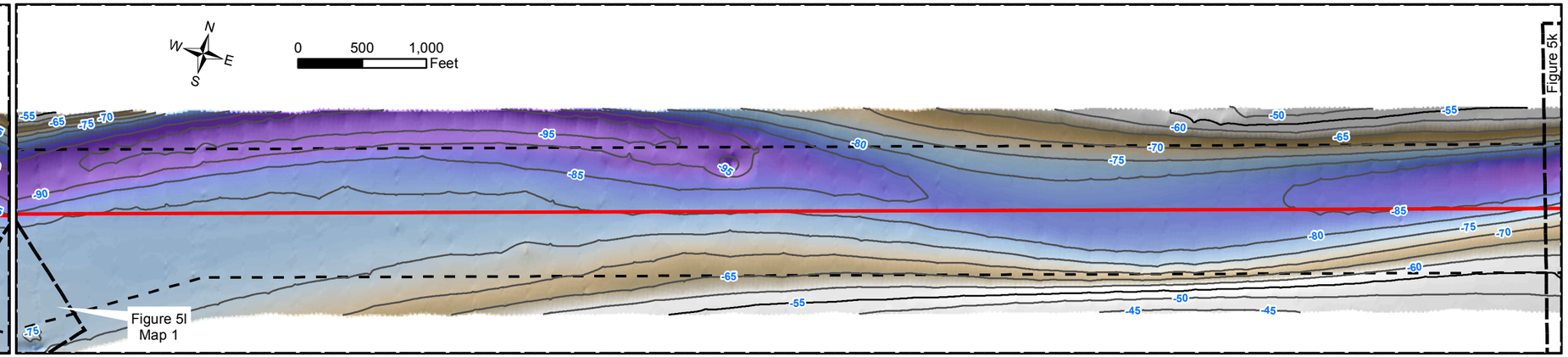
20 ft
1000 ft
Vertical exaggeration is 50x.

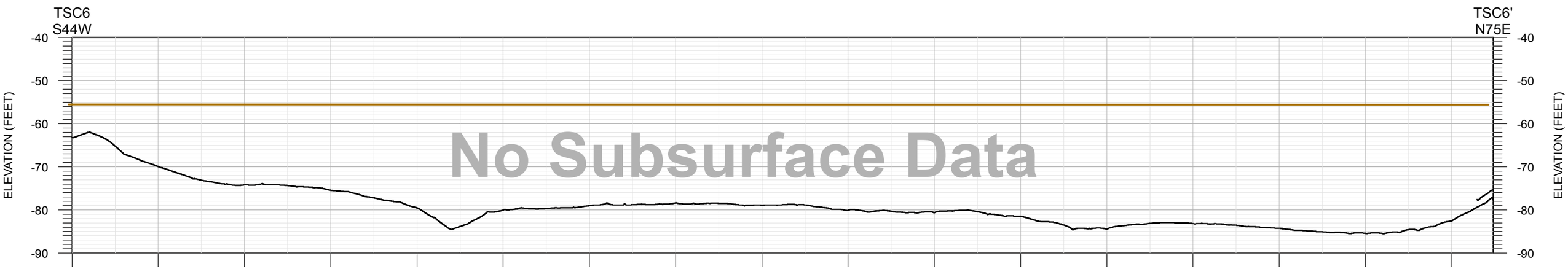
THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5k

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-k_Thimble_Shoal_Channel_5_XSection_Northern_Branch.mxd, 4/28/2016, wcupples







Material Type Zonation: Zone T6

Channel Reach: Thimble Shoal Channel Reach

End of Thimble Shoal Channel Reach

PLAN VIEW LEGEND

- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -60
- Low : -90
- Contour interval is 5 feet.

CROSS SECTION LEGEND

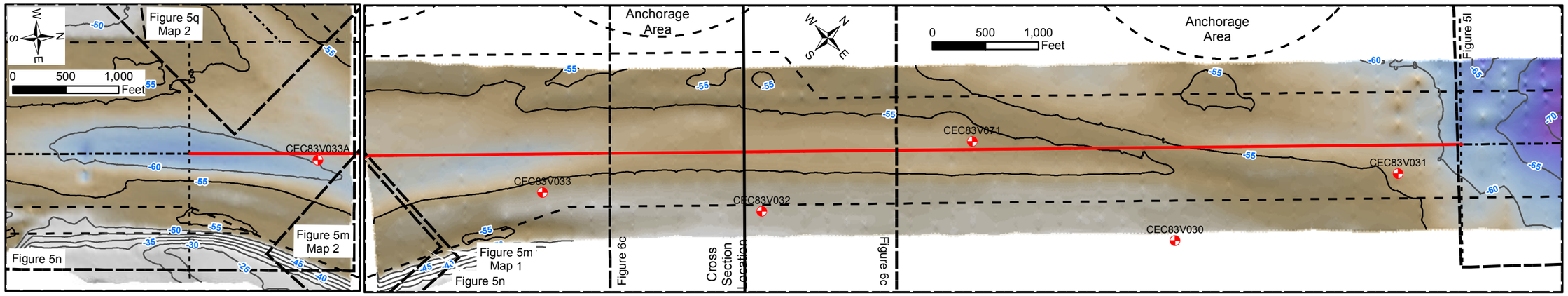
- 2014 Bathymetry
- Authorized Channel Depth

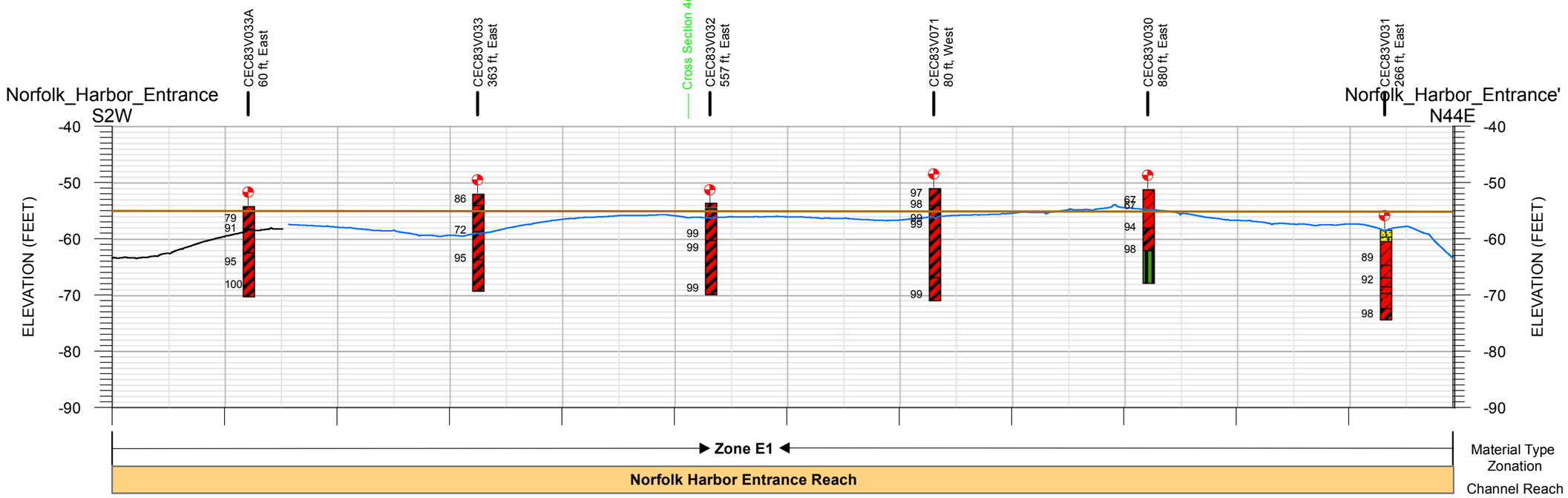
Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. Refer to Key to Subsurface Cross Sections.

20 ft
1000 ft
Vertical exaggeration is 50x.

THIMBLE SHOAL CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5l





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 1983 Vibracore
- Transverse Cross Section Location
- Cross Section Location
- Navigation Channel Limit

2010 and 2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- 2010 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR WOR 3 1 5

Fines Content (%)

Standard Penetration Test N-Value

Lithology Type

- Lean CLAY (CL)
- Fat CLAY (CH)
- Elastic Silt (MH)
- Poorly-Graded SAND with Silt (SP-SM)
- Silty SAND (SM)
- PEAT

20 ft

1000 ft

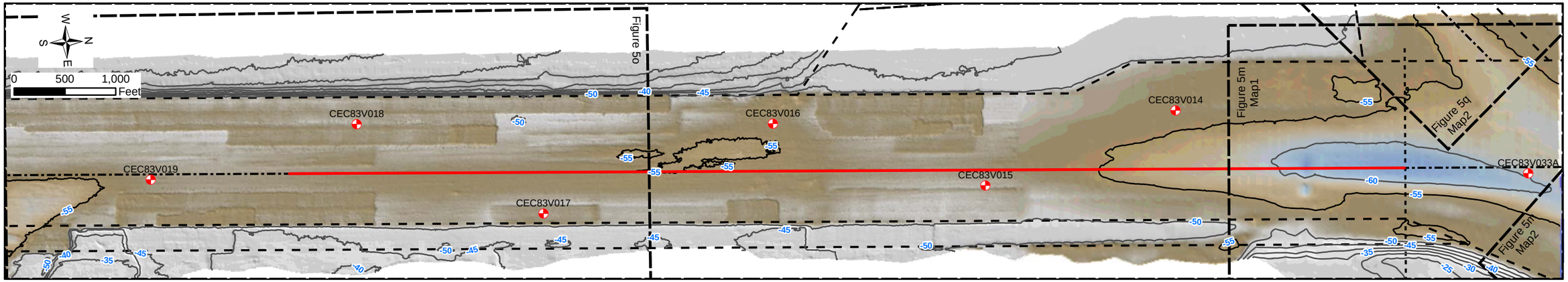
Vertical exaggeration is 50x.

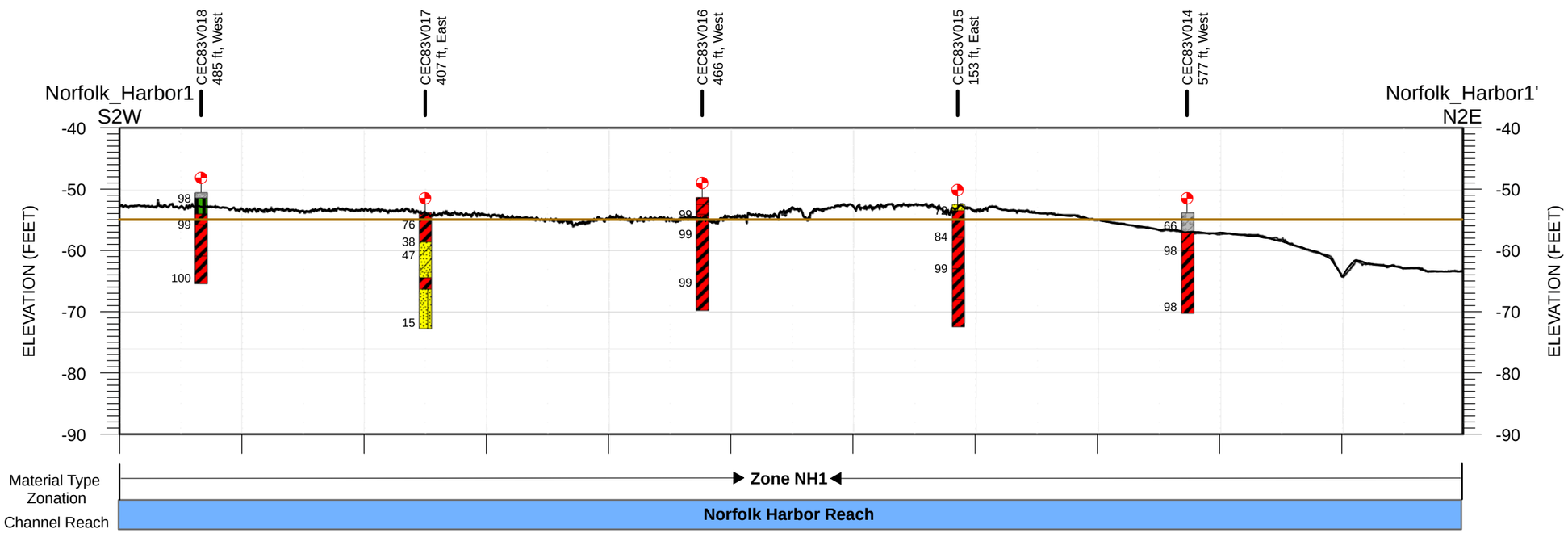
NORFOLK HARBOR ENTRANCE REACH CROSS SECTION

Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5m

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-m_Norfolk_Harbor_Entrance_Reach_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 1983 Vibracore
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -70
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

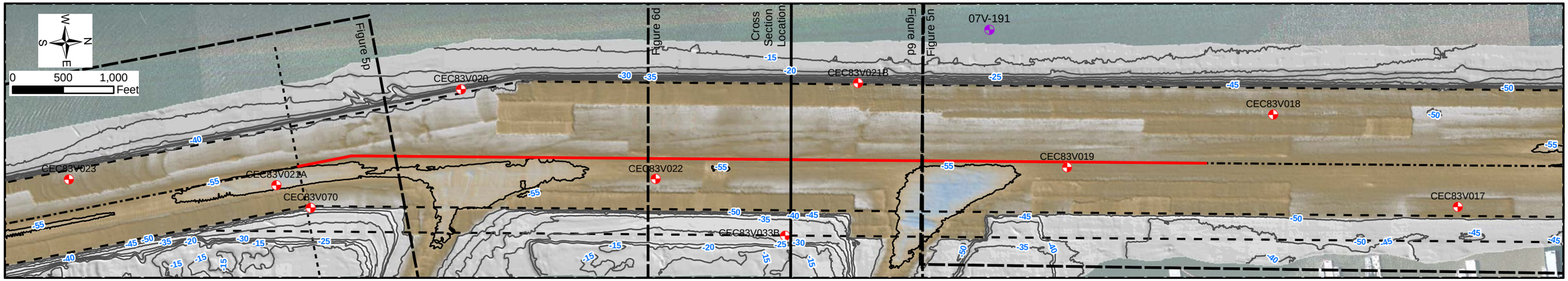
- Lean CLAY (CL)
- Fat CLAY (CH)
- Elastic Silt (MH)
- Clayey SAND (SC)
- Silty SAND (SM)
- High-Plasticity Organic (OH)

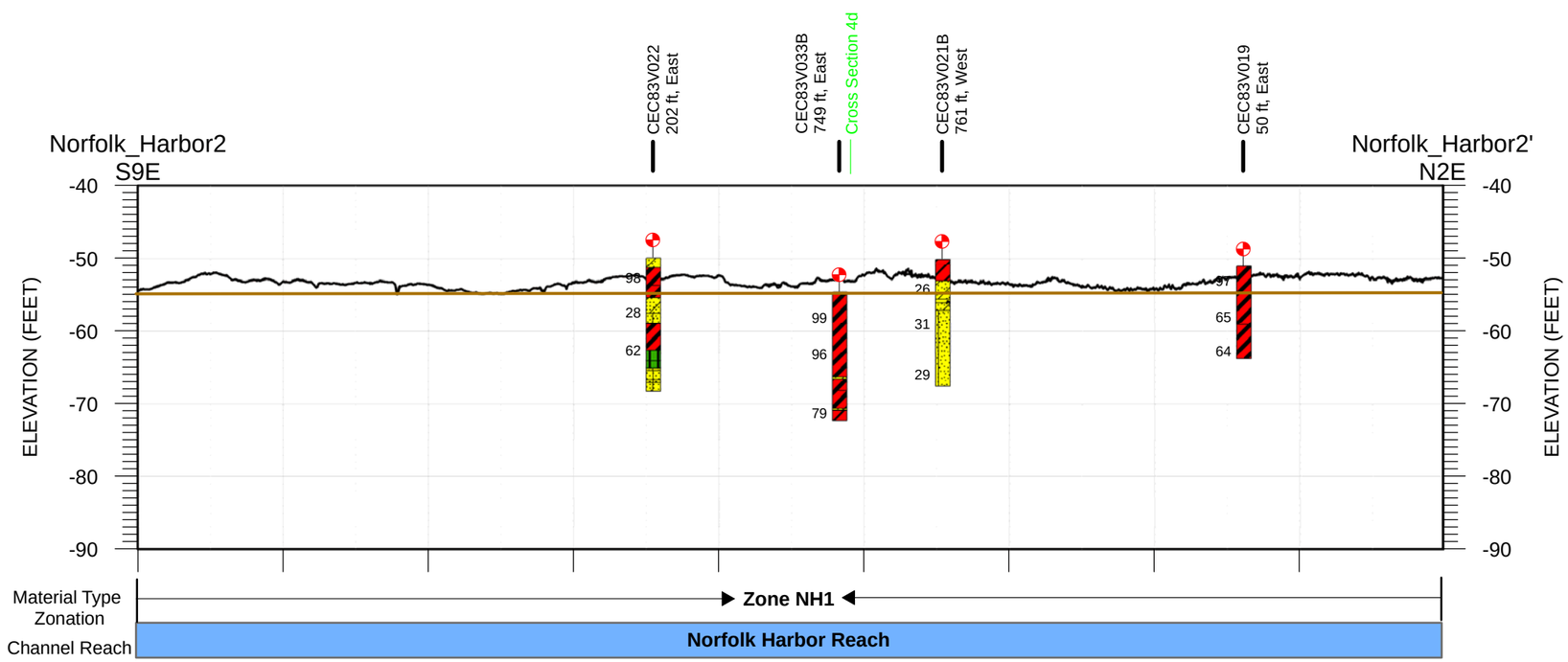
20 ft
1000 ft
Vertical exaggeration is 50x.

NORFOLK HARBOR REACH CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5n

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\April2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-n_Norfolk_Harbor_Reach_1_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





PLAN VIEW LEGEND

- 1983 Vibracore
- Transverse Cross Section Location
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

Fines Content (%) — Standard Penetration Test N-Value

Lithology Type

- Lean CLAY (CL)
- Fat CLAY (CH)
- Silt (ML)
- Poorly-Graded SAND with Silt (SP-SM)
- Clayey SAND (SC)
- Silty SAND (SM)
- Clayey GRAVEL (GC)

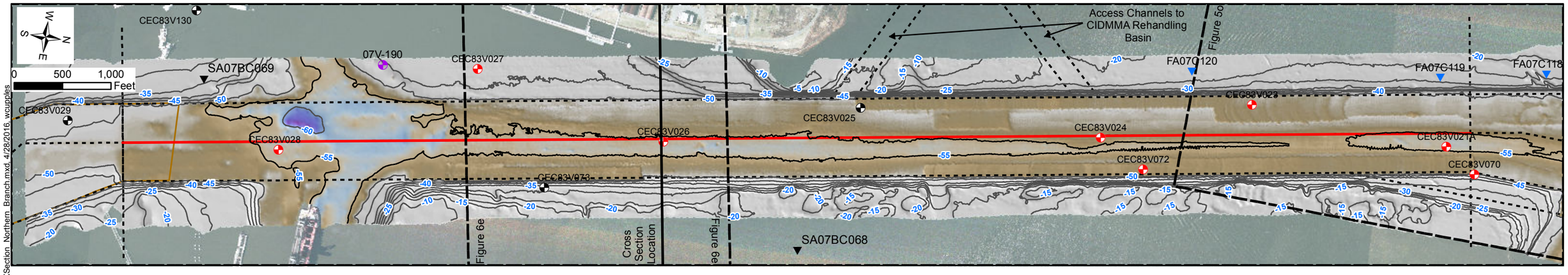
Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

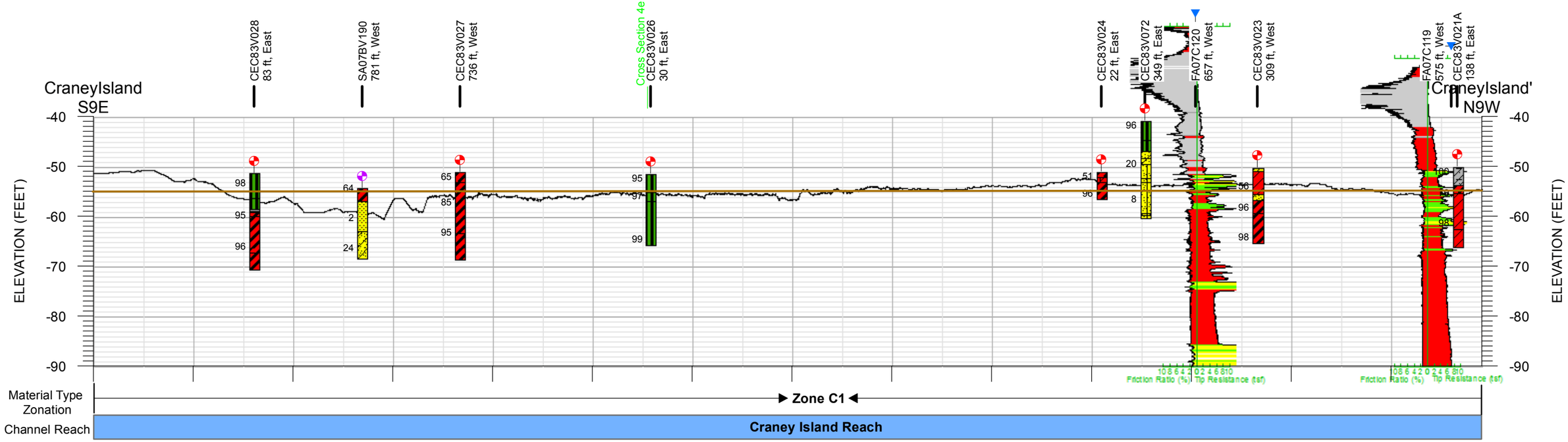
20 ft
1000 ft
Vertical exaggeration is 50x.

NORFOLK HARBOR REACH CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5o

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-o_Norfolk_Harbor_Reach_2_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 USACE Vibracore
- 1983 Vibracore
- 2007 Fugro CPT
- Transverse Cross Section Location
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

Fines Content (%) — Standard Penetration Test N-Value

Lithology Type

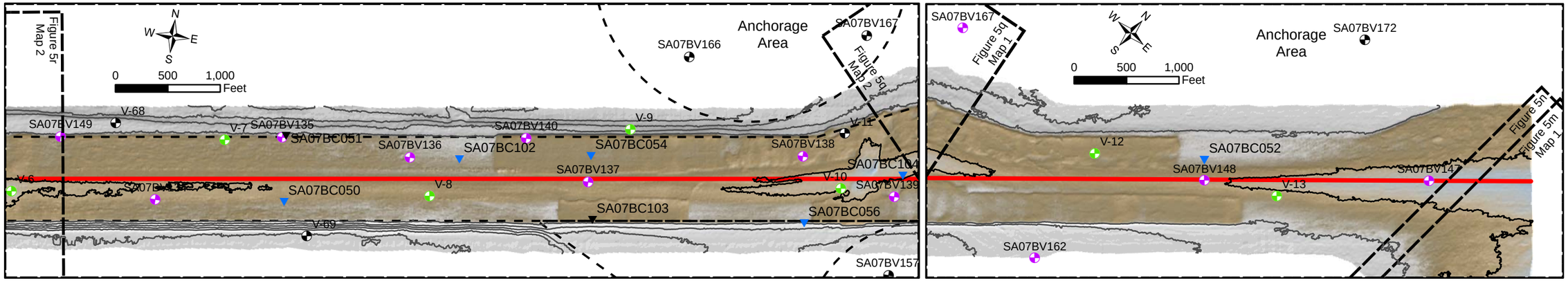
- Lean CLAY (CL)
- Silty CLAY (CL-ML)
- Fat CLAY (CH)
- Elastic Silt (MH)
- Poorly-Graded SAND (SP)
- Well-Graded SAND with Silt (SW-SM)
- Clayey SAND (SC)
- Silty SAND (SM)
- High-Plasticity Organic (OH)
- PEAT

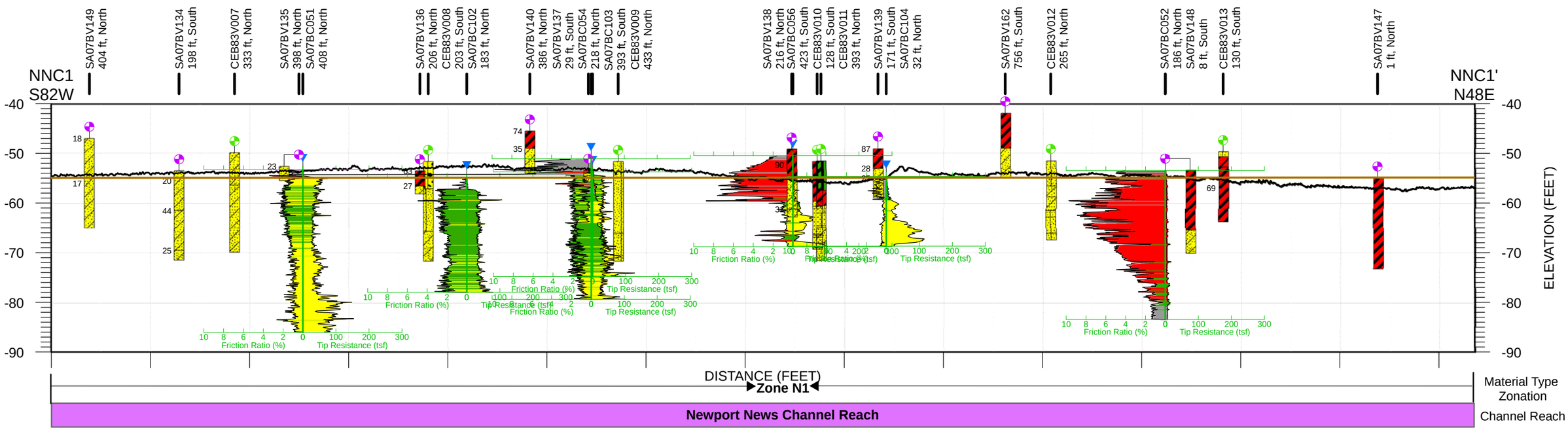
20 ft — 1000 ft
Vertical exaggeration is 50x.

CRANEY ISLAND REACH CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5p

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\April2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-p_Craney_Island_Reach_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 1983 Vibracore
- 2007 CPT
- Exploration (not shown on the cross section)
- Exploration (not shown on the cross section)
- Cross Section Location
- Navigation Channel Limit

2015 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2015 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

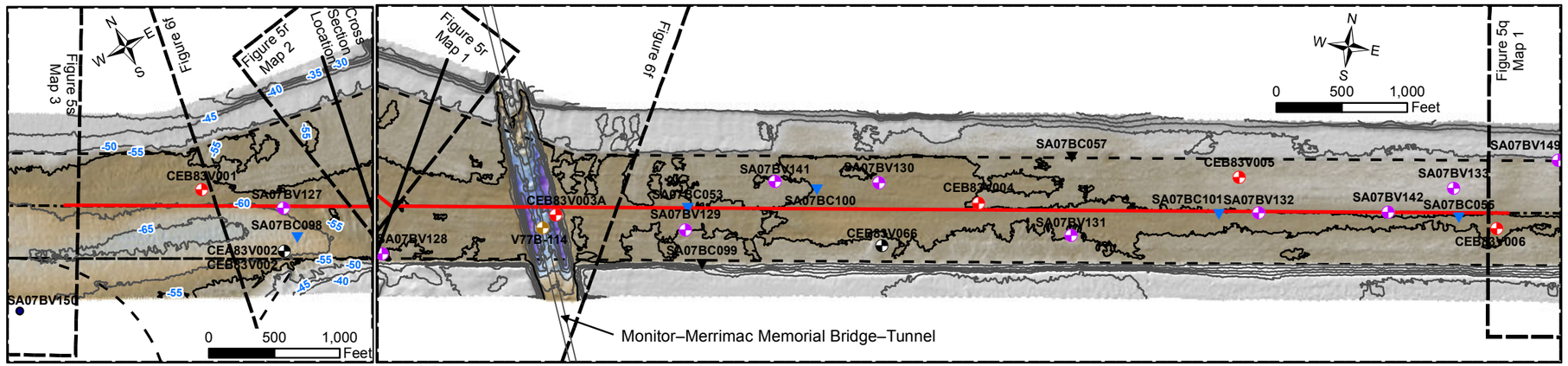
- Lean CLAY (CL)
- Fat CLAY (CH)
- Elastic Silt (MH)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Clayey SAND (SC)
- Silty SAND (SM)
- Poorly-Graded GRAVEL (GP)
- Silty Gravel (GM)

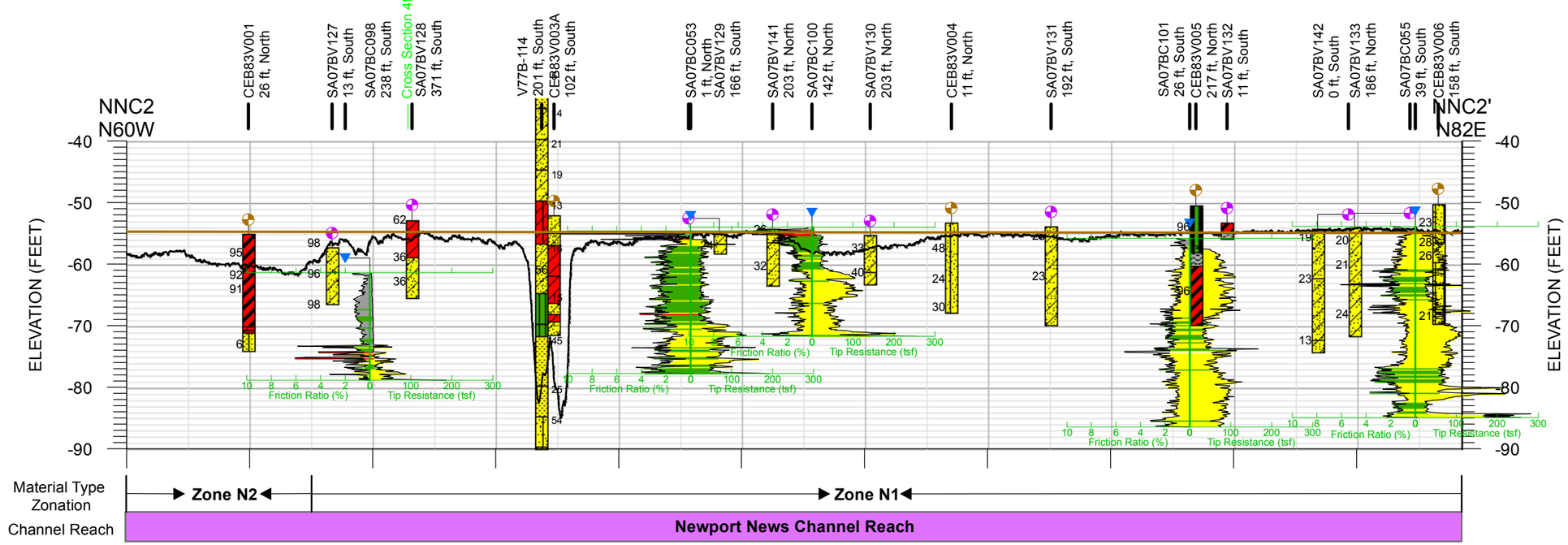
20 ft
1000 ft
Vertical exaggeration is 50x.

NEWPORT NEWS CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5q

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-q_Newport_News_Channel_1_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 1983 USACE Vibracore
- 1983 USACE Boring
- 1977 Boring
- 2007 Vibracore
- Exploration (not shown on the cross section)
- Exploration (not shown on the cross section)
- Transverse Cross Section Location
- Cross Section Location
- Navigation Channel Limit

2015 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -85
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2015 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

Fines Content (%) — Standard Penetration Test N-Value

Lithology Type

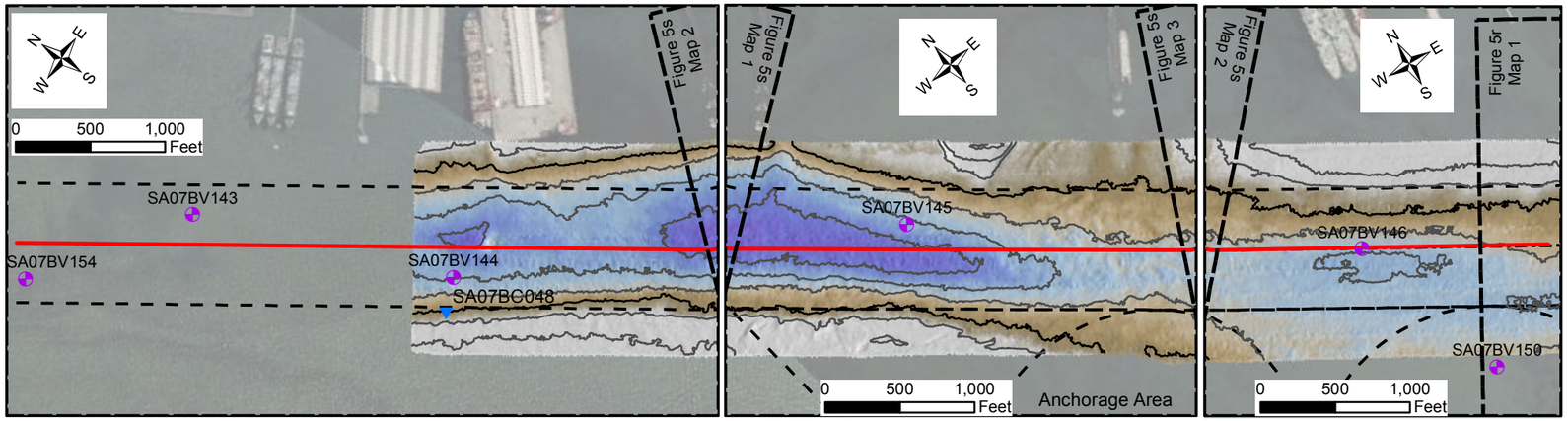
- Lean CLAY (CL)
- Silty CLAY (CL-ML)
- Fat CLAY (CH)
- Silt (ML)
- Elastic Silt (MH)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Clayey SAND (SC)
- Silty SAND (SM)
- PEAT

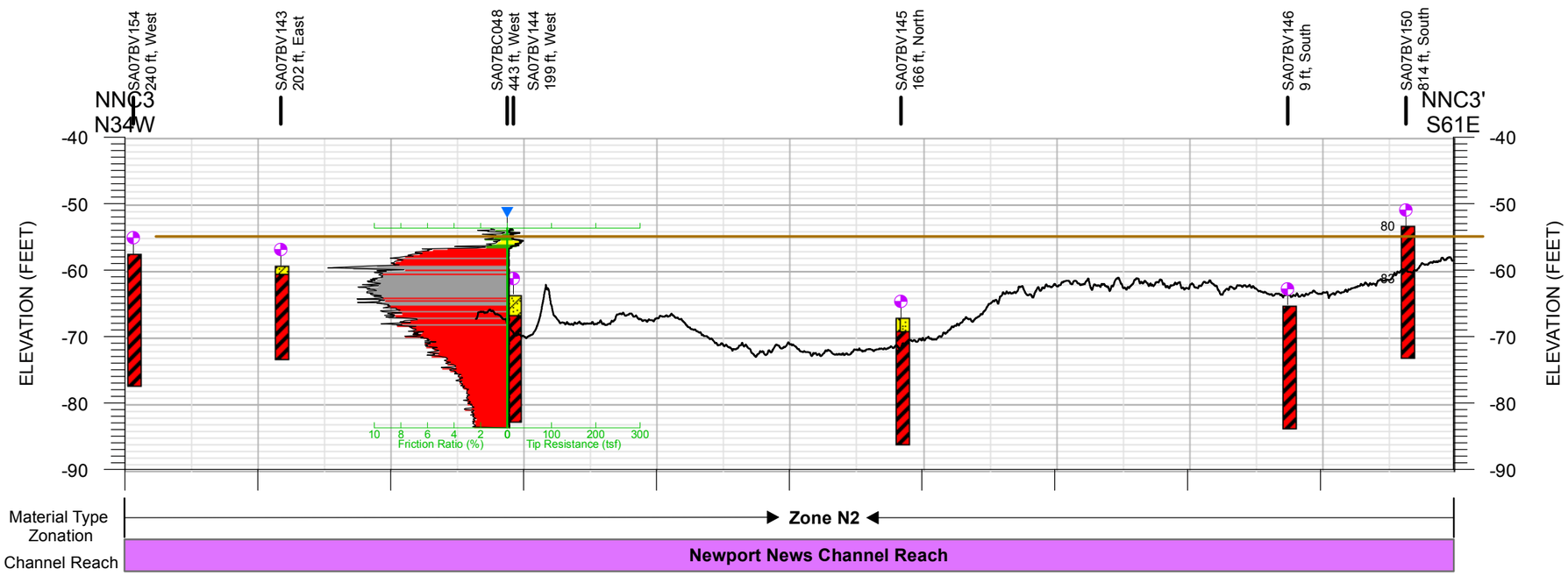
20 ft — 1000 ft
Vertical exaggeration is 50x.

NEWPORT NEWS CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5r

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-r_Newport_News_Channel_2_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 2007 Vibracore
- Cross Section Location
- Navigation Channel Limit

2015 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -75
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2015 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

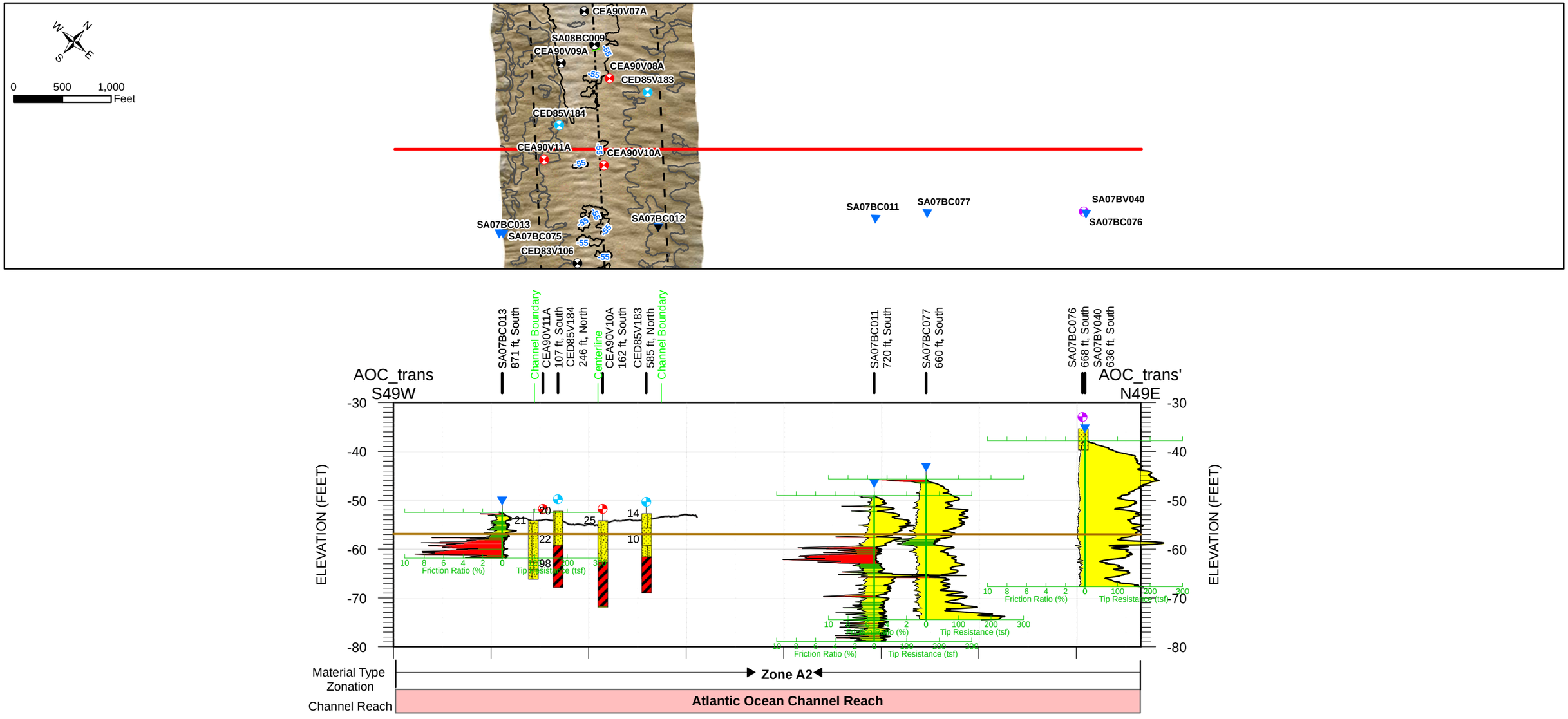
- Fat CLAY (CH)
- Clayey SAND (SC)
- Silty SAND (SM)

20 ft
1000 ft
Vertical exaggeration is 50x.

NEWPORT NEWS CHANNEL CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 5s

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_5-s_Newport_News_Channel_3_XSection_Northern_Branch.mxd, 4/28/2016, wcupples



PLAN VIEW LEGEND

- 2007 Vibracore
- 1990 Vibracore
- 1985 Vibracore
- Exploration (not shown on the cross section)
- 2007 CPT
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

- Fat CLAY (CH)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Silt (SP-SM)
- Silty SAND (SM)

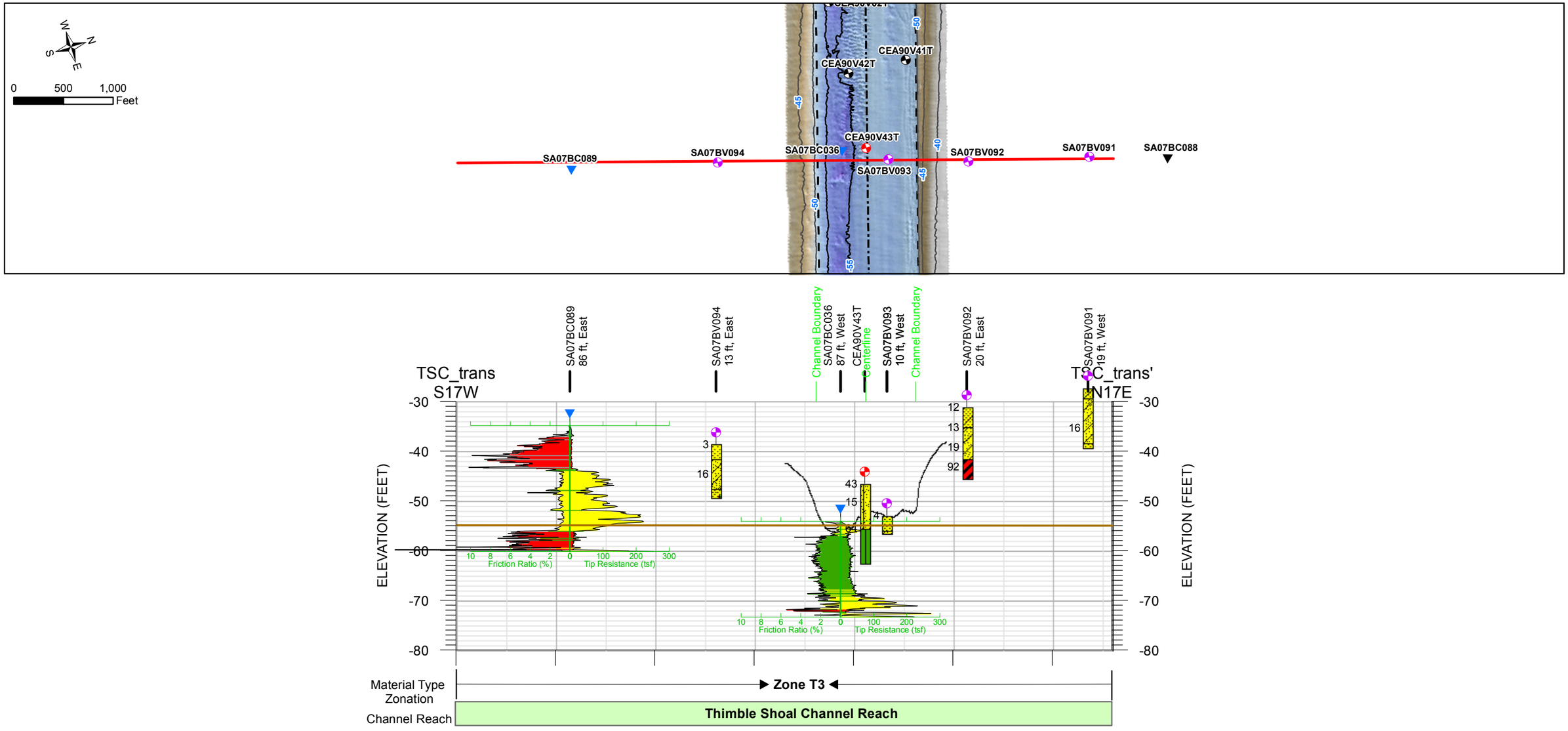
Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

20 ft
1000 ft
Vertical exaggeration is 50x.

ATLANTIC OCEAN CHANNEL TRANSVERSE CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 6a

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_6-a_Atlantic_Ocean_Channel_Transverse_XSection_Northern_Branch.mxd, 4/28/2016, wcupples



Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 1990 Vibracore
- Exploration (not shown on the cross section)
- 2007 CPT
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -40
- Low : -60
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

Fines Content (%) — Standard Penetration Test N-Value

Lithology Type

- Fat CLAY (CH)
- Silt (ML)
- Poorly-Graded SAND (SP)
- Poorly-Graded SAND with Clay (SP-SC)
- Gravelly Poorly-Graded SAND (SP)
- Clayey SAND (SC)
- Silty SAND (SM)

20 ft — 1000 ft

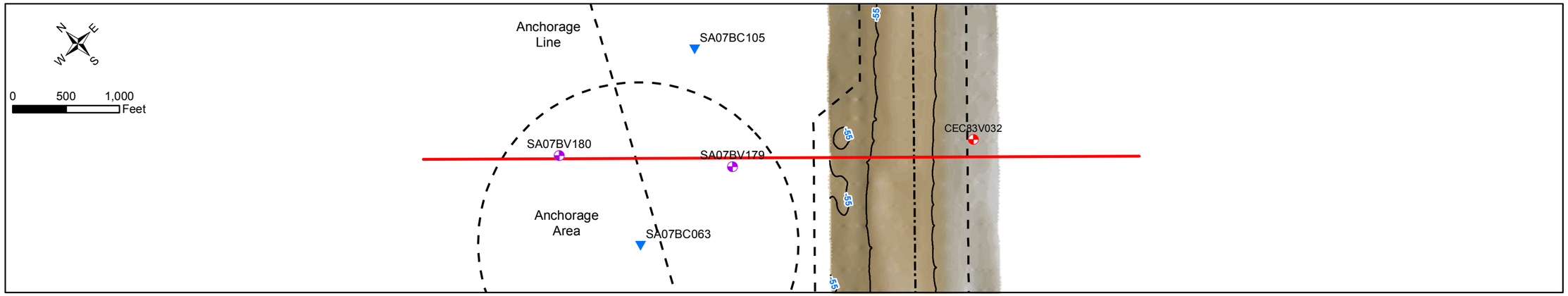
Vertical exaggeration is 50x.

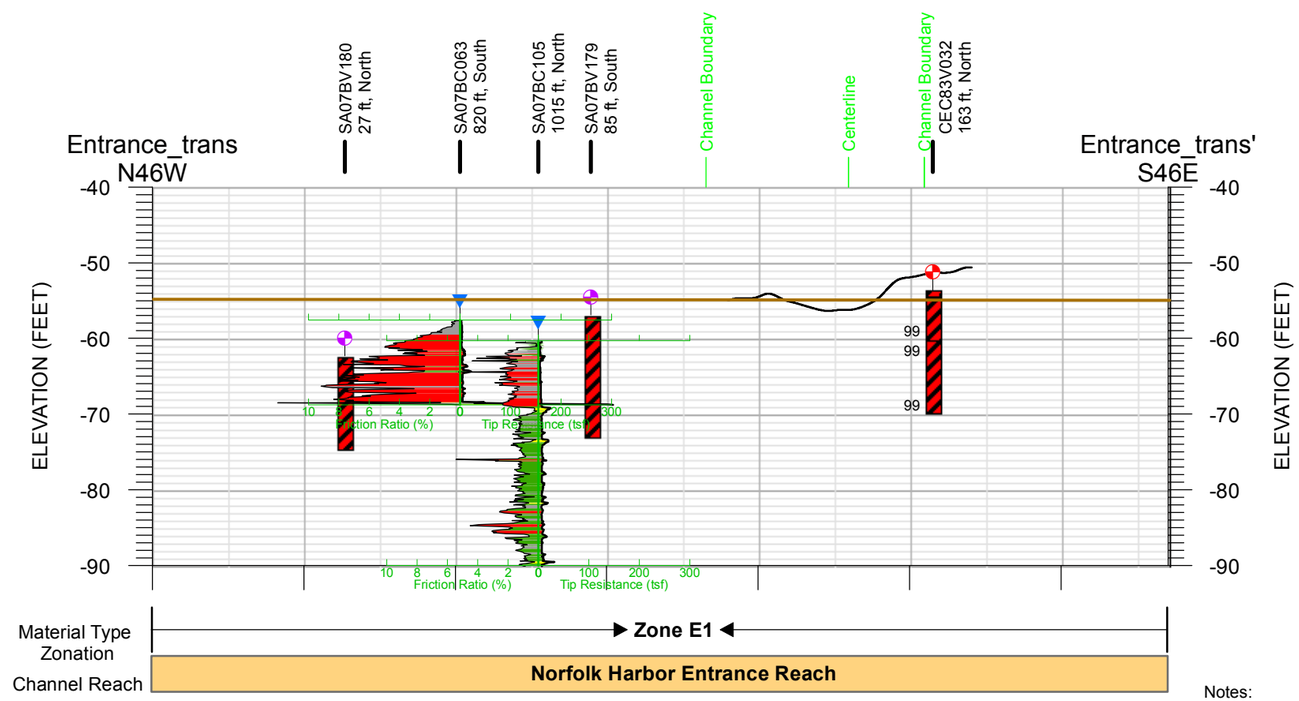
THIMBLE SHOAL CHANNEL TRANSVERSE CROSS SECTION

Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 6b

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_6-b_Thimble_Shoal_Channel_Transverse_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 1990 Vibracore
- Exploration (not shown on the cross section)
- 2007 CPT
- Cross Section Location
- Navigation Channel Limit

2010 USACE Bathymetry (Feet, MLLW)

- High : -40
- Low : -60
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR WOR
3 1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

- Fat CLAY (CH)
- PEAT

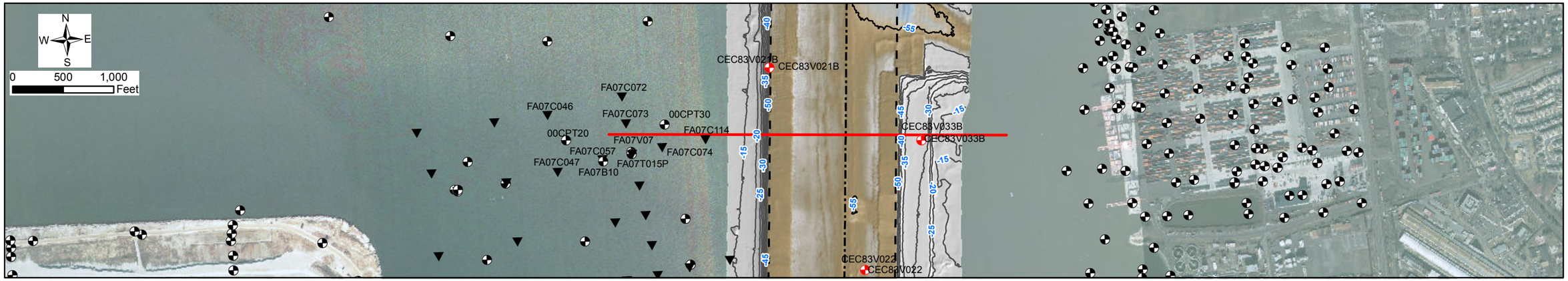
20 ft
1000 ft
Vertical exaggeration is 50x.

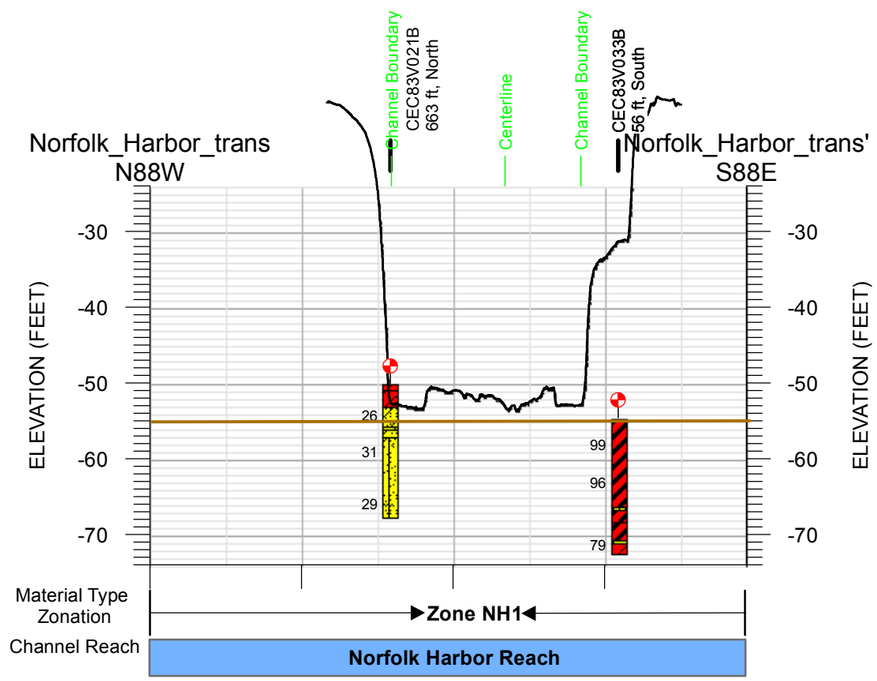
NORFOLK HARBOR ENTRANCE TRANSVERSE CROSS SECTION

Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 6c

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_6-c_Norfolk_Harbor_Entrance_Transverse_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





PLAN VIEW LEGEND

- 1983 Vibracore
- Exploration (not shown on the cross section)
- CPT (not shown on cross section)
- Cross Section Location
- Navigation Channel Limit

2010 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

96 WOR
WOR
3
1
5
Fines Content (%)
Standard Penetration Test N-Value

Lithology Type

- Lean CLAY (CL)
- Fat CLAY (CH)
- Clayey SAND (SC)
- Silty SAND (SM)
- Clayey GRAVEL (GC)

Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

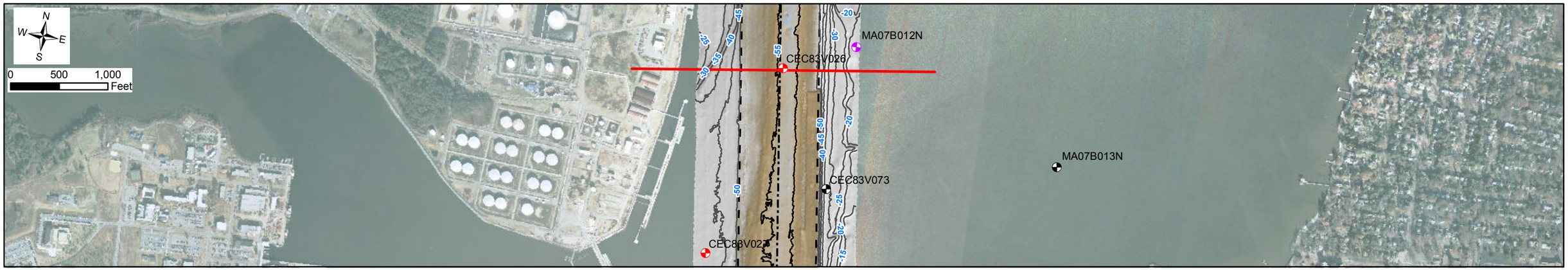
20 ft
1000 ft
Vertical Exaggeration is 50x.

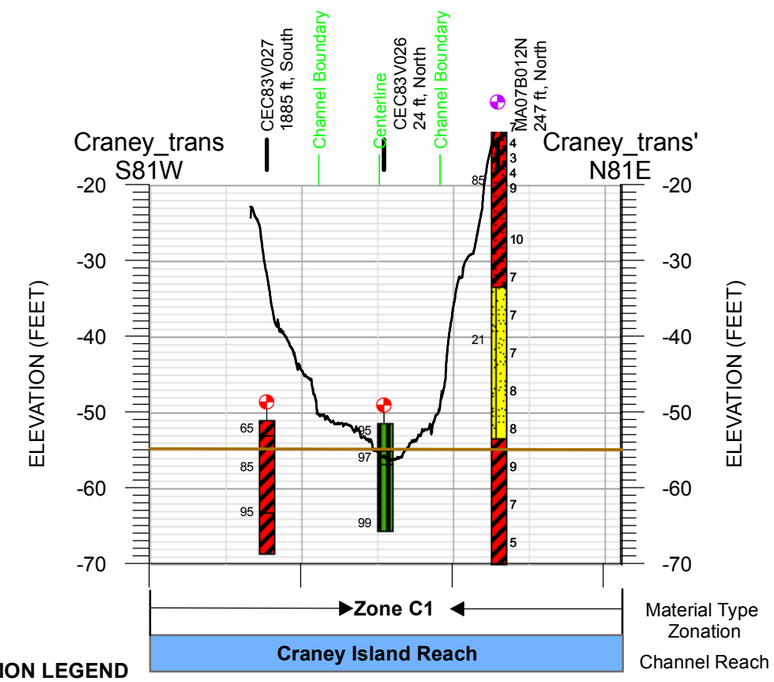
NORFOLK HARBOR REACH TRANSVERSE CROSS SECTION

Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 6d

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_6-d_Norfolk_Harbor_Reach_Transverse_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 1983 Vibracore
- Exploration (not shown on the cross section)
- CPT (not shown on cross section)
- Cross Section Location
- Navigation Channel Limit

2014 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2014 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology

Fines Content (%)

Standard Penetration Test N-Value

Lithology Type

- Fat CLAY (CH)
- Sandy Fat CLAY (CH)
- Elastic Silt (MH)
- Silty SAND (SM)

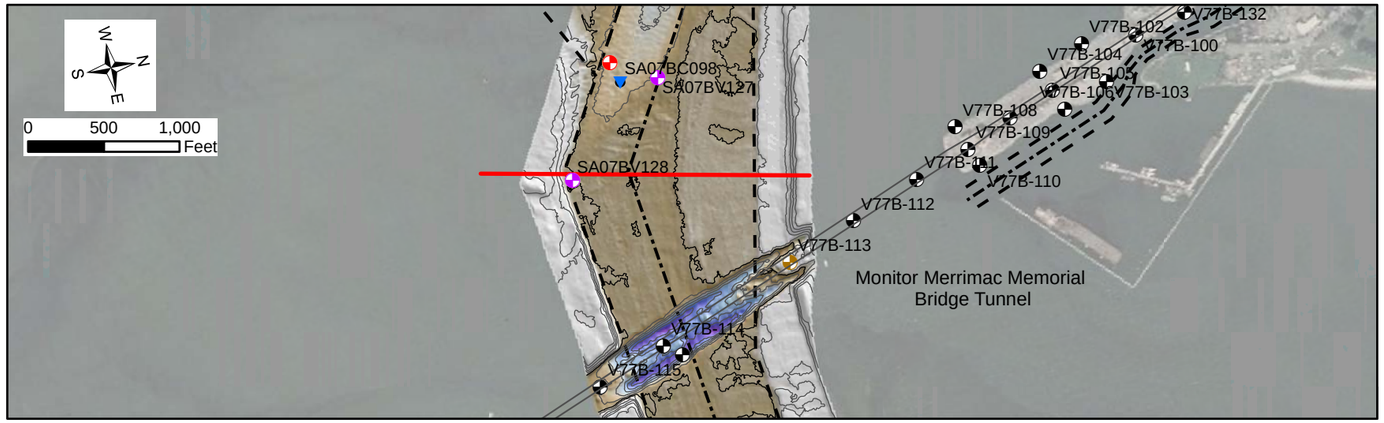
20 ft
1000 ft
Vertical exaggeration is 50x.

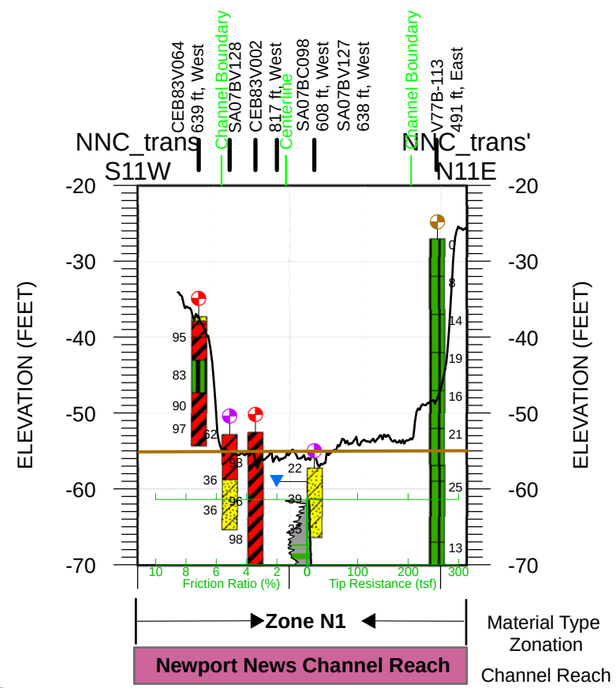
CRANEY ISLAND CHANNEL TRANSVERSE CROSS SECTION

Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 6e

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_6-e_Craney_Island_Reach_Transverse_XSection_Northern_Branch.mxd, 4/28/2016, wcupples





Notes:
1. Elevation is referenced to Mean Lower Low Water (MLLW).
2. CPT soil behavior type is based on Robertson and Campanella (1988).
3. Refer to Key to Subsurface Cross Sections.

PLAN VIEW LEGEND

- 2007 Vibracore
- 1983 Vibracore
- Exploration (not shown on the cross section)
- 2007 CPT
- Cross Section Location
- Navigation Channel Limit

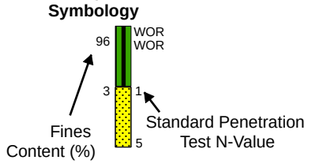
2015 USACE Bathymetry (Feet, MLLW)

- High : -50
- Low : -65
- Contour interval is 5 feet.

CROSS SECTION LEGEND

- 2015 Bathymetry
- Authorized Channel Depth

Boring/Vibracore Symbology



Lithology Type

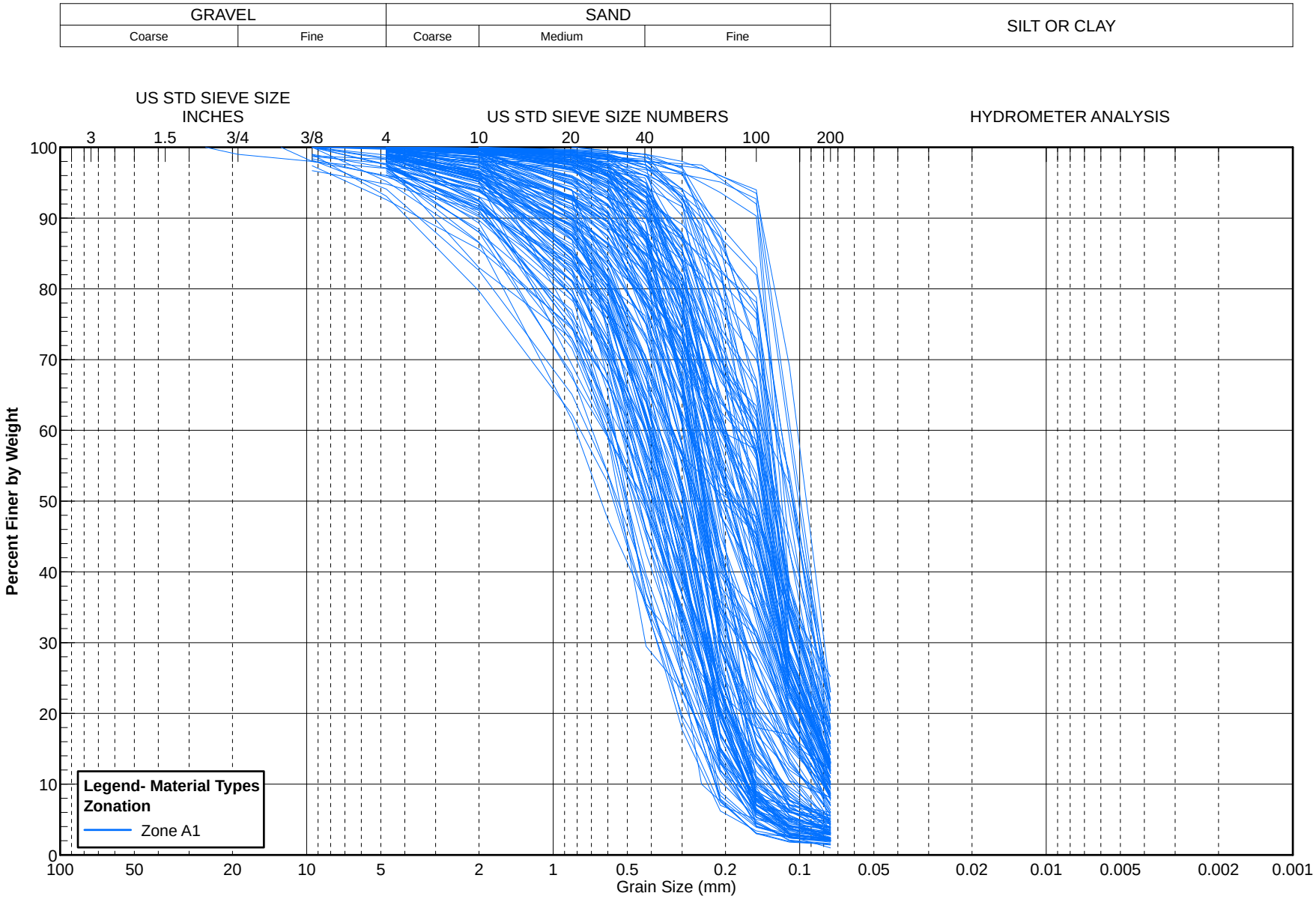
- Lean CLAY (CL)
- Fat CLAY (CH)
- Silt (ML)
- Elastic Silt (MH)
- Clayey SAND (SC)
- Silty SAND (SM)

20 ft
1000 ft
Vertical exaggeration is 50x.

NEWPORT NEWS CHANNEL TRANSVERSE CROSS SECTION
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 6f

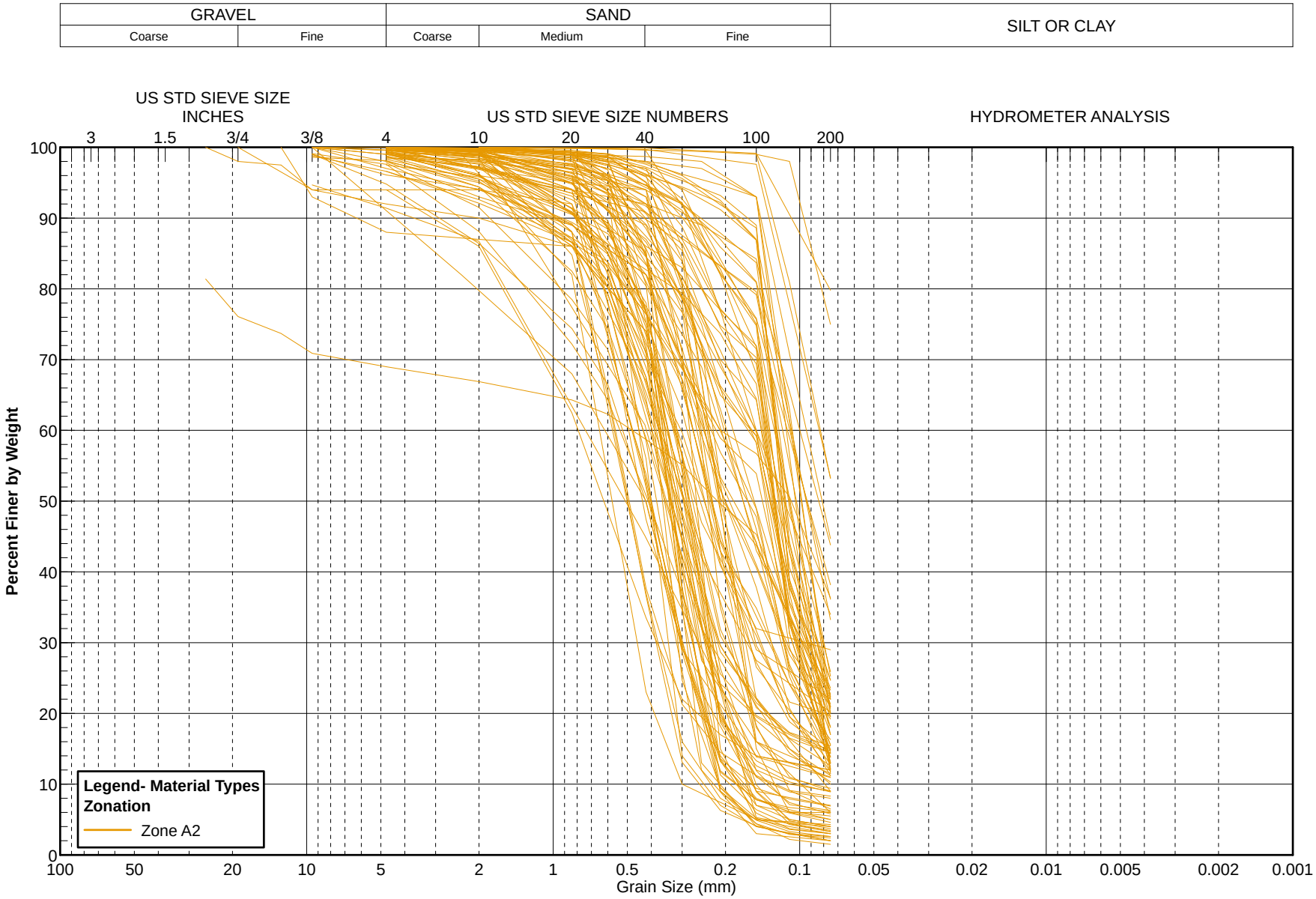
N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\CrossSection\Fig_6-f_NewportNews_Channel_Reach_Transverse_XSection_Northern_Branch.mxd, 4/28/2016, wcupples



GRAIN SIZE CURVES

Atlantic Ocean Channel Reach Zone A1
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

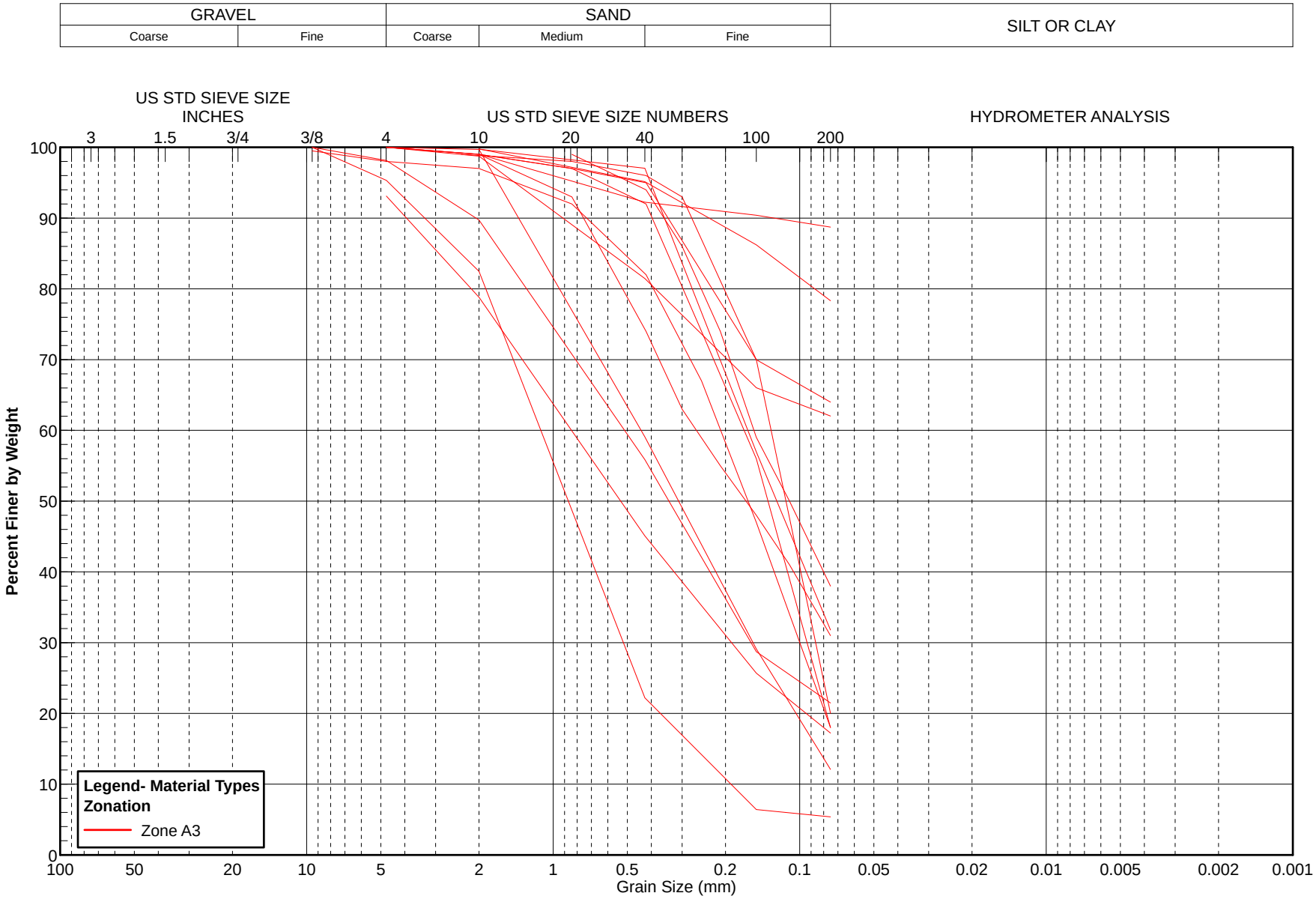
FIGURE 7a



GRAIN SIZE CURVES

Atlantic Ocean Channel Reach Zone A2
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

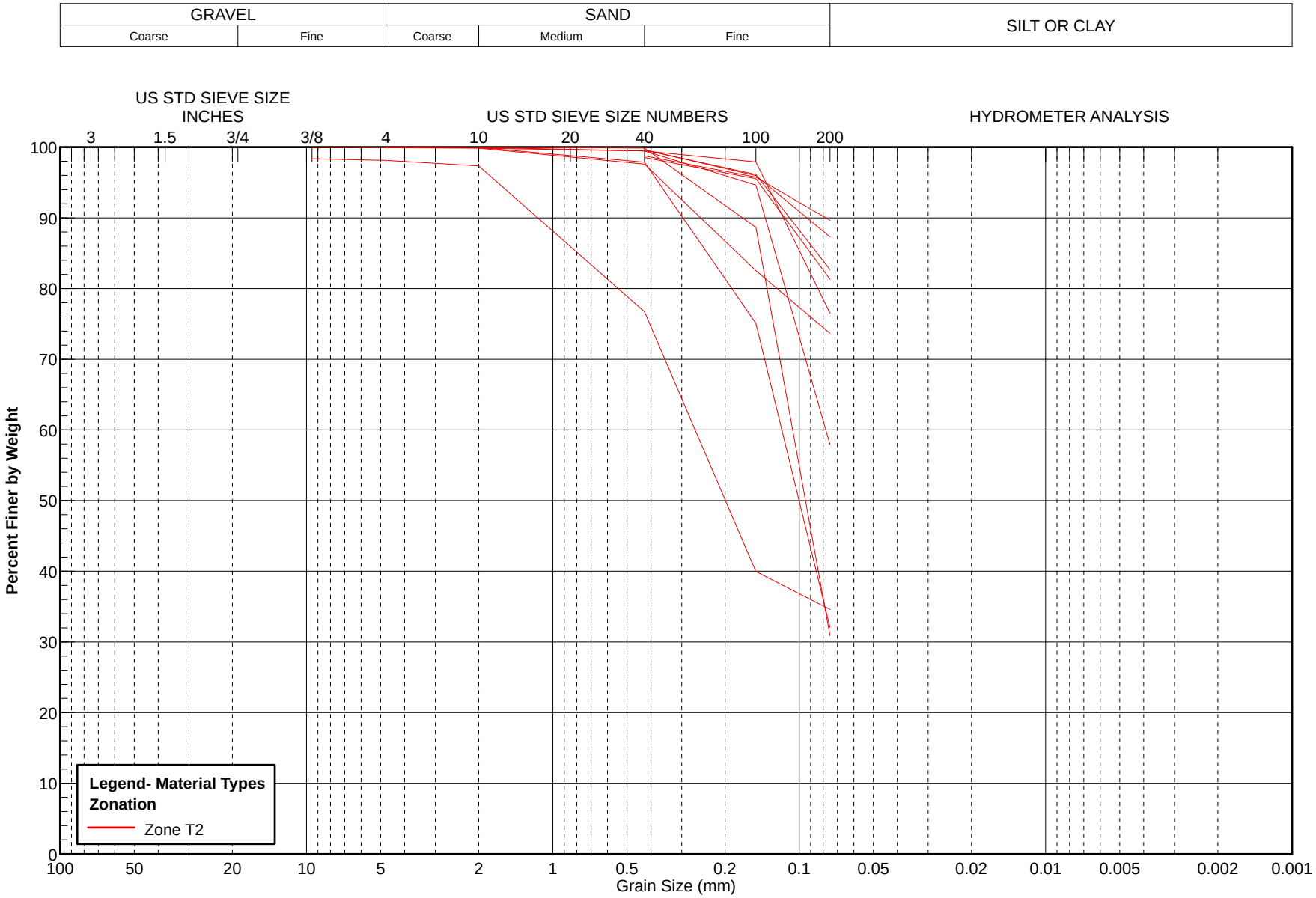
FIGURE 7b



GRAIN SIZE CURVES

Atlantic Ocean Channel Reach Zone A3
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

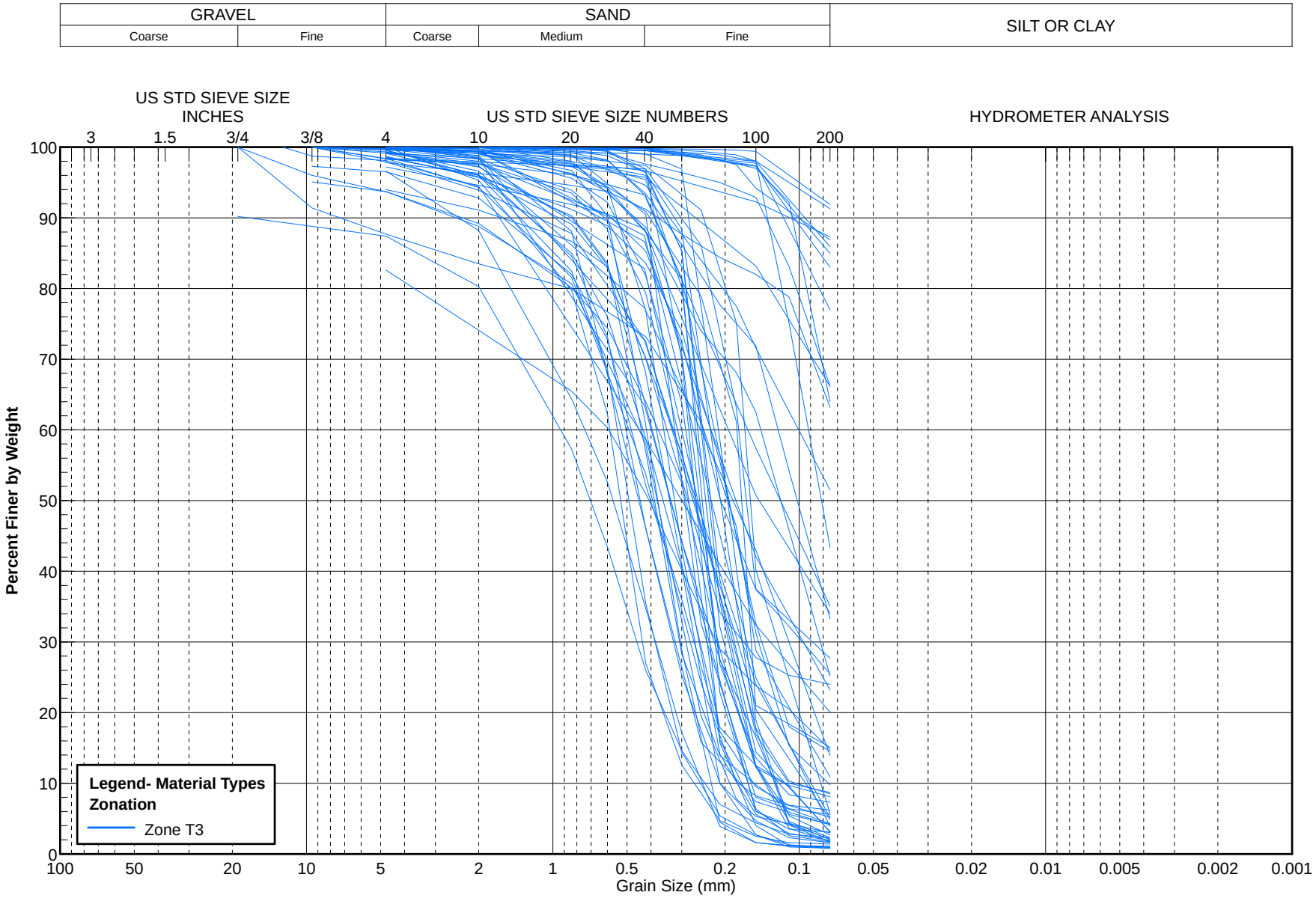
FIGURE 7c



GRAIN SIZE CURVES

Thimble Shoal Channel Reach T2
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

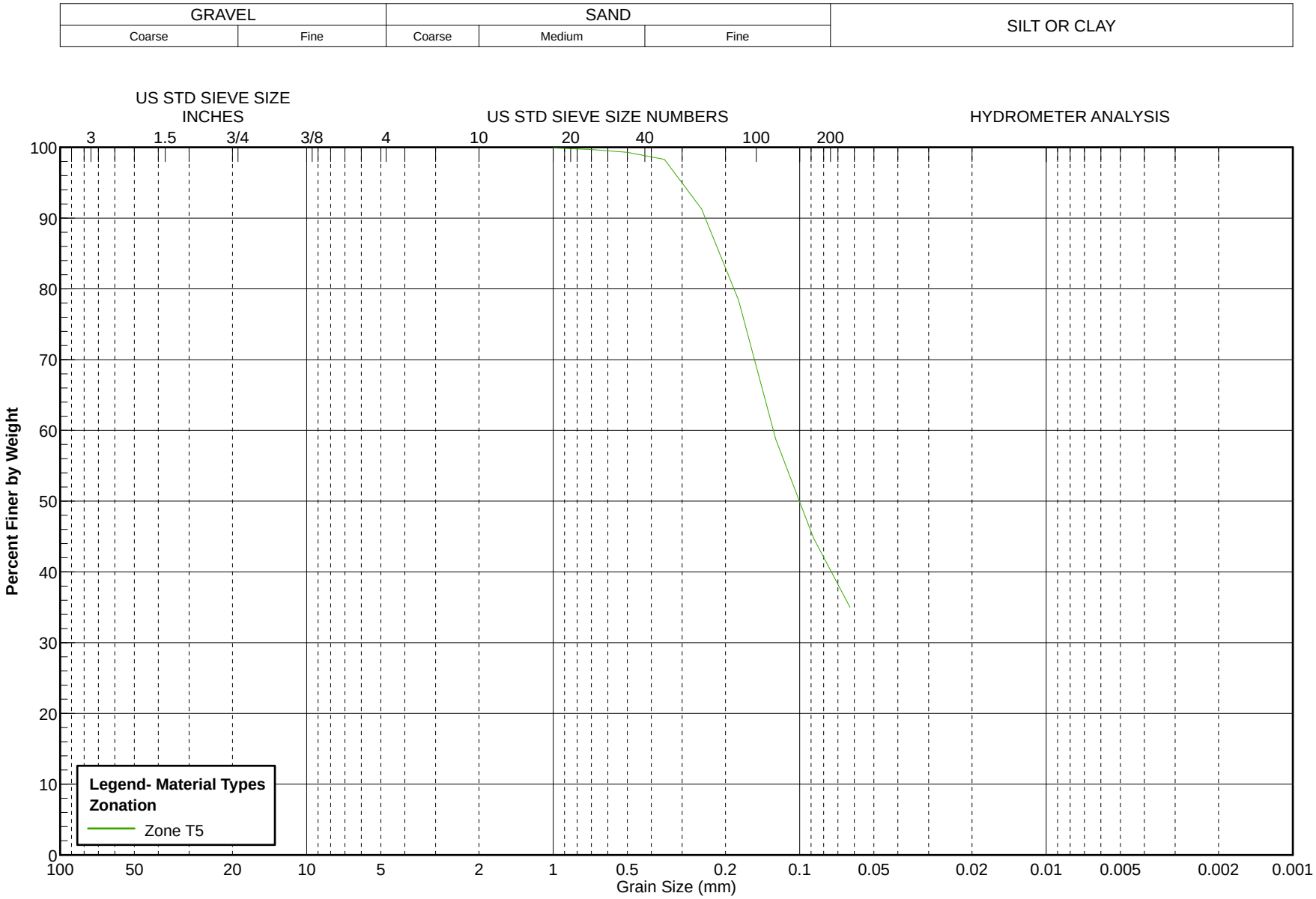
FIGURE 7d



GRAIN SIZE CURVES

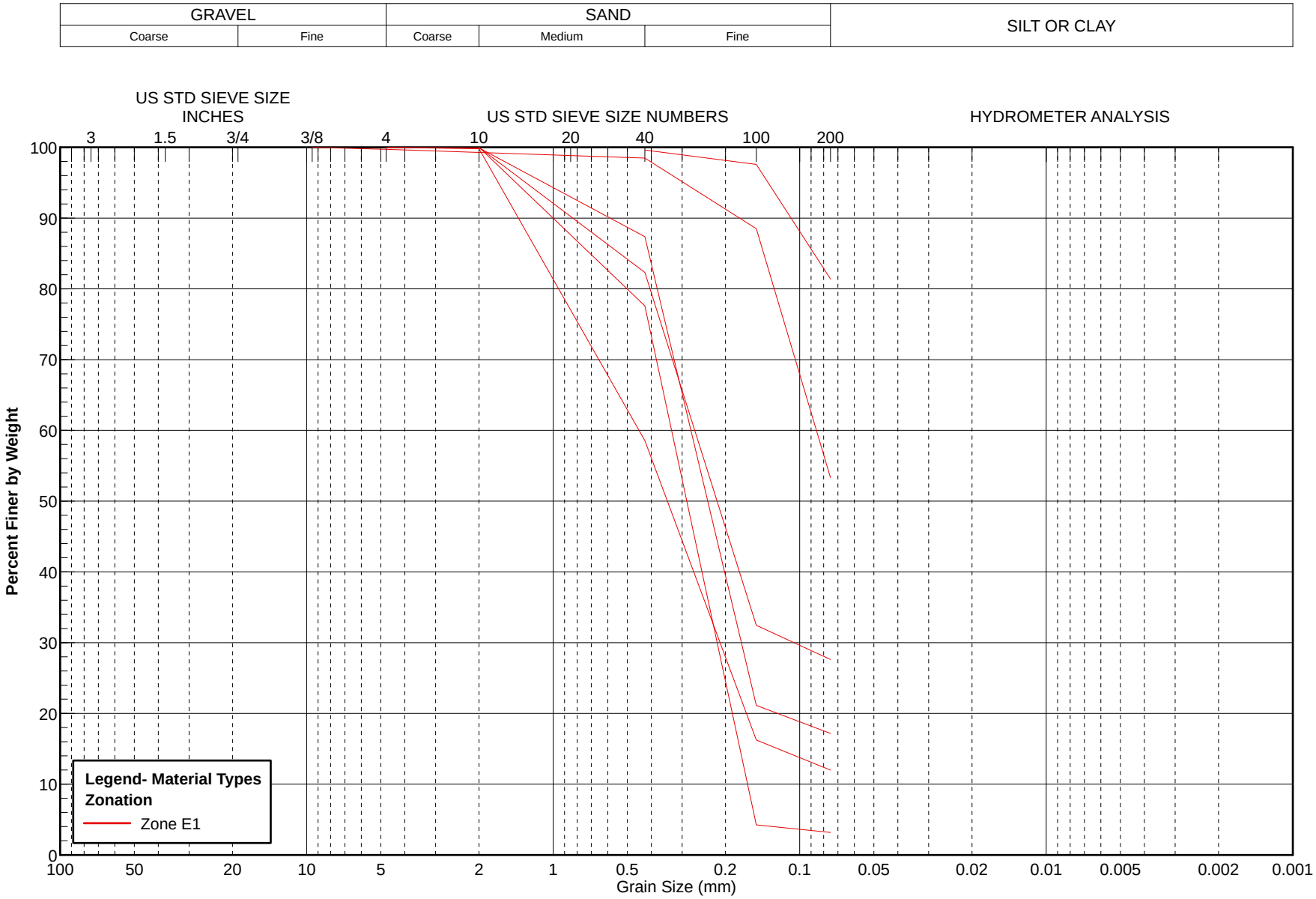
Thimble Shoal Channel Reach T3
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 7e



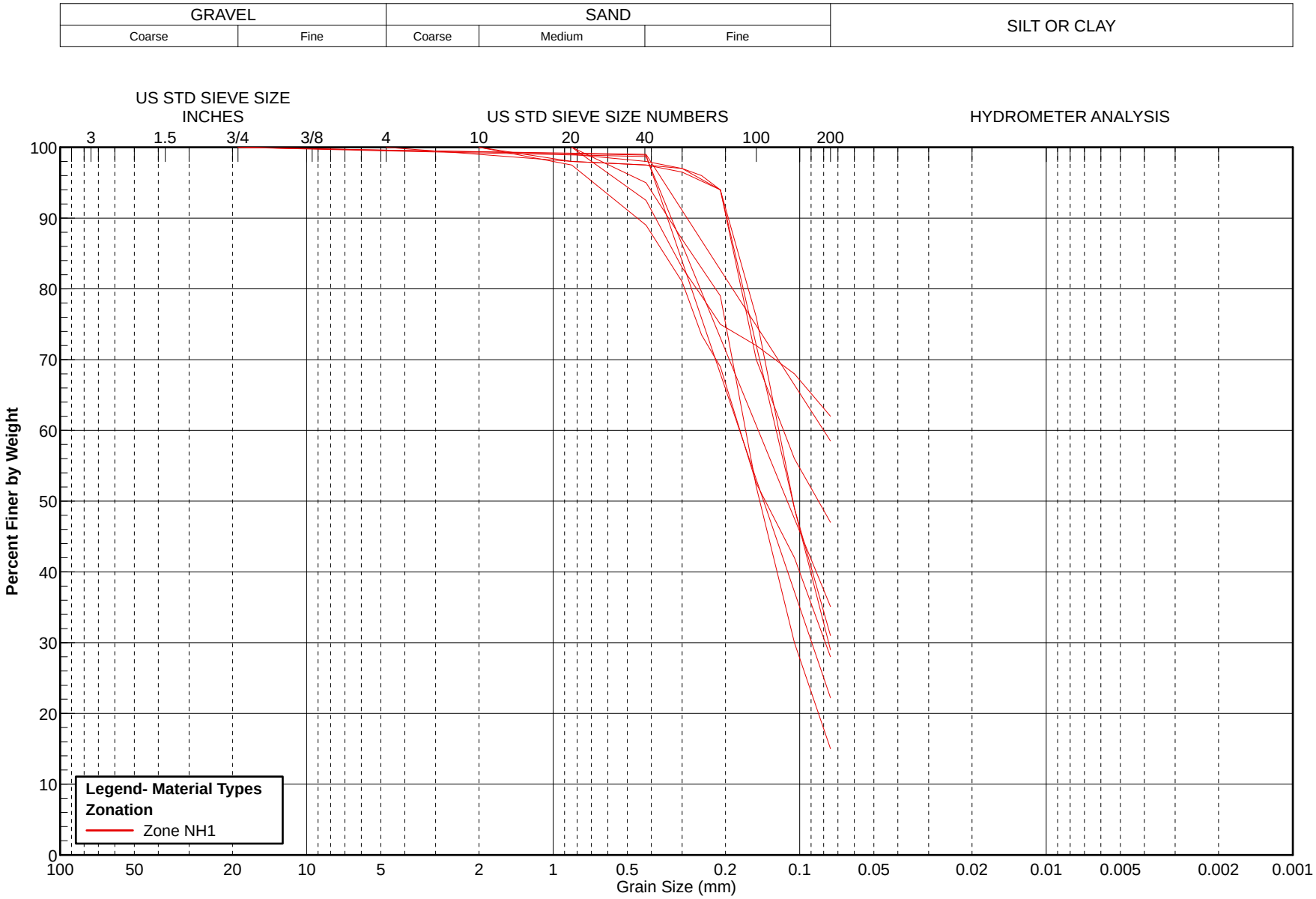
GRAIN SIZE CURVES
Thimble Shoal Channel Reach T5
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 7f



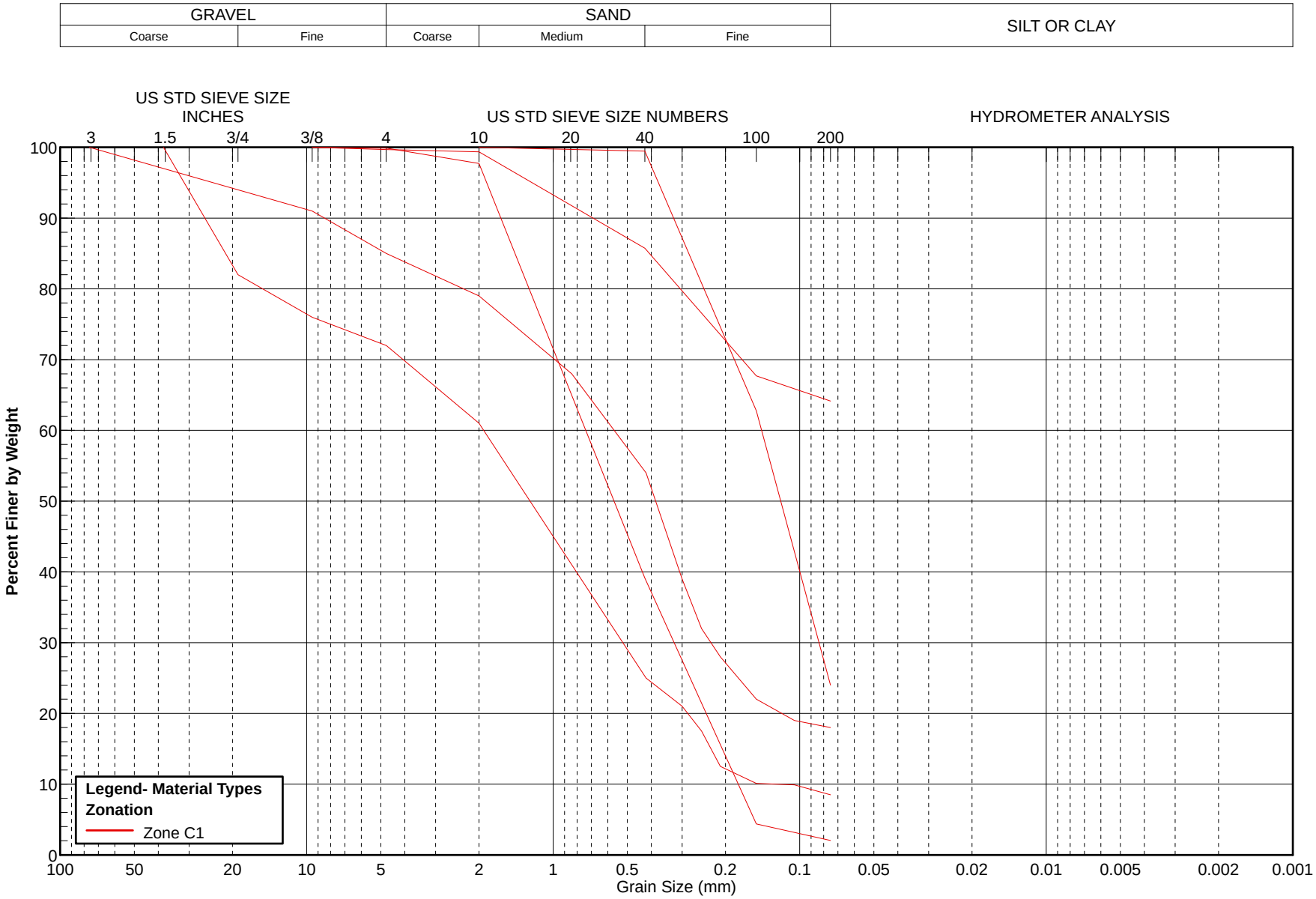
GRAIN SIZE CURVES
Norfolk Harbor Entrance Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 7g



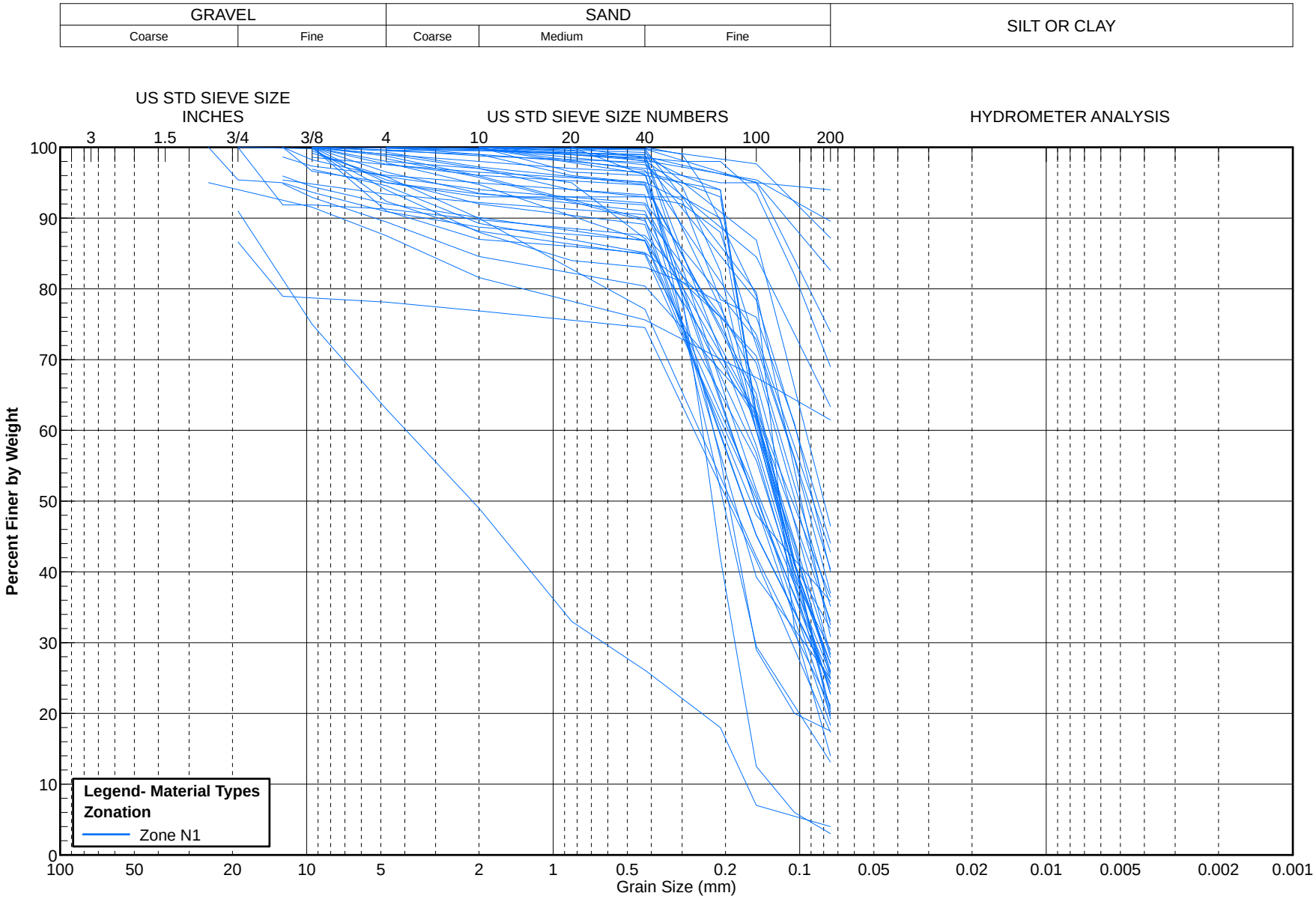
GRAIN SIZE CURVES
Norfolk Harbor Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 7h



GRAIN SIZE CURVES
Craney Island Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 7i



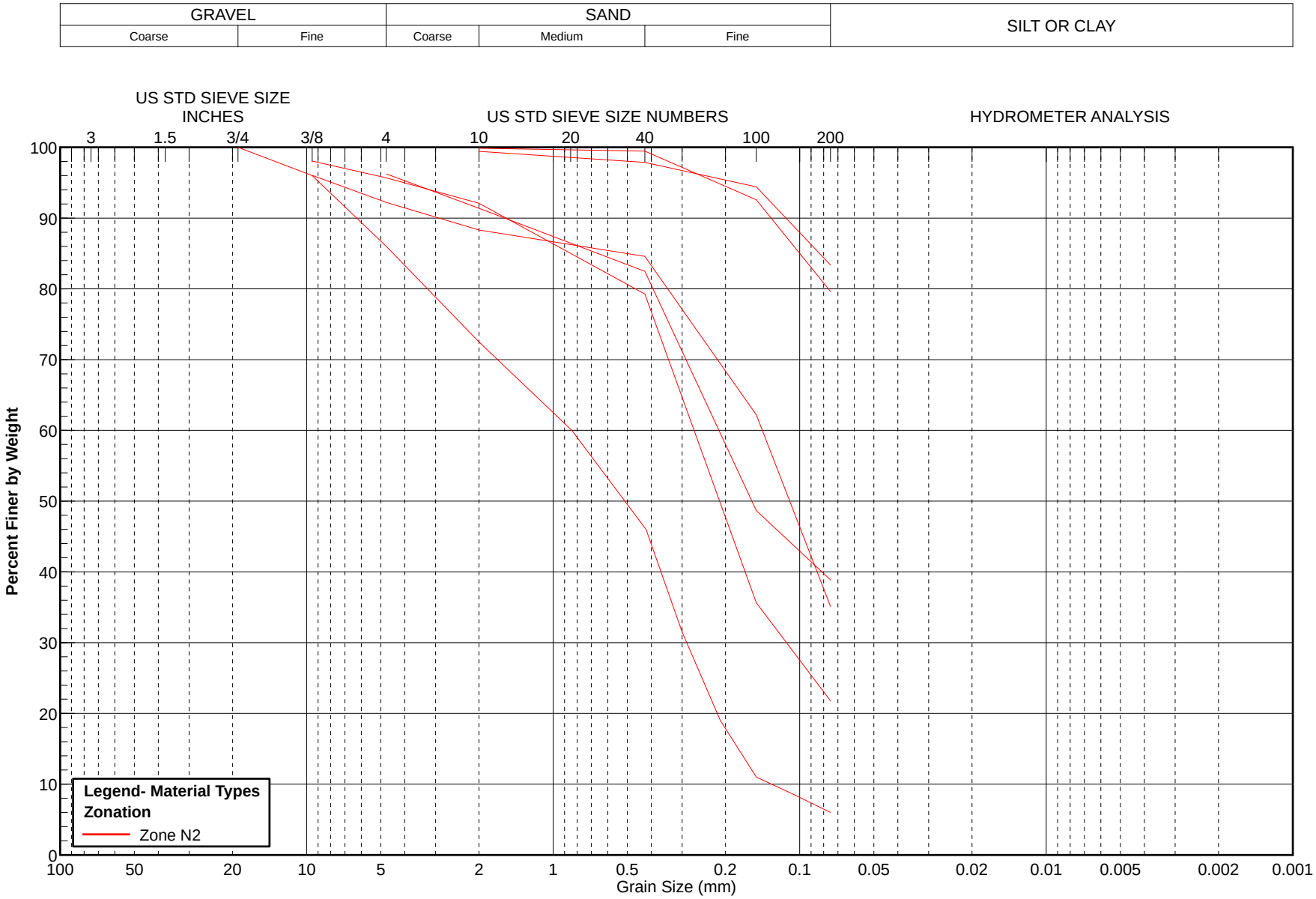
GRAIN SIZE CURVES

Newport News Reach N1

Norfolk Harbor Channels Deepening Study

Hampton Roads, Virginia

FIGURE 7j



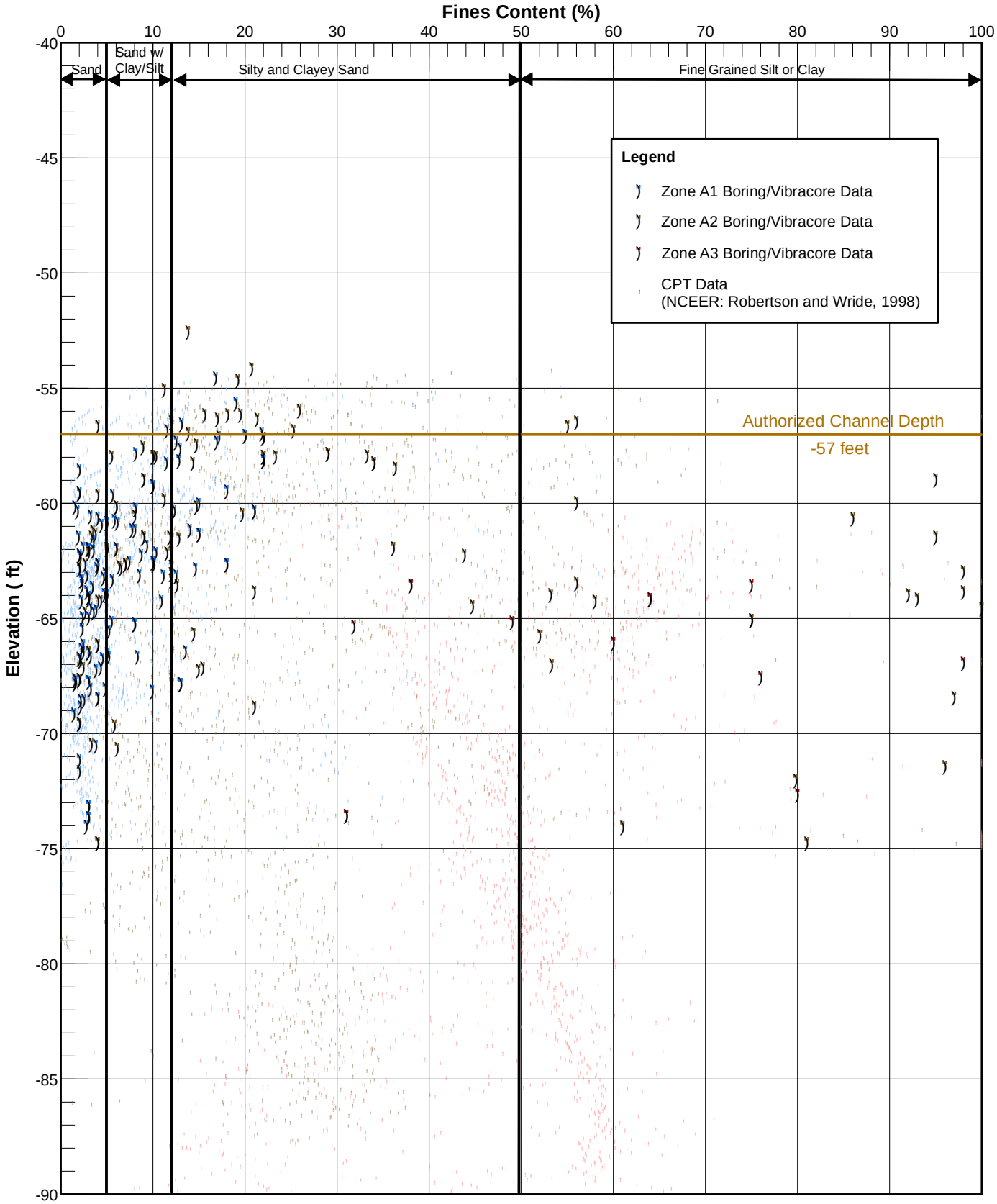
GRAIN SIZE CURVES

Newport News Reach N2

Norfolk Harbor Channels Deepening Study

Hampton Roads, Virginia

FIGURE 7k

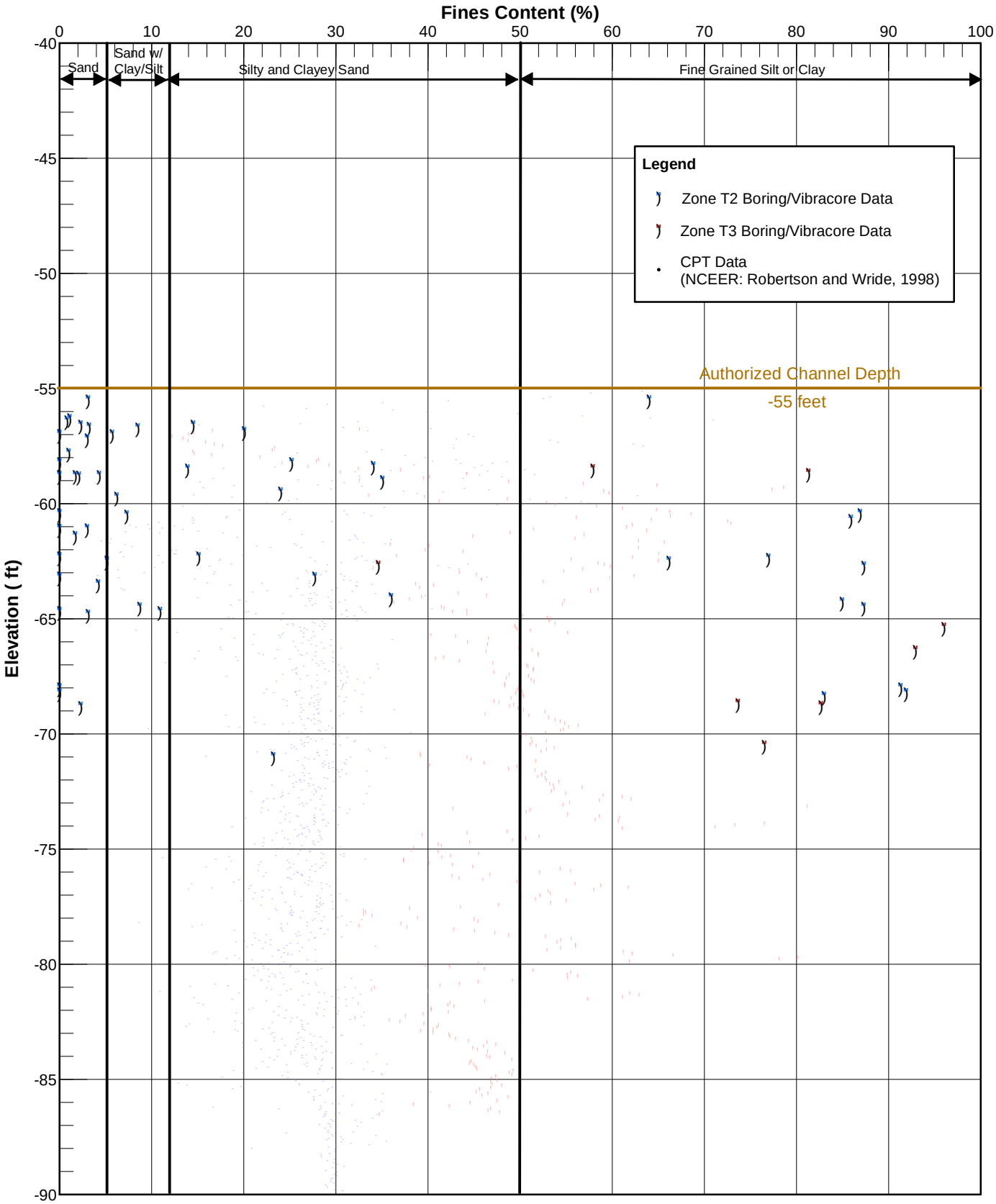


FINES CONTENT

Altantic Ocean Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 8a

N:\Projects\04_2015\04_8115_0012_Port_of_Virgnia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_8-a_FC_vs_Elev_AOC_Reach.mxd, 5/3/2016, SULLIVANS

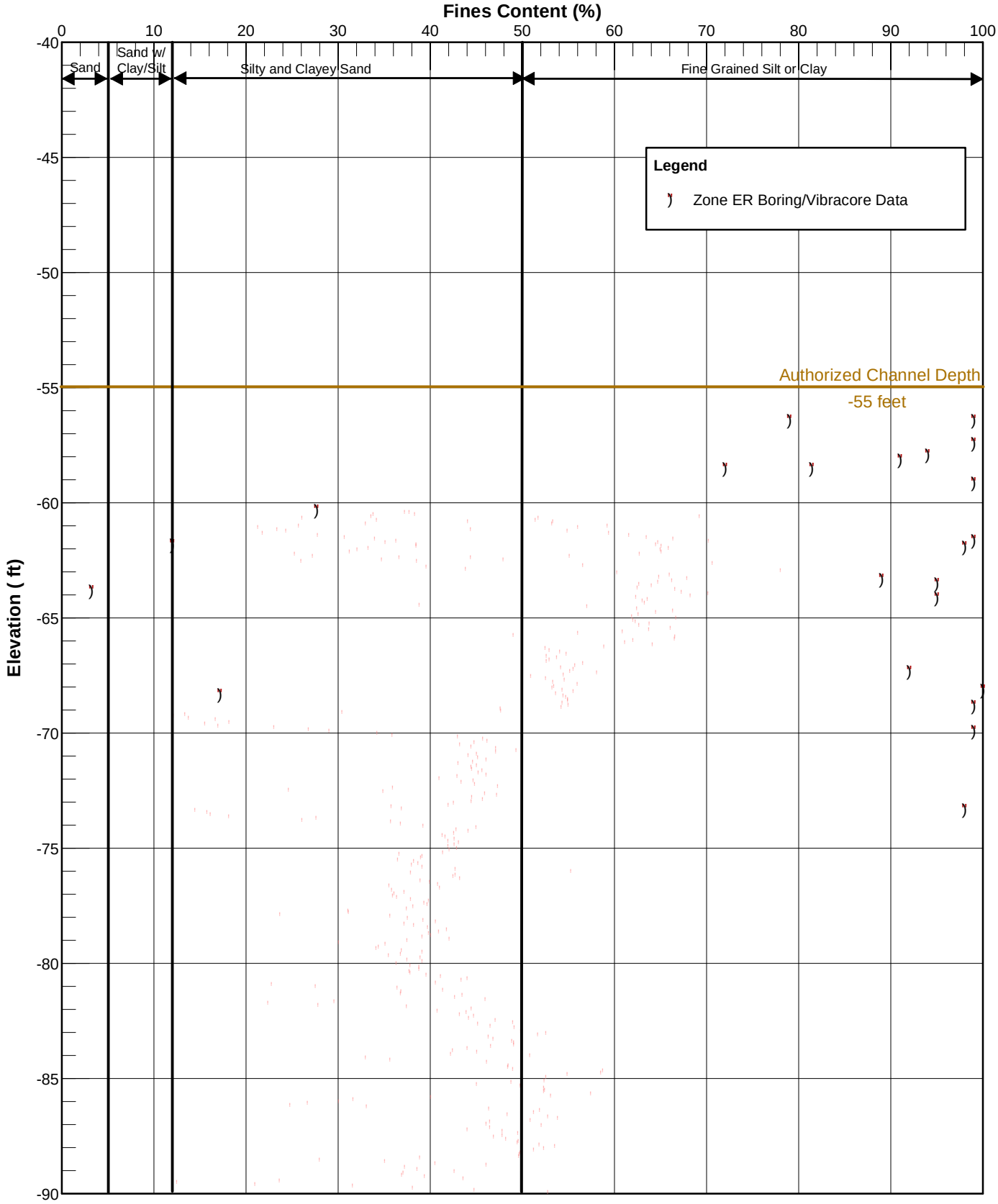


FINES CONTENT

Thimble Shoal Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 8b

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_8-b_FC_vs_Elev_TSC_Reach.mxd, 5/3/2016, SULLIVANS

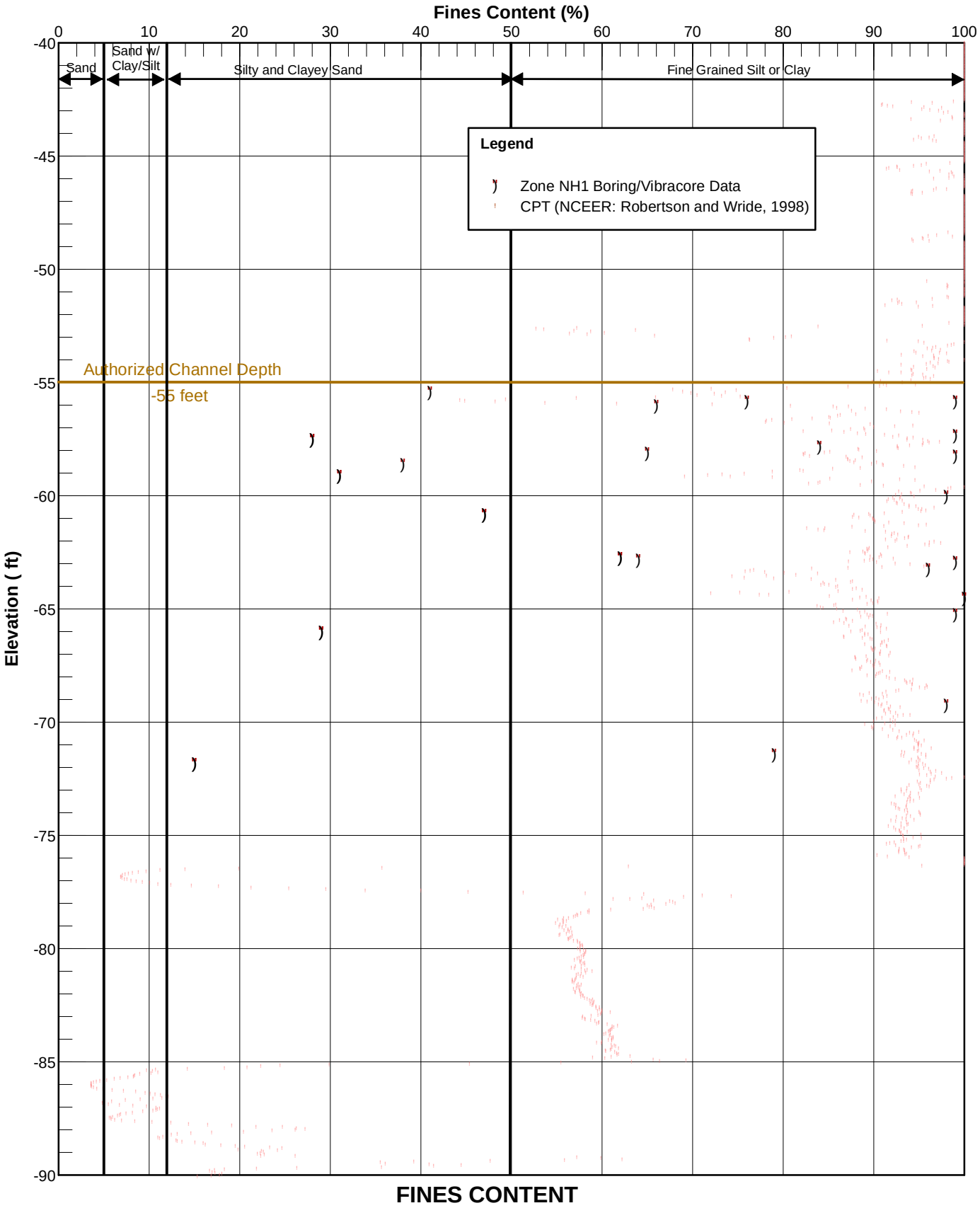


FINES CONTENT

Norfolk Harbor Entrance Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 8c

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_8-c_FC_vs_Elev_Entrance_Reach.mxd, 5/3/2016, SULLIVANS

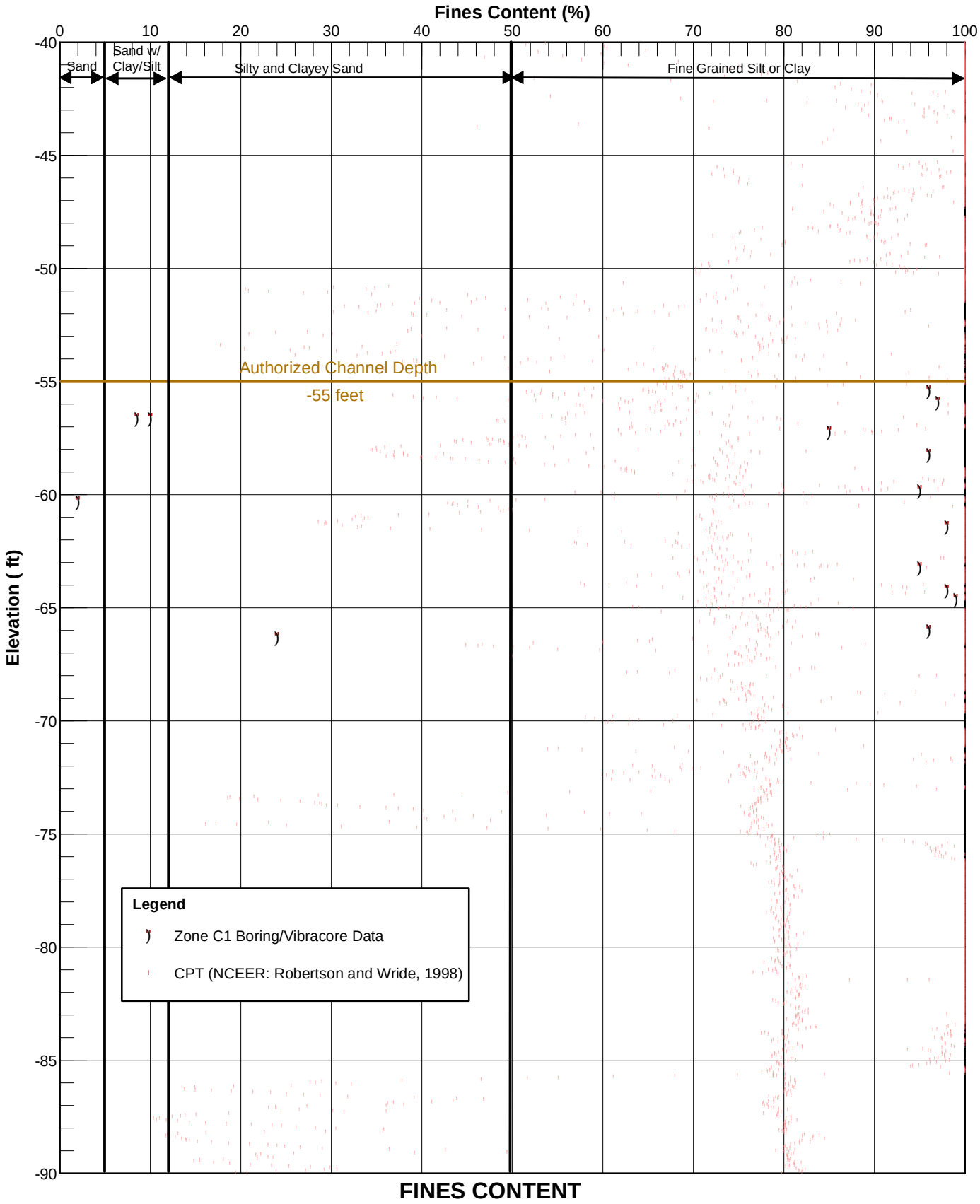


FINES CONTENT

Norfolk Harbor Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 8d

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_8-d_FC_vs_Elev_Norfolk_Harbor_Reach.mxd, 5/3/2016, SULLIVANS

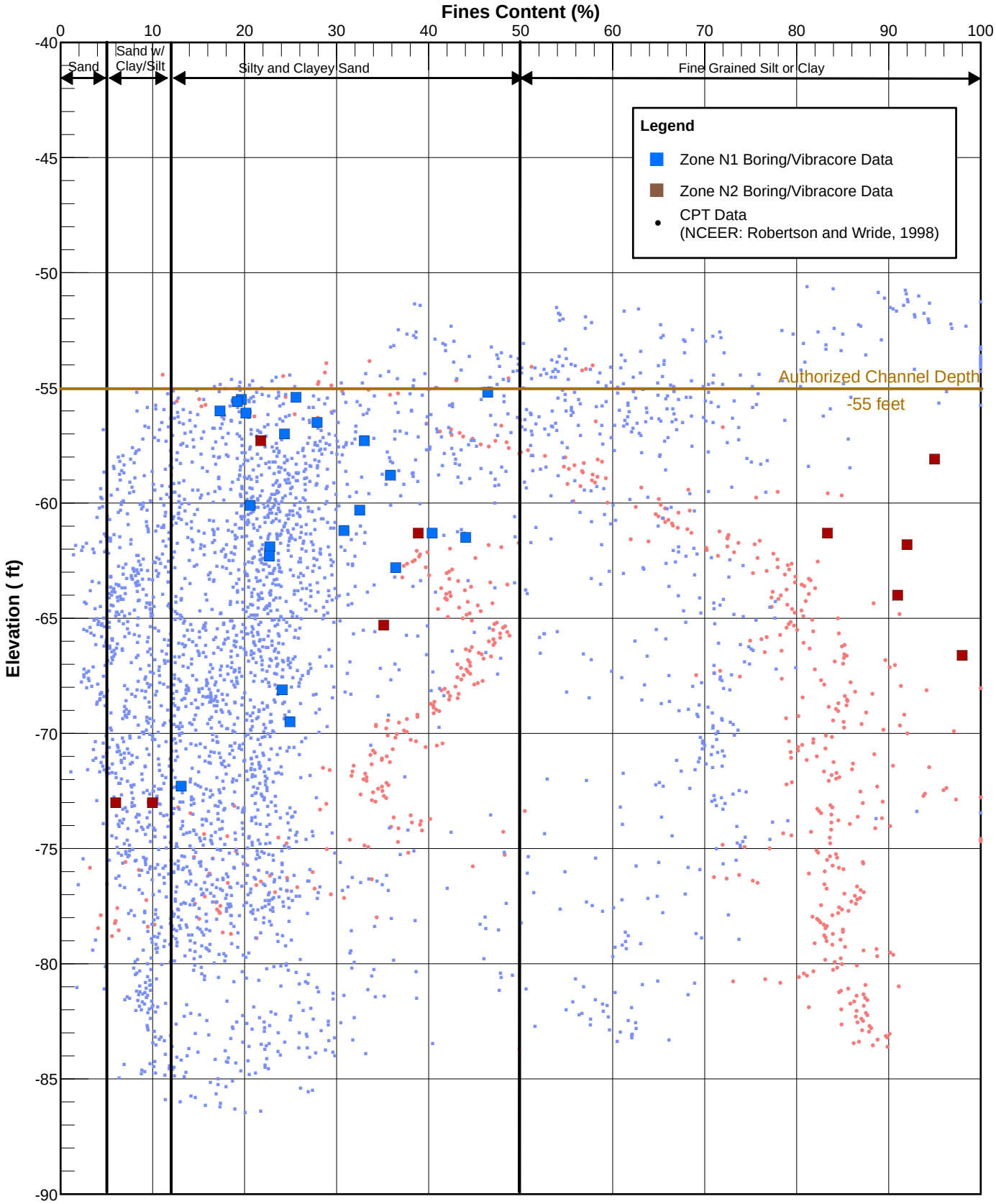


FINES CONTENT

Craney Island Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 8e

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_8-e_FC_vs_Elev_Craney_Island_Reach.mxd, 5/3/2016, SULLIVANS

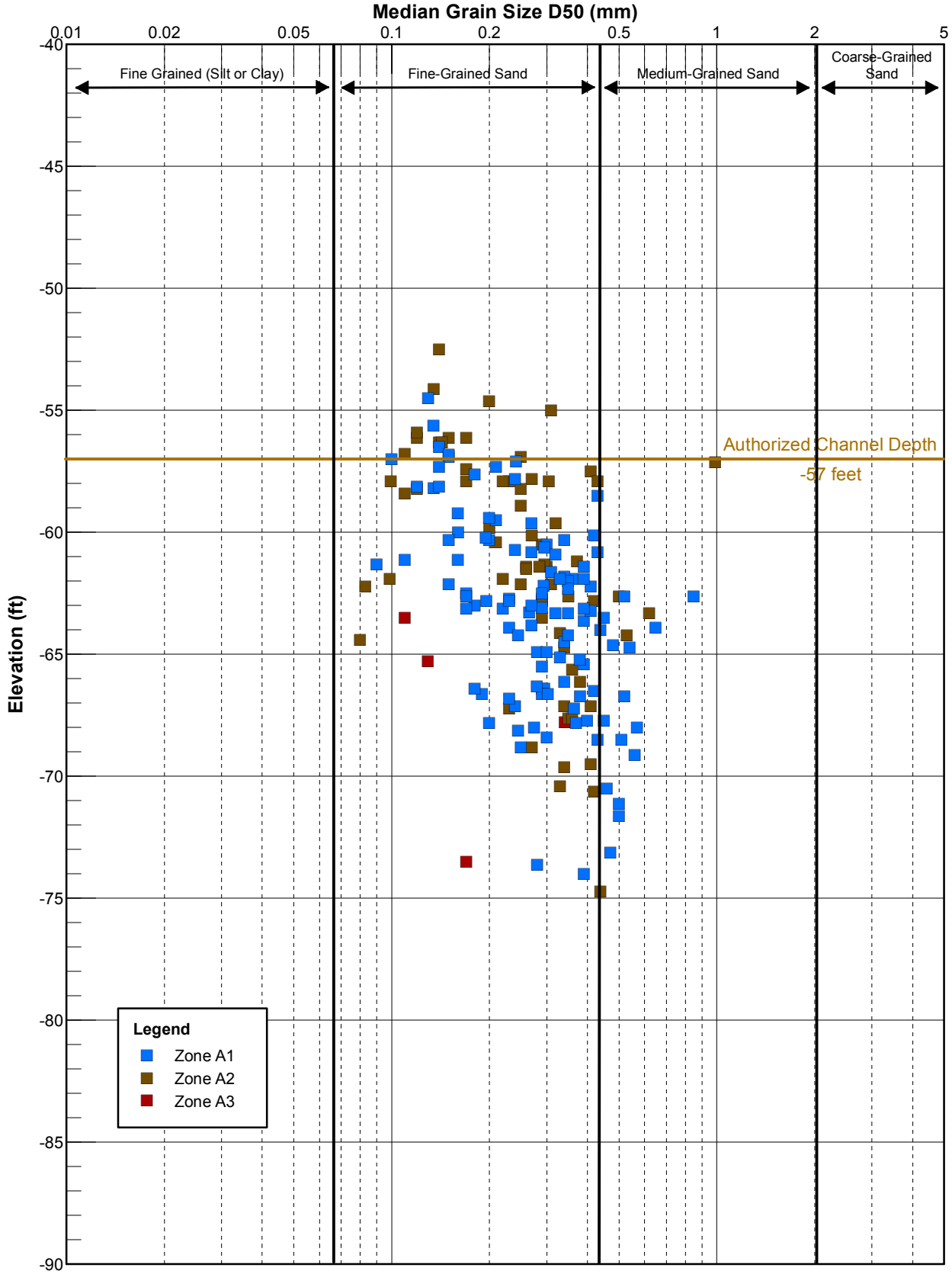


FINES CONTENT

Newport News Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 8f

N:\Projects\04_2015\04_8115_0012_Port_of_Virgnia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_8-f_FC_vs_Elev_NNC_Reach.mxd, 4/28/2016, wcupples

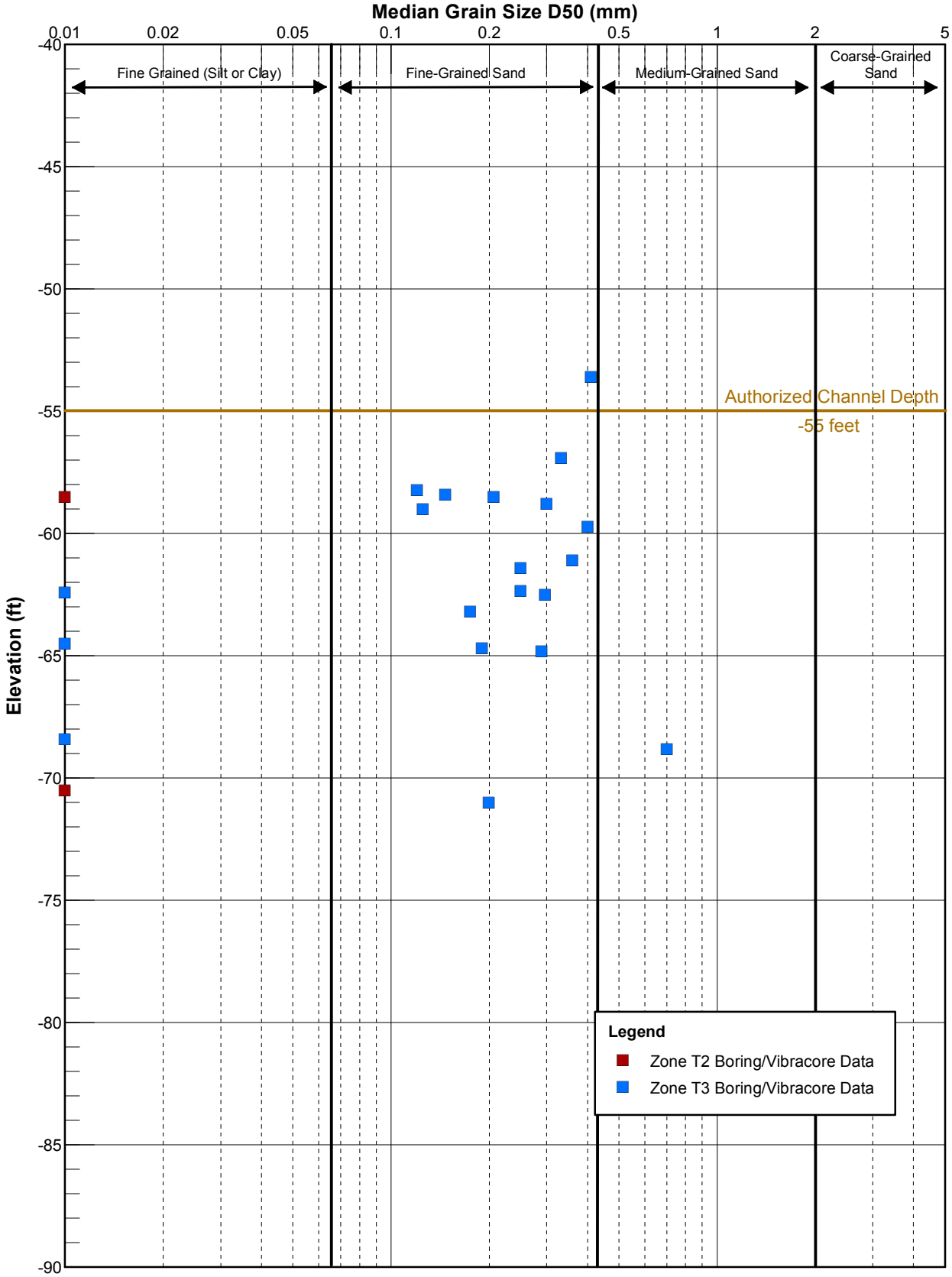


MEDIAN GRAIN SIZE (D_{50})

Atlantic Ocean Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 9a

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_9-a_D50_vs_Elev_AOC_Reach.mxd, 5/3/2016, SULLIVANS

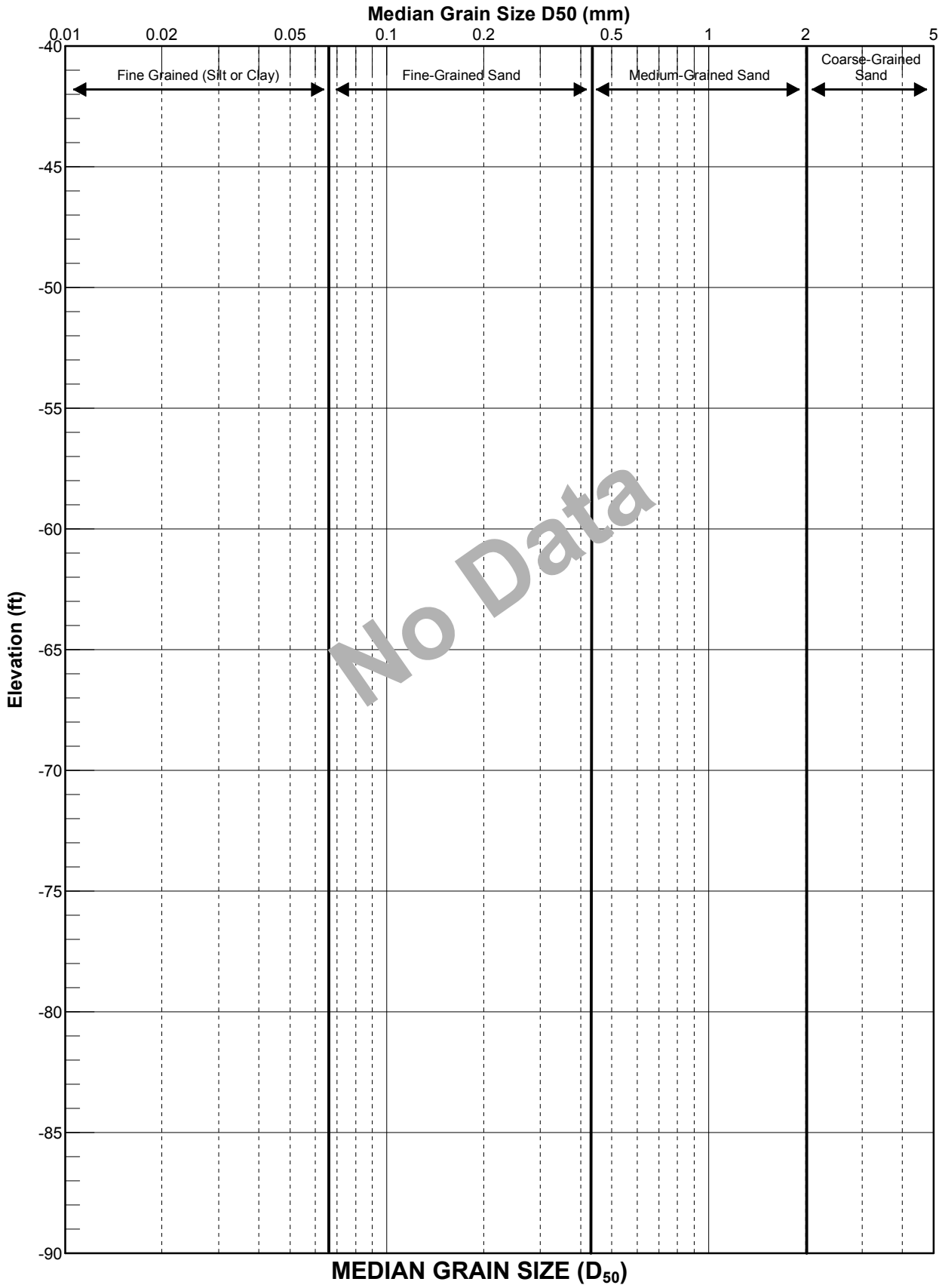


MEDIAN GRAIN SIZE (D_{50})

Thimble Shoal Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 9b

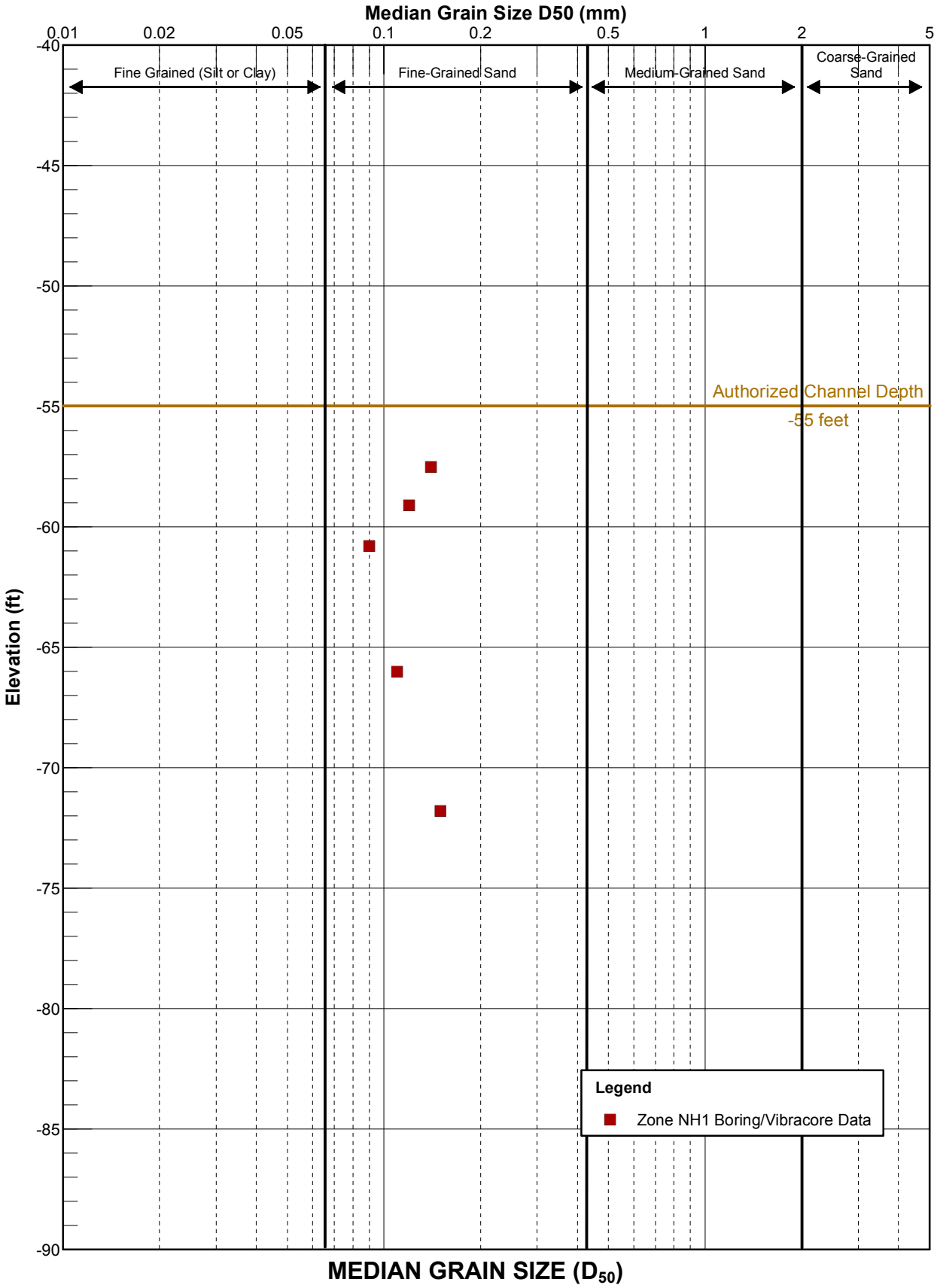
N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_9-b_D50_vs_Elev_TSC_Reach.mxd, 5/3/2016, SULLIVANS



Norfolk Harbor Entrance Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 9c

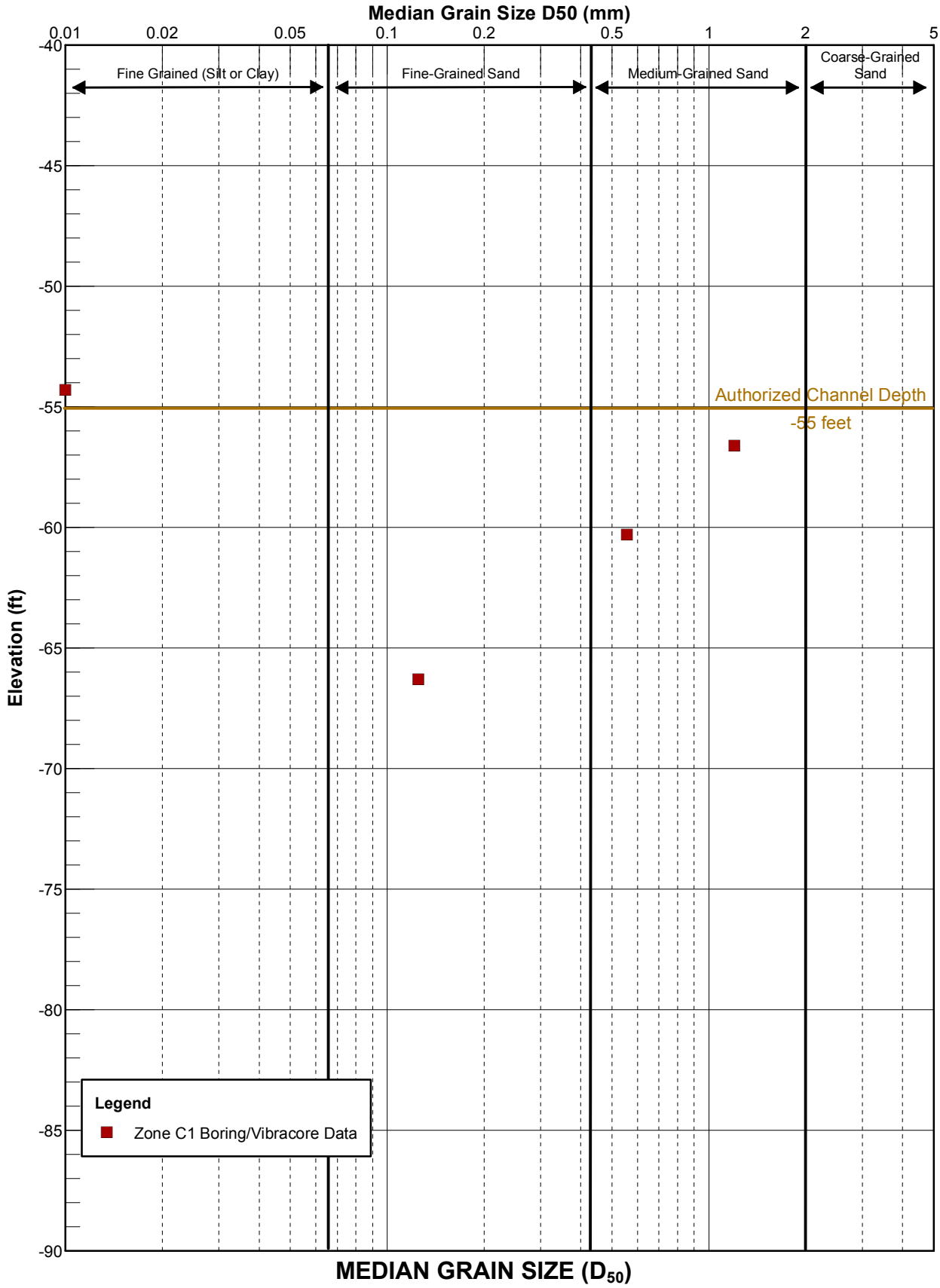
N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_9-c_D50_vs_Elev_Entrance_Reach.mxd, 5/3/2016, SULLIVANS



Norfolk Harbor Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 9d

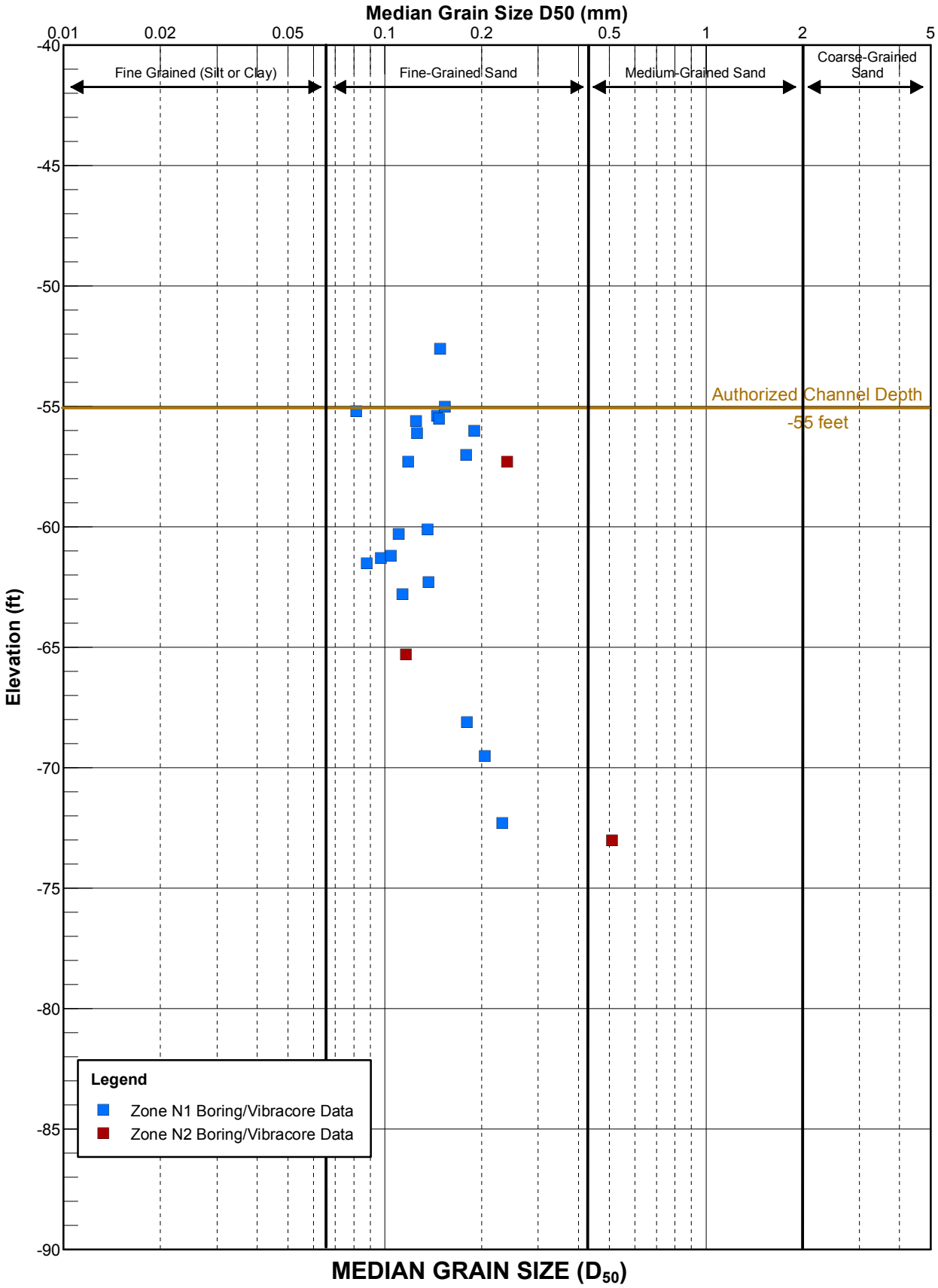
N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_9-d_D50_vs_Elev_Norfolk_Harbor_Reach.mxd, 5/3/2016, SULLIVANS



Craney Island Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 9e

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_9-e_D50_vs_Elev_Craney_Island_Reach.mxd, 5/3/2016, SULLIVANS

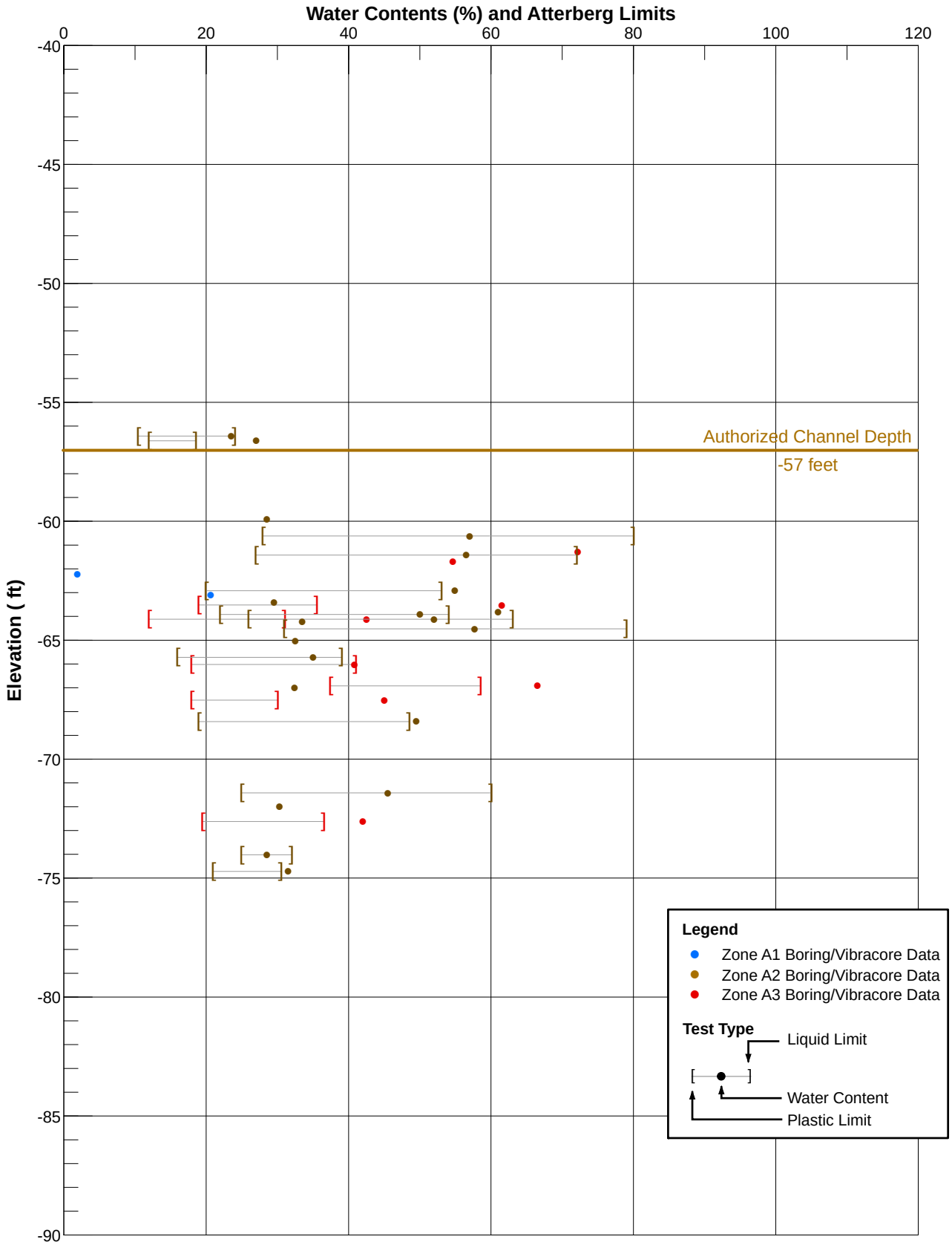


MEDIAN GRAIN SIZE (D_{50})

Newport News Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 9f

N:\Projects\04_2015\04_8115_0012_Port_of_Virginia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_9-f_D50_vs_Elev_NNC_Reach.mxd, 5/3/2016, SULLIVANS

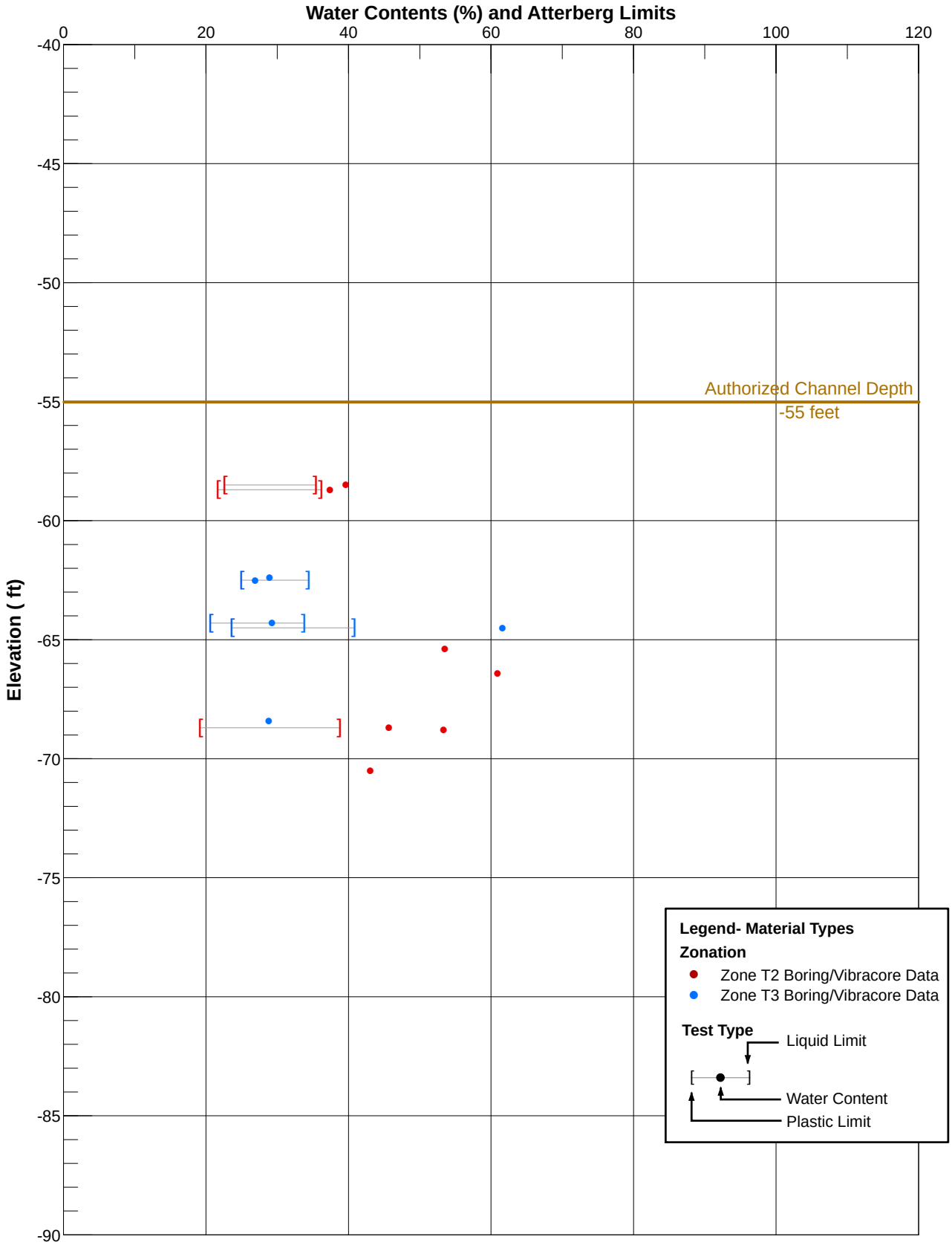


SUMMARY OF ATTERBERG LIMITS DATA

Atlantic Ocean Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 10a

N:\Projects\04_2015\04_8115_0012_Port_of_Virgnia_Deepening\Outputs\Arpil2016_Draft_Reports\NorfolkHarborChannels\MXD\Fig_10-a_Atterberg_Limit_vs_Elev_AOC_Reach.mxd, 4/28/2016, wcupples



SUMMARY OF ATTERBERG LIMITS DATA
Thimble Shoal Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 10b

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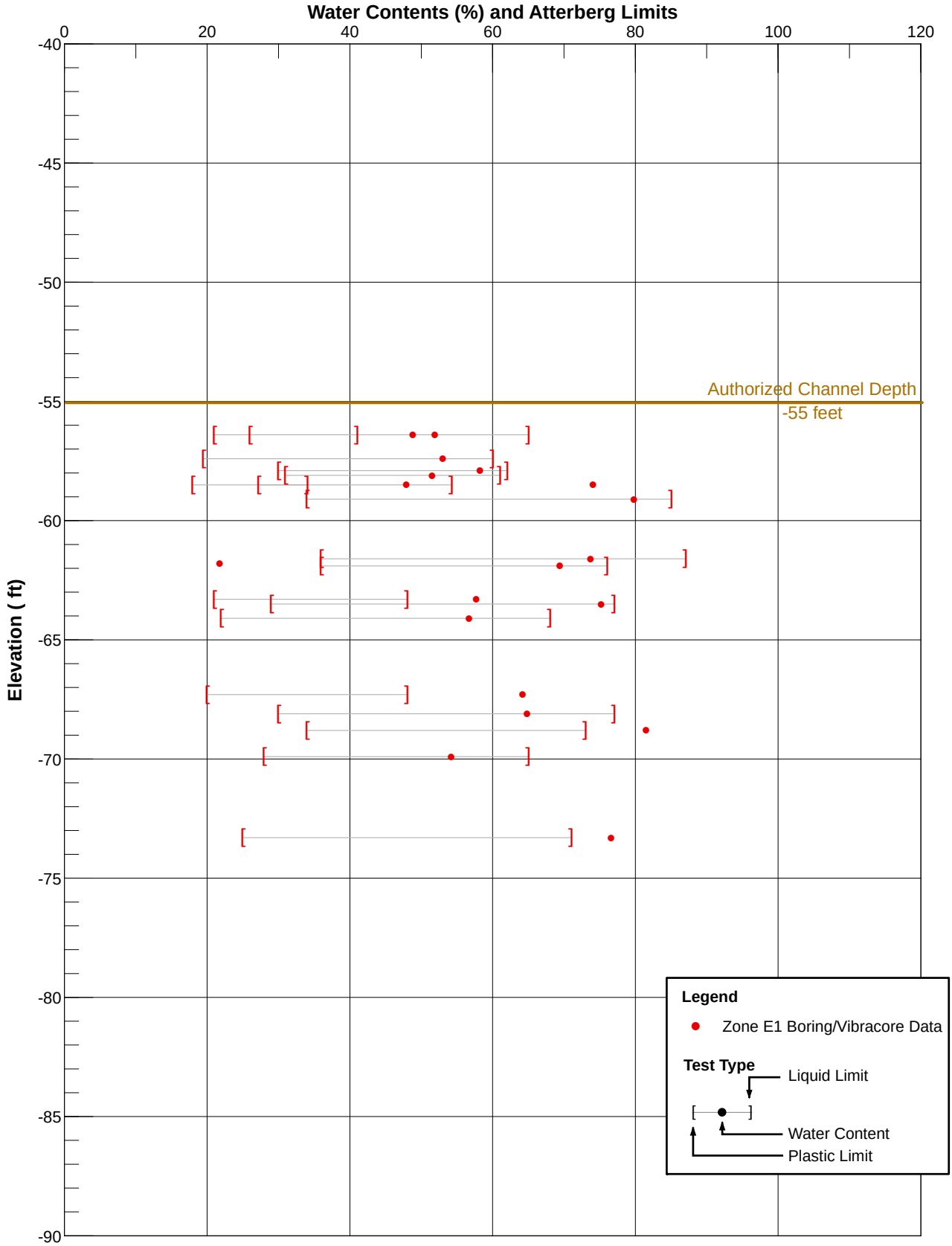

SUMMARY OF ATTERBERG LIMITS DATA

Norfolk Harbor Entrance Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 10c

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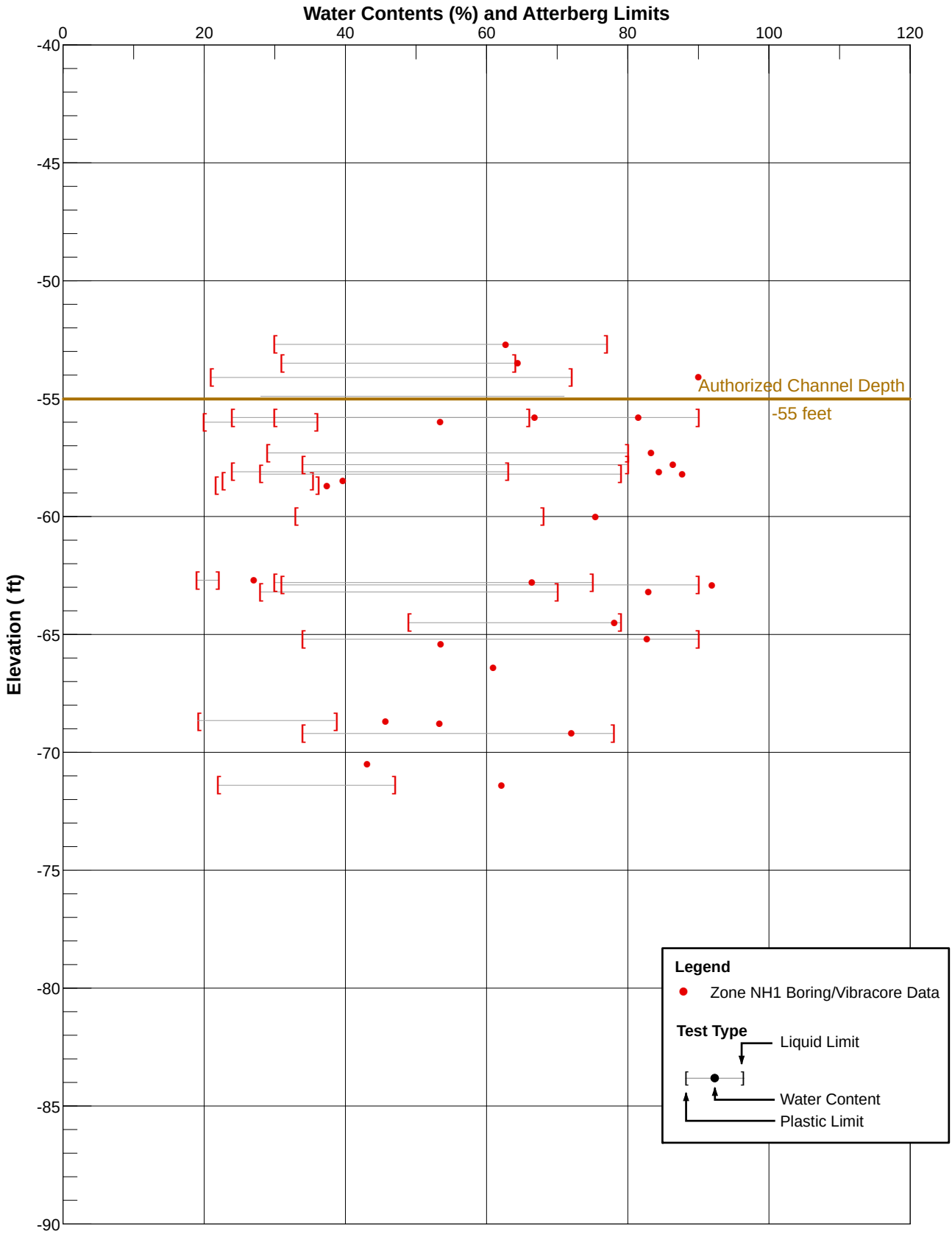

SUMMARY OF ATTERBERG LIMITS DATA

Norfolk Harbor Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 10d

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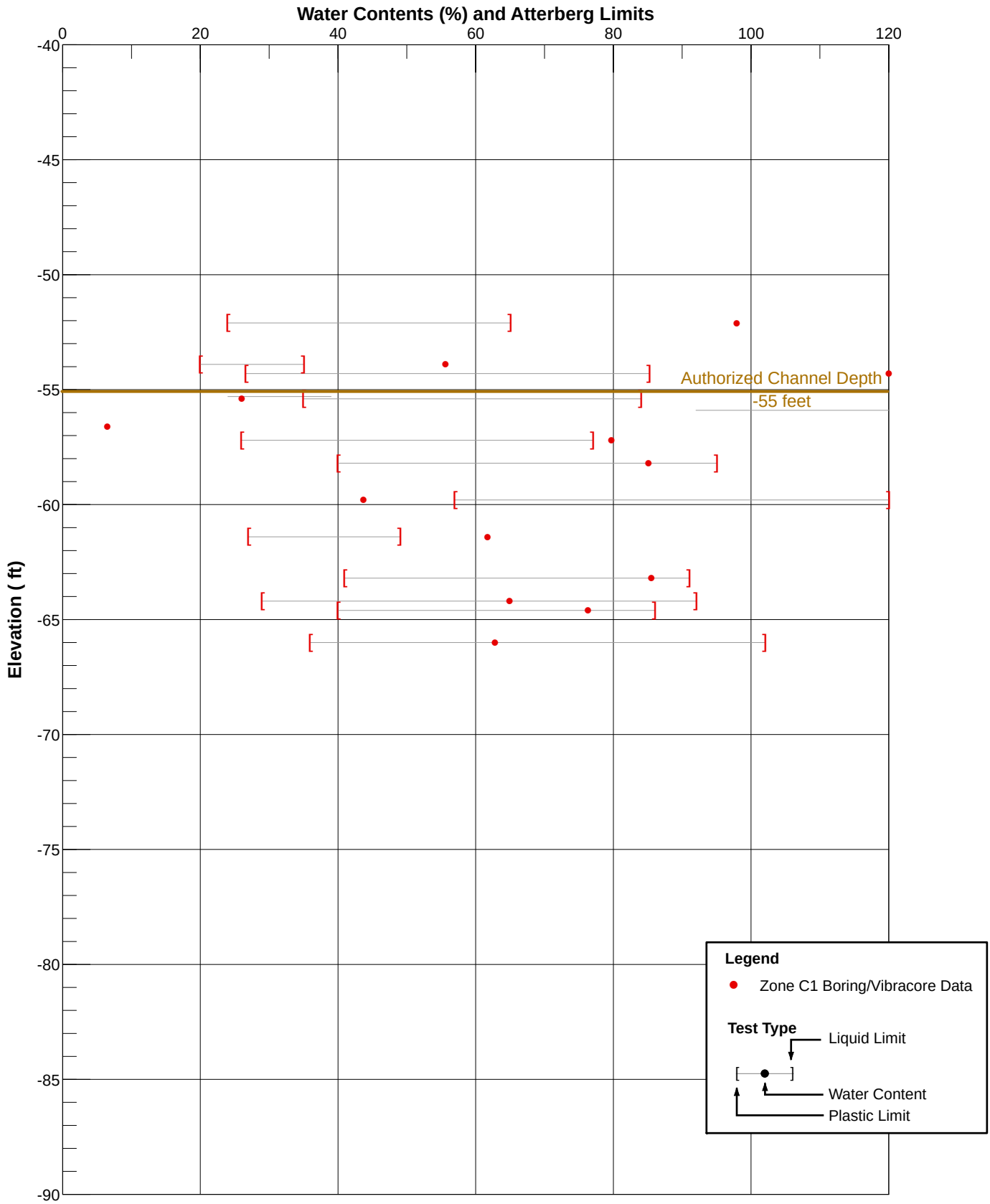

SUMMARY OF ATTERBERG LIMITS DATA

Craney Island Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 10e

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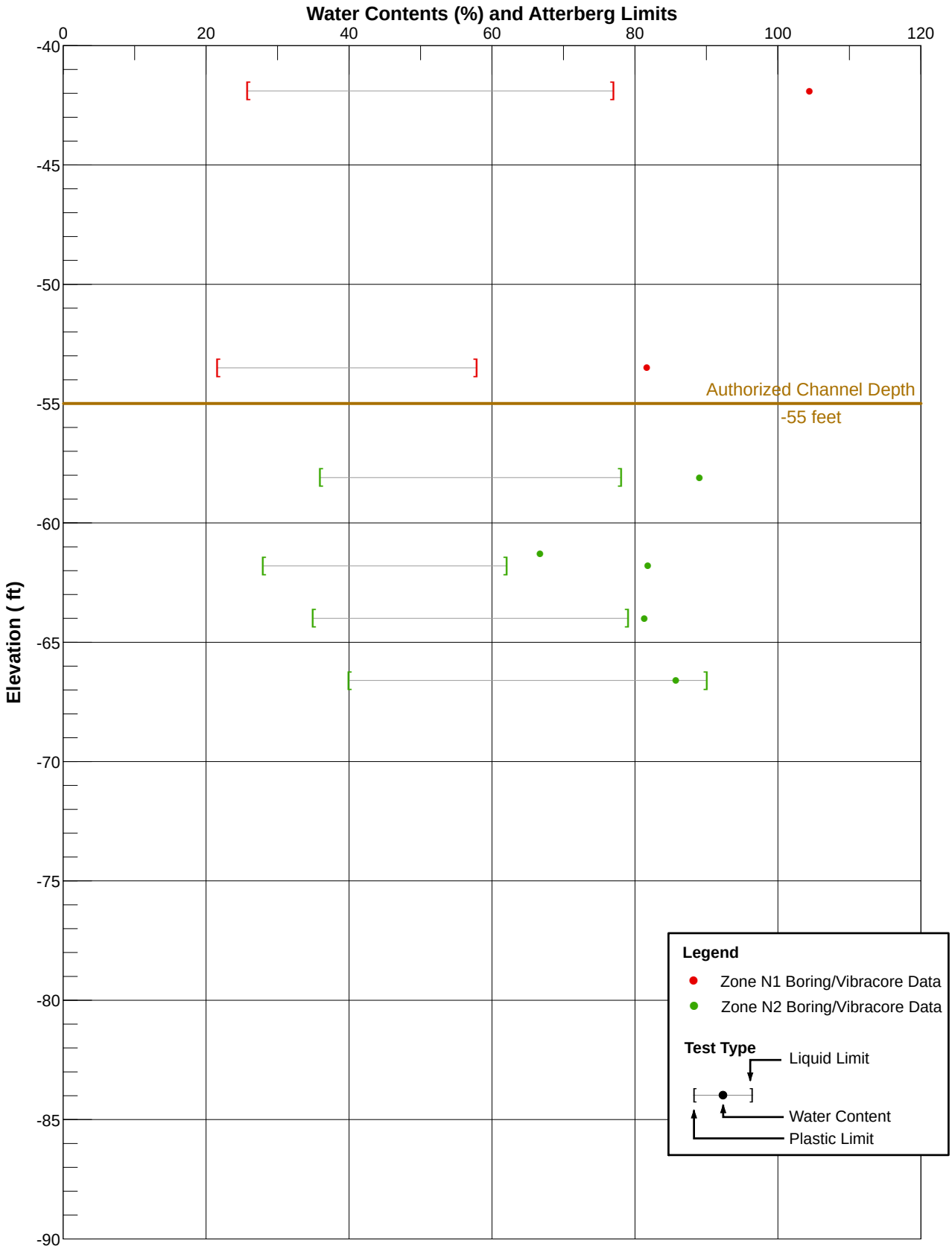

SUMMARY OF ATTERBERG LIMITS DATA

Newport News Channel Reach
Norfolk Harbor Channels Deepening Study
Hampton Roads, Virginia

FIGURE 10f

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Engineering Appendix C: CADET Modeling

Errata

Based on an Agency Technical Review (March 2018), the following comments and responses are provided to the reader of this report.

Comment 7244290 – Reference Page 8, Deepwater hindcast waves

Concern: Second paragraph of this section does not match with findings in the attached Godsey hindcast wave analysis (Page 3, Deepwater Hindcast Waves, 4th paragraph)

Basis for Concern: Wave data is a major component of determining UKC and should be presented consistently

Significance of Concern: LOW

Recommended Action: Recommend making presented wave information consistent between CADET and wave modeling reports.

RESPONSE: *Concur. Replace sentences 5 and 8 in paragraph 2 of the section "Deepwater hindcast waves" to read:*

Sentence 5: The most commonly occurring wave period band, with 32.6 percent (99,873) of the cases, is from 9 to 11 sec, with a mean of 9.9 sec.

Sentence 8: The most common wave height, with 50.3 percent (154,414) of the cases, is from 2 to 4 ft, with a mean of 2.9 ft.

Numerical Modeling & Evaluation of Deep-Draft Vessel Vertical Motion for Formulation of Channel Design Improvements

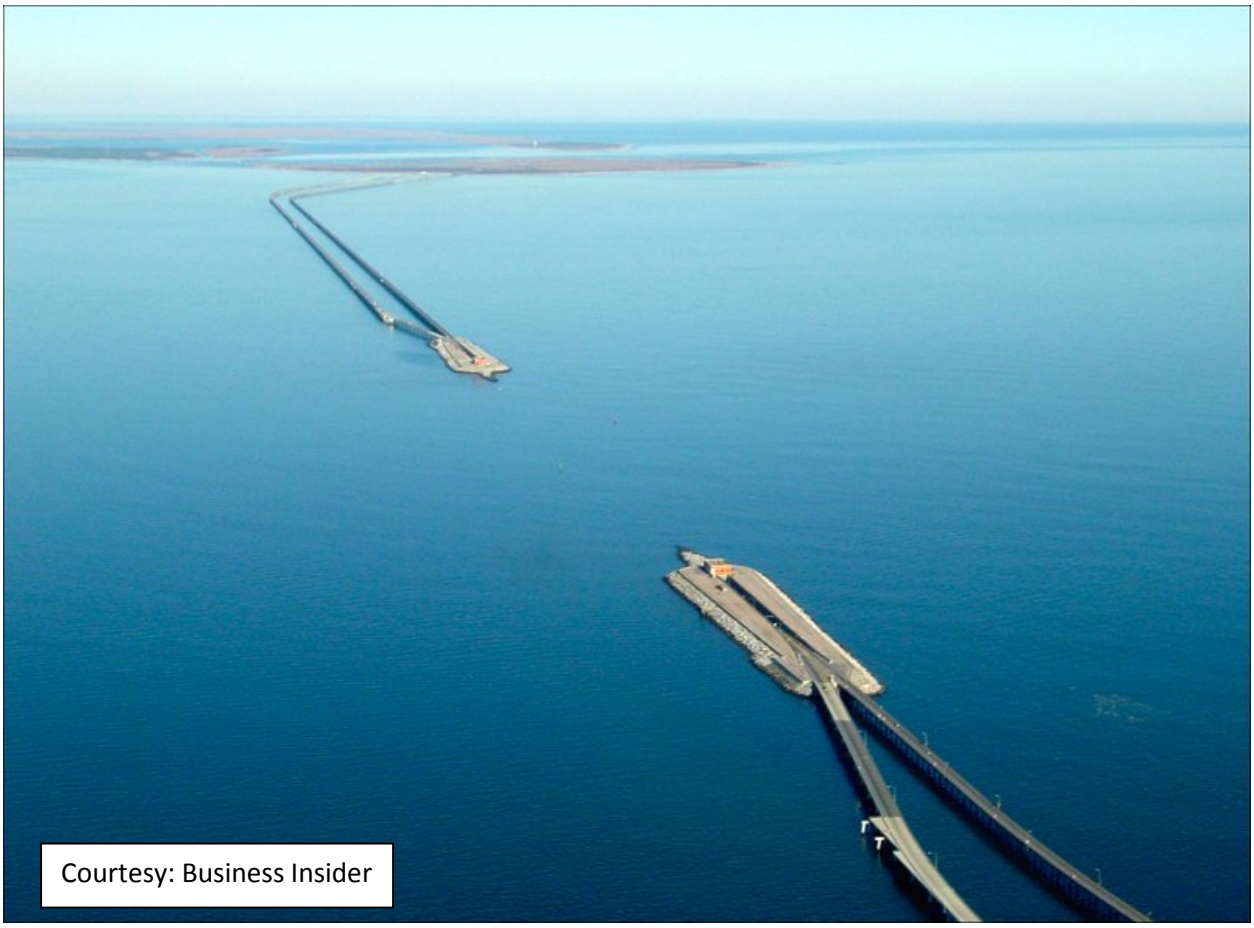
Norfolk Harbor, Virginia

Michael J. Briggs, PhD, PE, D.CE, D.OE

Briggs Group LLC

Contract W912HQ-17-P-0043

10 July 2017



Introduction

This report describes procedures and result of a vertical ship motion study for the Entrance Channel at Norfolk, VA. The study was performed in support of the Norfolk Harbor Phase 1 feasibility study. The purpose of this study was to determine the optimum depth for these existing channels to accommodate these newer and larger design vessels coming on line. It was conducted by Dr. Michael J. Briggs, Briggs Group LLC, at the request of the Virginia Port Authority (VPA), in conjunction with the Norfolk District (NAO) and the Institute for Water Resources (IWR). The study was conducted during the period April to September, 2017.

A "Design Team" provided input and weekly discussion during the course of the study and consisted of members from NAO, VPA, Moffatt & Nichol (M&N), David Miller & Associates (DMA), and IWR. Funding was provided by VPA through NAO and IWR, under contract W912HQ-17-P-0043.

The Norfolk Entrance Channel consists of two main channels: the offshore Atlantic Ocean Channel (AOC) and the transitional Thimble Shoals Channel (TSC). The Chesapeake Bay Bridge Tunnel (CBBT) is located in the TSC and is the primary depth constraint on the dredge depth for the channel reaches in the TSC. Four reaches were defined for the channel with two in each of the AOC and TSC channels. Two design vessels with two loading conditions each were selected for investigation. The risk-based "Channel Analysis and Design Evaluation Tool" (CADET) software was used in this study. It is a program to determine the 'optimum' dredge depth for the offshore portions of entrance channels. This 'optimum' dredge depth is defined as the depth that provides the greatest accessibility for the least amount of dredging and is determined by predicting ship underkeel clearance (UKC) for different wave, ship, and channel combinations. It is based on probabilistic risk analysis techniques to evaluate the accessibility of a series of channel reaches for multiple vessel geometries, loading, and wave conditions.

PIANC and Ankudinov ship squat were calculated and compared with the Beck, Newman, Tuck (BNT) squat predictions used in CADET. The CADET days of accessibility, vertical ship motion allowances, and net underkeel clearance were calculated based on these vertical ship motion components to provide a risk-based method of evaluating different channel depths.

This report is divided into the following sections or chapters: (a) design vessels, (b) channel reaches, (c) tides, (d) waves, (e) ship squat, (f) days of accessibility, and (g) summary and conclusions.

Design vessels

Two design vessels and two loading conditions were selected for this study. The design ships include a Gen III containership similar to the **MSC Daniella** and a Gen II bulk (coal) carrier. After considerable discussion among the Design Team, the NorC15b and NorB10L ships were selected based on the CADET Ship Hull Lines Library, developed in conjunction with the Institute for Water Resources. Minor revisions were provided by Herbert Engineering Corporation (HEC) and the Naval Surface Warfare Center. Table 1 lists ship particulars for the target and CADET model ships.

Table 1. Target and CADET model ship parameters.

	Containership		Bulker Coal Carrier	
	Target	NorC15b	Target	NorB10L
Capacity	13,800 TEU	13,800 TEU	---	180,000 m³
DWT (mt)	162,867	163,239	182,060	162,977
L_{oa} (ft)	1201.0	1210.2	958.0	962.2
L_{pp} (ft)	1148.3	1158.3	931.8	931.8
Beam *B* (ft)	168.0	168.0	148.0	147.6
Full Draft (ft)	---	45.8	---	51.1
SLL Draft (ft)	51.2	51.2	59.5	55.9

Notes:
1. Full draft = design load
2. SLL = Summer load line draft, maximum draft based on structural limits.

Two loading conditions were selected for each ship. For the NorC15b containership, a Full load (FL) representing the design load and a Medium load (ML) with a deeper draft were modeled. For the NorB10L bulk coal carrier, a Heavy load (HL) and a Full load (FL) with deeper draft were selected. Table 2 lists the CADET loading parameters for each loading condition.

According to the Design Team, ship speeds ranging from V_k=10 to 13 kt in the AOC reaches and V_k=10 to 17 kt in the TSC reaches were examined. The minimal speed of V_k=10 kt is required for ship maneuverability. For the CADET modeling, speeds ranging from V_k=10 to 18 kts were evaluated.

Table 2. Norfolk model ship parameters.

Parameter	Symbol	Units	NorC15b		NorB10L	
			FL	ML	HL	FL
Even keel draft	T	ft	45.8	49.0	49.0	51.1
Block coefficient	C_B	---	0.707	0.714	0.853	0.856
Roll damping factor	R	---	0.08	0.08	0.029	0.029
Vert center gravity (from waterline)	V_{CG}	ft	27.93	21.50	-7.4	-7.4
Vert center gravity (from keel)	K_G	ft	73.73	70.50	41.60	43.70
Metacentric height	GM	ft	3.04	5.14	20.25	17.76
Longitudinal center of gravity	L_{CG}	ft	603.66	605.27	437.89	438.80
Roll Gyradius	k_4	ft	67.2	67.2	51.7	51.7
Pitch Gyradius	k_6	ft	289.6	289.6	233.0	233.0

Channel reaches

Four channel reaches were defined after discussion and consensus among Design Team members. Typically, reaches are defined where the channel depth, width, and/or alignment changes. Reaches R1 to R4 are shown in Figure 1. Reaches R1 and R2 are in the AOC and R3 and R4 in the TSC. Note that the CBBT is located between reaches R3 & R4.

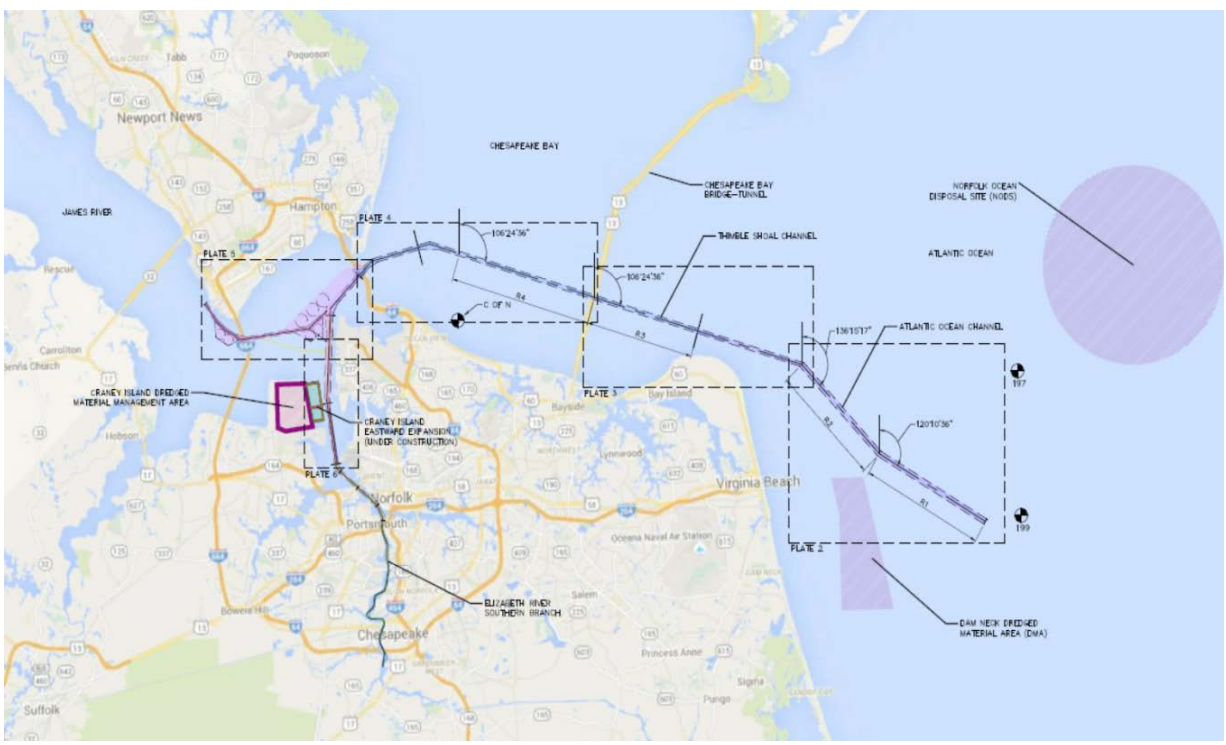


Figure 1. Norfolk Entrance Channel.

The CBBT is the primary depth constraint for this project since the maximum project depth is restricted to 55 ft. This insures that there is a minimum 5 ft of cover over the top of the tunnel that varies from a depth of 63 to 65 ft. The advance maintenance of 1 ft and the overdredge of 2 ft then brings the deepest project depth to 55 ft for a 63 ft tunnel top.

Table 3 lists the channel particulars for these four reaches. Included are reach number and ID, beginning and ending stations, length in feet and nautical miles, and alignment angle. Table 4 lists the channel parameters important in ship squat predictions.

Table 3. Norfolk Channel parameters.

Reach		Station		Length		Angle (deg)
No.	ID	Begin	End	(ft)	(NM)	
R1	AOC-E	0	305	30,500	5.02	120.18
R2	AOC-W	305	585	28,000	4.61	136.25
N/A	TSC-D	0	250	25,000	4.11	106.41
R3	TSC-E	250	540	29,000	4.77	106.41
R4	TSC-W	540	965	42,500	6.99	106.41
			Total:	155,000	25.51	

Notes:
1. Deep reach TSC-D between R2 and R3 for estimating total travel time through Norfolk channel. Not modeled in CADET for ship motions since very deep channel segment does not pose a problem.

Table 4. Norfolk Channel parameters for ship squat.

Reach		Width (ft)	Depth (ft)		Outside Depth (ft)		
No.	ID		Existing	Proposed	North	South	Ave
R1	AOC-E	1,300	53	61	48	48	48
R2	AOC-W	1,300	53	61	51	49	50
N/A	TSC-D	1,000	60	N/A	65	57	61
R3	TSC-E	1,000 (1,400)	50	55	32	37	34
R4	TSC-W	1,000 (1,400)	50	55	29	30	30

Notes:
1. Channel side slopes 1:3
2. TSC meeting areas both sides could increase width by 200 ft, => *W*=1,400 ft vs. 1,000 ft.
3. Total Overdredge = 3 ft, which includes Advance Maintenance = 1 ft and overdredge = 2 ft.
4. Average Outside Depth used for calculating ship squat in a restricted channel for all reaches.

Tides

Tidal information is important for most projects as the budget does not allow for additional dredging to accommodate vertical ship motions due to larger and more extreme wave conditions. CADET calculates the tidal window (i.e., duration) so that the effect of the extra water depth can be included in the calculated days of accessibility. Pilots will want to know how much time (i.e., tidal window duration) is available at shat water levels as a function of ship speed to transit the different reaches.

Travel times

Minimum travel times in individual reaches and the entire channel are listed in Table 5 as a function of ship speed from 10 to 18 kt. Depending on speed, 1.4 to 2.6 hr is required to safely transit the entire Norfolk channel. Reaches R1 and R2 in AOC require only 0.6 to 1.0 hr, and R3 and R4 in TSC 0.9 to 1.6 hr duration (includes TSC-D since part of the TSC). The most critical passage is probably over the CBBT between R3 and R4 since it is not possible to exceed a project depth of 55 ft due to tunnel safety requirements. Of course, the travel time over the CBBT is only of the order of a couple of minutes. The reader might want to round up these travel times to insure safe transits in the event of unexpected delays and variability in ship speed.

Table 5. Travel times in hours for safe transit, Norfolk Entrance Channel.

Reach		Distance		Ship speed V_k (kt)		
No.	ID	(ft)	(nm)	10	14	18
R1	AOC-E	30,500	5.0	0.5	0.4	0.3
R2	AOC-W	28,000	4.6	0.5	0.3	0.3
---	TSC-D	25,000	4.1	0.4	0.3	0.2
R3	TSC-E	29,000	4.8	0.5	0.3	0.3
R4	TSC-W	42,500	7.0	0.7	0.5	0.4
	Total:	155,000	25.5	2.6	1.8	1.4

Notes:
1. Does not include inner channel reaches south and west of R4.
2. Yellow highlight represent total travel time for entire Norfolk channel based on ship speed.

Tidal predictions

Tide levels for the Norfolk Entrance Channel are based on the predictions at CBBT. At the ocean boundary or outer portions of R1, one might expect that these durations and water levels could be reduced from those predicted at CBBT. This reduction is due to the changes in geometry and channel configuration at the ocean boundary relative to the

inner portions of the channel. Since these reductions are assumed to be less than 10 percent, no reduction has been included for offshore reaches R1 and R2.

Table 6 lists days of higher water levels from the CADET tidal duration prediction module. The tide ranges from +1 to +3 ft in Chesapeake Bay. The top half of the table lists the number of days per year as a function of the duration in hours for water levels of 1 to 3 ft above the MLLW datum of 55 ft for reaches R3 and R4 and 61 ft for reaches R1 and R2. The bottom half of the table lists the corresponding percentage values relative to 365 days per year. For instance, for a depth of 57 ft (i.e., +2 ft) and 3 hr duration, 289 days/365 days = 79 percent are available. Application of these tidal window durations are discussed in the Days of accessibility chapter for each ship and loading condition.

Table 6. Effect of tides on water levels in Norfolk Channel.

Duration (hr)	Reaches 1 & 2			Reaches 3 & 4		
	62 (+1)	63 (+2)	64 (+3)	56 (+1)	57 (+2)	58 (+3)
Days of higher water level						
1	365	359	44	365	359	44
2	365	340	20	365	340	20
3	365	289	3	365	289	3
4	365	180	0	365	180	0
5	365	71	0	365	71	0
6	361	0	0	361	0	0
7	248	0	0	248	0	0
8	84	0	0	84	0	0
9	15	0	0	15	0	0
10	1	0	0	1	0	0
Percentage based on 365 days per year						
1	100%	98%	12%	100%	98%	12%
2	100%	93%	5%	100%	93%	5%
3	100%	79%	1%	100%	79%	1%
4	100%	49%	0%	100%	49%	0%
5	100%	19%	0%	100%	19%	0%
6	99%	0%	0%	99%	0%	0%
7	68%	0%	0%	68%	0%	0%
8	23%	0%	0%	23%	0%	0%
9	4%	0%	0%	4%	0%	0%
10	0%	0%	0%	0%	0%	0%

Notes:
1. Assumes minimal reduction in durations and water levels in R1 and R2.
2. Yellow highlight represent minimum required durations for safe transit for range of ship speed.

Waves

Since waves drive CADET's predictions of vertical ship motions, it is important to provide accurate estimates of the wave environment. The steps in this process involved estimating (a) deepwater hindcast waves, (b) deepwater joint probability distributions, (c) wave transformation, and (d) directional wave spectra. Ms. Liz Godsey (CESAM-EN-HH) performed the first three steps with guidance from Dr. Briggs. She has prepared a separate report documenting her efforts (Godsey 2017). Therefore, only summary information is presented in this report.

Deepwater hindcast waves

The 34-year hindcast wave data for this study were provided by the Wave Information Study (WIS). Both WIS197 and WIS199 were compared with the Norfolk 32 Gage dataset (Figure 1). WIS199 was selected for the offshore boundary conditions since its location in deepwater is nearest to the where the Norfolk Channel daylights. The Norfolk 32 Gage dataset indicated that waves were driven by northerly storm winds within the bay and tended to have shorter wave periods and less occurrences that the deepwater WIS199.

For WIS199 the overall mean wave direction is 108.2 deg. The most common wave direction, with 24.5 percent (75,145) of the cases, is between 101.3 and 123.8 deg, with a mean of 112.9 deg. Both of these wave directions are nearly parallel with the channel alignments. Wave periods range from 1 to 23 sec, with variable band limits. The overall mean wave period is 8.8 sec. The most commonly occurring wave period band, with 31.9 percent (98,006) of the cases, is from 9 to 11 sec, with a mean of 9.5 sec. Significant wave heights range from 0 to 21.4 ft, with variable band limits. The overall mean wave height is 3.6 ft. The most common wave height, with 50.0 percent (153,462) of the cases, is from 2 to 4 ft, with a mean of 2.9 ft. The largest significant wave height is 21.4 ft, with corresponding peak period of 16.1 sec and wave direction of 112.9 deg. However, this is a very rare occurrence, with very low probability of occurrence.

Deepwater joint probability distributions

The next step in the wave processing was to separate the data into joint probability or percent occurrence tables of peak wave period T_p vs. significant wave height H_s for a realistic set of direction-limited bands. Direction bands are in 22.5 deg increments encompassing waves from 60 deg to 132 deg, which is equivalent to ±50 deg on either side of shore normal. Waves approaching the coast from directions outside this arc are not a significant consideration because they will be refracted and reduced in height before reaching the Norfolk channel. The total number of observations for the entire 34-

year hindcast dataset is 306,815. The direction-limited dataset has 69.1 percent of these observations, or 212,056 observations.

The four direction bands (67.5, 90, 112.5 and 135 deg) included waves with directions between 56.25 to 146.25 deg in 22.5 deg increments. Percent and number of occurrence histograms of wave period versus height were made for each of the four wave direction bands. There are a total of 245 bands in the four direction-limited histograms, representing 245 different wave combinations of height, period and direction. The most common wave direction, with 35.4 percent (75,145) of the cases, is between 101.3 and 123.8 deg, with a mean of 112.9 deg. The most commonly occurring wave period band, with 37.4 percent (79,265) of the cases, is from 9 to 11 sec, with a mean of 9.9 sec. The most common wave height, with 49.2 percent (104,284) of the cases, is from 2 to 4 ft, with a mean of 2.9 ft. The largest significant wave height is 21.4 ft, with corresponding peak period of 16.1 sec and wave direction of 112.5 deg. As noted previously, this is a very rare occurrence.

Wave transformation

The WIS199 direction-limited dataset provided the incident deepwater wave conditions at the offshore boundary of the Norfolk channel. These waves typically transform as they travel along the channel into shallower water due to shoaling, refraction, diffraction, reflection, and other nonlinear factors. The numerical model STWAVE (Smith et al. 2001) was used to define this wave transformation. In general, wave height will be reduced in traveling from the AOC deepwater reaches to the shallower TSC reaches.

It was not necessary to simulate all wave cases of the direction-limited dataset for the STWAVE wave transformation runs. One set of 24 cases represented the lower wave height waves for all four direction bands. These waves all had a wave height of 4.8 ft, representing the average wave height for the dataset. Wave periods were selected based on the most frequently occurring periods in each direction band. A second set of 25 waves were selected for wave transformation since these waves give a more realistic view of design wave conditions during ship transits. They are representative of the larger waves in the highest 3-5 percent of wave heights within the direction-limited dataset. A wave height of 8.9 ft was used for this second set of incident waves. Wave periods again were selected based on the number of occurrences.

These 49 wave cases were used in the simulation of directional wave spectra for the STWAVE model. One set was run with a water depth at the location of WIS199 with zero MLLW and a second set at +2 ft MLLW tide advantage to investigate water level sensitivity. These waves were run and the wave transformation factors (i.e., incident

wave height/transformed wave height) at eleven stations were saved. Figure 2 shows the locations of Stations 1 to 11.

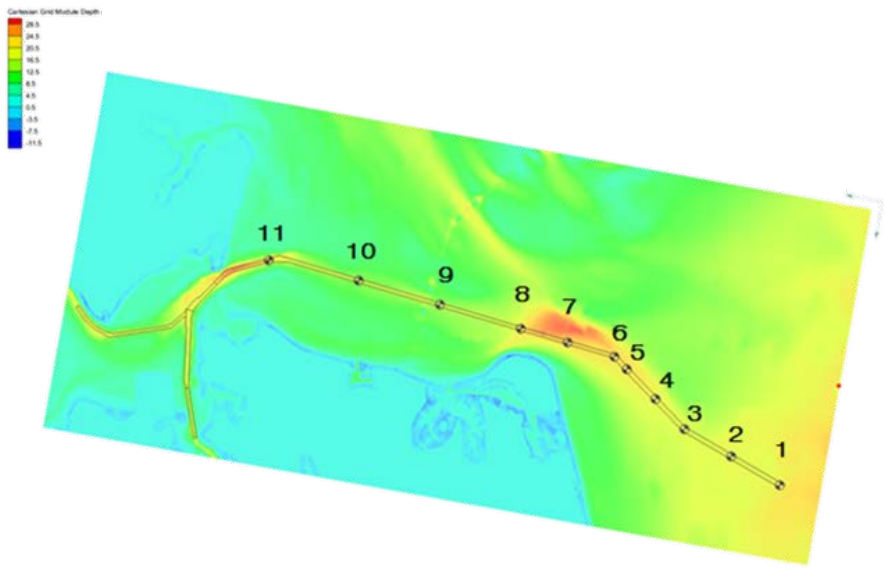


Figure 2. STWAVE save stations 1 to 11 (Courtesy: Godsey 2017).

Directional wave spectra

From deepwater joint probability distributions of T_p vs. H_s, wave parameter statistics were gathered for generating empirical directional wave spectra representative of the WIS199 deepwater data. Out of a total of 247 different combinations of T_p, H_s, and θ_p, 155 were selected for testing in CADET. Wave bins that had less than 0.03 percent (i.e., 0.0003) of the total number of occurrences were eliminated as these represent very rare events on high ends (i.e., larger wave heights and period combinations) of the dataset where ships would not attempt transits. These 92 waves out of total of 247 waves represent very rare "extreme" occurrences with a total of only 3.3 days per year (1 percent of a year). Thus, CADET was not run for these waves as they were explicitly removed. Appendix A lists the wave parameters for the 155 wave cases at the WIS199 buoy (Table A1). Table A2 contains the wave parameters for the 92 extreme waves that were eliminated.

Table A1 shows the incident wave heights at WIS199 for the 155-wave CADET dataset. The wave transformation factors at the STWAVE save stations were used to transform the wave height of the 155 empirical directional wave spectra for the four reaches from the offshore Station 1 to the inshore Station 11. Since there were eleven save stations, there were more factors than reaches. Thus, the factors in each reach were averaged. If a

wave case did not have an exact match with the wave parameters used in STWAVE, the factor was interpolated between adjacent wave heights and periods within the same direction band. Factors associated with the 4.9 ft wave height cases were used for all waves with wave heights less than or equal to 4.9 ft. Factors were interpolated for waves with wave heights between 4.9 and 8.9 ft. Finally, factors associated with the 8.9 ft wave height cases were used for all larger wave height wave cases.

The differences in the wave transformation factors for water levels between +0 and +2 ft MLLW were very small. However, the factors based on the water level of +2 ft were used as it was considered the more conservative estimate for waves since they have potentially larger wave heights due to the deeper water. Table A3 lists the wave height transformation factors and corresponding wave heights for each of the 155 waves in the four reaches (see Table A1).

The directional wave spectra were then generated using a TMA frequency spectrum and a $\cos^n$ spreading function. Spectral frequencies ranged from 0.01 Hz to 0.30 Hz in 0.01-Hz intervals to cover frequencies corresponding to one half to three times the peak frequency. Because of directional spreading and CADET requirements, the full circle of 360 deg was modeled in 15 deg increments. Spectral wave parameters were selected for each wave based on wave period, a standard approach for CHL (Coastal and Hydraulics Laboratory) studies. For the TMA spectrum, frequency spreading is a function of the γ parameter that varied between 3.3 (broad) to 8 (narrow). For the directional $\cos^n$ spreading function, the "*n*" parameter ranged from 4 (broad) to 30 (narrow). The DSp3 Fortran program calculated the Phillip's constant α in the TMA spectral formulation. These spectra formed the wave input for the four reaches R1 to R4 in the Norfolk Channel. The directional spectra were identical for each reach except for the change in wave height due to the wave transformation factors. All the other spectral parameters remained unchanged between reaches since they did not indicate any significant differences.

Finally, the main difference between inbound and outbound transit directions is the relative angle of the wave to the ship, which alters the wave encounter frequency and leads to different ship response and vertical motions. Figure 3 illustrates the effect of the four peak wave directions (67.5, 90, 112.5 and 135 deg) on the relative angle of the wave to the ship for inbound and outbound transits for each of the four reaches. In general, inbound ships will experience beam, stern quartering, and following seas; whereas, outbound ships will see beam, bow quartering, and head seas.

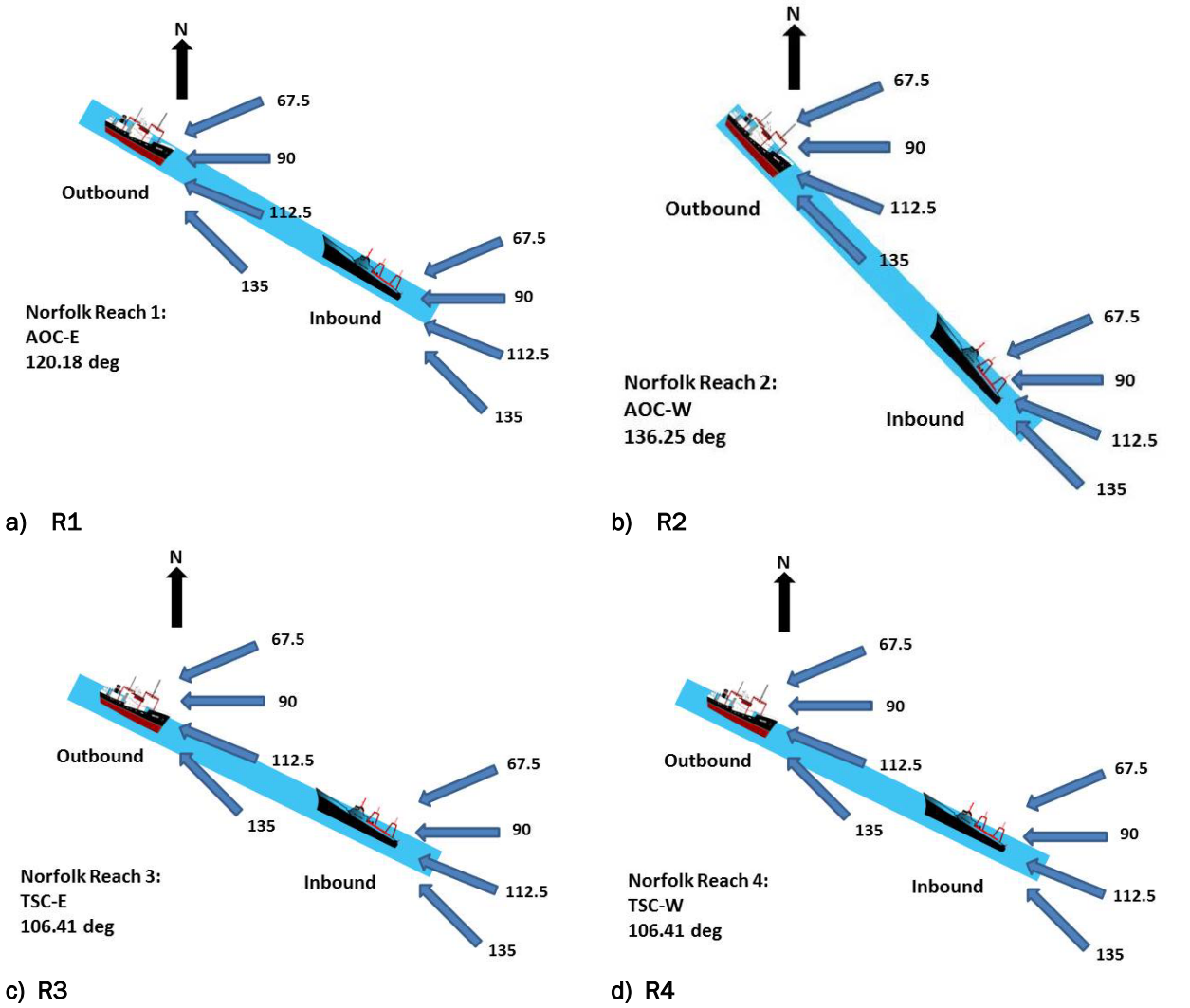


Figure 3. Relative wave angles for inbound and outbound transits for reaches (a) R1, (b) R2, (c) R3, and (d) R4.

Ship squat

This chapter compares PIANC, Ankudinov, and CADET predicted ship squat (sinkage and trim) for both loading conditions of the NorC15b containership and the NorB10L coal carrier in the four reaches. Due to the relatively wide channels in all four reaches and the deep channels in the AOC reaches R1 and R2, the channels were modeled as unrestricted or open channels. However, for the narrower and shallower TSC reaches R3 and R4, a comparison is made for comparable restricted channels.

Theory

PIANC has many empirical formulas for predicting ship squat in entrance channels (PIANC Marcom WG49 2014). Each formula has certain constraints based on the ship and channel conditions for which they were developed. No one formula works best for all channel and ship types. Thus, it is necessary to examine the squat predictions with more than one formula and compare the results based on the type of ship, channel, and formula constraints. Five of the most "user friendly" and "popular" PIANC squat formulas include those of Barrass, Eryuzlu, Huuska, Römisch, and Yoshimura.

The Ankudinov squat formulas (Briggs 2009, Briggs and Daggett 2009) are much more complicated than the PIANC squat formulas and were originally used in the WES Ship Tow Simulator (STS). The Ankudinov prediction is one of the most thorough, but also the most complicated formulas for predicting ship squat. These components include factors to account for the effects of the ship and channel.

Ship squat is typically estimated within CADET (Kopp and Silver 2016) using the Beck-Newman-Tuck (BNT) algorithm. The BNT prediction is based on early work in 1966 and 1967 by Tuck investigating the dynamics of a slender ship in shallow water at various speeds for an infinitely wide channel and for a finite width channel such as a canal. This work was expanded by Beck in 1975 to include a dredged channel with a finite-width inner channel and depth and an infinitely-wide outside channel of shallower depth.

In the BNT model, the fluid is assumed to be inviscid and irrotational and the hull long and slender. The underwater area of the hull is modeled and the dynamic pressure is obtained by differentiating the velocity potential along the length of the hull for each Depth Froude Number F_{nh}. The sinkage and trim predictions are obtained from the dynamic pressure by calculating the vertical force and pitching moment.

Figure 4 is a schematic of the simplified channel cross-section used in BNT. In addition to the automatically-specified inside channel depth H, the user has the option to include the channel width W and outside channel depth H_{out} (i.e., similar to PIANC h_T trench height for restricted channels, but measured from the water surface to the top of the trench instead of from the trench bottom to the top of the trench).

NorC15b containership squat

Full load (FL, T=45.8 ft)

Figure 5 shows maximum predicted ship squat as a function of ship speed for the full load (FL, T=45.8 ft) NorC15b containership in a water depth of h=61 ft (h/T=1.33) in

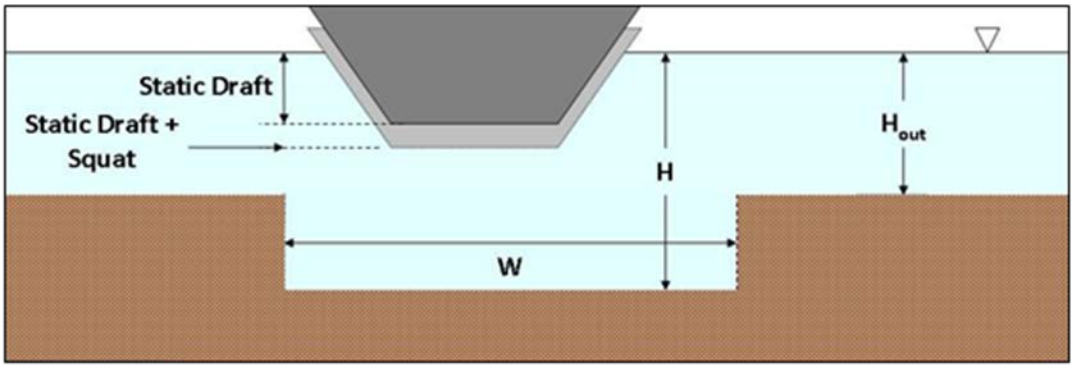
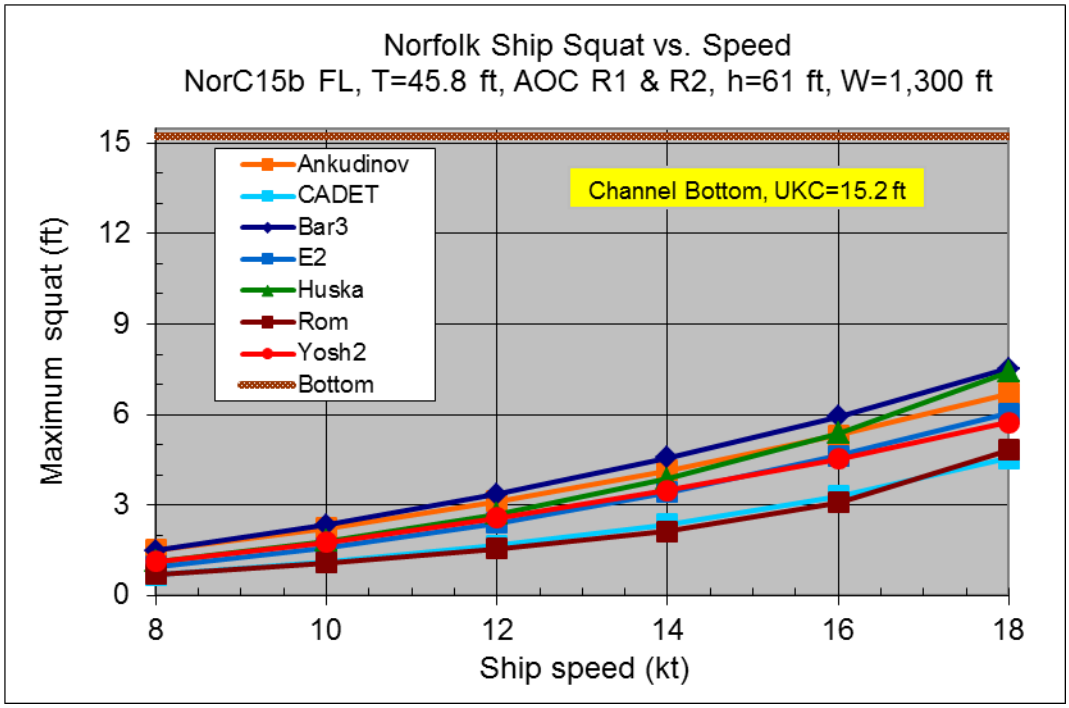


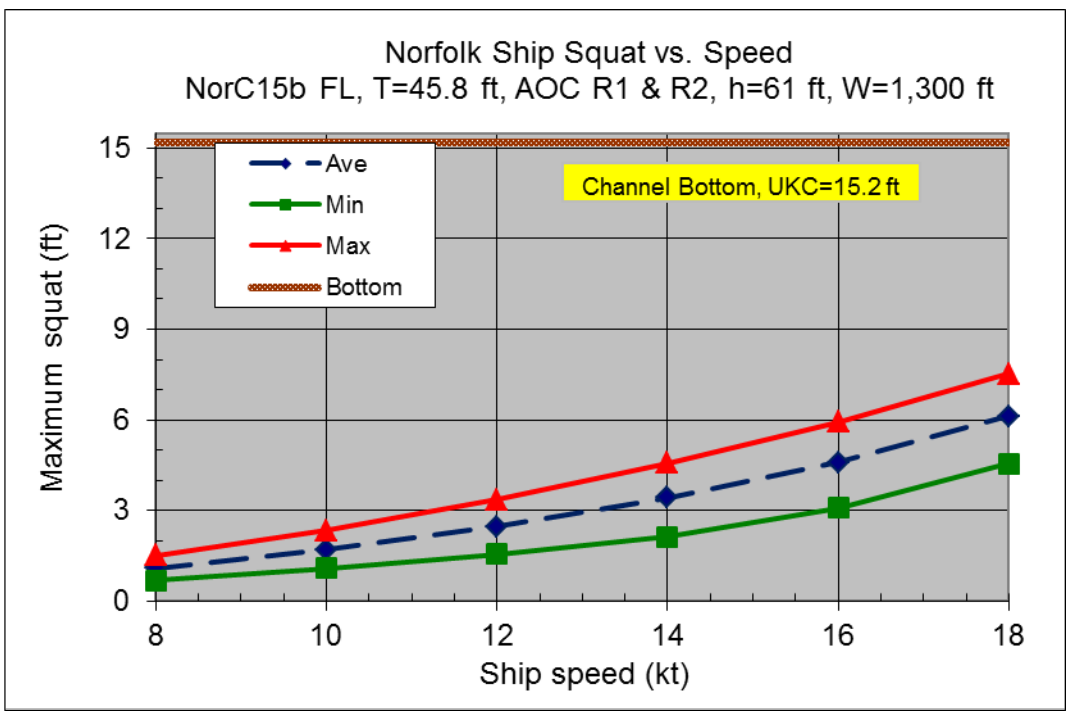
Figure 4. CADET BNT channel geometry variables (Courtesy: Kopp and Silver 2016).

AOC reaches R1 and R2. Figure 6 is the comparable figure for the shallower water depth of h=55 ft (h/T=1.20) in TSC reaches R3 and R4. This maximum squat can occur at the bow or stern of the ship. The top plot in each figure shows the individual predictions for the Ankudinov, CADET, Barrass, Eryuzlu, Huuska/Guliev, Römisch, and Yoshimura methods. The last five predictors are the PIANC empirical predictions. The bottom plot is a summary of these seven predictions showing average, minimum, and maximum values. In general, the "average" squat prediction line is probably a good "design" value. The "maximum" squat prediction is the value that one could feel would not be exceeded. The solid brown horizontal line represents the bottom of the channel for this particular water depth. Although ship speeds from V_k=8 to 18 kt are shown for comparison, a speed on the slow end is probably advisable, especially in the shallower TSC R3 and R4 reaches during passage over the CBBT. The faster speeds are included mainly to indicate the effects of these speeds on available underkeel clearance (UKC) if allowed.

Table 7 lists the squat values that are plotted in Figures 5 and 6 for the reach groups AOC and TSC with the FL load condition. In the AOC reaches R1 and R2 with the deeper water, UKC is not a problem (i.e., 61-45.8=15.2 ft). For a V_k =12 kt, predicted squat (yellow shading) ranges between 1.54 to 3.35 ft, with an average of 2.47 ft. This would leave a clearance ranging from a low of 11.85 to a high of 13.66 ft, with an average of 12.73 ft. Similarly, for TSC reaches R3 and R4, UKC=9.2 ft (i.e., 55-45.8 ft) and is not a problem for this relatively shallow draft ship loading condition. For a V_k =12 kt, predicted squat (yellow shading) ranges between 1.67 to 3.51 ft, with an average of 2.69 ft. Note the increased squat due to the smaller UKC. Finally, the clearance ranges from a low of 5.69 to a high of 7.53 ft, with an average of 6.51 ft. Of course, this UKC does not include any wave-induced vertical motions for heave, pitch, and roll.

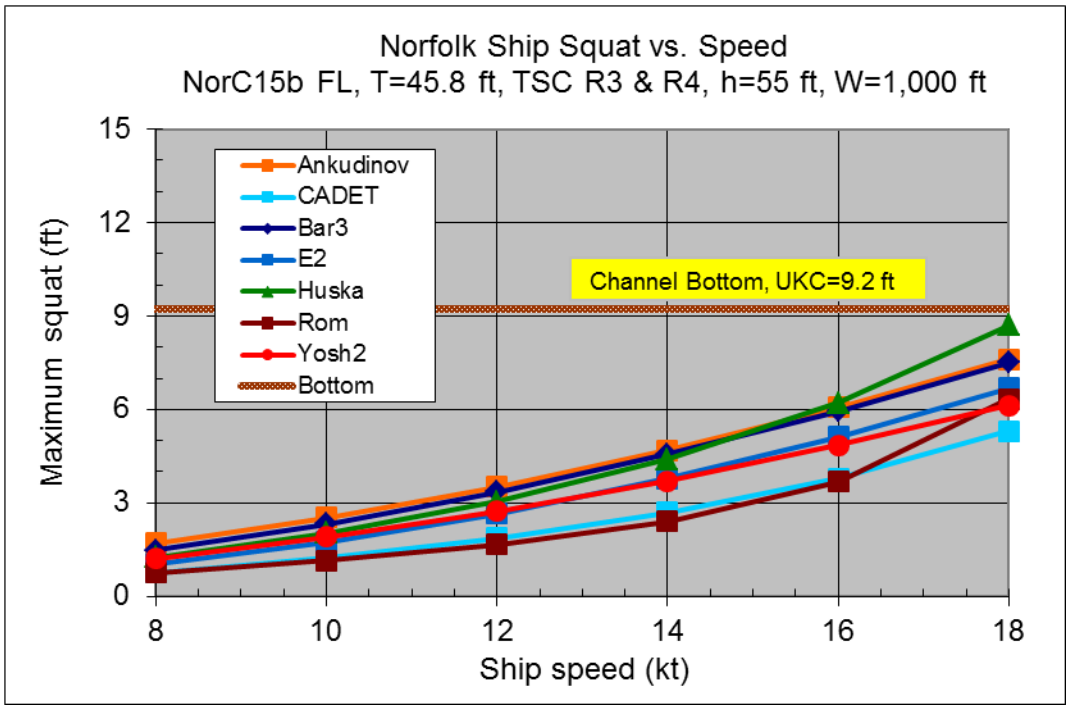


a)

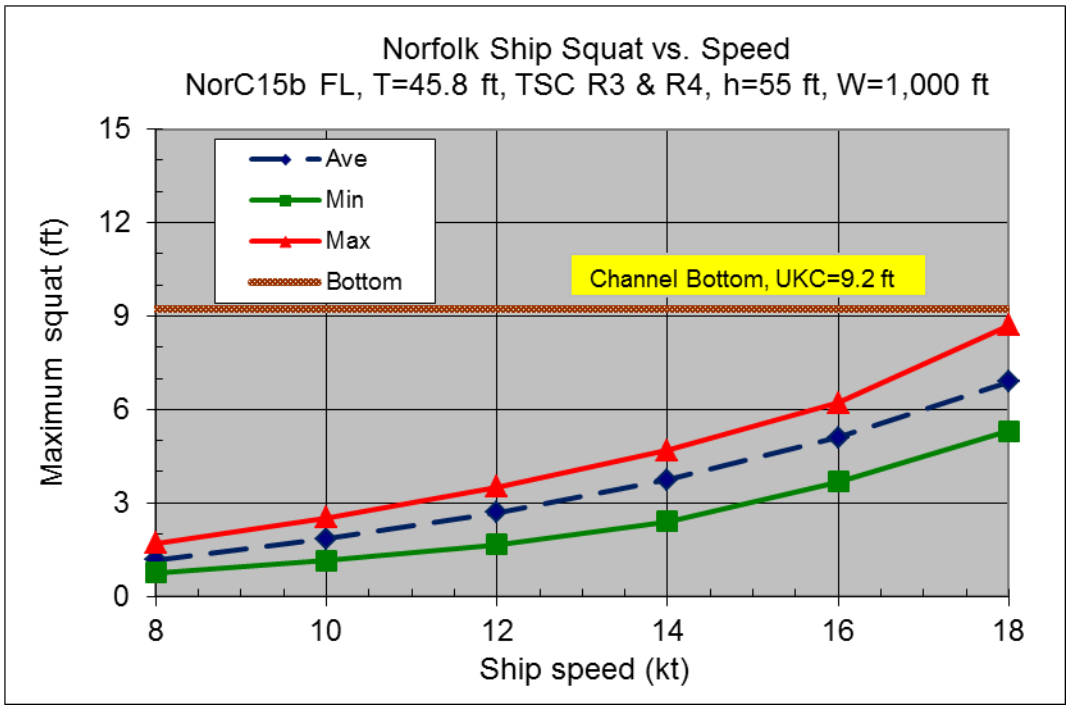


b)

Figure 5. Ship squat for FL (*T*=45.8 ft) NorC15b containership, AOC R1 and R2 (*h*=61 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.



a)



b)

Figure 6. Ship squat for FL (*T*=45.8 ft) NorC15b containership, TSC R3 and R4 (*h*=55 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.

Table 7. Ship squat predictions for Full Load (FL, *T*=45.8 ft) NorC15b containership.

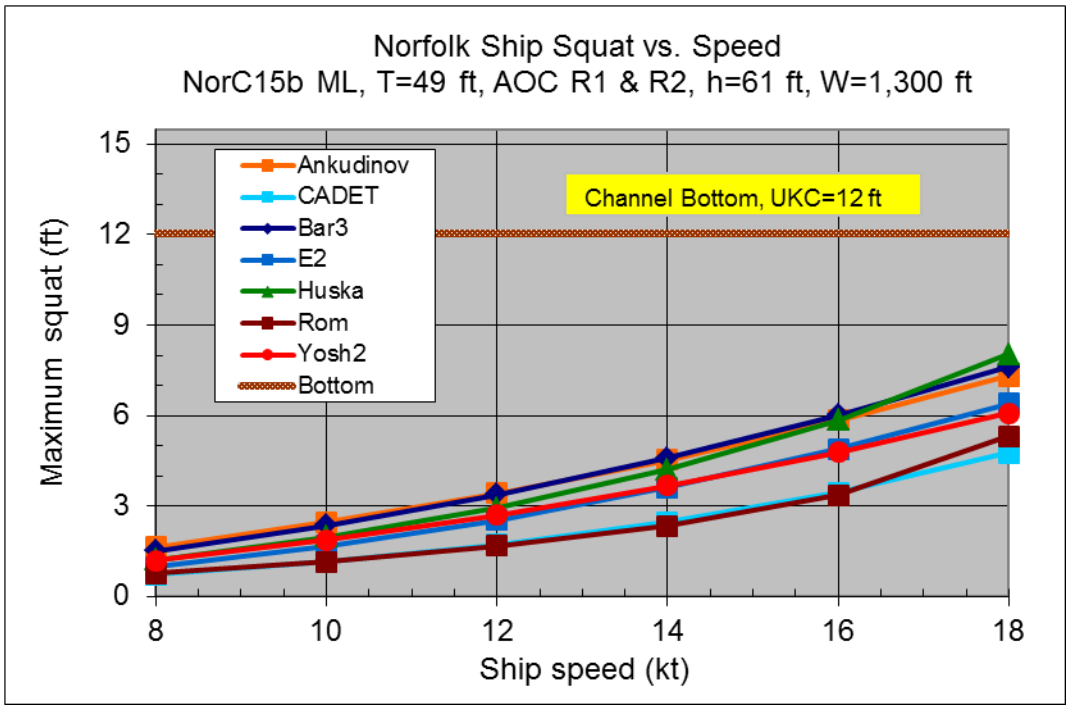
Speed V_k (kt)	Ank (ft)	CAD (ft)	B3 (ft)	E2 (ft)	Hus (ft)	Röm (ft)	Yosh (ft)	Ave (ft)	Min (ft)	Max (ft)
AOC R1 & R2: *h*=61 ft (UKC=15.2 ft)										
8	1.51	0.69	1.48	0.95	1.12	0.69	1.12	1.08	0.69	1.51
10	2.23	1.10	2.33	1.57	1.80	1.08	1.77	1.70	1.08	2.33
12	3.12	1.65	3.35	2.40	2.69	1.54	2.56	2.47	1.54	3.35
14	4.13	2.37	4.56	3.41	3.87	2.13	3.48	3.42	2.13	4.56
16	5.31	3.30	5.94	4.63	5.38	3.08	4.53	4.60	3.08	5.94
18	6.69	4.55	7.51	6.04	7.41	4.82	5.74	6.11	4.55	7.51
TSC R3 & R4: *h*=55 ft (UKC=9.2 ft)										
8	1.71	0.77	1.48	1.05	1.25	0.75	1.21	1.17	0.75	1.71
10	2.53	1.24	2.33	1.74	2.03	1.15	1.90	1.85	1.15	2.53
12	3.51	1.86	3.35	2.66	3.05	1.67	2.72	2.69	1.67	3.51
14	4.69	2.68	4.56	3.77	4.40	2.40	3.71	3.74	2.40	4.69
16	6.07	3.78	5.94	5.12	6.20	3.67	4.86	5.09	3.67	6.20
18	7.61	5.31	7.51	6.69	8.69	6.33	6.14	6.90	5.31	8.69

Notes:
1. Ank = Ankudinov, CAD = CADET, B3 = Barrass version 3, E2 = Eryuzlu version 2 Hus = Huuska/Guliev, Röm = Römisch, Yosh = Yoshimura.
2. Ave, Min, Max = Average, Minimum, or Maximum of all 7 squat predictions.
3. Red = Squat exceeds available UKC, Yellow shade = Ave, Min, Max at V_k =12 kt.

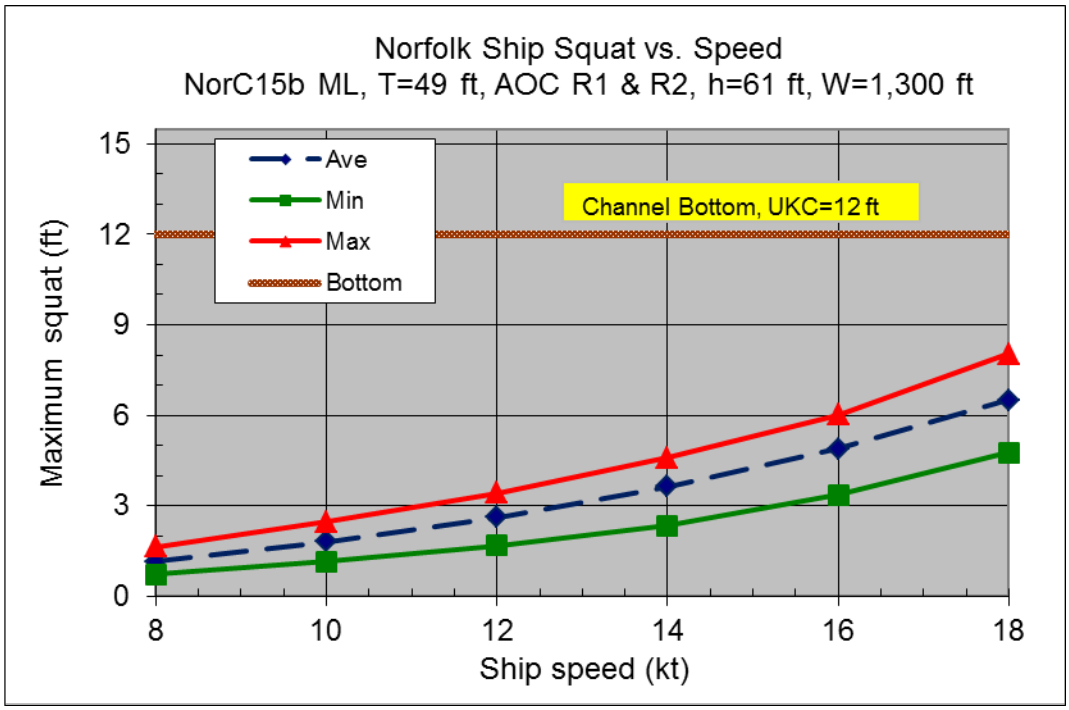
Medium load (ML, T=49 ft)

Figures 7 and 8 are analogous figures for the Medium load (ML, *T*=49 ft) loading condition for the AOC and TSC reaches, respectively. Table 8 is the comparable table to Table 7 for this loading condition. As before, the grounding situations are highlighted in red and the squat statistics are shaded in yellow for a ship speed of V_k =12 kt.

In the AOC reaches R1 and R2 (Figure 7), the available UKC is still relatively large with a value of UKC=12 ft (h/T=1.24). The predicted squat at a speed of V_k=12 kt ranges from 1.67 to 3.41 ft, with an average of 2.62 ft. UKC values would still remain relatively large. In the TSC reaches R3 and R4, however, the UKC is much less with a value of only 6 ft (h/T=1.12). Thus, the predicted squat at a speed of V_k=12 kt ranges from 1.80 to 3.87 ft, with an average of 2.86 ft. This leaves a reduced clearance of 2.13 to 4.2 ft, with an average of 3.14 ft. The red highlighted values indicate that a speed greater than or equal to V_k=16 kt might result in grounding just due to squat.

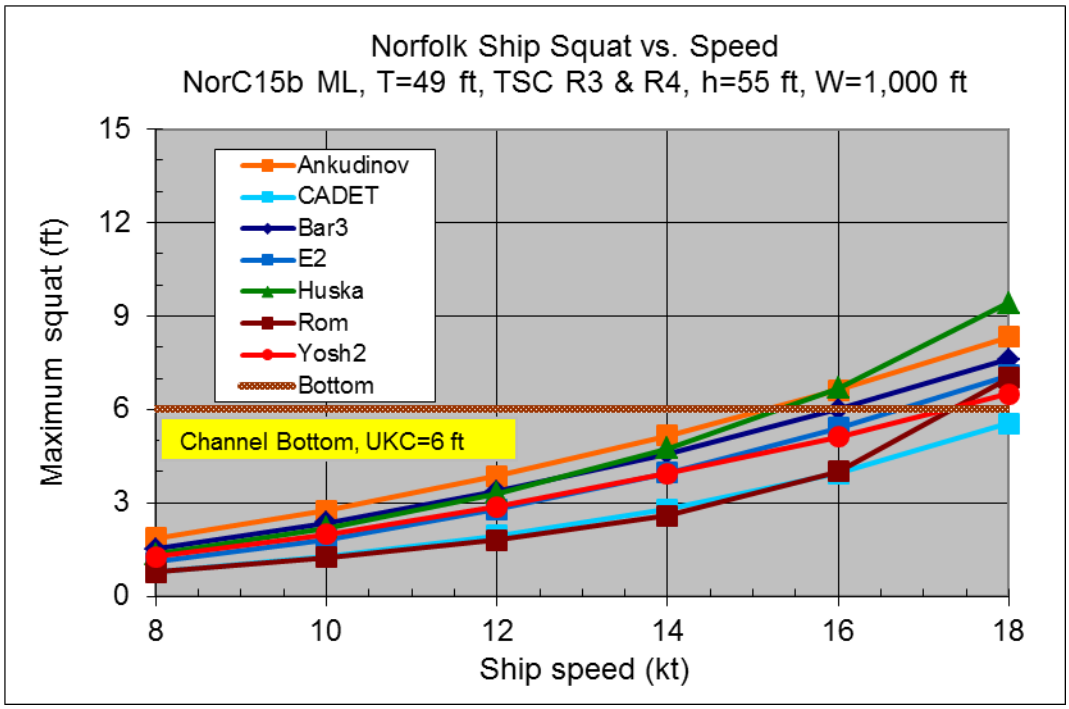


a)

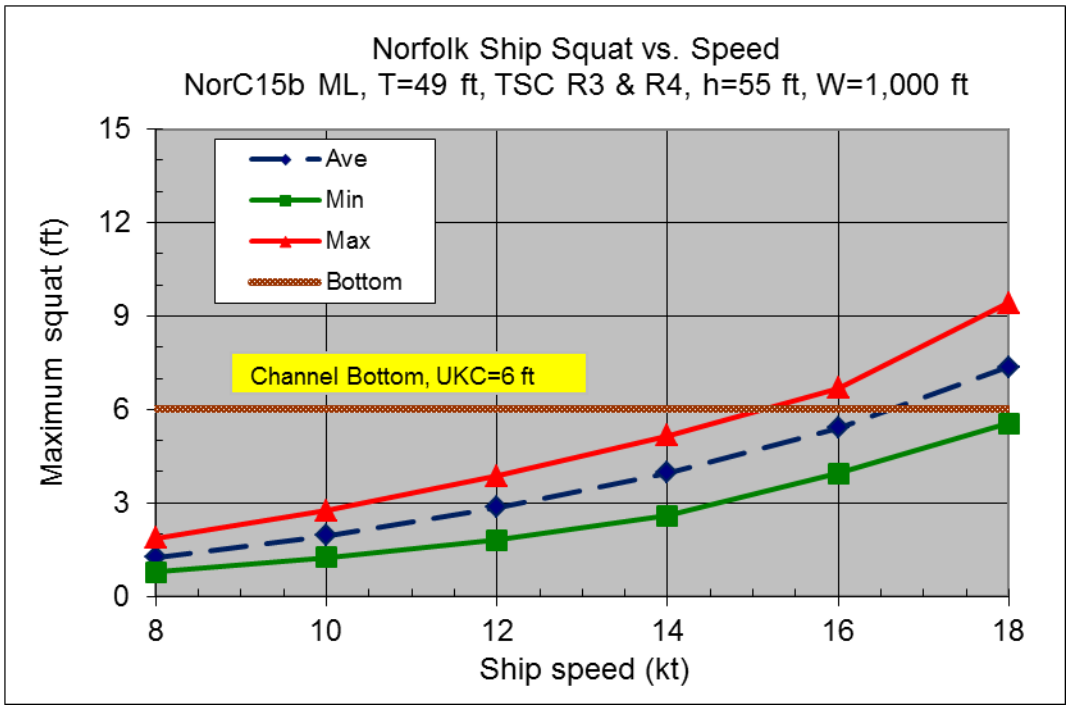


b)

Figure 7. Ship squat for ML (*T*=49 ft) NorC15b containership, AOC R1 and R2 (*h*=61 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.



a)



b)

Figure 8. Ship squat for ML (*T*=49 ft) NorC15b containership, AOC R3 and R4 (*h*=55 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.

Table 8. Ship squat predictions for Medium Load (ML, *T*=49 ft)) NorC15b containership.

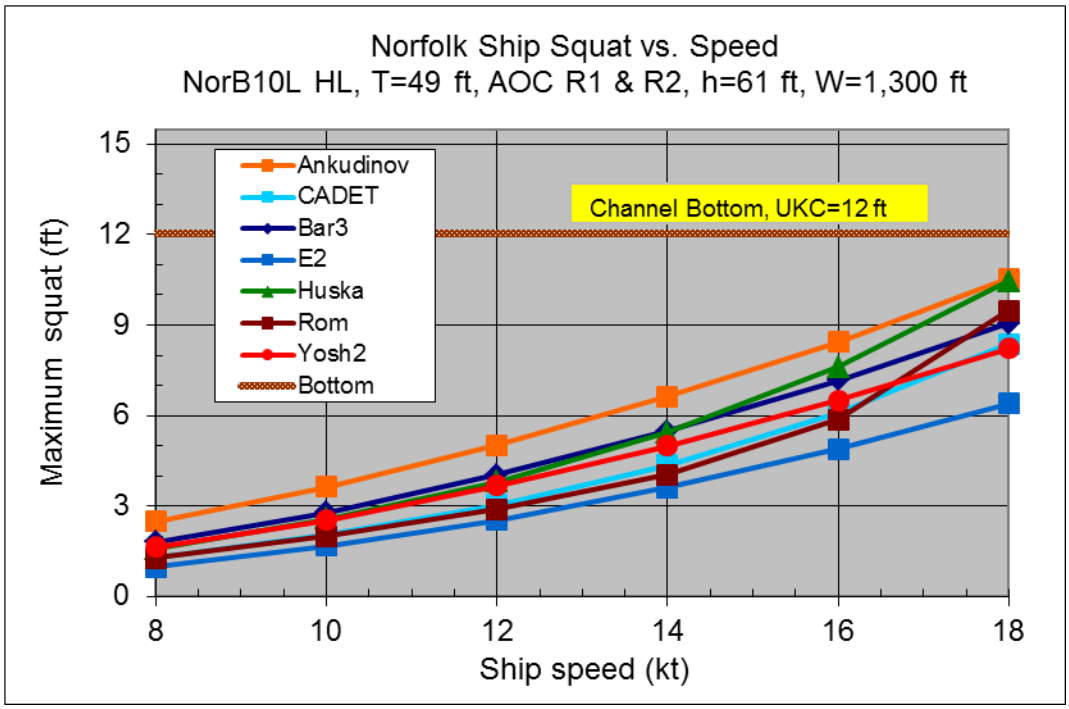
Speed V_k (kt)	Ank (ft)	CAD (ft)	B3 (ft)	E2 (ft)	Hus (ft)	Röm (ft)	Yosh (ft)	Ave (ft)	Min (ft)	Max (ft)
AOC R1 & R2: *h*=61 ft (UKC=12 ft)										
8	1.64	0.72	1.51	0.98	1.21	0.75	1.18	1.14	0.72	1.64
10	2.46	1.15	2.36	1.67	1.97	1.15	1.87	1.81	1.15	2.46
12	3.41	1.73	3.38	2.53	2.92	1.67	2.69	2.62	1.67	3.41
14	4.53	2.47	4.59	3.61	4.20	2.33	3.67	3.63	2.33	4.59
16	5.84	3.45	6.00	4.89	5.84	3.35	4.79	4.88	3.35	6.00
18	7.32	4.75	7.61	6.40	8.04	5.31	6.07	6.50	4.75	8.04
TSC R3 & R4: *h*=55 ft (UKC=6 ft)										
8	1.87	0.80	1.51	1.12	1.35	0.79	1.28	1.24	0.79	1.87
10	2.76	1.29	2.36	1.84	2.20	1.25	2.00	1.96	1.25	2.76
12	3.87	1.94	3.38	2.79	3.31	1.80	2.89	2.86	1.80	3.87
14	5.15	2.80	4.59	3.97	4.76	2.59	3.94	3.97	2.59	5.15
16	6.63	3.95	6.00	5.41	6.69	4.00	5.12	5.40	3.95	6.69
18	8.33	5.54	7.61	7.09	9.42	7.02	6.50	7.36	5.54	9.42

Notes:
1. Ank = Ankudinov, CAD = CADET, B3 = Barrass version 3, E2 = Eryuzlu version 2 Hus = Huuska/Guliev, Röm = Römisch, Yosh = Yoshimura.
2. Ave, Min, Max = Average, Minimum, or Maximum of all 7 squat predictions.
3. Red = Squat exceeds available UKC, Yellow shade = Ave, Min, Max at V_k =12 kt.

NorB10L coal carrier squat

Heavy load (HL, T=49 ft)

Figures 9 and 10 and Table 9 are the analogous figures and table of ship squat for the NorB10L coal carrier at the Heavy load (HL, T=49 ft) condition. The UKC for AOC and TSC reaches is 12 ft (h/T=1.24) and 6 ft (h/T=1.12), respectively. Again, squat is not a particular problem on its own for the larger UKC in the AOC reaches R1 and R2. Values range from 2.53 to 5.02 ft, with an average of 3.57 ft. This should leave sufficient room to accommodate vertical wave-induced ship motions for all but the most extreme waves. With the reduced UKC in the TSC reaches, however, the squat values of 2.79 to 5.41 ft, with an average of 3.89 ft, barely leave sufficient room to handle ship motions. Squat alone could use all the UKC when speeds exceed V_k=13 to 14 kt.



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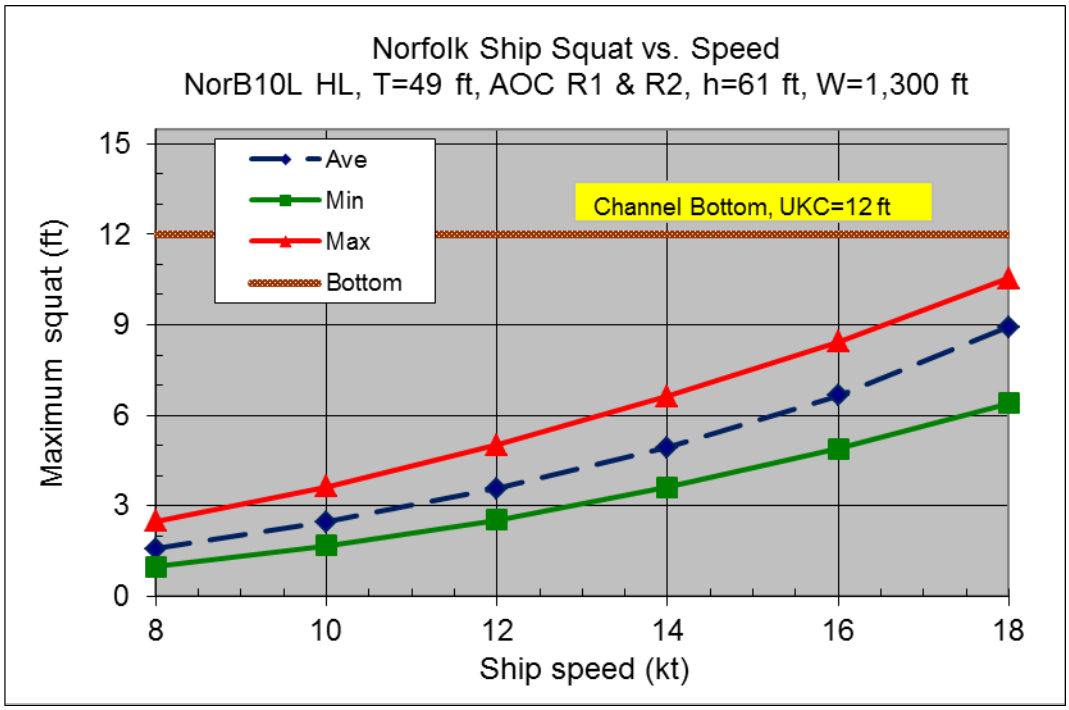
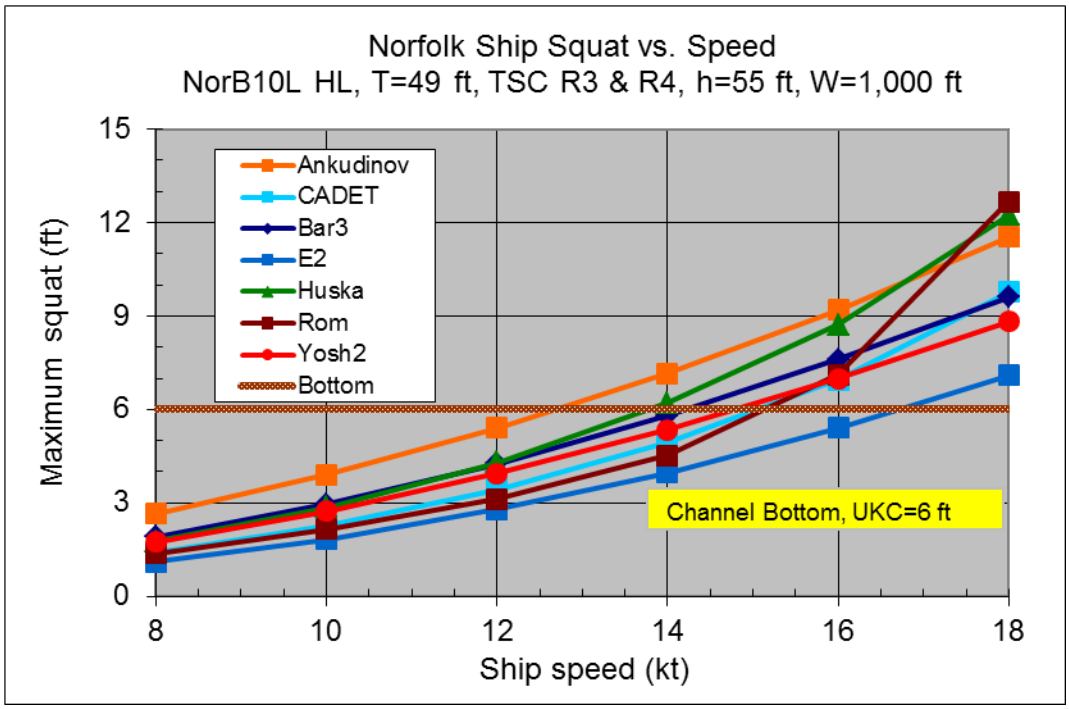
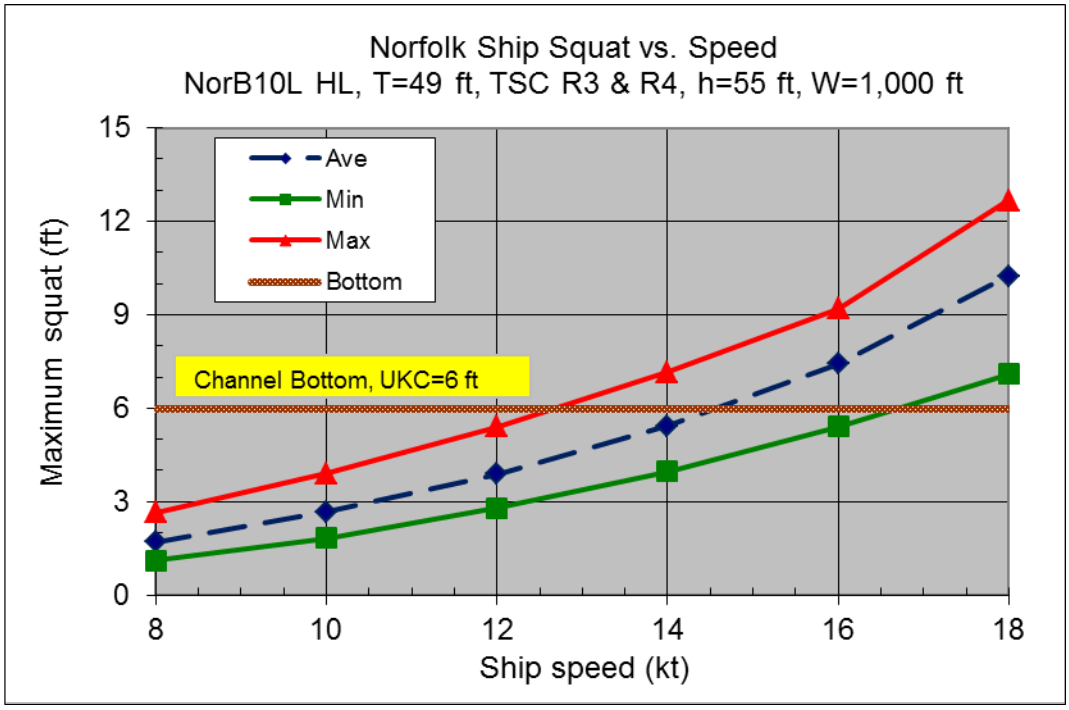


b)

Figure 9. Ship squat for HL (*T*=49 ft) NorB10L coal carrier, AOC R1 and R2 (*h*=61 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.



a)



b)

Figure 10. Ship squat for HL (*T*=49 ft) NorB10L coal carrier, TSC R3 and R4 (*h*=55 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.

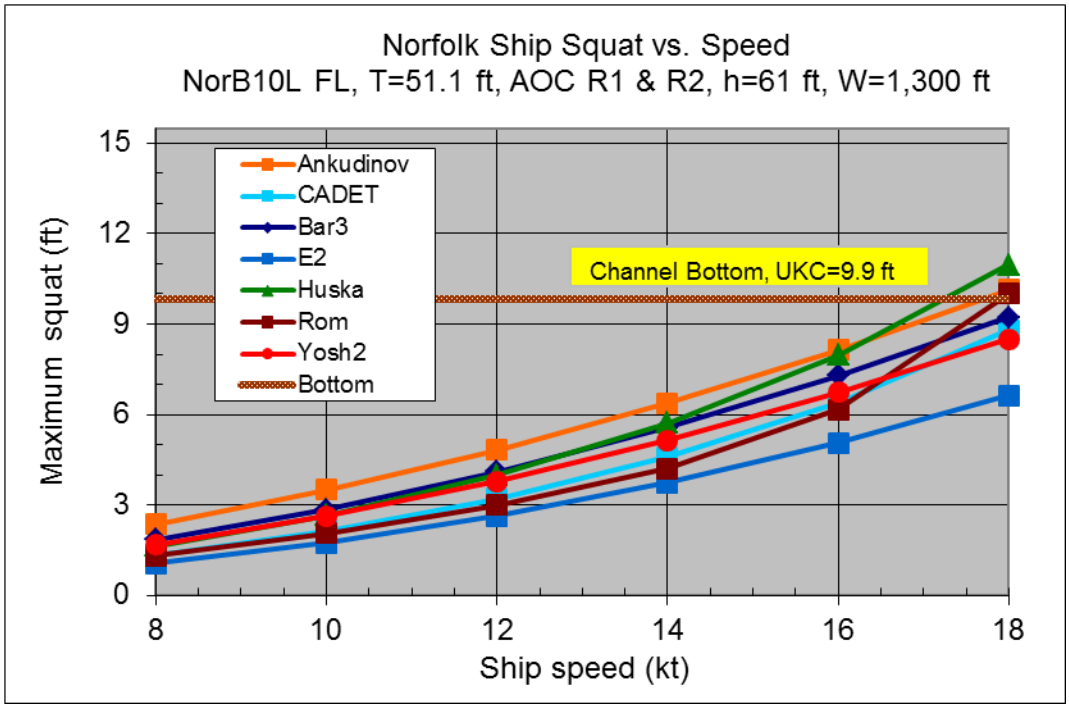
Table 9. Ship squat predictions for Heavy Load (HL, *T*=49 ft) NorB10L coal carrier.

Speed V_k (kt)	Ank (ft)	CAD (ft)	B3 (ft)	E2 (ft)	Hus (ft)	Röm (ft)	Yosh (ft)	Ave (ft)	Min (ft)	Max (ft)
AOC R1 & R2: *h*=61 ft (UKC=12 ft)										
8	2.49	1.26	1.80	0.98	1.57	1.28	1.64	1.58	0.98	2.49
10	3.64	2.03	2.79	1.67	2.56	2.00	2.53	2.46	1.67	3.64
12	5.02	3.04	4.04	2.53	3.81	2.89	3.67	3.57	2.53	5.02
14	6.63	4.35	5.48	3.61	5.45	4.04	4.99	4.93	3.61	6.63
16	8.43	6.07	7.15	4.89	7.61	5.87	6.50	6.65	4.89	8.43
18	10.53	8.37	9.06	6.40	10.47	9.48	8.23	8.93	6.40	10.53
TSC R3 & R4: *h*=55 ft (UKC=6 ft)										
8	2.66	1.41	1.90	1.12	1.77	1.38	1.74	1.71	1.12	2.66
10	3.90	2.27	2.95	1.84	2.85	2.17	2.72	2.67	1.84	3.90
12	5.41	3.42	4.27	2.79	4.30	3.12	3.94	3.89	2.79	5.41
14	7.15	4.94	5.81	3.97	6.20	4.53	5.35	5.42	3.97	7.15
16	9.19	6.96	7.61	5.41	8.73	7.12	6.99	7.43	5.41	9.19
18	11.55	9.77	9.61	7.09	12.24	12.66	8.83	10.25	7.09	12.66

Notes:
1. Ank = Ankudinov, CAD = CADET, B3 = Barrass version 3, E2 = Eryuzlu version 2 Hus = Huuska/Guliev, Röm = Römisch, Yosh = Yoshimura.
2. Ave, Min, Max = Average, Minimum, or Maximum of all 7 squat predictions.
3. Red = Squat exceeds available UKC, Yellow shade = Ave, Min, Max at V_k =12 kt.

Full load (FL, T=51.1 ft)

Figures 11 and 12 and Table 10 shows the ship squat for the full load (FL, T=51.1. ft) loading condition. The UKC is 9.9 (h/T=1.20) and 3.9 ft (h/T=1.08) for the AOC and TSC reaches, respectively. For ship speeds of V_k=12 kt in AOC reaches R1 and R2, the predicted squat ranges from 2.62 to 4.82 ft, with an average of 3.64 ft. The corresponding UKC is probably sufficient to handle ship motions with a range of 5.08 to 7.28 ft, with an average of 6.26 ft. The situation is not very good, however, for TSC reaches R3 and R4. The average squat at V_k=12 kt is 4.00 ft, which exceeds the allowable UKC of 3.9 ft. Therefore, pilots would most likely choose to go much slower if the draft is this deep. At V_k=10 kt the squat ranges from 1.90 to 3.81 ft, with an average of 2.75 ft. This still would require transits on fairly benign wave conditions while traversing the TSC R3 and R4 reaches. Of course for all small UKC conditions, pilots could wait until the water level increases +1 to +3 ft due to the tide.



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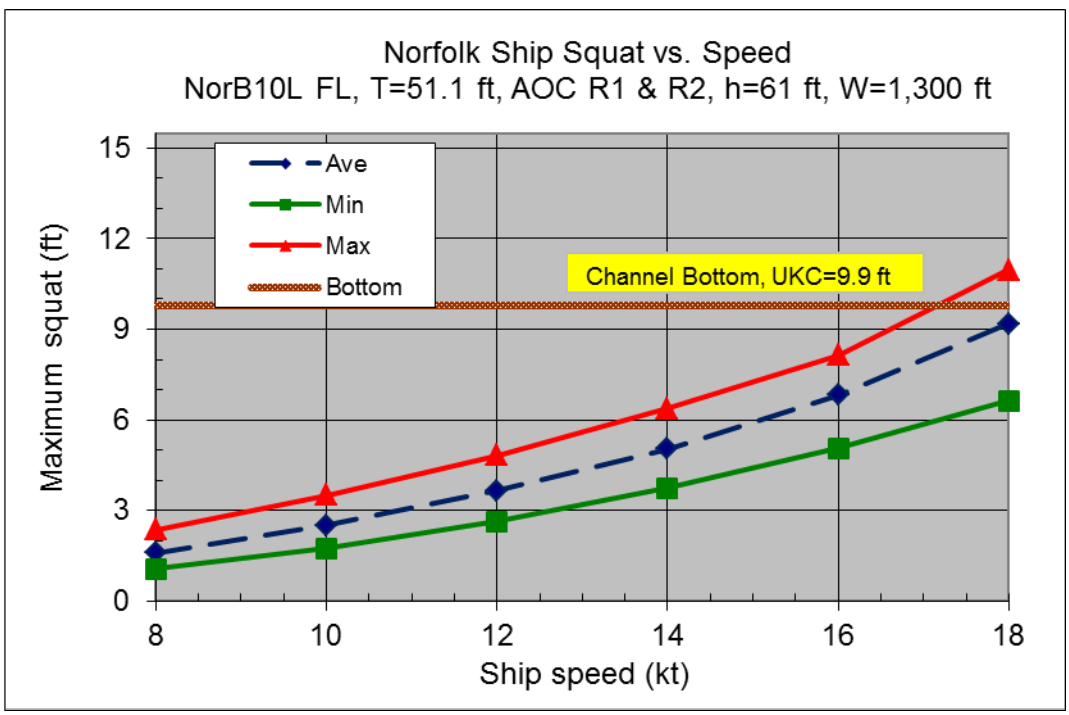
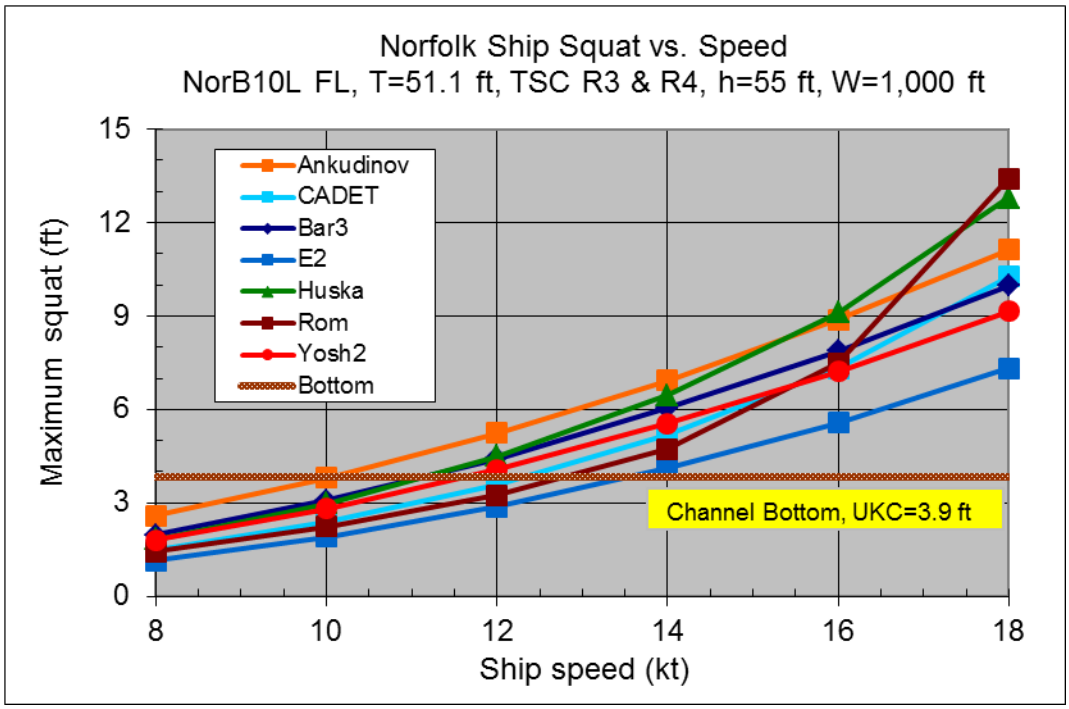


b)

Figure 11. Ship squat for FL (*T*=51.1 ft) NorB10L coal carrier, AOC R1 and R2 (*h*=61 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.



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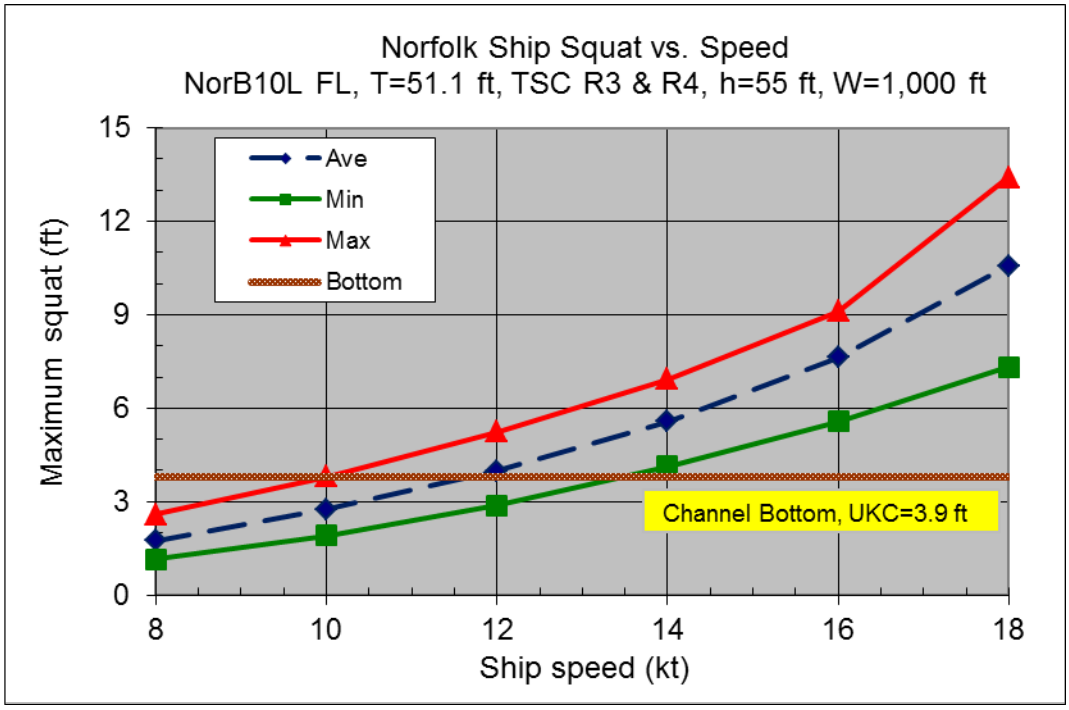


b)

Figure 12. Ship squat for FL (*T*=51.1 ft) NorB10L coal carrier, AOC R3 and R4 (*h*=55 ft) Norfolk Channel for (a) Ankudinov, CADET, Barrass, Eryuzlu, Huuska, Romisch, and Yoshimura predictions, and (b) average, minimum, and maximum squat for all seven predictors.

Table 10. Ship squat predictions for Full Load (FL, T=51.1 ft) NorB10L coal carrier.

Speed V_k (kt)	Ank (ft)	CAD (ft)	B3 (ft)	E2 (ft)	Hus (ft)	Röm (ft)	Yosh (ft)	Ave (ft)	Min (ft)	Max (ft)
AOC R1 & R2: h=61 ft (UKC=9.9 ft)										
8	2.36	1.33	1.84	1.05	1.64	1.31	1.67	1.60	1.05	2.36
10	3.51	2.14	2.85	1.74	2.66	2.07	2.62	2.51	1.74	3.51
12	4.82	3.20	4.10	2.62	4.00	2.99	3.77	3.64	2.62	4.82
14	6.36	4.58	5.58	3.74	5.71	4.20	5.15	5.05	3.74	6.36
16	8.14	6.38	7.28	5.05	7.97	6.17	6.73	6.82	5.05	8.14
18	10.14	8.80	9.22	6.63	10.96	10.01	8.50	9.18	6.63	10.96
TSC R3 & R4: h=55 ft (UKC=3.9 ft)										
8	2.59	1.48	1.97	1.15	1.84	1.44	1.80	1.75	1.15	2.59
10	3.81	2.39	3.08	1.90	2.99	2.23	2.82	2.75	1.90	3.81
12	5.25	3.60	4.43	2.89	4.49	3.25	4.07	4.00	2.89	5.25
14	6.92	5.19	6.04	4.13	6.46	4.72	5.54	5.57	4.13	6.92
16	8.89	7.32	7.87	5.58	9.12	7.48	7.22	7.64	5.58	9.12
18	11.12	10.27	9.97	7.32	12.80	13.42	9.15	10.58	7.32	13.42

Notes:
1. Ank = Ankudinov, CAD = CADET, B3 = Barrass version 3, E2 = Eryuzlu version 2 Hus = Huuska/Guliev, Röm = Römisch, Yosh = Yoshimura.
2. Ave, Min, Max = Average, Minimum, or Maximum of all 7 squat predictions.
3. Red = Squat exceeds available UKC, Yellow shade = Ave, Min, Max at V_k =12 kt.

Restricted channel

All of the squat calculations have assumed an unrestricted or open channel cross-section. In this section, squat for the unrestricted channel is compared with a restricted channel. A restricted channel has a "trench" type of cross section versus the open cross section of the unrestricted channel (Figure 4). Ship squat for restricted channels may be larger depending on the (a) ship beam, length and speed, and (b) channel depth, width, side slopes, and outside water depths. According to Barrass (PIANC 2014) for the NorC15b containership, an effective channel width of W_{Eff}=9.4 B, or 1580 ft, in a restricted channel is equivalent to an unrestricted or open channel. For the NorB10L coal carrier bulker, the equivalent effective channel width is smaller, requiring only a width of W_{Eff}=8.0 B, or 1180 ft. The width of the AOC R1 and R2 and TSC R3 and R4 reaches are W=1,300 and 1,000 ft, respectively. Since the project depth and corresponding UKC are much larger in the AOC R1 and R2 reaches, only the shallower and narrower TSC R3 and R4 reaches are modeled as restricted channel for comparison with all four ship loading conditions.

Table 2 listed the width, and channel and outside depth for the restricted channel cross-section in the four reaches. These input values are considered very conservative as the width in R3 and R4 is modeled at W=1,000 ft even though a good portion of these reaches will be 1,400 ft wide for the passing and overtaking lanes. Also, the shallowest outside depths are modeled since this is the most conservative assumption which would lead to the most squat.

Figure 13 compares ship squat for unrestricted versus restricted channels for all four ship loading conditions in the TSC R3 and R4 reaches. The average ship squat consisting of the average of the Ankudinov, CADET, and five PIANC squat predictions is used in these comparisons (Table 12). The V_k=12 kt is highlighted as this is the maximum speed for these shallow reaches based on the unrestricted channel assumption. For all four loading conditions, the difference between restricted and unrestricted squat is of the order of 0.5 ft. Although there are larger differences in squat for faster speeds, these are unrealistic as there is not sufficient UKC to allow these faster speeds. Thus, it is safe to assume that the entire Norfolk channel can be modeled as an open or unrestricted channel cross-section as it is assumed that the effect of a trench is minimal and any increase in predicted squat is included by using the average of all the squat predictors instead of the minimal predicted squat.

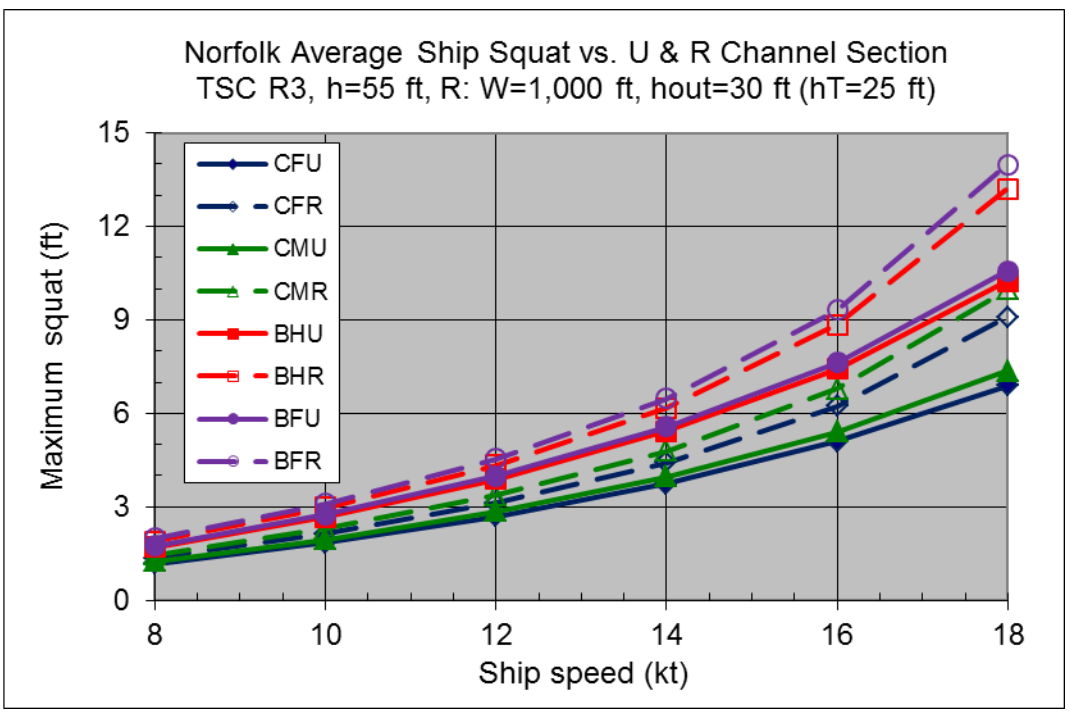


Figure 13. Comparison of unrestricted vs. restricted average ship squat for all four ship loading conditions in TSC R3 and R4 reaches.

Table 12. Average ship squat for unrestricted (U) vs. restricted (R) channel cross-sections for all four ship loading conditions, Norfolk Channel.

Speed V_k (kt)	NorC15b				NorB10L			
	FL, T=45.8 ft		ML, T=49 ft		HL, T=49 ft		FL, T=51.1 ft	
	CFU (ft)	CFR (ft)	CMU (ft)	CMR (ft)	BHU (ft)	BHR (ft)	BFU (ft)	BFR (ft)
8	1.17	1.35	1.24	1.45	1.71	1.89	1.75	1.98
10	1.85	2.13	1.96	2.30	2.67	2.97	2.75	3.10
12	2.69	3.12	2.86	3.37	3.89	4.34	4.00	4.55
14	3.74	4.42	3.97	4.78	5.42	6.17	5.57	6.48
16	5.09	6.23	5.40	6.79	7.43	8.84	7.64	9.31
18	6.90	9.09	7.36	9.98	10.25	13.20	10.58	13.99

Notes:
1. Ship and loading condition ID: C=containership, B=bulker coal carrier, F=full load, M=medium load, H=heavy load, U=unrestricted channel, R=restricted channel.

Squat UKC summary

Table 13 summarizes the available UKC for all combinations of ship loading, reaches (channel depth), and ship speed. The remaining UKC is listed for the average and maximum (or worst case) ship squat predictions after subtracting from the gross UKC. Negative UKC values are highlighted in red and represent a grounded ship. In summary, these represent only the ship squat values and do not include wave-induced vertical ship motions of heave, pitch, and roll. These will add to the required clearance values and will result in smaller available UKC when added to these squat predictions.

For the deeper AOC reaches R1 and R2, only a speed of V_k=18 kt for the full load NorB10L coal carrier will pose a problem with UKC due to squat only. This is also assuming that the worst case predictor of squat is accurate for this case as the average squat would have predicted an available clearance of 0.72 ft.

As noted previously, the shallower TSC reaches of R3 and R4 will experience ship grounding for both ships, depending on loading conditions and ship speed. The ML NorC15b containership should proceed with caution if attempting ship speeds faster than V_k=14 kt, especially if any significant wave activity is present. For NorB10L coal carrier transits, pilots should exercise extreme caution if attempting to move at speeds as high as V_k=12 kt under HL loading conditions and V_k=10 kts with FL loading. These speeds are probably not even possible unless wave heights and periods are relatively small. When tides are present, squat will be reduced slightly so that the UKC will increase by approximately the increase in the water level. Of course, pilots should be vigilant at higher speeds as ship squat can always be reduced by slowing down.

Table 13. UKC summary for NorC15b and NorB10L, Norfolk Channel.

Speed V_k (kt)	NorC15b				NorB10L			
	FL, *T*=45.8 ft		ML, *T*=49 ft		HL, *T*=49 ft		FL, *T*=51.1 ft	
	Ave (ft)	Max (ft)	Ave (ft)	Max (ft)	Ave (ft)	Max (ft)	Ave (ft)	Max (ft)
AOC R1 & R2: *h*=61 ft								
8	14.12	13.69	10.86	10.36	10.42	9.51	8.30	7.54
10	13.50	12.87	10.19	9.54	9.54	8.36	7.39	6.39
12	12.73	11.85	9.38	8.59	8.43	6.98	6.26	5.08
14	11.78	10.64	8.37	7.41	7.07	5.37	4.85	3.54
16	10.60	9.26	7.12	6.00	5.35	3.57	3.08	1.76
18	9.09	7.69	5.50	3.96	3.07	1.47	0.72	-1.06
TSC R3 & R4: *h*=55 ft								
8	8.03	7.49	4.76	4.13	4.29	3.34	2.15	1.31
10	7.35	6.67	4.04	3.24	3.33	2.10	1.15	0.09
12	6.51	5.69	3.14	2.13	2.11	0.59	-0.10	-1.35
14	5.46	4.51	2.03	0.85	0.58	-1.15	-1.67	-3.02
16	4.11	3.00	0.60	-0.69	-1.43	-3.19	-3.74	-5.22
18	2.30	0.51	-1.36	-3.42	-4.25	-6.66	-6.68	-9.52

Notes:
1. Negative (Red) values represent grounded ship.

Ship accessibility

CADET predicts days/year of accessibility based on ship parameters, channel configuration, wave conditions, and risk of grounding. This accessibility is generated for each reach, inbound and outbound transit directions, and ship loading condition. Based on these values, the design team can select the optimum dredge depth which is defined as the shallowest dredge depth with the largest percentage of time the channel could be safely transited each year based on required or expected usage requirements. Appendix B contains tables with days of accessibility for inbound and outbound transits for each ship and loading condition as a function of reach and water depth.

This chapter presents results for the NorC15b containership and the NorB10L coal carrier and their two loading conditions for absolute water levels. These water levels represent a combined water depth that includes tides. The project depth is assumed to be *h*=61 ft in reaches R1 and R2 and *h*=55 ft in R3 and R4. The shallower reaches R3 and R4 are the controlling depths due to the crossing of the CBBT and its associated safety requirements. As discussed previously, tides can be expected to permit depths up to +2 ft for most days, with a maximum tidal advantage of +3 ft for a few days each year.

NorC15b containership

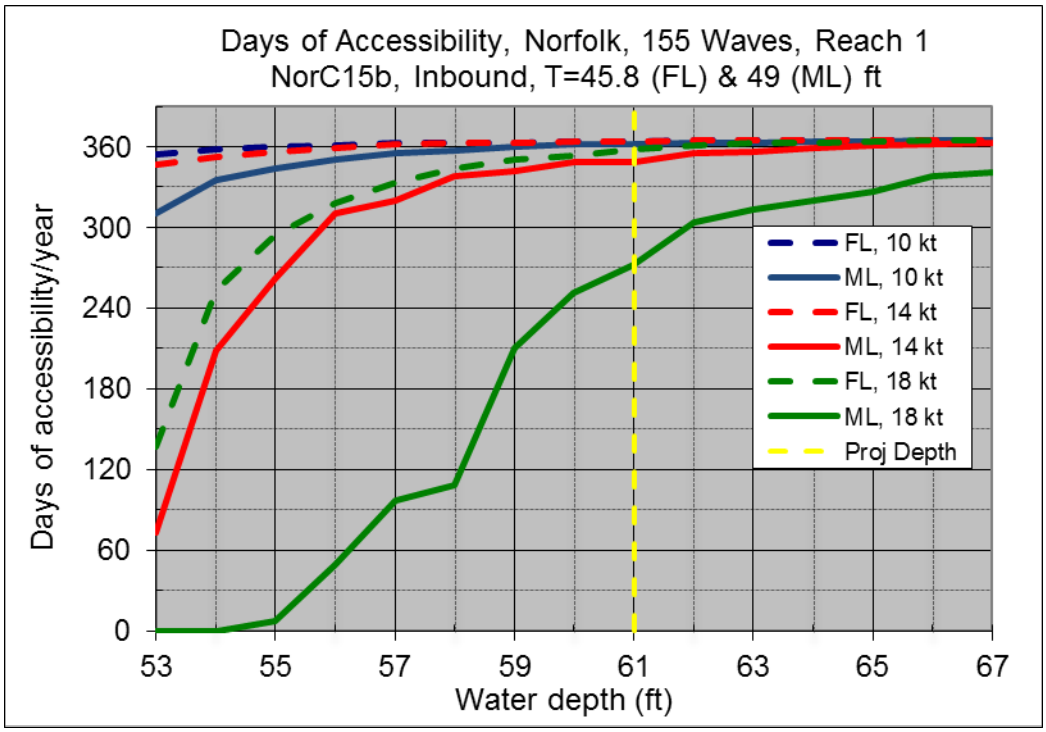
The effects of loading condition (FL and ML) and transit direction on days of accessibility are shown in Figures 14 to 17 as a function of water depth and ship speed for reaches R1 to R4, respectively. These plots assume an unrestricted or open channel cross-section. The top plot ("a") is for inbound and the bottom plot ("b") for outbound transits. Inbound and outbound transits are assumed to have the same loading and draft, although in reality transit drafts often differ for inbound versus outbound movements. Ship speeds of V_k=10 to 18 kt are shown for inbound and outbound transits in all reaches except for inbound ML transits in TSC R3 and R4 for a maximum speed of V_k=16 kt due to possible resonant rolling. In reaches R3 and R4 the project depth is only h=55 ft, so they are the controlling reaches due to the much shallower depths. Remember that the gross underkeel clearance (UKC) at h=55 ft is only 6 ft (i.e., 55-49) for ML in the static condition.

As an example for V_k=18 kt inbound transits in R1 at h=61 ft (Figure 14a); FL and ML transits will have 358 and 272 days of accessibility/yr, respectively. Neither loading condition poses a problem for outbound transits in R1 (Figure 14b) as both loading conditions have 362 days or better. Similarly, accessibility is slightly better due to smaller waves in R2, with 360 and 298 days/yr accessibility for FL and ML, respectively (Figure 15a). Again, outbound transits do not pose a problem as accessibility is 364 and 357 days/yr for the two loading conditions.

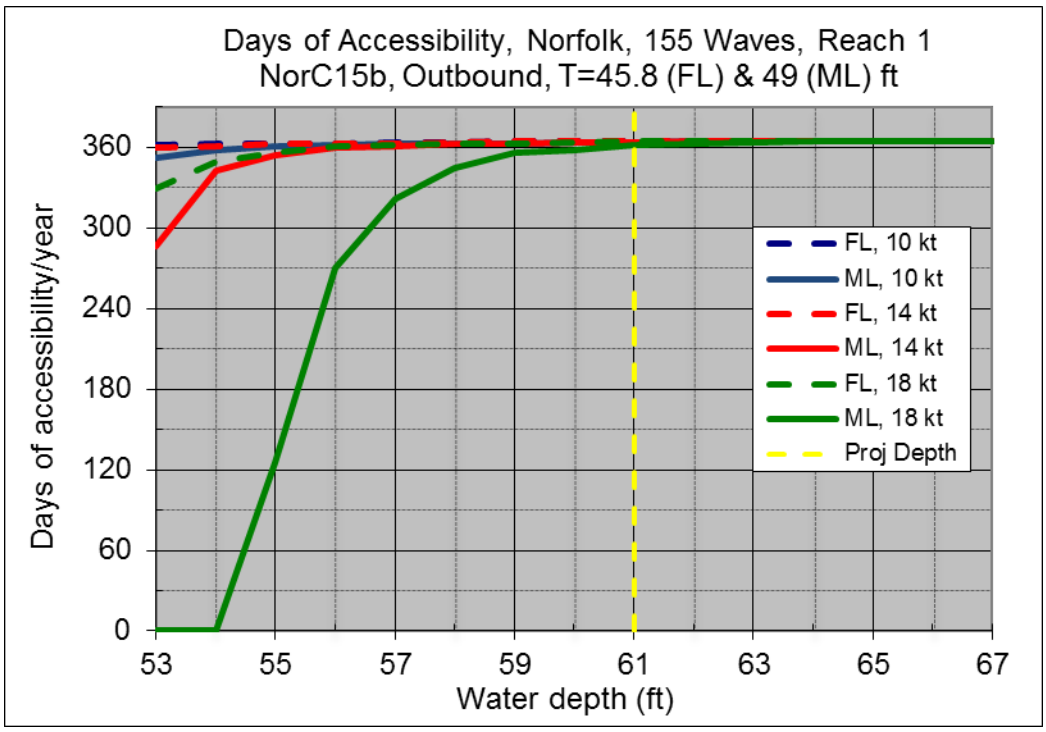
The FL condition has the same accessibility of 347 and 364 days/yr in both R3 and R4 at h=55 ft for V_k=18 kt inbound and outbound transits (Figures 16a and 17a), respectively. The ML condition, however, has reduced accessibility of 169 and 186 days/yr for slower V_k=16 kt inbound transits in R3 and R4, respectively. The outbound transits in R3 and R4 have the same 207 days/yr accessibility at V_k=18 kt.

NorB10L coal carrier

The effects of NorB10L loading condition (HL and FL) and transit direction on days of accessibility are shown in Figures 18 to 21 as a function of water depth and ship speed for reaches R1 to R4, respectively. Again, these plots assume an unrestricted or open channel cross-section. Ship speeds vary between V_k=10 to 18 kt for reaches R1 and R2. For the shallower TSC R3 and R4 reaches, however, the speeds are shown between 10 and a maximum of V_k=14 kt. The NorB10L coal carrier drafts are as deep as or deeper than the loading conditions for the NorC15b containership so that there is less UKC available. The gross underkeel clearance (UKC) at h=55 ft is only 3.9 ft (i.e., 55-51.1) for the FL in R3 and R4.

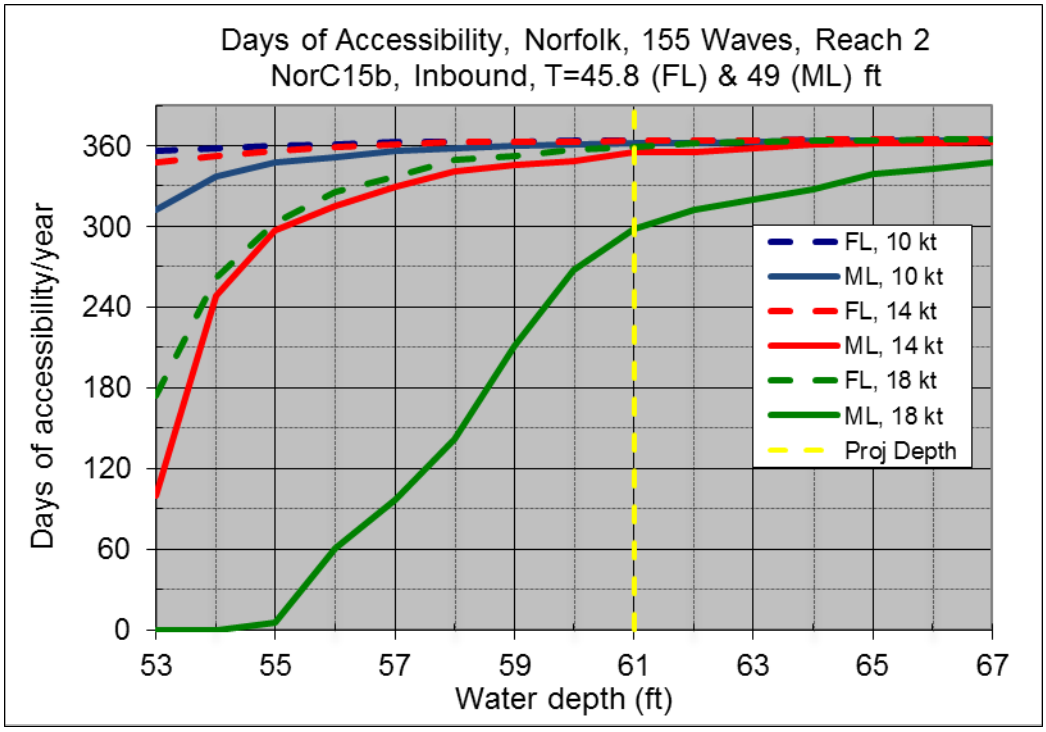


a)

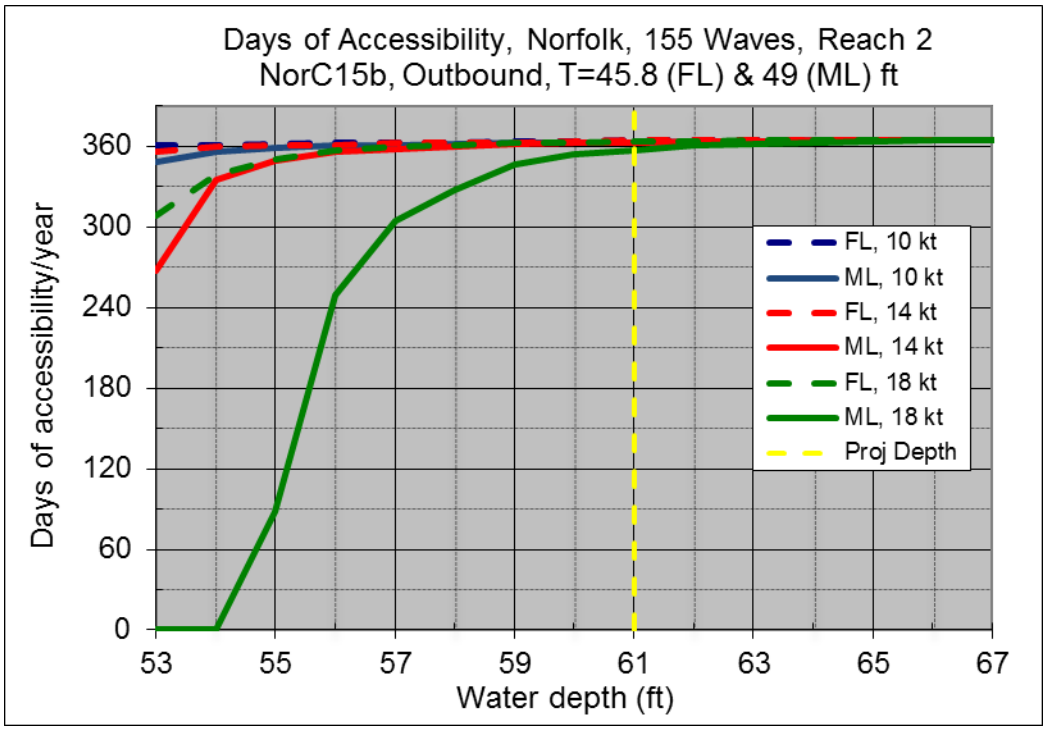


b)

Figure 14. CADET predictions of days of accessibility for Reach 1 for Full (FL) and Medium (ML) loaded NorC15b containership as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.

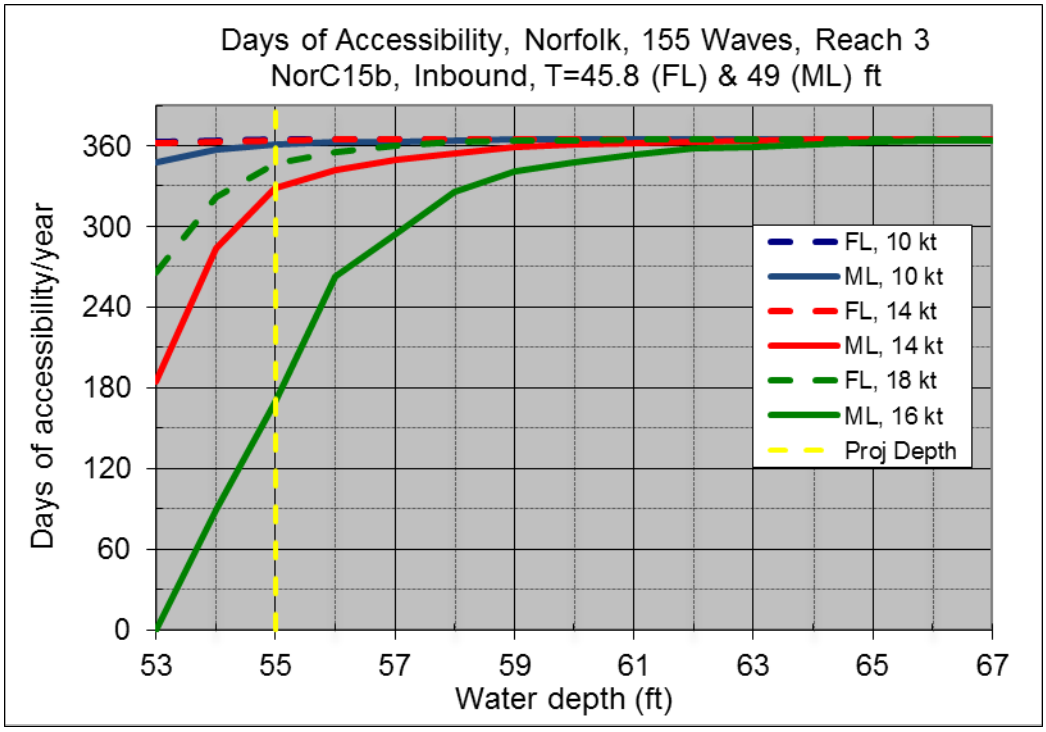


a)

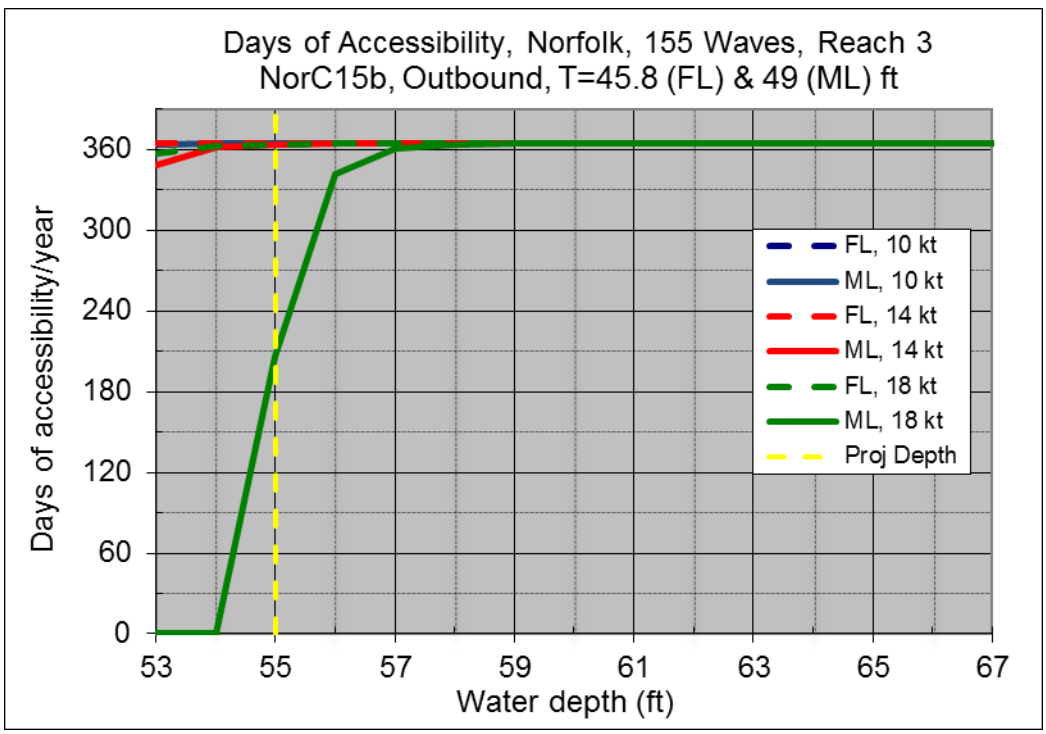


b)

Figure 15. CADET predictions of days of accessibility for Reach 2 for Full (FL) and Medium (ML) loaded NorC15b containership as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.

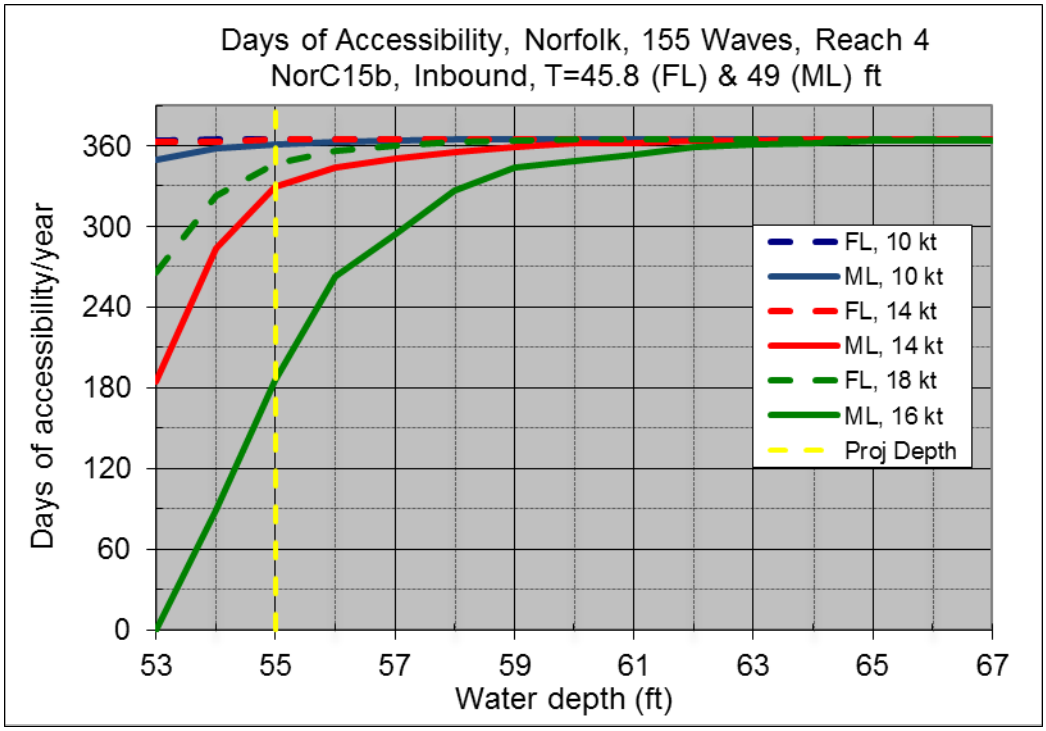


a)

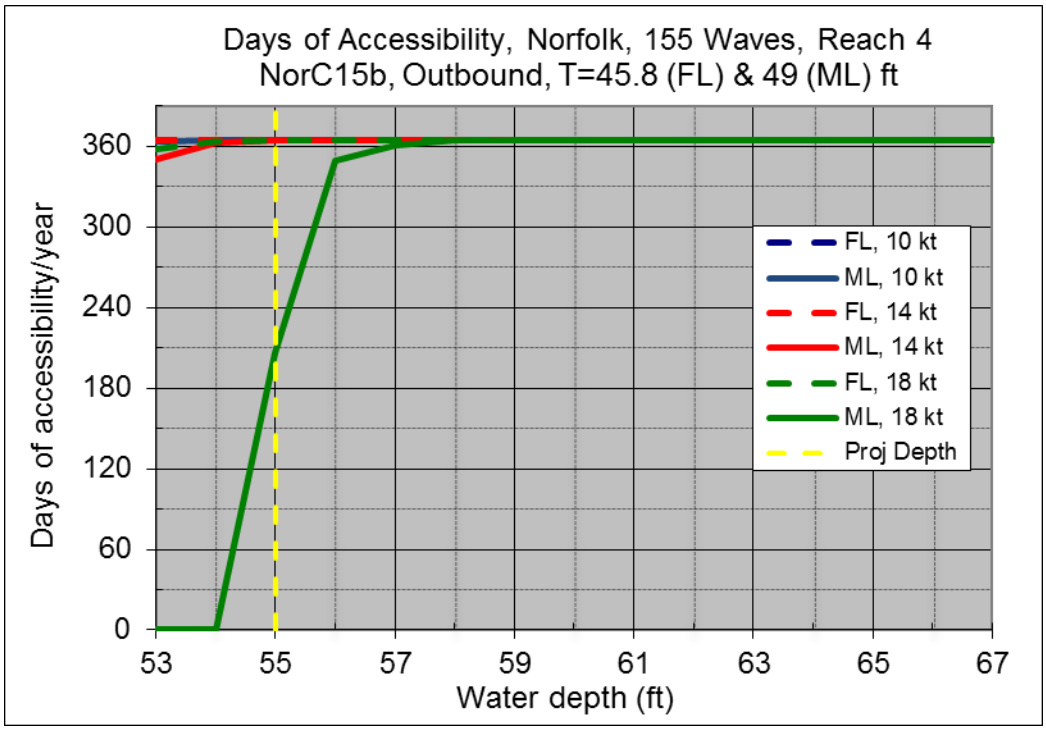


b)

Figure 16. CADET predictions of days of accessibility for Reach 3 for Full (FL) and Medium (ML) loaded NorC15b containership as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.

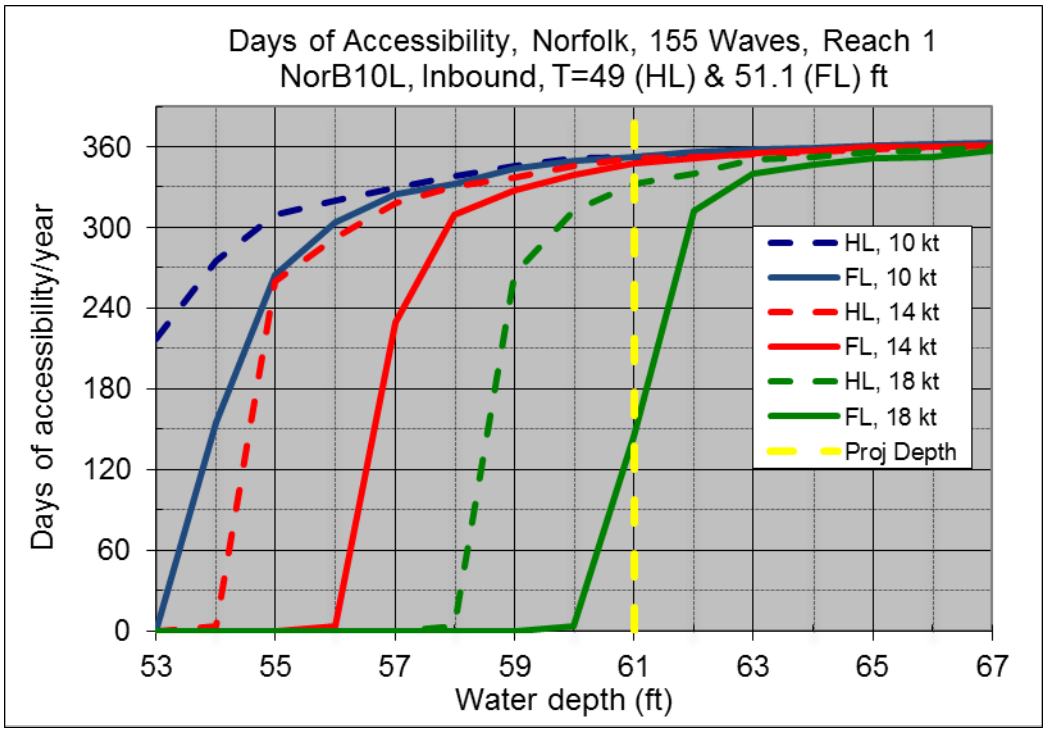


a)

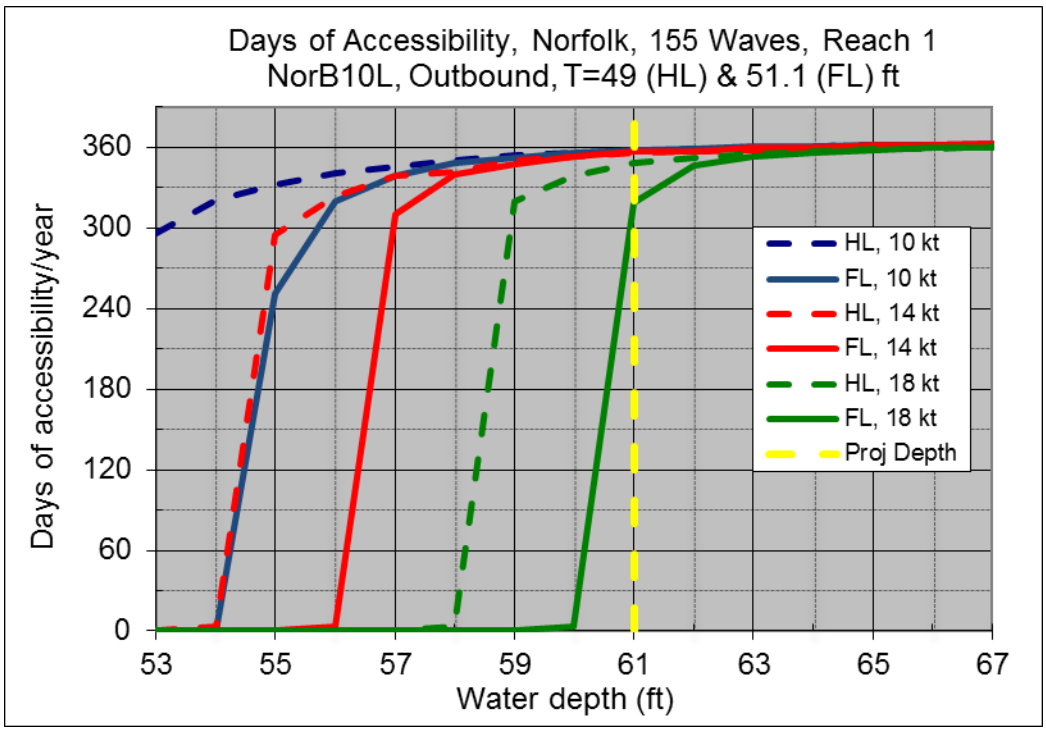


b)

Figure 17. CADET predictions of days of accessibility for Reach 4 for Full (FL) and Medium (ML) loaded NorC15b containership as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.

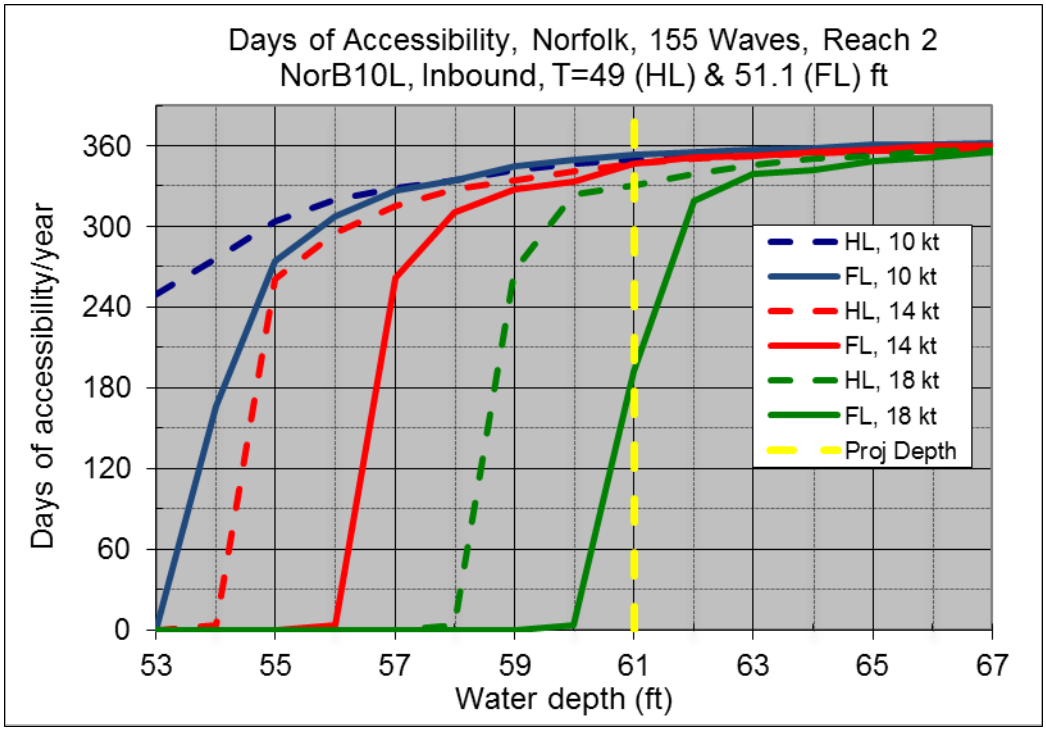


a)

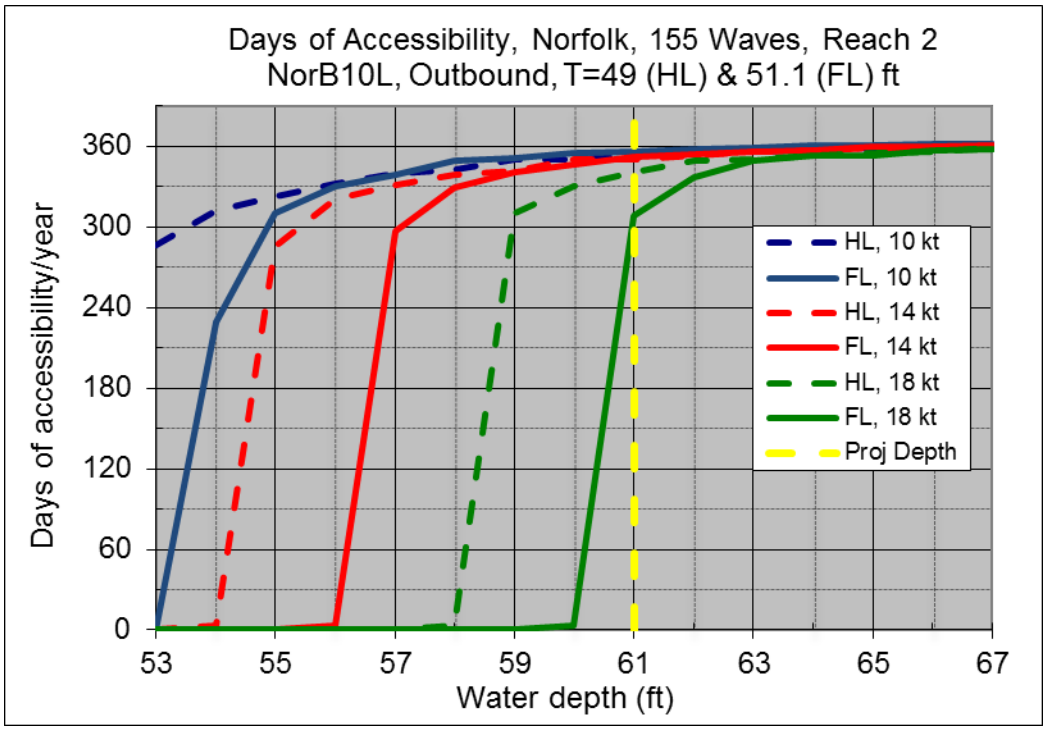


b)

Figure 18. CADET predictions of days of accessibility for Reach 1 for heavy (HL) and full loaded (FL) NorB10L coal carrier as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.

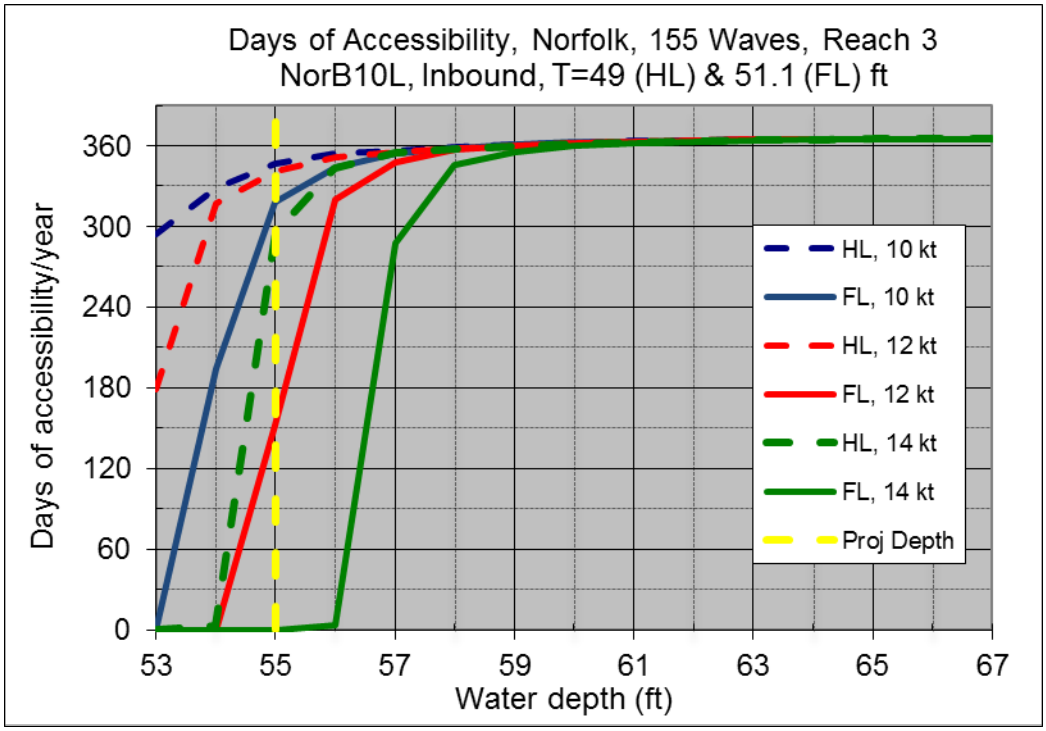


a)

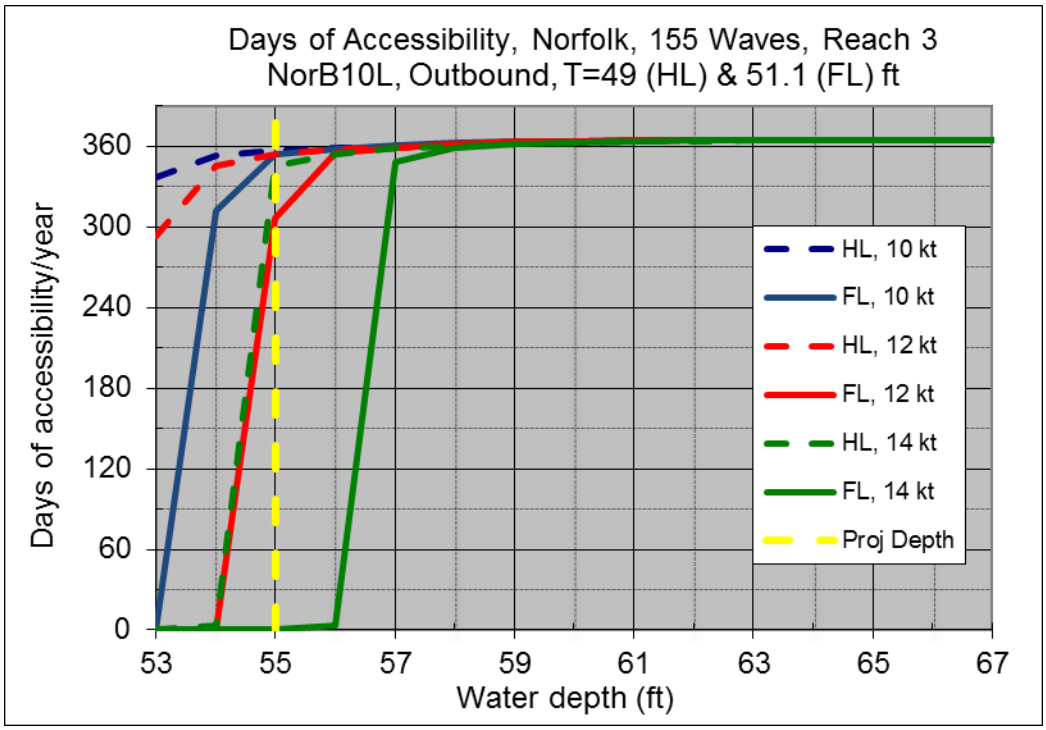


b)

Figure 19. CADET predictions of days of accessibility for Reach 1 for heavy (HL) and full (FL) loaded NorB10L coal carrier as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.

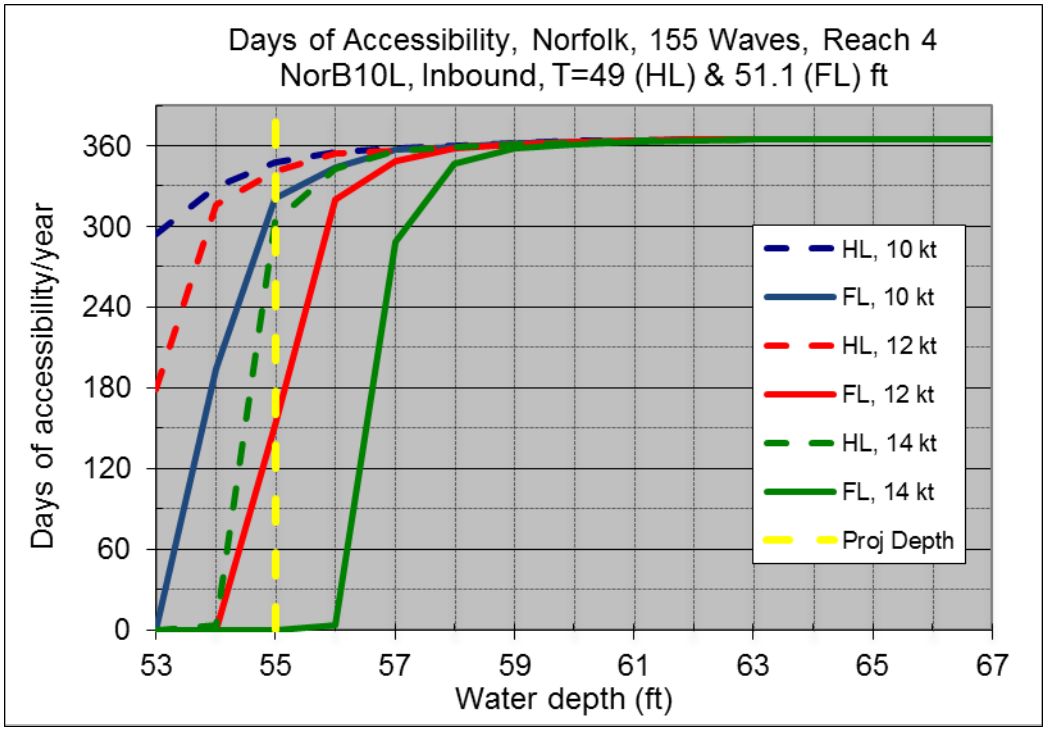


a)

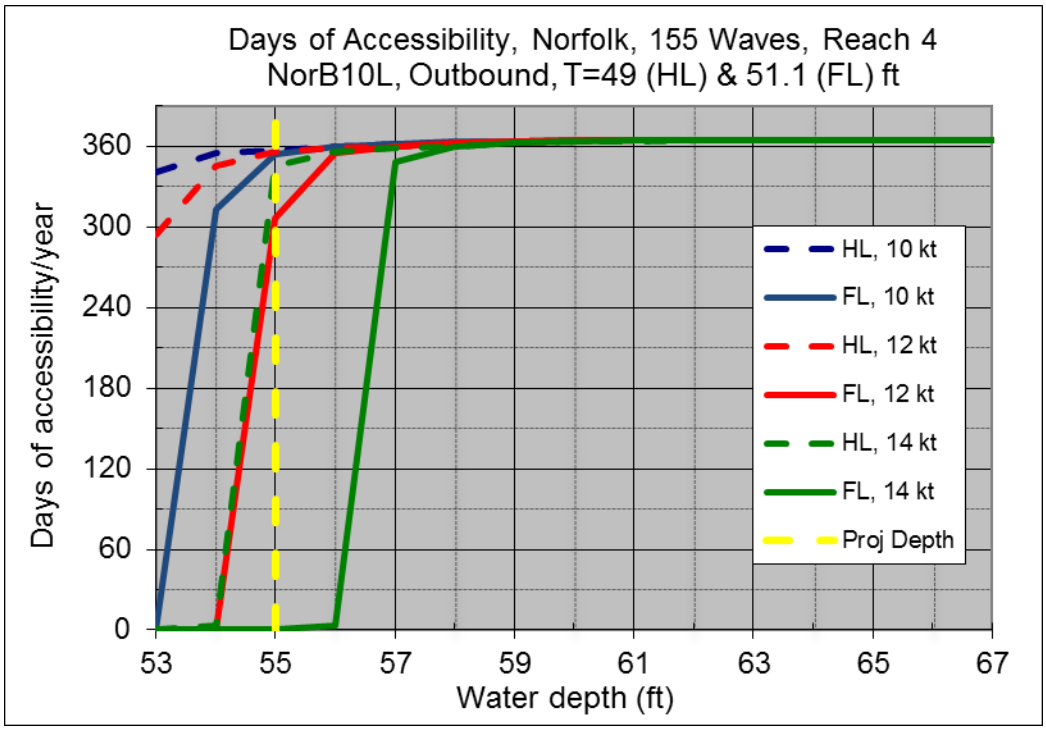


b)

Figure 20. CADET predictions of days of accessibility for Reach 3 for heavy (HL) and full (FL) loaded NorB10L coal carrier as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.



a)



b)

Figure 21. CADET predictions of days of accessibility for Reach 4 for heavy (HL) and full (FL) loaded NorB10L coal carrier as a function of channel depth and ship speed using 155 waves for (a) inbound and (b) outbound transits.

As an example for V_k=18 kt inbound transits in R1 at h=61 ft (Figure 18a); HL and FL transits will have 332 and 145 days of accessibility/yr, respectively. Neither loading condition poses a problem for outbound transits in R1 (Figure 18b) as HL and FL loading conditions will have accessibility of 349 and 319 days/yr, respectively. Similarly, accessibility is similar or slightly better due to smaller waves in AOC R2, with 331 and 193 days/yr accessibility for HL and FL, respectively (Figure 19a). Again, outbound transits do not pose a problem as accessibility is 341 and 308 days/yr for the two loading conditions.

Due to the deeper drafts of the NorB10L in the shallower TSC R3 and R4 reaches at h=55 ft, ship speeds are limited to V_k=14 kt for the HL and V_k=12 kt for the deeper draft FL condition. For the HL condition, days of accessibility are 296 and 304 days/yr for inbound transits at V_k=14 kt in R3 and R4, respectively. Outbound transits have the same 345 days/yr accessibility in both R3 and R4. For the FL condition at V_k=12 kts in both R3 and R4, inbound and outbound transits have accessibility of 153 and 307 days/yr, respectively.

In general for all ship loading conditions, accessibility can be improved substantially and ship speed increased if travel is restricted to the times when the tide advantage is +1 to +2 ft (see example below).

Accessibility summary

Table 14 is a summary of squat and days of accessibility for the two loading conditions of the NorC15b containership. Note that the squat values are the same for both reaches in the AOC and TSC channels since they have the same depth. For the NorC15b FL loading condition, days of accessibility for outbound transits are usually the same or slightly better than inbound transits. R2 accessibility is slightly worse than R1, probably due to the difference in relative wave angle to the ship even though the waves are usually smaller. The R4 accessibility is generally the same as the R3 values. For the deeper draft NorC15b ML, outbound accessibility is always better than inbound values. The R2 and R4 accessibility values are the same or slightly better than their counterpart reaches R1 and R3.

Table 14. Squat and accessibility summary for NorC15b containership, Norfolk Channel.

Loading condition ID	Reach	Depth (ft)	Speed (kt)	Squat (ft)		Days of accessibility	
				Ave	UKC	Inbound	Outbound
FL (*T*=45.8 ft)	R1	61	10	1.70	13.50	364	365
			12	2.47	12.73	364	365
			14	3.42	11.78	364	365
	R2		10	1.70	13.50	363	364
			12	2.47	12.73	363	364
			14	3.42	11.78	363	364
	R3	55	10	1.85	7.35	365	365
			12	2.69	6.51	365	365
			14	3.74	5.46	364	365
	R4		10	1.85	7.35	365	365
			12	2.69	6.51	365	365
			14	3.74	5.46	365	365
ML (*T*=49 ft)	R1	61	10	1.81	10.19	362	364
			12	2.62	9.38	360	364
			14	3.63	8.37	348	364
	R2		10	1.81	10.19	362	363
			12	2.62	9.38	361	363
			14	3.63	8.37	355	363
	R3	55	10	1.96	4.04	361	365
			12	2.86	3.14	353	365
			14	3.97	2.03	328	365
	R4		10	1.96	4.04	361	365
			12	2.86	3.14	354	365
			14	3.97	2.03	329	364

Table 15 lists the summary squat and accessibility results for the NorB10L coal carrier. For the NorB10L FL loading condition, the outbound accessibility is again better than the inbound values. The R2 and R4 accessibility values are the same or slightly better than the R1 and R3 values. For the deeper draft NorB10L FL, the outbound accessibility follows the trend of being the same or better than the inbound transits. The R2 and R4 accessibility values are similar to the corresponding R1 and R3 reaches.

Table 15. Squat and accessibility summary for NorB10L coal carrier, Norfolk Channel.

Loading condition ID	Reach	Depth (ft)	Speed (kt)	Squat (ft)		Days of accessibility	
				Ave	UKC	Inbound	Outbound
HL (*T*=49 ft)	R1	61	10	2.46	9.54	352	357
			12	3.57	8.43	352	357
			14	4.93	7.07	352	356
	R2		10	2.46	9.54	350	354
			12	3.57	8.43	347	350
			14	4.93	7.07	347	350
	R3	55	10	2.67	3.33	346	357
			12	3.89	2.11	341	354
			14	5.42	0.58	296	345
	R4		10	2.67	3.33	348	357
			12	3.89	2.11	341	356
			14	5.42	0.58	304	345
FL (*T*=51.1 ft)	R1	61	10	2.51	7.39	353	359
			12	3.64	6.26	353	359
			14	5.05	4.85	348	357
	R2		10	2.51	7.39	353	356
			12	3.64	6.26	351	355
			14	5.05	4.85	347	352
	R3	55	10	2.75	1.15	318	354
			12	4.00	-.10	153	307
			14	5.57	-1.67	0	0
	R4		10	2.75	1.15	321	355
			12	4.00	-.10	153	307
			14	5.57	-1.67	0	0

Notes:
1. Red highlight = squat exceeds available UKC or accessibility is zero.
2. Yellow highlight = minimal accessibility available.

Note that in reaches R3 and R4, accessibility values are not very good for speeds greater than V_k=12 kt. Table 16 list the accessibility values for R3 and R4 assuming tidal windows of +1 ft (i.e., *h*=56 ft) to +3 (i.e., *h*=58 ft) are available. The safe window for transits then increases to more practical values. The pilots can choose to wait for the tidal windows and/or reduce speed to insure safe transits. Remember that the accessibility values will still need to be reduced by the tidal window correction factor (see below).

Table 16. Days of accessibility for FL NorB10L coal carrier, R3 & R4 reaches, Norfolk Channel.

Reach	Speed V_k (kt)	Inbound water depth (ft)				Outbound water depth (ft)			
		55	56	57	58	55	56	57	58
R3	10	318	344	354	358	354	358	361	363
	12	153	320	347	358	307	355	359	362
	14	0	3	288	346	0	3	348	359
R4	10	321	344	357	359	355	360	362	363
	12	153	320	349	358	307	356	360	362
	14	0	3	289	347	0	3	349	360

Notes:
1. Red highlight = Accessibility too low for safe transit.
2. Yellow highlight = Accessibility marginal for safe transit.

Extreme waves

All of the days of accessibility values are based on the assumption that 100 percent of the waves were included in the wave dataset. Remember that the 3.3 days/yr (approximately 1 percent) that represent extreme waves with very low probability of occurrence were removed from the wave dataset since it is unlikely that any ship would attempt a transit under these extreme conditions. Therefore, to be completely accurate, one should subtract this 3.3 days/yr from all the calculated values of days of accessibility. Of course, since this is a very small number of days relative to a 365 day year and is within other statistical accuracy assumptions in the predictions, it can probably be ignored.

Tidal advantage

As noted earlier, the use of the tides will be advantageous to achieve water levels for safe transit. In the tides section, travel times in each reach and for the entire channel were discussed as a function of the duration of tide levels from +1 to +3 ft. Depending on ship speed, 1.4 to 2.6 hr is required to safely transit the entire Norfolk channel.

Continuing with the earlier example for +2 ft for a depth of 57 ft in TSC R3 and a 3 hr duration, 289 days/365 days = 79 percent are available. This tidal percentage factor can be used to multiply the days of accessibility for any ship, loading, and speed to determine the actual days of accessibility due to the limited tidal window.

For instance for the NorB10L FL loading condition (Table B4 and Figure 21a), a speed of V_k=12 kts in TSC R3 had a limited accessibility of only 153 days/yr. If the depth is increased by +2 ft to 57 ft, the days of accessibility increases to 347 days/yr. However, we need to adjust this for the fact that this +2 ft tide does not exist except for a limited

duration. Thus, the adjusted accessibility would be (0.79) (347 days/yr) = 274 days/yr, which is better than the 153 days/yr at *h*=55 ft.

Of course, this assumes that (1) the tide and waves are in phase which is not likely to occur simultaneously every time in a real world situation, and (2) the tide actually occurs at the time the NorC15b is planning to transit the channel since the 3 hr duration is only equivalent to 79 percent of each day. The CADET days of accessibility are based on a full 24-hr day. Therefore, there might be some instances where ships will be forced to wait on the tide if their transits do not coincide with these tide levels. These tidal predictions are only a statistical representation of the tides and should only be used as a planning tool for evaluating the suitability and cost benefit of the channel depth.

Summary and Conclusions

The Norfolk District (NAO) is finalizing the Phase 1 feasibility study for deepening the Norfolk entrance channel. The purpose of this study was to determine the optimum channel depth required to accommodate the proposed design ships and loading conditions given constraints of the Chesapeake Bay Bridge Tunnel (CBBT). Dr. Michael J. Briggs, Briggs Group LLC, used the "Channel Analysis and Design Evaluation Tool" (CADET) to predict vertical ship motions due to wave-induced heave, pitch, and roll. PIANC and Ankudinov ship squat were calculated and compared with the CADET squat predictions. The CADET days of accessibility were calculated based on these vertical ship motion components to provide a risk-based method of evaluating different channel depths.

Two design vessels and two loading conditions were selected for this study. The design ships include a Gen III containership similar to the **MSC Daniella** and a Gen II bulk (coal) carrier. The Design Team specified the two design ships, the NorC15b and NorB10L ships, based on the CADET Ship Hull Lines Library which was developed in conjunction with the Institute for Water Resources.

The Norfolk Entrance Channel consists of two main channels: the offshore Atlantic Ocean Channel (AOC) and the transitional Thimble Shoals Channel (TSC). The CBBT is located in the TSC and with a project depth of *h*=55 ft is the primary depth constraint on the dredge depth for the channel reaches in the TSC. Four reaches were defined for the channel with two in each of the AOC (R1 and R2) and TSC (R3 and R4) channels. The project depth in the AOC was set at *h*=61 ft.

The tide ranges from +1 to +3 ft in Chesapeake Bay with varying durations from 1 to 10 hr. CADET calculates the tidal window (i.e., duration) so that the effect of the extra

water depth can be included in the calculated days of accessibility. Tides can be expected to permit depths up to +2 ft for most days, with a maximum tidal advantage of +3 ft for only a few days each year.

A joint probability distribution of wave height and period was created in four 22.5-deg direction bands between 56.25 to 146.25 deg. It consisted of 212,056 observations representing 69.1 percent of the deepwater data from the WIS 34-year hindcast buoy WIS199. A total of 155 out of 245 empirical directional wave spectra were created from this joint probability distribution. The 92 wave conditions were removed since they represent extreme waves during which a ship would not be expected to transit the channel. Parameters for these directional spectra were based on wave period and height for a TMA frequency spectrum and $\cos^n$ directional spreading function. The spectra wave heights were reduced at each reach along the Norfolk Channel according to the wave transformation study of Godsey.

Ship squat (sinkage and trim) was compared for PIANC, Ankudinov, and CADET/BNT predictions. The five PIANC empirical squat formulas included those of Barrass, Eryuzlu, Huuska, Römisch, and Yoshimura. The Ankudinov formula was originally used in the STS. The CADET squat formula is based on the work of Beck, Newman, and Tuck. Due to the relatively wide channels in all four reaches and the deep channels in the AOC reaches R1 and R2, the channels were modeled as unrestricted or open channels. A comparison of squat from unrestricted and equivalent restricted channel for reaches R3 and R4 indicated only a very small increase in squat for expected ship speeds of V_k=12 kt, which is within the variability between minimum and maximum unrestricted squat.

For the deeper AOC reaches R1 and R2, only a speed of V_k=18 kt for the FL NorB10L coal carrier will pose a problem with UKC due to squat only. The shallower TSC reaches of R3 and R4 will experience ship grounding for both ships, depending on loading conditions and ship speed. The ML NorC15b containership should proceed with caution if attempting ship speeds faster than V_k=14 kt, especially if any significant wave activity is present. For NorB10L coal carrier transits, pilots should exercise extreme caution if attempting to move at speeds as high as V_k=12 kt under HL loading conditions and V_k=10 kts with FL loading. These speeds are probably not even possible unless wave heights and periods are relatively small. When tides are present, squat will be reduced slightly so that the UKC will increase by approximately the increase in the water level. Of course, pilots should be vigilant at higher speeds as ship squat can always be reduced by slowing down.

CADET predicts days/year of accessibility based on ship parameters, channel configuration, wave conditions, and risk of grounding. This accessibility is generated for

each reach, inbound and outbound transit directions, and ship loading condition. Based on these accessibility values, the design team can select the optimum dredge depth which is defined as the shallowest dredge depth with the largest percentage of time the channel could be safely transited each year based on required or expected usage requirements.

The main difference between inbound and outbound transit directions is the relative angle of the wave to the ship, which alters the wave encounter frequency and leads to different ship response and vertical motions. In general for Norfolk channel, inbound ships will experience beam, stern quartering, and following seas; whereas, outbound ships will see beam, bow quartering, and head seas.

In general, days of accessibility increase for slower ship speeds, outbound transits, interior reaches with smaller waves, deeper depths, and reduced load/smaller draft. Accessibility can be improved substantially in most cases and ship speed increased if travel is restricted to the times when the tide advantage is +1 to +3 ft.

Accessibility should not be a problem for inbound or outbound transits for both FL and ML NorC15b in R1 and R2 due to the deeper depths. The worst case is for the inbound ML ship at V_k=18 kt with a value of 272 days of accessibility/yr. The shallower R3 and R4 do pose a constraint as speeds for the inbound ML ship should be limited to V_k=16 kt with a corresponding 169 days/yr in R3. Outbound transits also have reduced accessibility, but not as much as inbound.

The HL NorB10L coal carrier does not have any constraints on inbound or outbound speed in R1 and R2 since it has a relatively shallower draft. The FL NorB10L, however, does have serious speed constraints. For the inbound transits at V_k=18 kt in R1, it has 145 days of accessibility/yr. Accessibility is better in R2 and not a problem for outbound transits in R1 or R2. In R3 and R4 reaches for the HL loading condition, a maximum inbound speed of V_k=14 kt will provide 296 and 304 days/yr accessibility, respectively. For the FL condition in R3 and R4, inbound and outbound V_k=12 kt transits have reduced accessibility of 153 and 307 days/yr, respectively. These values can be improved by taking advantage of the tidal window and/or going slower to improve accessibility.

Wave-induced vertical ship motions are composed of the combined effects of heave, pitch, and roll at the nine critical points on the bottom of the ship. CADET calculates these vertical motion allowances for each ship loading condition, channel reach, and water depth. The net UKC is obtained by subtracting draft, squat, and ship vertical motion allowances from the water depth (i.e., net UKC = gross UKC – squat – ship vertical motion allowance). In general, net UKC increases with change in transit

direction from inbound to outbound, increases in water depth, and decreases in speed. Although these allowances and net UKC were not included in the scope for this study, they can easily be incorporated if desired.

In summary, all four ships and respective loading conditions should be able to safely transit AOC R1 and R2 reaches in both inbound and outbound directions for reasonable speeds. The FL NorB10L coal carrier with the deepest draft will only work with slower speeds and/or using the tidal advantage in the TSC R3 and R4 reaches.

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Appendix A: Wave Climatology in the Norfolk Channel Reaches

Table A1. Incident waves at Buoy WIS199, Norfolk Channel.

ID	Dir (deg)	Tp (sec)	Hs (ft)	γ	n	Prob.	Days/yr
1	67.5	3.6	1.0	3.3	4	0.0003	0.1
2	67.5	3.6	3.0	3.3	4	0.0007	0.3
3	67.5	4.6	1.0	3.3	4	0.0006	0.2
4	67.5	4.6	3.0	3.3	4	0.0035	1.3
5	67.5	4.6	4.9	3.3	4	0.0004	0.2
6	67.5	6.2	1.0	3.3	4	0.0024	0.9
7	67.5	6.2	3.0	3.3	4	0.0115	4.2
8	67.5	6.2	4.9	3.3	4	0.0073	2.7
9	67.5	6.2	6.9	3.3	4	0.0020	0.7
10	67.5	8.2	1.0	3.3	4	0.0065	2.4
11	67.5	8.2	3.0	3.3	4	0.0269	9.8
12	67.5	8.2	4.9	3.3	4	0.0139	5.1
13	67.5	8.2	6.9	3.3	4	0.0081	2.9
14	67.5	8.4	8.9	3.3	4	0.0016	0.6
15	67.5	10	1.0	3.3	4	0.0085	3.1
16	67.5	10	3.0	3.3	4	0.0318	11.6
17	67.5	10	4.9	3.3	4	0.0193	7.1
18	67.5	10	6.9	3.3	4	0.0090	3.3
19	67.5	10.2	8.9	3.3	4	0.0045	1.6
20	67.5	10	10.8	3.3	4	0.0019	0.7
21	67.5	10	12.8	3.3	4	0.0006	0.2
22	67.5	11.8	1.0	4	8	0.0036	1.3
23	67.5	11.8	3.0	4	8	0.0097	3.6
24	67.5	11.8	4.9	4	8	0.0086	3.1
25	67.5	11.8	6.9	4	8	0.0041	1.5
26	67.5	11.8	8.9	4	8	0.0034	1.2
27	67.5	11.8	10.8	4	8	0.0023	0.9
28	67.5	11.8	12.8	4	8	0.0007	0.3
29	67.5	13.8	1.0	5	12	0.0008	0.3
30	67.5	13.8	3.0	5	12	0.0018	0.7
31	67.5	13.8	4.9	5	12	0.0022	0.8
32	67.5	13.8	6.9	5	12	0.0017	0.6
33	67.5	14.1	8.9	5	12	0.0012	0.4
34	67.5	13.8	10.8	5	12	0.0011	0.4
35	67.5	13.8	12.8	5	12	0.0006	0.2
36	67.5	15.3	8.9	6	18	0.0003	0.1
37	67.5	15.8	1.0	6	18	0.0005	0.2
38	67.5	15.8	3.0	6	18	0.0006	0.2
39	67.5	15.8	4.9	6	18	0.0006	0.2
40	67.5	15.8	6.9	6	18	0.0005	0.2

ID	Dir (deg)	Tp (sec)	Hs (ft)	γ	n	Prob.	Days/yr
41	67.5	15.8	10.8	6	18	0.0004	0.2
42	67.5	18	1.0	7	26	0.0001	0.0
43	67.5	18	3.0	7	26	0.0001	0.0
44	90	3.6	1.0	3.3	4	0.0002	0.1
45	90	3.6	2.9	3.3	4	0.0004	0.2
46	90	4.6	1.0	3.3	4	0.0005	0.2
47	90	4.6	2.9	3.3	4	0.0020	0.7
48	90	4.6	4.8	3.3	4	0.0003	0.1
49	90	6.3	1.0	3.3	4	0.0057	2.1
50	90	6.3	2.9	3.3	4	0.0138	5.0
51	90	6.3	4.8	3.3	4	0.0043	1.6
52	90	6.3	6.8	3.3	4	0.0007	0.3
53	90	8.1	1.0	3.3	4	0.0187	6.8
54	90	8.1	2.9	3.3	4	0.0523	19.1
55	90	8.1	4.8	3.3	4	0.0164	6.0
56	90	8.1	6.8	3.3	4	0.0042	1.5
57	90	8.4	8.9	3.3	4	0.0006	0.2
58	90	9.9	1.0	3.3	4	0.0150	5.5
59	90	9.9	2.9	3.3	4	0.0490	17.9
60	90	9.9	4.8	3.3	4	0.0261	9.5
61	90	9.9	6.8	3.3	4	0.0077	2.8
62	90	10.1	8.9	3.3	4	0.0036	1.3
63	90	9.9	10.9	3.3	4	0.0011	0.4
64	90	9.9	12.8	3.3	4	0.0003	0.1
65	90	11.8	1.0	4	8	0.0038	1.4
66	90	11.8	2.9	4	8	0.0157	5.7
67	90	11.8	4.8	4	8	0.0130	4.7
68	90	11.8	6.8	4	8	0.0064	2.3
69	90	11.9	8.9	4	8	0.0034	1.3
70	90	11.8	10.9	4	8	0.0021	0.8
71	90	11.8	12.8	4	8	0.0011	0.4
72	90	13.8	1.0	5	12	0.0011	0.4
73	90	13.8	2.9	5	12	0.0018	0.7
74	90	13.8	4.8	5	12	0.0031	1.1
75	90	13.8	6.8	5	12	0.0023	0.9
76	90	13.7	8.9	5	12	0.0014	0.5
77	90	13.8	10.9	5	12	0.0011	0.4
78	90	13.8	12.8	5	12	0.0007	0.3
79	90	13.8	14.8	5	12	0.0005	0.2
80	90	13.8	16.9	5	12	0.0007	0.2
81	90	15.8	1.0	6	18	0.0005	0.2

ID	Dir (deg)	Tp (sec)	Hs (ft)	γ	n	Prob.	Days/yr
82	90	15.8	2.9	6	18	0.0007	0.3
83	90	15.8	4.8	6	18	0.0005	0.2
84	90	18	1.0	7	26	0.0002	0.1
85	90	18	2.9	7	26	0.0002	0.1
86	112.5	3.5	1.0	3.3	4	0.0003	0.1
87	112.5	3.5	2.8	3.3	4	0.0004	0.2
88	112.5	4.6	1.0	3.3	4	0.0002	0.1
89	112.5	4.6	2.8	3.3	4	0.0014	0.5
90	112.5	4.6	4.8	3.3	4	0.0002	0.1
91	112.5	6.4	1.0	3.3	4	0.0113	4.1
92	112.5	6.4	2.8	3.3	4	0.0149	5.4
93	112.5	6.4	4.8	3.3	4	0.0026	0.9
94	112.5	6.4	6.8	3.3	4	0.0005	0.2
95	112.5	8.1	1.0	3.3	4	0.0432	15.8
96	112.5	8.1	2.8	3.3	4	0.0724	26.4
97	112.5	8.1	4.8	3.3	4	0.0136	5.0
98	112.5	8.1	6.8	3.3	4	0.0030	1.1
99	112.5	8.4	8.9	3.3	4	0.0009	0.3
100	112.5	9.9	1.0	3.3	4	0.0298	10.9
101	112.5	9.9	2.8	3.3	4	0.0840	30.7
102	112.5	9.9	4.8	3.3	4	0.0205	7.5
103	112.5	9.9	6.8	3.3	4	0.0061	2.2
104	112.5	10.1	8.9	3.3	4	0.0026	1.0
105	112.5	9.9	10.9	3.3	4	0.0011	0.4
106	112.5	11.8	1.0	4	8	0.0039	1.4
107	112.5	11.8	2.8	4	8	0.0187	6.8
108	112.5	11.8	4.8	4	8	0.0125	4.6
109	112.5	11.8	6.8	4	8	0.0040	1.5
110	112.5	11.9	8.9	4	8	0.0012	0.4
111	112.5	11.8	10.9	4	8	0.0011	0.4
112	112.5	11.8	12.8	4	8	0.0007	0.3
113	112.5	13.8	1.0	5	12	0.0010	0.4
114	112.5	13.8	2.8	5	12	0.0021	0.8
115	112.5	13.8	4.8	5	12	0.0033	1.2
116	112.5	13.8	6.8	5	12	0.0031	1.1
117	112.5	13.7	8.9	5	12	0.0009	0.3
118	112.5	13.8	10.9	5	12	0.0004	0.2
119	112.5	15.8	1.0	6	18	0.0003	0.1
120	112.5	15.8	2.8	6	18	0.0009	0.3
121	112.5	15.8	4.8	6	18	0.0008	0.3
122	112.5	15.8	6.8	6	18	0.0004	0.1

ID	Dir (deg)	Tp (sec)	Hs (ft)	γ	n	Prob.	Days/yr
123	112.5	16.1	8.9	6	18	0.0004	0.1
124	112.5	15.8	10.9	6	18	0.0004	0.1
125	112.5	17.6	1.0	7	22	0.0001	0.0
126	112.5	17.6	2.8	7	22	0.0002	0.1
127	135	3.5	1.0	3.3	4	0.0002	0.1
128	135	3.5	2.7	3.3	4	0.0002	0.1
129	135	4.6	1.0	3.3	4	0.0001	0.0
130	135	4.6	2.7	3.3	4	0.0010	0.4
131	135	4.6	4.8	3.3	4	0.0001	0.0
132	135	6.4	1.0	3.3	4	0.0077	2.8
133	135	6.4	2.7	3.3	4	0.0088	3.2
134	135	6.4	4.8	3.3	4	0.0021	0.8
135	135	8	1.0	3.3	4	0.0178	6.5
136	135	8	2.7	3.3	4	0.0298	10.9
137	135	8	4.8	3.3	4	0.0065	2.4
138	135	8	6.9	3.3	4	0.0017	0.6
139	135	8.5	8.8	3.3	4	0.0003	0.1
140	135	9.9	1.0	3.3	4	0.0123	4.5
141	135	9.9	2.7	3.3	4	0.0299	10.9
142	135	9.9	4.8	3.3	4	0.0055	2.0
143	135	9.9	6.9	3.3	4	0.0019	0.7
144	135	9.9	8.8	3.3	4	0.0009	0.3
145	135	11.7	1.0	4	8	0.0007	0.2
146	135	11.7	2.7	4	8	0.0039	1.4
147	135	11.7	4.8	4	8	0.0022	0.8
148	135	11.7	6.9	4	8	0.0007	0.3
149	135	13.8	1.0	5	12	0.0003	0.1
150	135	13.8	2.7	5	12	0.0003	0.1
151	135	13.8	6.9	5	12	0.0004	0.2
152	135	15.7	1.0	6	18	0.0000	0.0
153	135	15.7	2.7	6	18	0.0002	0.1
154	135	17.6	1.0	7	22	0.0000	0.0
155	135	17.6	2.7	7	22	0.0000	0.0
			Total Days:			0.99	361.7

Table A2. Rare, eliminated waves at Buoy WIS199, Norfolk Channel.

ID	Dir (deg)	Tp (sec)	Hs (ft)	γ	n	Prob.	Days/yr
1	67.5	6.2	8.9	3.3	4	0.0000	0.02
2	67.5	8.2	10.8	3.3	4	0.0002	0.06
3	67.5	10.0	14.7	3.3	4	0.0000	0.01
4	67.5	11.8	14.7	4.0	8	0.0002	0.09
5	67.5	11.8	16.8	4.0	8	0.0001	0.03
6	67.5	13.8	14.7	5.0	12	0.0002	0.08
7	67.5	13.8	16.8	5.0	12	0.0001	0.05
8	67.5	15.8	12.8	6.0	18	0.0003	0.10
9	67.5	15.8	14.7	6.0	18	0.0001	0.04
10	67.5	15.8	16.8	6.0	18	0.0001	0.03
11	67.5	15.8	18.2	6.0	18	0.0000	0.01
12	67.5	18.0	4.9	7.0	26	0.0000	0.01
13	67.5	18.0	6.9	7.0	26	0.0000	0.01
14	67.5	18.0	8.9	7.0	26	0.0001	0.04
15	67.5	18.0	10.8	7.0	26	0.0001	0.04
16	67.5	18.0	12.8	7.0	26	0.0002	0.06
17	67.5	18.0	14.7	7.0	26	0.0001	0.02
18	90.0	6.3	8.9	3.3	4	0.0000	0.01
19	90.0	8.1	10.9	3.3	4	0.0001	0.03
20	90.0	8.1	12.8	3.3	4	0.0000	0.01
21	90.0	9.9	14.8	3.3	4	0.0000	0.02
22	90.0	11.8	14.8	4.0	8	0.0003	0.10
23	90.0	11.8	16.9	4.0	8	0.0001	0.02
24	90.0	13.8	18.4	5.0	12	0.0001	0.05
25	90.0	15.8	6.8	6.0	18	0.0003	0.11
26	90.0	15.8	8.9	6.0	18	0.0001	0.04
27	90.0	15.8	10.9	6.0	18	0.0002	0.09
28	90.0	15.8	12.8	6.0	18	0.0002	0.09
29	90.0	15.8	14.8	6.0	18	0.0002	0.06
30	90.0	15.8	16.9	6.0	18	0.0001	0.03
31	90.0	15.8	18.4	6.0	18	0.0001	0.03
32	90.0	18.0	4.8	7.0	26	0.0001	0.05
33	90.0	18.0	6.8	7.0	26	0.0000	0.00
34	90.0	18.0	8.9	7.0	26	0.0000	0.01
35	90.0	18.0	10.9	7.0	26	0.0001	0.04
36	90.0	18.0	12.8	7.0	26	0.0000	0.00
37	112.5	6.4	8.9	3.3	4	0.0000	0.01
38	112.5	8.1	10.9	3.3	4	0.0002	0.06
39	112.5	8.1	12.8	3.3	4	0.0000	0.00
40	112.5	9.9	12.8	3.3	4	0.0002	0.06

ID	Dir (deg)	Tp (sec)	Hs (ft)	γ	n	Prob.	Days/yr
41	112.5	9.9	14.9	3.3	4	0.0001	0.03
42	112.5	9.9	16.9	3.3	4	0.0000	0.00
43	112.5	11.8	14.9	4.0	8	0.0002	0.08
44	112.5	11.8	16.9	4.0	8	0.0001	0.02
45	112.5	13.8	12.8	5.0	12	0.0001	0.05
46	112.5	13.8	14.9	5.0	12	0.0003	0.10
47	112.5	13.8	16.9	5.0	12	0.0002	0.07
48	112.5	13.8	18.7	5.0	12	0.0001	0.02
49	112.5	13.8	20.8	5.0	12	0.0000	0.00
50	112.5	15.8	12.8	6.0	18	0.0002	0.09
51	112.5	15.8	14.9	6.0	18	0.0001	0.05
52	112.5	15.8	16.9	6.0	18	0.0002	0.08
53	112.5	15.8	18.7	6.0	18	0.0001	0.05
54	112.5	15.8	20.8	6.0	18	0.0000	0.01
55	112.5	17.6	4.8	7.0	22	0.0001	0.04
56	112.5	17.6	6.8	7.0	22	0.0001	0.05
57	112.5	17.6	8.9	7.0	22	0.0001	0.04
58	112.5	17.6	10.9	7.0	22	0.0001	0.02
59	112.5	17.6	12.8	7.0	22	0.0001	0.03
60	112.5	17.6	14.9	7.0	22	0.0001	0.03
61	112.5	17.6	16.9	7.0	22	0.0000	0.02
62	112.5	17.6	18.7	7.0	22	0.0000	0.00
63	112.5	17.6	20.8	7.0	22	0.0000	0.01
64	135.0	6.4	6.9	3.3	4	0.0003	0.10
65	135.0	8.0	10.8	3.3	4	0.0000	0.01
66	135.0	9.9	10.8	3.3	4	0.0002	0.09
67	135.0	9.9	13.1	3.3	4	0.0001	0.02
68	135.0	9.9	14.7	3.3	4	0.0000	0.01
69	135.0	11.7	10.8	4.0	8	0.0001	0.05
70	135.0	11.7	13.1	4.0	8	0.0001	0.05
71	135.0	11.7	14.7	4.0	8	0.0001	0.03
72	135.0	11.7	16.8	4.0	8	0.0001	0.03
73	135.0	11.7	20.1	4.0	8	0.0000	0.00
74	135.0	12.4	8.8	4.0	8	0.0002	0.07
75	135.0	13.8	4.8	5.0	12	0.0002	0.08
76	135.0	14.0	8.8	5.0	12	0.0002	0.09
77	135.0	13.8	10.8	5.0	12	0.0002	0.06
78	135.0	13.8	13.1	5.0	12	0.0001	0.02
79	135.0	13.8	14.7	5.0	12	0.0000	0.01
80	135.0	13.8	16.8	5.0	12	0.0000	0.01
81	135.0	13.8	19.1	5.0	12	0.0000	0.01

ID	Dir (deg)	Tp (sec)	Hs (ft)	γ	n	Prob.	Days/yr
82	135.0	15.7	4.8	6.0	18	0.0001	0.03
83	135.0	15.7	6.9	6.0	18	0.0000	0.01
84	135.0	15.7	8.8	6.0	18	0.0001	0.04
85	135.0	15.7	10.8	6.0	18	0.0000	0.01
86	135.0	15.7	13.1	6.0	18	0.0000	0.00
87	135.0	15.7	14.7	6.0	18	0.0000	0.00
88	135.0	15.7	20.1	6.0	18	0.0000	0.00
89	135.0	17.6	4.8	7.0	22	0.0000	0.01
90	135.0	17.6	6.9	7.0	22	0.0000	0.00
91	135.0	17.6	8.8	7.0	22	0.0000	0.01
92	135.0	17.6	10.8	7.0	22	0.0000	0.00
			Total Storm Days:			0.01	3.33

Table A3. Wave factors and heights, Norfolk Channel, Reaches R1 to R4.

ID	Dir (deg)	Tp (sec)	Factors				Hs (ft)			
			R1	R2	R3	R4	R1	R2	R3	R4
1	67.5	3.6	1.1	1.1	1.0	0.9	1.1	1.1	1.0	0.9
2	67.5	3.6	1.1	1.1	1.0	0.9	3.4	3.4	3.0	2.8
3	67.5	4.6	1.1	1.1	1.0	0.9	1.1	1.1	1.0	0.9
4	67.5	4.6	1.1	1.1	1.0	0.9	3.4	3.4	3.0	2.8
5	67.5	4.6	1.1	1.1	1.0	0.9	5.5	5.6	4.9	4.6
6	67.5	6.2	1.1	1.1	1.0	0.9	1.1	1.1	1.0	0.9
7	67.5	6.2	1.1	1.1	1.0	0.9	3.4	3.4	3.0	2.8
8	67.5	6.2	1.1	1.1	1.0	0.9	5.5	5.6	4.9	4.6
9	67.5	6.2	1.1	1.1	1.0	0.9	7.8	7.9	6.9	6.5
10	67.5	8.2	1.1	1.1	0.9	0.8	1.1	1.1	0.9	0.8
11	67.5	8.2	1.1	1.1	0.9	0.8	3.2	3.2	2.6	2.4
12	67.5	8.2	1.1	1.1	0.9	0.8	5.2	5.3	4.2	3.9
13	67.5	8.2	1.0	1.0	0.8	0.7	7.1	7.1	5.3	4.8
14	67.5	8.4	1.0	1.0	0.7	0.6	8.8	8.8	6.1	5.3
15	67.5	10	1.0	1.0	0.7	0.6	1.0	1.0	0.7	0.6
16	67.5	10	1.0	1.0	0.7	0.6	3.0	3.0	2.1	1.9
17	67.5	10	1.0	1.0	0.7	0.6	4.9	4.8	3.4	3.2
18	67.5	10	1.0	1.0	0.7	0.6	6.8	6.8	4.6	4.2
19	67.5	10.2	1.0	1.0	0.6	0.6	8.8	8.8	5.7	5.0
20	67.5	10	1.0	1.0	0.6	0.6	10.7	10.6	6.9	6.0
21	67.5	10	1.0	1.0	0.6	0.6	12.7	12.6	8.2	7.1
22	67.5	11.8	1.0	1.0	0.7	0.6	1.0	1.0	0.7	0.6
23	67.5	11.8	1.0	1.0	0.7	0.6	3.0	3.1	2.0	1.9
24	67.5	11.8	1.0	1.0	0.7	0.6	5.0	5.1	3.2	3.1
25	67.5	11.8	1.0	1.0	0.6	0.6	6.9	7.0	4.4	4.1

ID	Dir (deg)	Tp (sec)	Factors				Hs (ft)			
			R1	R2	R3	R4	R1	R2	R3	R4
26	67.5	11.8	1.0	1.0	0.6	0.5	8.9	8.8	5.6	4.9
27	67.5	11.8	1.0	1.0	0.6	0.5	10.8	10.7	6.7	5.9
28	67.5	11.8	1.0	1.0	0.6	0.5	12.7	12.6	8.0	7.0
29	67.5	13.8	1.1	1.0	0.7	0.7	1.1	1.0	0.7	0.7
30	67.5	13.8	1.1	1.0	0.7	0.7	3.2	3.1	2.2	2.1
31	67.5	13.8	1.1	1.0	0.7	0.7	5.3	5.1	3.6	3.4
32	67.5	13.8	1.0	1.0	0.7	0.6	7.2	7.0	4.6	4.2
33	67.5	14.1	1.0	1.0	0.6	0.5	8.9	8.7	5.3	4.7
34	67.5	13.8	1.0	1.0	0.6	0.5	10.8	10.6	6.5	5.7
35	67.5	13.8	1.0	1.0	0.6	0.5	12.8	12.6	7.6	6.8
36	67.5	15.3	1.0	1.0	0.6	0.5	8.9	8.7	5.2	4.6
37	67.5	15.8	1.0	1.0	0.6	0.6	1.0	1.0	0.6	0.6
38	67.5	15.8	1.0	1.0	0.6	0.6	3.0	2.9	1.9	1.8
39	67.5	15.8	1.0	1.0	0.6	0.6	4.9	4.8	3.0	2.9
40	67.5	15.8	1.0	1.0	0.6	0.6	6.9	6.8	4.2	3.9
41	67.5	15.8	1.0	1.0	0.6	0.5	10.8	10.6	6.3	5.6
42	67.5	18	1.0	0.9	0.5	0.5	1.0	0.9	0.5	0.5
43	67.5	18	1.0	0.9	0.5	0.5	2.9	2.8	1.6	1.5
44	90	3.6	1.0	1.1	0.8	0.8	1.0	1.1	0.8	0.8
45	90	3.6	1.0	1.1	0.8	0.8	3.0	3.1	2.4	2.2
46	90	4.6	1.0	1.1	0.8	0.8	1.0	1.1	0.8	0.8
47	90	4.6	1.0	1.1	0.8	0.8	3.0	3.1	2.4	2.2
48	90	4.6	1.0	1.1	0.8	0.8	5.0	5.1	4.0	3.6
49	90	6.3	1.0	1.1	0.8	0.8	1.0	1.1	0.8	0.8
50	90	6.3	1.0	1.1	0.8	0.8	3.0	3.1	2.4	2.2
51	90	6.3	1.0	1.1	0.8	0.8	5.0	5.1	4.0	3.6
52	90	6.3	1.0	1.1	0.8	0.8	7.1	7.3	5.7	5.1
53	90	8.1	1.0	1.0	0.6	0.6	1.0	1.0	0.6	0.6
54	90	8.1	1.0	1.0	0.6	0.6	2.9	2.8	1.8	1.6
55	90	8.1	1.0	1.0	0.6	0.6	4.7	4.6	3.0	2.7
56	90	8.1	1.0	1.0	0.6	0.5	6.7	6.6	4.0	3.6
57	90	8.4	1.0	1.0	0.6	0.5	8.8	8.6	5.1	4.4
58	90	9.9	1.0	1.0	0.6	0.5	1.0	1.0	0.6	0.5
59	90	9.9	1.0	1.0	0.6	0.5	2.9	2.8	1.6	1.5
60	90	9.9	1.0	1.0	0.6	0.5	4.8	4.6	2.7	2.5
61	90	9.9	1.0	1.0	0.5	0.5	6.7	6.5	3.7	3.4
62	90	10.1	1.0	0.9	0.5	0.5	8.8	8.4	4.6	4.1
63	90	9.9	1.0	0.9	0.5	0.5	10.7	10.3	5.6	5.0
64	90	9.9	1.0	0.9	0.5	0.5	12.6	12.1	6.6	5.8
65	90	11.8	1.1	1.0	0.6	0.6	1.1	1.0	0.6	0.6

ID	Dir (deg)	Tp (sec)	Factors				Hs (ft)			
			R1	R2	R3	R4	R1	R2	R3	R4
66	90	11.8	1.1	1.0	0.6	0.6	3.1	3.0	1.8	1.8
67	90	11.8	1.1	1.0	0.6	0.6	5.1	4.9	3.0	2.9
68	90	11.8	1.0	1.0	0.6	0.5	7.0	6.6	3.8	3.6
69	90	11.9	1.0	0.9	0.5	0.4	8.8	8.3	4.3	3.8
70	90	11.8	1.0	0.9	0.5	0.4	10.7	10.2	5.3	4.7
71	90	11.8	1.0	0.9	0.5	0.4	12.6	12.0	6.2	5.5
72	90	13.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5
73	90	13.8	1.0	1.0	0.5	0.5	2.9	2.8	1.5	1.5
74	90	13.8	1.0	1.0	0.5	0.5	4.8	4.6	2.5	2.4
75	90	13.8	1.0	0.9	0.5	0.5	6.8	6.4	3.3	3.1
76	90	13.7	1.0	0.9	0.5	0.4	8.8	8.2	4.1	3.7
77	90	13.8	1.0	0.9	0.5	0.4	10.7	10.1	5.0	4.6
78	90	13.8	1.0	0.9	0.5	0.4	12.6	11.9	5.9	5.3
79	90	13.8	1.0	0.9	0.5	0.4	14.6	13.7	6.8	6.2
80	90	13.8	1.0	0.9	0.5	0.4	16.7	15.7	7.8	7.1
81	90	15.8	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5
82	90	15.8	1.0	1.0	0.5	0.5	2.9	2.8	1.6	1.5
83	90	15.8	1.0	1.0	0.5	0.5	4.8	4.6	2.6	2.5
84	90	18	1.0	1.0	0.5	0.5	1.0	1.0	0.5	0.5
85	90	18	1.0	1.0	0.5	0.5	2.9	2.8	1.6	1.5
86	112.5	3.5	1.1	1.1	0.7	0.7	1.1	1.1	0.7	0.7
87	112.5	3.5	1.1	1.1	0.7	0.7	3.1	3.1	2.1	1.9
88	112.5	4.6	1.1	1.1	0.7	0.7	1.1	1.1	0.7	0.7
89	112.5	4.6	1.1	1.1	0.7	0.7	3.1	3.1	2.1	1.9
90	112.5	4.6	1.1	1.1	0.7	0.7	5.3	5.3	3.6	3.3
91	112.5	6.4	1.1	1.1	0.7	0.7	1.1	1.1	0.7	0.7
92	112.5	6.4	1.1	1.1	0.7	0.7	3.1	3.1	2.1	1.9
93	112.5	6.4	1.1	1.1	0.7	0.7	5.3	5.3	3.6	3.3
94	112.5	6.4	1.0	1.0	0.6	0.6	7.1	7.0	4.4	3.9
95	112.5	8.1	1.1	1.0	0.6	0.6	1.1	1.0	0.6	0.6
96	112.5	8.1	1.1	1.0	0.6	0.6	3.0	2.8	1.7	1.6
97	112.5	8.1	1.1	1.0	0.6	0.6	5.2	4.8	2.9	2.7
98	112.5	8.1	1.0	0.9	0.5	0.5	7.0	6.4	3.6	3.3
99	112.5	8.4	1.0	0.9	0.5	0.4	8.8	8.0	4.1	3.6
100	112.5	9.9	1.2	1.1	0.7	0.7	1.2	1.1	0.7	0.7
101	112.5	9.9	1.2	1.1	0.7	0.7	3.3	3.0	2.0	1.9
102	112.5	9.9	1.2	1.1	0.7	0.7	5.6	5.1	3.4	3.2
103	112.5	9.9	1.1	1.0	0.6	0.5	7.3	6.6	3.8	3.6
104	112.5	10.1	1.0	0.9	0.4	0.4	8.8	7.8	3.7	3.4
105	112.5	9.9	1.0	0.9	0.4	0.4	10.7	9.6	4.5	4.2

ID	Dir (deg)	Tp (sec)	Factors				Hs (ft)			
			R1	R2	R3	R4	R1	R2	R3	R4
106	112.5	11.8	1.0	0.9	0.5	0.5	1.0	0.9	0.5	0.5
107	112.5	11.8	1.0	0.9	0.5	0.5	2.9	2.5	1.4	1.3
108	112.5	11.8	1.0	0.9	0.5	0.5	4.9	4.3	2.3	2.2
109	112.5	11.8	1.0	0.9	0.4	0.4	6.8	6.0	3.0	2.8
110	112.5	11.9	1.0	0.9	0.4	0.4	8.8	7.6	3.4	3.3
111	112.5	11.8	1.0	0.9	0.4	0.4	10.7	9.4	4.2	4.0
112	112.5	11.8	1.0	0.9	0.4	0.4	12.6	11.0	4.9	4.7
113	112.5	13.8	1.0	0.9	0.6	0.6	1.0	0.9	0.6	0.6
114	112.5	13.8	1.0	0.9	0.6	0.6	2.9	2.6	1.6	1.5
115	112.5	13.8	1.0	0.9	0.6	0.6	4.9	4.5	2.7	2.6
116	112.5	13.8	1.0	0.9	0.5	0.5	6.9	6.0	3.2	3.1
117	112.5	13.7	1.0	0.8	0.4	0.4	8.8	7.5	3.3	3.2
118	112.5	13.8	1.0	0.8	0.4	0.4	10.7	9.2	4.0	3.9
119	112.5	15.8	1.0	0.8	0.4	0.4	1.0	0.8	0.4	0.4
120	112.5	15.8	1.0	0.8	0.4	0.4	2.7	2.3	1.0	1.0
121	112.5	15.8	1.0	0.8	0.4	0.4	4.7	3.9	1.8	1.8
122	112.5	15.8	1.0	0.8	0.4	0.4	6.7	5.6	2.5	2.5
123	112.5	16.1	1.0	0.8	0.4	0.4	8.8	7.4	3.1	3.1
124	112.5	15.8	1.0	0.8	0.4	0.4	10.8	9.1	3.8	3.9
125	112.5	17.6	1.0	0.8	0.4	0.4	1.0	0.8	0.4	0.4
126	112.5	17.6	1.0	0.8	0.4	0.4	2.7	2.3	1.0	1.0
127	135	3.5	1.1	1.0	0.5	0.5	1.1	1.0	0.5	0.5
128	135	3.5	1.1	1.0	0.5	0.5	2.9	2.7	1.5	1.4
129	135	4.6	1.1	1.0	0.5	0.5	1.1	1.0	0.5	0.5
130	135	4.6	1.1	1.0	0.5	0.5	2.9	2.7	1.5	1.4
131	135	4.6	1.1	1.0	0.5	0.5	5.1	4.8	2.6	2.5
132	135	6.4	1.1	1.0	0.5	0.5	1.1	1.0	0.5	0.5
133	135	6.4	1.1	1.0	0.5	0.5	2.9	2.7	1.5	1.4
134	135	6.4	1.1	1.0	0.5	0.5	5.1	4.8	2.6	2.5
135	135	8	1.0	0.9	0.4	0.3	1.0	0.9	0.4	0.3
136	135	8	1.0	0.9	0.4	0.3	2.7	2.3	1.0	0.9
137	135	8	1.0	0.9	0.4	0.3	4.8	4.1	1.8	1.6
138	135	8	1.0	0.9	0.4	0.3	6.9	5.9	2.6	2.3
139	135	8.5	1.0	0.9	0.4	0.4	8.8	7.5	3.3	3.1
140	135	9.9	1.0	0.8	0.5	0.4	1.0	0.8	0.5	0.4
141	135	9.9	1.0	0.8	0.5	0.4	2.8	2.3	1.2	1.2
142	135	9.9	1.0	0.8	0.5	0.4	4.9	4.1	2.2	2.1
143	135	9.9	1.0	0.8	0.4	0.4	7.0	5.8	2.8	2.7
144	135	9.9	1.0	0.8	0.4	0.3	8.8	7.3	3.1	3.0
145	135	11.7	1.0	0.8	0.4	0.4	1.0	0.8	0.4	0.4

ID	Dir (deg)	Tp (sec)	Factors				Hs (ft)			
			R1	R2	R3	R4	R1	R2	R3	R4
146	135	11.7	1.0	0.8	0.4	0.4	2.8	2.3	1.1	1.2
147	135	11.7	1.0	0.8	0.4	0.4	4.9	4.0	2.0	2.1
148	135	11.7	1.0	0.8	0.4	0.4	7.0	5.6	2.6	2.7
149	135	13.8	1.1	0.9	0.7	0.7	1.1	0.9	0.7	0.7
150	135	13.8	1.1	0.9	0.7	0.7	3.0	2.5	1.9	1.8
151	135	13.8	1.1	0.9	0.7	0.7	7.8	6.4	4.8	4.7
152	135	15.7	1.0	0.8	0.3	0.3	1.0	0.8	0.3	0.3
153	135	15.7	1.0	0.8	0.3	0.3	2.7	2.1	0.8	0.9
154	135	17.6	1.0	0.8	0.3	0.3	1.0	0.8	0.3	0.3
155	135	17.6	1.0	0.8	0.3	0.3	2.7	2.1	0.8	0.9

Appendix B: Days of Accessibility for Norfolk Channel FL and ML NorC15b Containership and HL and FL NorB10L Coal Carrier

Table B1. Days of accessibility for Norfolk Unrestricted Channel, Reaches R1 to R4, Full Load (FL) NorC15b containership, inbound and outbound transits.

Depth	Inbound Ship Speed (kt)					Outbound Ship Speed (kt)				
(ft)	10	12	14	16	18	10	12	14	16	18
Reach R1: AOC-E										
53	354	351	346	310	137	361	361	360	355	330
54	358	356	352	336	253	363	363	361	359	350
55	360	359	356	346	294	363	363	363	361	356
56	361	361	359	352	318	363	363	363	363	360
57	362	362	362	358	333	364	363	363	363	362
58	363	362	362	361	344	364	364	364	363	363
59	363	363	363	362	351	364	364	364	364	363
60	364	363	364	363	354	364	364	365	364	364
61	364	364	364	364	358	365	365	365	365	364
62	364	364	364	364	361	365	365	365	365	365
63	364	364	364	364	363	365	365	365	365	365
64	365	365	365	365	363	365	365	365	365	365
65	365	365	365	365	364	365	365	365	365	365
66	365	365	365	365	364	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365
Reach R2: AOC-W										
53	356	350	348	313	174	361	359	356	349	309
54	358	355	353	338	261	361	361	359	356	339
55	360	358	356	348	303	362	361	361	359	351
56	361	360	359	352	326	363	362	361	361	357
57	362	361	361	358	337	363	363	363	361	360
58	362	362	362	360	349	363	363	363	363	361
59	363	362	362	362	352	364	363	363	363	363
60	363	363	363	363	357	364	364	364	364	363
61	363	363	363	363	360	364	364	364	364	364
62	364	364	364	364	362	364	364	364	364	364
63	364	364	364	364	363	364	364	365	364	364
64	364	364	364	364	364	365	365	365	365	364
65	365	365	364	364	364	365	365	365	365	365
66	365	365	365	365	364	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365
Reach R3: TSC-E										
53	363	363	362	350	266	365	365	365	364	357
54	364	364	363	357	322	365	365	365	365	363
55	365	365	364	361	347	365	365	365	365	364
56	365	365	365	363	355	365	365	365	365	365
57	365	365	365	364	360	365	365	365	365	365
58	365	365	365	365	363	365	365	365	365	365
59	365	365	365	365	363	365	365	365	365	365
60	365	365	365	365	364	365	365	365	365	365
61	365	365	365	365	364	365	365	365	365	365
62	365	365	365	365	365	365	365	365	365	365
63	365	365	365	365	365	365	365	365	365	365
64	365	365	365	365	365	365	365	365	365	365
65	365	365	365	365	365	365	365	365	365	365
66	365	365	365	365	365	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365
Reach R4: TSC-W										
53	364	363	363	352	266	365	365	365	364	358
54	365	365	363	359	323	365	365	365	365	364
55	365	365	365	362	347	365	365	365	365	365
56	365	365	365	364	356	365	365	365	365	365
57	365	365	365	365	360	365	365	365	365	365
58	365	365	365	365	363	365	365	365	365	365

59	365	365	365	365	364	365	365	365	365	365
60	365	365	365	365	364	365	365	365	365	365
61	365	365	365	365	365	365	365	365	365	365
62	365	365	365	365	365	365	365	365	365	365
63	365	365	365	365	365	365	365	365	365	365
64	365	365	365	365	365	365	365	365	365	365
65	365	365	365	365	365	365	365	365	365	365
66	365	365	365	365	365	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365
Notes: 1. Yellow highlight represents project depth plus +3 tide.										

Table B2. Days of accessibility for Norfolk Unrestricted Channel, Reaches R1 to R4, Medium Load (ML) NorC15b containership, inbound and outbound transits.

Depth	Inbound Ship Speed (kt)					Outbound Ship Speed (kt)				
(ft)	10	12	14	16	18	10	12	14	16	18
Reach R1: AOC-E										
53	310	260	73	0	0	352	342	286	0	0
54	335	310	208	33	0	358	356	343	250	0
55	344	321	262	85	8	361	360	354	324	126
56	351	340	311	163	49	361	361	360	347	271
57	355	348	320	210	97	363	363	361	356	322
58	357	351	338	264	108	363	363	363	360	344
59	360	355	342	301	210	363	363	363	362	357
60	361	357	348	314	251	364	364	364	363	358
61	362	360	348	326	272	364	364	364	363	362
62	362	361	355	338	304	364	364	364	364	363
63	363	362	356	342	313	364	365	365	364	364
64	363	362	359	344	320	365	365	365	365	364
65	364	363	361	352	327	365	365	365	365	365
66	364	364	362	353	338	365	365	365	365	365
67	365	364	362	355	341	365	365	365	365	365
Reach R2: AOC-W										
53	312	261	100	0	0	349	333	268	0	0
54	337	310	248	57	0	356	351	335	213	0
55	348	330	297	90	6	359	357	349	305	88
56	351	341	315	163	61	361	359	356	337	250
57	357	348	329	254	97	361	361	358	347	304
58	358	352	341	282	141	362	361	360	353	328
59	360	357	345	310	212	363	363	362	358	346
60	361	358	348	323	267	363	363	363	360	355
61	362	361	355	337	298	363	363	363	363	357
62	362	361	355	341	313	364	364	364	363	361
63	363	362	358	348	320	364	364	364	364	362
64	363	363	361	351	327	364	364	364	364	363
65	364	363	361	353	339	364	364	364	364	363
66	364	364	362	355	343	364	365	365	364	364
67	364	364	363	359	348	365	365	365	365	364
Reach R3: TSC-E										
53	348	322	184	0	0	364	361	348	0	0
54	357	341	284	89	0	364	364	362	325	0
55	361	353	328	169	21	365	365	364	358	207
56	363	358	342	263	98	365	365	365	363	342
57	363	361	349	294	170	365	365	365	365	361
58	364	363	354	326	262	365	365	365	365	364
59	365	364	359	341	290	365	365	365	365	365
60	365	364	361	348	322	365	365	365	365	365
61	365	365	362	354	338	365	365	365	365	365

62	365	365	363	359	346	365	365	365	365	365
63	365	365	364	359	352	365	365	365	365	365
64	365	365	364	361	356	365	365	365	365	365
65	365	365	365	363	357	365	365	365	365	365
66	365	365	365	363	358	365	365	365	365	365
67	365	365	365	364	361	365	365	365	365	365
Reach R4: TSC-W										
53	349	323	185	0	0	364	362	350	0	0
54	358	343	284	89	0	365	364	363	332	0
55	361	354	329	186	26	365	365	364	360	207
56	363	358	343	263	99	365	365	365	364	349
57	364	361	351	295	194	365	365	365	365	361
58	365	363	356	326	256	365	365	365	365	365
59	365	364	359	344	294	365	365	365	365	365
60	365	364	362	349	323	365	365	365	365	365
61	365	365	362	354	343	365	365	365	365	365
62	365	365	364	359	348	365	365	365	365	365
63	365	365	364	361	353	365	365	365	365	365
64	365	365	365	362	357	365	365	365	365	365
65	365	365	365	363	358	365	365	365	365	365
66	365	365	365	364	361	365	365	365	365	365
67	365	365	365	364	362	365	365	365	365	365
Notes: 1. Yellow highlight represents project depth plus +3 tide.										

Table B3. Days of accessibility for Norfolk Unrestricted Channel, Reaches R1 to R4, Heavy Load (HL) NorB10L coal carrier, inbound and outbound transits.

Depth	Inbound Ship Speed (kt)					Outbound Ship Speed (kt)				
(ft)	10	12	14	16	18	10	12	14	16	18
Reach R1: AOC-E										
53	217	91	0	0	0	296	196	0	0	0
54	275	266	3	0	0	321	296	3	0	0
55	309	288	260	0	0	332	321	295	0	0
56	320	309	293	49	0	341	339	324	158	0
57	329	329	318	266	0	346	341	339	317	0
58	338	332	331	314	3	350	347	341	339	3
59	346	343	337	332	266	354	352	350	341	319
60	351	347	345	337	312	356	354	353	350	339
61	352	352	352	345	332	357	357	356	353	349
62	354	352	353	352	340	359	357	357	356	353
63	356	354	354	354	350	359	359	358	358	356
64	357	357	357	356	352	360	360	359	359	357
65	359	357	358	357	356	362	361	360	360	359
66	360	360	360	359	357	362	362	362	361	359
67	361	360	361	361	360	362	362	362	362	360
Reach R2: AOC-W										
53	250	134	0	0	0	286	196	0	0	0
54	276	267	3	0	0	312	296	3	0	0
55	304	296	261	0	0	322	321	286	0	0
56	320	307	296	54	0	332	327	321	152	0
57	329	328	315	267	0	340	334	331	303	0
58	334	331	328	315	3	343	342	339	327	3
59	342	341	334	329	267	350	344	342	339	310
60	346	342	341	339	323	350	350	350	342	331
61	350	347	347	342	331	354	350	350	350	341
62	351	351	350	349	339	356	354	354	350	349
63	354	353	353	351	346	357	356	356	355	350
64	356	354	354	354	350	358	357	357	357	354

65	356	356	356	356	352	359	359	359	358	355
66	358	356	356	356	356	360	359	359	359	357
67	360	359	359	359	356	361	360	360	359	359
Reach R3: TSC-E										
53	294	179	0	0	0	337	293	0	0	0
54	328	317	3	0	0	353	346	3	0	0
55	346	341	296	0	0	357	354	345	0	0
56	355	352	343	89	0	359	358	355	255	0
57	356	356	354	325	0	360	359	359	351	0
58	359	358	358	352	3	362	361	360	358	3
59	361	359	359	358	311	363	363	362	360	352
60	362	362	361	359	350	364	364	363	362	359
61	364	363	363	362	359	364	364	364	363	361
62	364	364	364	363	361	364	364	364	364	363
63	364	364	364	364	362	365	365	364	364	364
64	364	364	364	364	363	365	365	365	365	364
65	365	365	365	364	364	365	365	365	365	364
66	365	365	365	365	365	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365
Reach R4: TSC-W										
53	294	179	0	0	0	340	294	0	0	0
54	330	316	3	0	0	355	346	3	0	0
55	348	341	304	0	0	357	356	345	0	0
56	355	354	343	92	0	360	359	356	253	0
57	358	357	356	326	0	361	360	359	353	0
58	360	359	359	353	3	363	362	360	359	3
59	362	361	361	358	319	364	363	362	360	354
60	364	362	362	360	351	364	364	364	363	360
61	364	364	364	362	359	364	364	364	364	362
62	364	364	364	364	361	365	365	364	364	364
63	364	364	364	364	363	365	365	365	364	364
64	365	365	365	364	364	365	365	365	365	364
65	365	365	365	365	365	365	365	365	365	365
66	365	365	365	365	365	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365

Notes:
1. Yellow highlight represents project depth plus +3 tide.

Table B4. Days of accessibility for Norfolk Unrestricted Channel, Reaches R1 to R4, Full Load (FL) NorB10L coal carrier, inbound and outbound transits.

Depth	Inbound Ship Speed (kt)					Outbound Ship Speed (kt)				
(ft)	10	12	14	16	18	10	12	14	16	18
Reach R1: AOC-E										
53	0	0	0	0	0	0	0	0	0	0
54	155	0	0	0	0	251	0	0	0	0
55	265	80	0	0	0	320	228	0	0	0
56	303	265	3	0	0	339	323	3	0	0
57	325	312	229	0	0	348	340	310	0	0
58	332	328	309	5	0	353	350	340	47	0
59	344	336	328	266	0	356	353	347	324	0
60	350	348	339	313	3	358	357	353	342	3
61	353	353	348	329	145	359	359	357	351	319
62	356	356	351	339	312	361	360	357	354	347
63	358	356	355	347	340	361	361	360	357	354
64	359	359	357	352	347	361	361	360	358	356
65	361	361	360	353	351	362	362	362	360	358
66	362	362	360	357	352	363	363	362	361	360
67	362	362	361	358	357	363	363	363	362	360

Reach R2: AOC-W										
53	0	0	0	0	0	0	0	0	0	0
54	166	0	0	0	0	229	0	0	0	0
55	274	80	0	0	0	310	227	0	0	0
56	308	267	3	0	0	330	318	3	0	0
57	327	310	262	0	0	339	333	297	0	0
58	334	328	311	5	0	349	341	329	42	0
59	344	338	328	267	0	351	350	341	311	0
60	350	347	334	314	3	355	353	347	339	3
61	353	351	347	329	193	356	355	352	342	308
62	355	354	352	334	319	358	356	354	351	337
63	357	355	352	343	339	359	359	356	352	349
64	358	359	356	349	342	361	360	357	354	353
65	361	359	357	352	348	361	361	360	357	353
66	361	360	360	354	352	362	361	360	358	357
67	362	362	360	357	356	362	362	361	360	358
Reach R3: TSC-E										
53	0	0	0	0	0	0	0	0	0	0
54	194	0	0	0	0	312	0	0	0	0
55	318	153	0	0	0	354	307	0	0	0
56	344	320	3	0	0	358	355	3	0	0
57	354	347	288	0	0	361	359	348	0	0
58	358	358	346	19	0	363	362	359	74	0
59	361	360	355	322	0	364	364	362	356	0
60	363	362	360	349	3	364	364	363	361	3
61	363	363	362	357	272	365	365	364	363	350
62	364	364	363	359	350	365	365	365	364	360
63	365	365	364	362	359	365	365	365	365	362
64	365	365	365	364	361	365	365	365	365	364
65	365	365	365	364	363	365	365	365	365	365
66	365	365	365	365	364	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365
Reach R4: TSC-W										
53	0	0	0	0	0	0	0	0	0	0
54	194	0	0	0	0	313	0	0	0	0
55	321	153	0	0	0	355	307	0	0	0
56	344	320	3	0	0	360	356	3	0	0
57	357	349	289	0	0	362	360	349	0	0
58	359	358	347	15	0	363	362	360	84	0
59	362	361	358	322	0	364	364	363	356	0
60	363	363	361	351	3	364	364	364	361	3
61	364	364	363	358	276	365	365	365	363	352
62	365	365	364	361	351	365	365	365	364	361
63	365	365	365	363	359	365	365	365	365	363
64	365	365	365	364	362	365	365	365	365	364
65	365	365	365	365	363	365	365	365	365	365
66	365	365	365	365	365	365	365	365	365	365
67	365	365	365	365	365	365	365	365	365	365

Notes:
1. Yellow highlight represents project depth plus +3 tide.

Resume

Dr. Michael J. Briggs is an ocean and coastal engineer with over 40 years of experience, the last 31 years at the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center. After retiring from CHL in January 2014 he formed Briggs Group LLC. His research interests and areas of expertise include vertical ship motions, underway ship sinkage and trim (squat), harbor resonance, physical and numerical modeling of directional waves and floating breakwaters, wave transformation, wave-current interaction, and tsunami wave run-up. Dr. Briggs has been active in the deep-draft navigation research community since 1990. He has been CHL's leader and representative in the development of the Channel Analysis and Design Evaluation Tool (CADET), having worked with IWR and the U.S. Navy to insure the successful modification and application of this software for commercial ships. CADET is on the Corp's Hydrology, Hydraulics, and Coastal Community of Practice Preferred List of numerical models. He has also been active in comparing and recommending various analytical and empirical methods of predicting ship sinkage and trim (ship squat). As the leader of the vertical subgroup of PIANC WG 49, his team defined and recommended the significant factors involved in designing deep-draft entrance channels. Dr. Briggs has published over 200 journal articles, book chapters, technical reports, and conference papers. He holds a B.S. in Petroleum Engineering from the University of Texas at Austin, an M.S. in Ocean Engineering from the University of Southern California, an Ocean Engineers from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institute Joint Program, and a PhD in Civil (Ocean) Engineering from Texas A&M University.

Norfolk Harbor Channel
Vertical Ship Motion Study for Norfolk, VA Entrance Channel

September 26, 2017

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Errata

Based on an Agency Technical Review (March 2018), the following comments and responses are provided to the reader of this report.

Comment Number 7244292 - Reference Page 9, Wave Transformation

Concern: This section presents design wave heights for the "lower wave height waves" and the higher waves (taken from the highest 3-5percent of wave heights). It is unclear both in the Briggs report and the attached Godsey report, how a value of 4.8feet was determined as the lower design wave height. The Godsey report places the lower end average between 2ft and 4ft. The 4.8ft values is not explained.

Basis for Concern: Wave data is a major component of determining UKC. The development of design wave conditions should be fully presented.

Significance of Concern: Low (as the 4.8ft low wave height condition gives a more conservative result).

Recommended Action: Recommend providing an explanation either in the Briggs report or (probably more appropriately) the Godsey report, detailing how the 4.8ft lower design wave height was developed/selected.

RESPONSE*: Concur, the Joint Probability Distribution Section of the Godsey, et. al report will be revised to include discussion on selection of the 4.8 feet as the lower design wave height for wave transformation. Table 4 combined the significant wave height from the direction limited cases and the top 3 to 5% cases with wave direction and period bins with greater than 106 occurrences or 0.05 percent of the 212,056 points of the direction limited dataset. Not all wave bends from the direction-limited dataset that met this criteria were included for the STWAVE wave transformation runs. The lower direction limited wave bins with a mean wave height of 2.9 feet and less were excluded from the wave transformation modeling to develop wave transformation factors due to the insignificant ship motions associated with these lower heights.*

Comment Number 7244293 - Reference Table 4.

Concern: This section presents design wave heights for the "lower wave height waves" and the higher waves (taken from the highest 3-5percent of wave heights) combined with an array of wave periods. It is unclear how the array of periods was determined. A detailed discussion of the WIS data is provided and a discussion of the final input conditions, but the connection between the two is not fully defined.

Basis for Concern: Wave data is a major component of determining UKC. The development of design wave conditions should be fully presented.

Significance of Concern: Low

Recommended Action: Provide a section between presentation of the WIS data and presentation of the design wave data that describes how the wave periods were developed as STWAVE input conditions.

RESPONSE*: Concur, Godsey, et. al report will be revised to include discussion to define the connection between the WIS data and the final input conditions. Wave periods were selected based on the most frequent occurring periods in each direction band developed from the WIS data.*

PURPOSE: The purpose of this report is to describe the analysis for estimating (a) deepwater hindcast waves, (b) deepwater joint probability distributions, and (c) the setup and analysis of a series of STWAVE model simulations conducted to determine wave transformation at eleven CADET savepoint locations in the Norfolk Entrance Channel of the Norfolk Harbor.

INTRODUCTION: When waves propagate into coastal regions, they become increasingly susceptible to the influence of the bathymetry and shallower depths found in nearshore areas. As waves reach the shoreline, they experience the effects of shoaling and breaking, leading to significant variation in wave conditions within even relatively small areas. In the area occupied by the Norfolk Entrance Channel in Norfolk, VA (Figure 1), there is a need for data regarding horizontal and vertical ship motion, which allows for the accurate calculation of underkeel. To predict these ship motions, the model CADET requires directional wave spectra as input.

DEEPWATER HINDCAST WAVES: The 34-year hindcast wave data for this study were provided by the Wave Information Study (WIS). Figure 1 shows the location of WIS Station 197 (WIS197) and WIS199 that were selected due to their proximity to the Norfolk Harbor Entrance Channel (Table 1). The WIS hindcast data is provided at 1-hour intervals over the 34-year time period. It includes significant wave height H_s, peak period T_p, and peak direction θ_p. The θ_p represents the dominant wave direction for wave energy within the frequency band of peak energy. Wave directions in degrees are directions from which the waves are traveling, the same as meteorological conventions. In addition, to WIS Station 197 (WIS197) and WIS199, analysis of data from the City of Norfolk's Thirty-Second (32nd) wave gage was made to determine potential significance of northerly winds within the bay, which could have influence on the Thimble Shoal Channel reach.

Table 1. Wave climate information.

Source	Years	Depth (ft)	Latitude (deg N)	Longitude (deg W)
WIS197	1980-2014	55.8	36.92	-75.75
WIS199	1980-2014	62.3	39.83	-75.75
32 Wave Gage	2006-2016	--	36.96	-76.23

Figure 2, 4 and 6 are percent occurrence histograms of wave direction, period, and height. Figure 3, 5 and 7 are equivalent number of occurrence histograms. Direction bands are in 22.5 deg increments from 0 to 360 deg. The numbers on top of the bars are the percentages or number of occurrences and the numbers on the bottom of the bars are the mean values. The total number of points for each WIS dataset is 306,815. The

total number of points following removal of null values for the City of Norfolk Gage 32 nd dataset is 81,461.

For WIS197 the most common wave direction, with 26.7 percent (81,864) of the cases, is between 101.3 and 123.8 deg, with a mean of 112.8 deg. The overall mean wave direction is 109.8 deg. Wave periods range from 1 to 23 sec, with variable band limits. The most commonly occurring wave period band, with 34.9 percent (107,057) of the cases, is from 9 to 11 sec, with a mean of 9.9 sec. The overall mean wave period is 8.8 sec. Significant wave heights range from 0 to 20.2 ft, with variable band limits. The most common wave height, with 51.8 percent (158,934) of the cases, is from 2 to 4 ft, with a mean of 2.9 ft. The overall mean wave height is 3.3 ft. The largest significant wave height is 20.2 ft, with corresponding peak period of 16.4 sec and wave direction of 112.8 deg. However, this is a rare occurrence.

For WIS199 the most common wave direction, with 24.5 percent (75,145) of the cases, is between 101.3 and 123.8 deg, with a mean of 112.9 deg. The overall mean wave direction is 108.2 deg. Wave periods range from 1 to 23 sec, with variable band limits. The most commonly occurring wave period band, with 32.6 percent (99,873) of the cases, is from 9 to 11 sec, with a mean of 9.9 sec. The overall mean wave period is 8.8 sec. Significant wave heights range from 0 to 21.4 ft, with variable band limits. The most common wave height, with 50.3 percent (154,414) of the cases, is from 2 to 4 ft, with a mean of 2.9 ft. The overall mean wave height is 3.6 ft. The largest significant wave height is 21.4 ft, with corresponding peak period of 16.1 sec and wave direction of 112.9 deg. However, this is a rare occurrence.

For the City of Norfolk's 32 wave gage the most common wave direction, with 24.3 percent (19,819) of the cases, is between 78.8 and 101.3 deg, with a mean of 88.8 deg. The overall mean wave direction is 89.9 deg. Wave periods range from 1 to 33.3 sec, with variable band limits. The most commonly occurring wave period band, with 48.4 percent (39,430) of the cases, is from 0 to 4 sec, with a mean of 2.9 sec. The overall mean wave period is 5.1 sec. Significant wave heights range from 0 to 8.7 ft, with variable band limits. The most common wave height, with 84.2 percent (68,588) of the cases, is from 0 to 2 ft, with a mean of 0.9 ft. The overall mean wave height is 1.2 ft. The largest significant wave height is 8.7 ft, with corresponding peak period of 33.3 sec and wave direction of 2.3 deg. However, this is a rare occurrence.

Figure 1. Harbor Plan View (Source: Moffatt and Nichol).

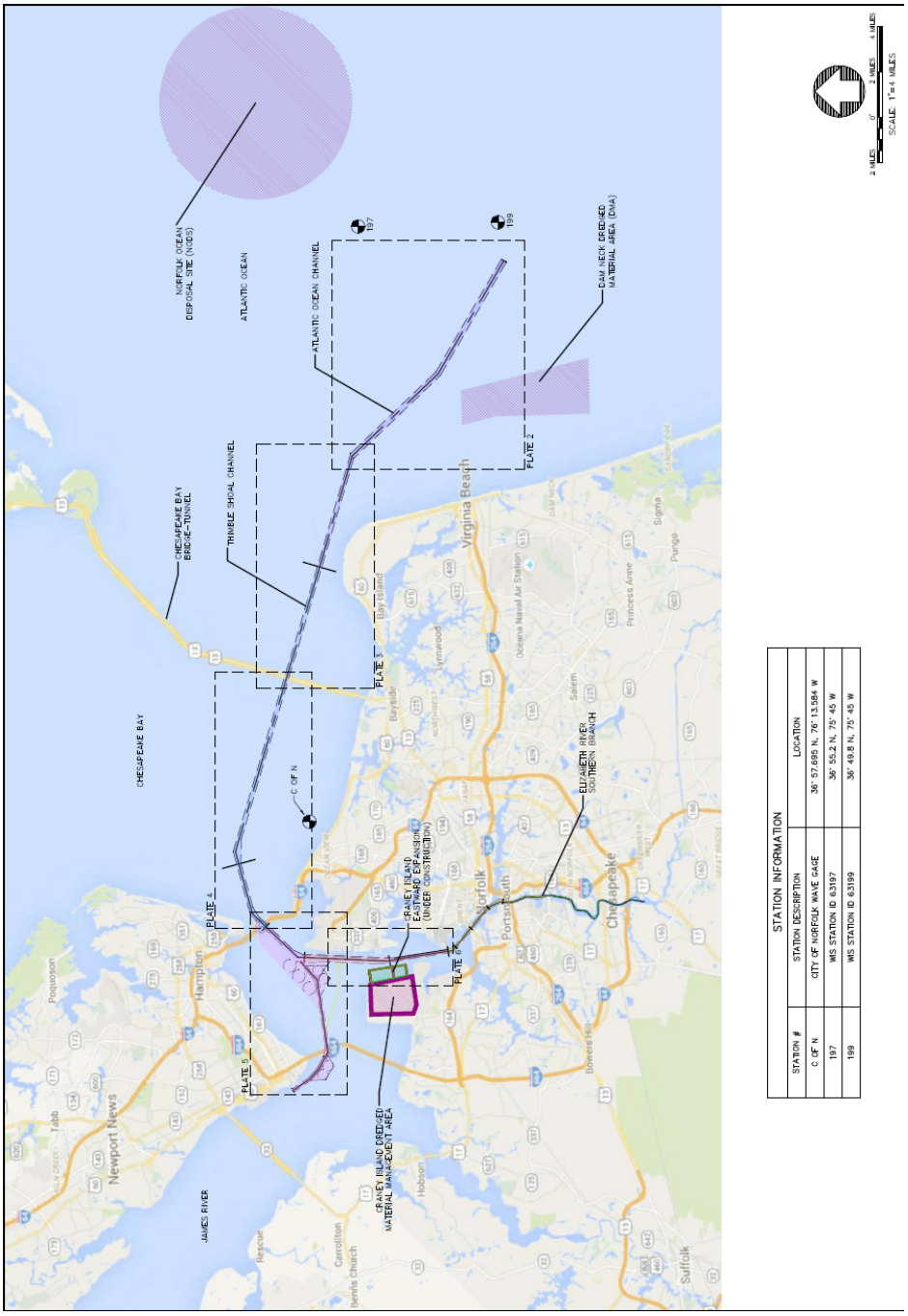

Figure 8, 10 and 12 are roses of H_s that illustrate the percentage of waves coming from different directions. Figure 9, 11 and 13 are similar roses for T_p. The length of the radial bars indicates the percentage from that particular wave direction. Thicker bars represent smaller H_s or T_p bands. The lowest bands are shown nearest the center of the rose. The radial bars become narrower toward the outer end of each bar, indicating increasing wave heights or periods.

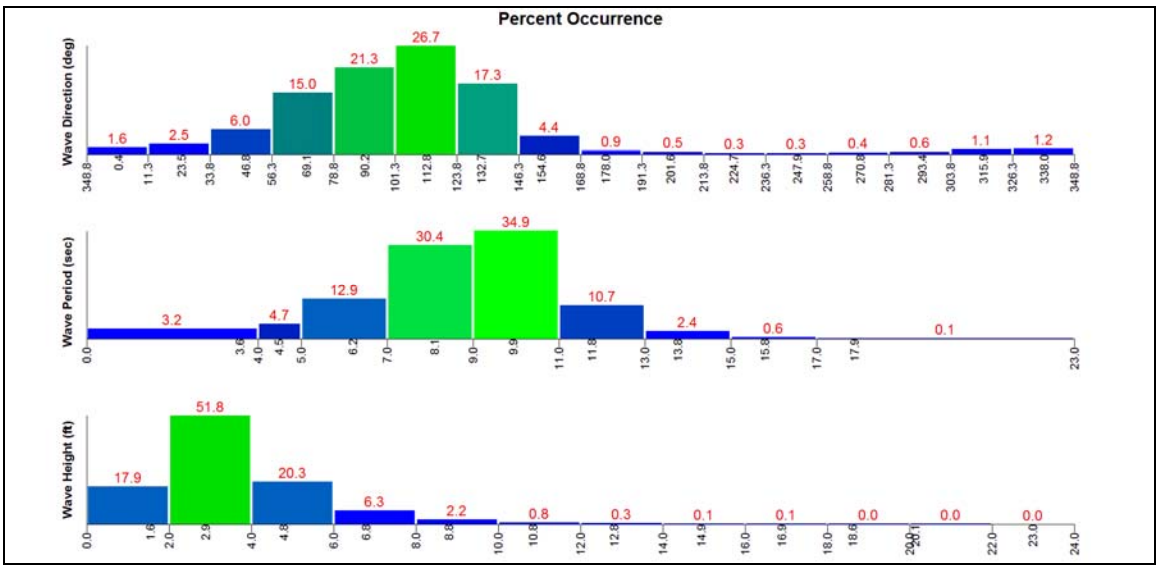

Figure 2. WIS197 percent occurrence histogram of wave direction, period, and height, 1980 to 2014, h = 55.8ft, 306,815 points, all cases (WIS197_allyrs_histogram%.bmp)

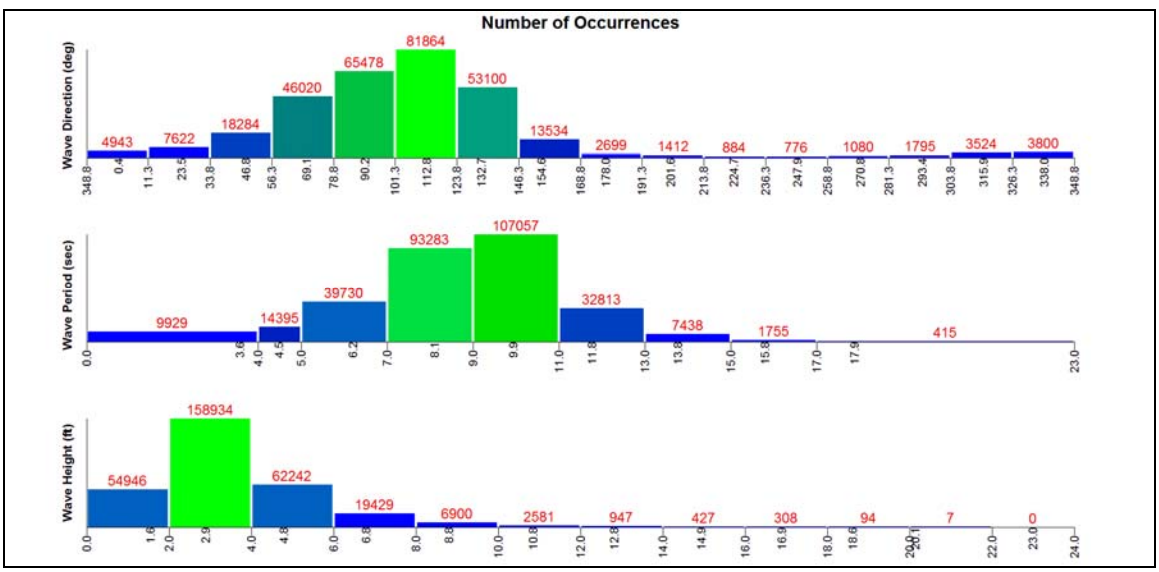

Figure 3. WIS197 number of occurrences histogram of wave direction, period, and height, 1980 to 2014, h = 55.8ft, 306,815 points, all cases (WIS197_allyrs_histogramnum.bmp).

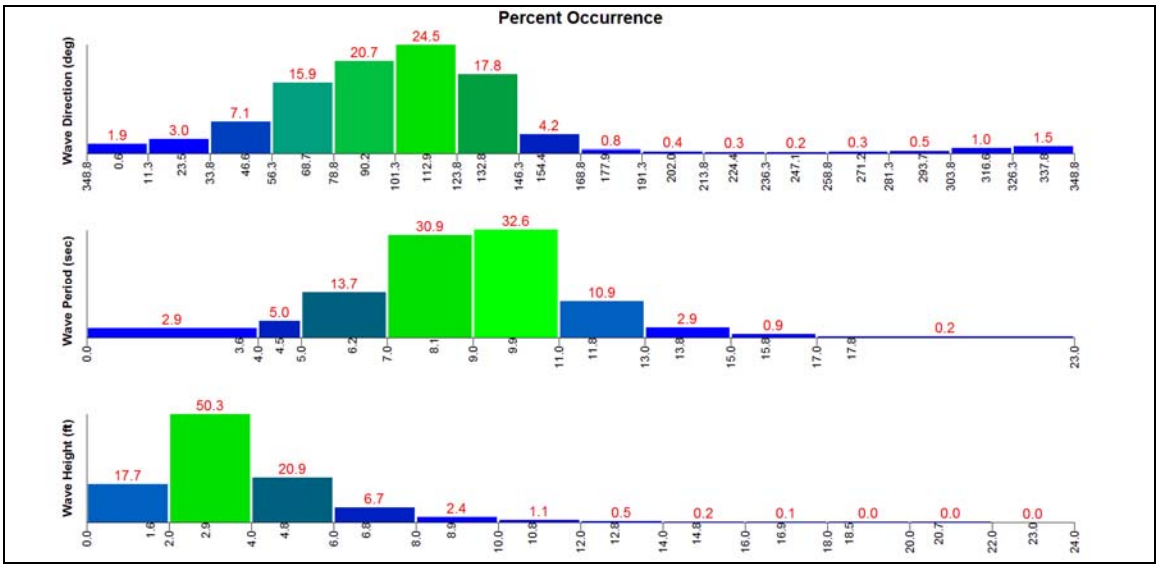

Figure 4. WIS199 percent occurrence histogram of wave direction, period, and height, 1980 to 2014, h = 62.3 ft, 306,815 points, all cases (WIS199_allyrs_histogram%.bmp)

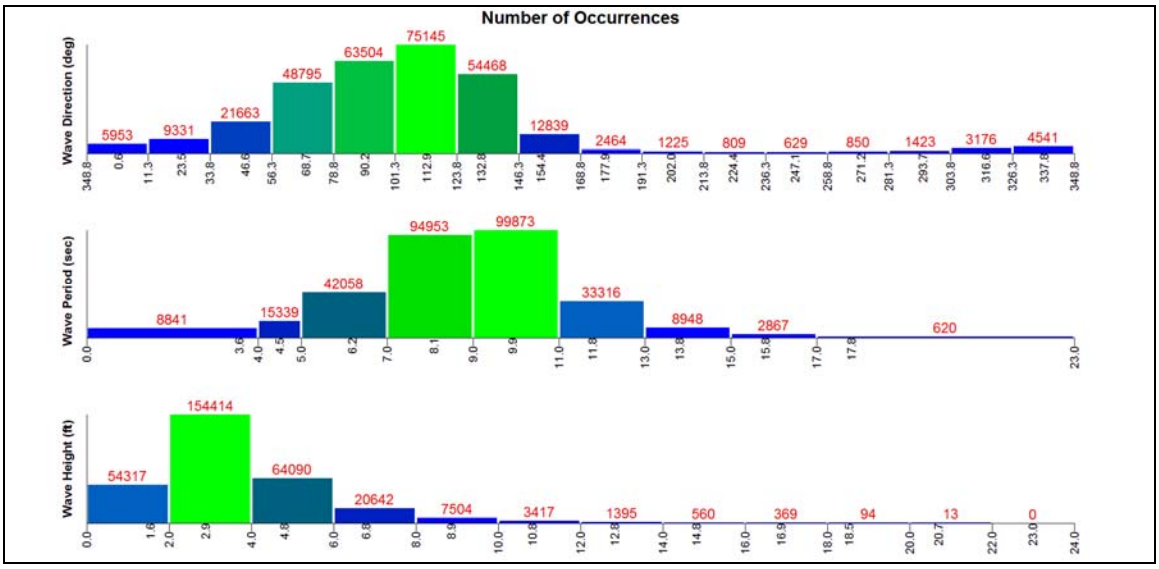

Figure 5. WIS199 number of occurrences histogram of wave direction, period, and height, 1980 to 2014, h = 62.3 ft, 306,815 points, all cases (WIS199_allyrs_histogramnum.bmp).

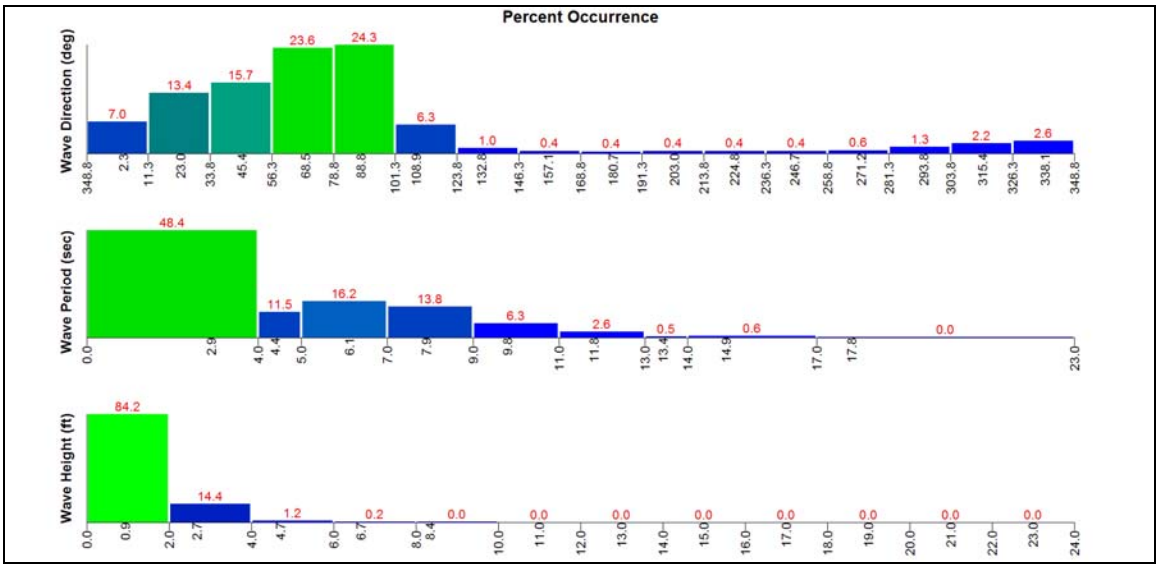

Figure 6. Norfolk 32nd Gage percent occurrence histogram of wave direction, period, and height, 2006 to 2016, 81,461 points, all cases (wavsum32_allyrs_histogram%.bmp)

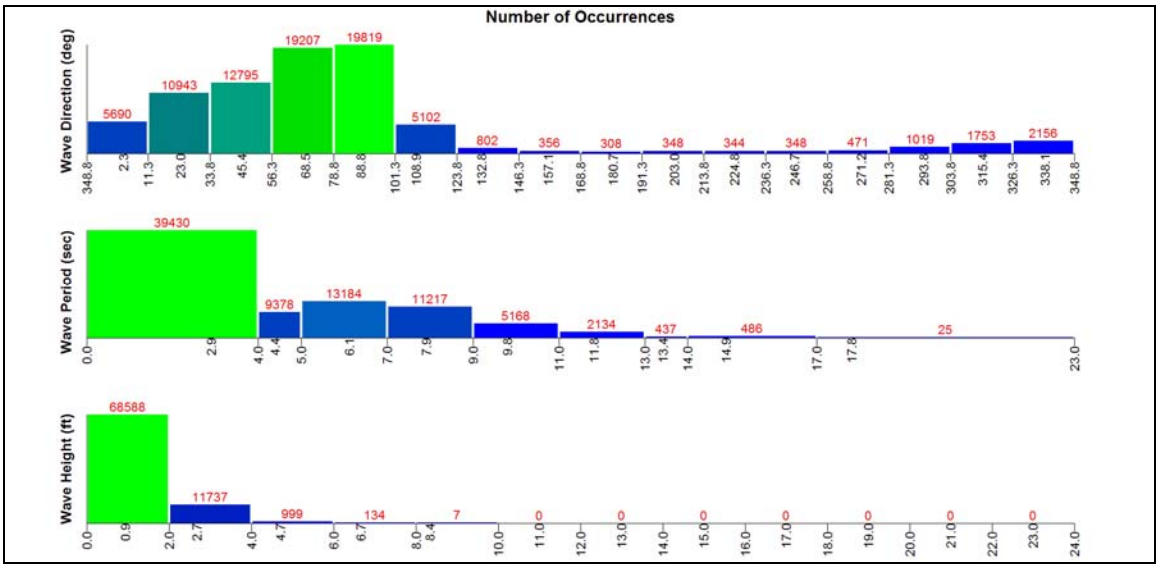

Figure 7. Norfolk 32nd Gage number of occurrences histogram of wave direction, period, and height, 2006 to 2016, 81,461 points, all cases (wavsum32_allyrs_ histogramnum.bmp)

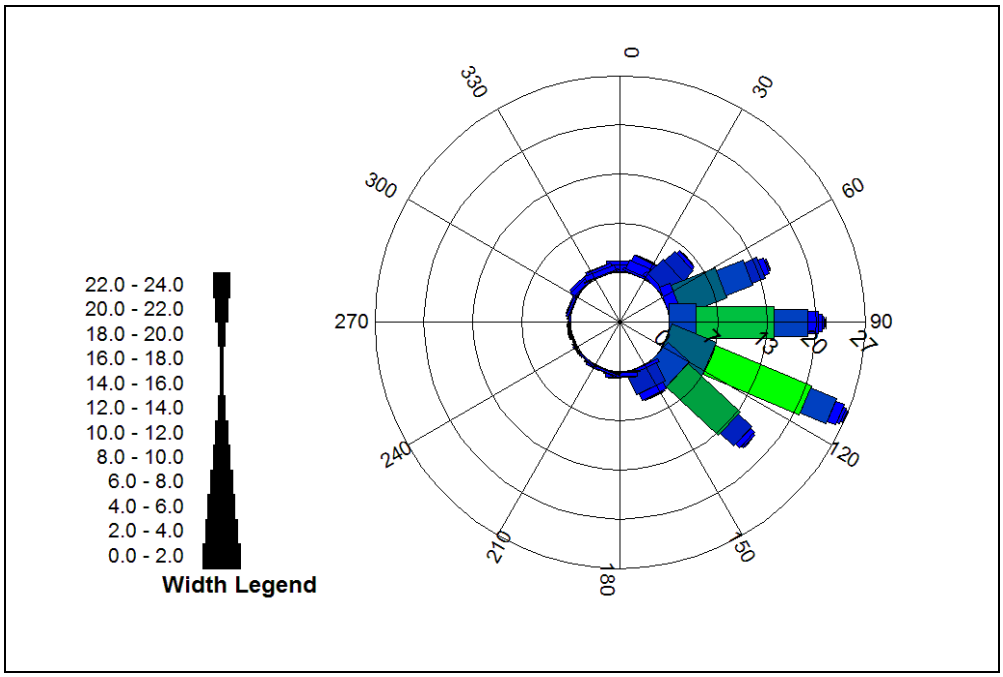

Figure 8. WIS197 wave height rose, 1980 to 2014, h=55.8 ft, 306,815 points, all cases (WIS197_allyrs_rose_hs.bmp).

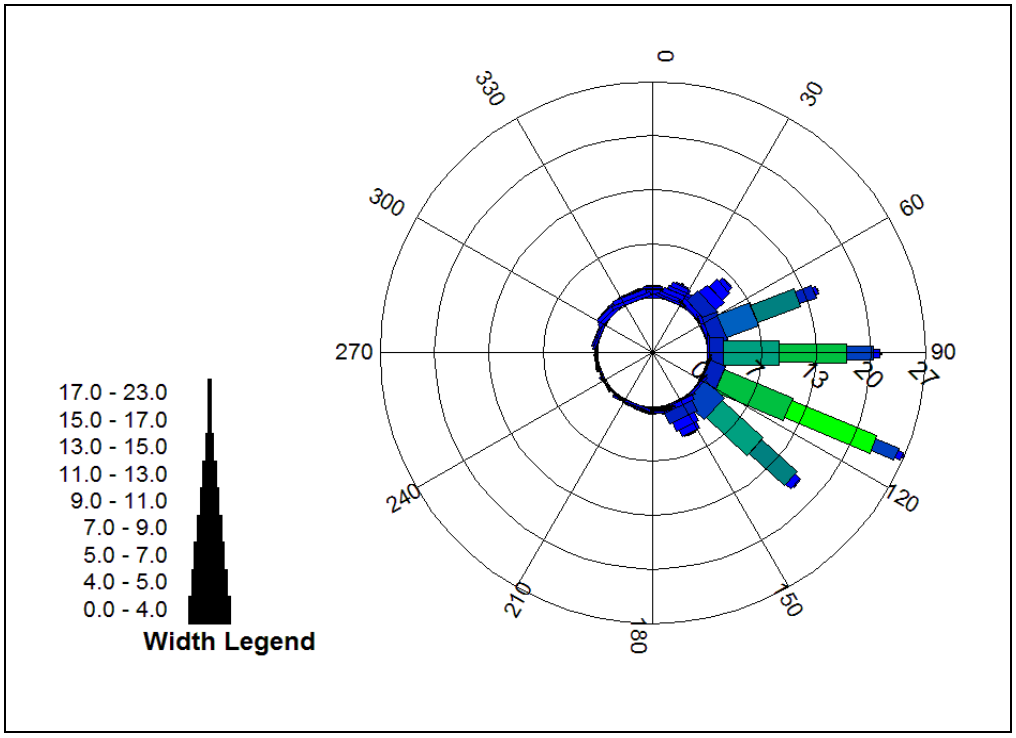

Figure 9. WIS197 wave period rose, 1980 to 1999, h=55.8 ft, 306,815 points, all cases (WIS197_allyrs_rose_tp.bmp).

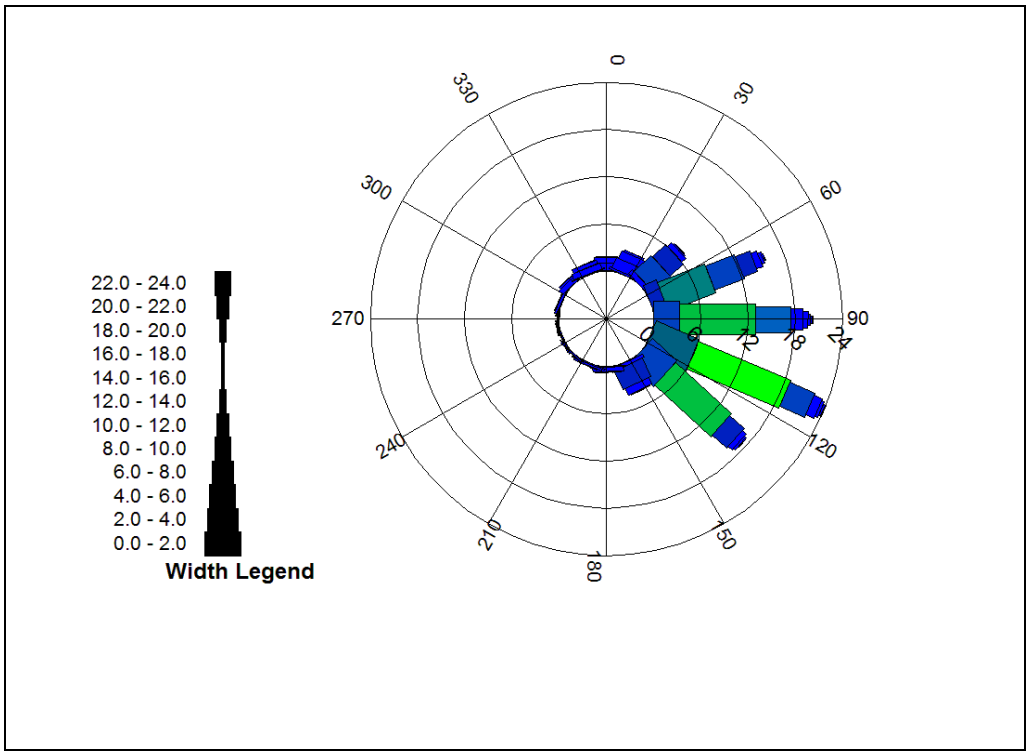

Figure 10. WIS199 wave height rose, 1980 to 2014, h=62.3 ft, 306,815 points, all cases (WIS199_allyrs_rose_hs.bmp).

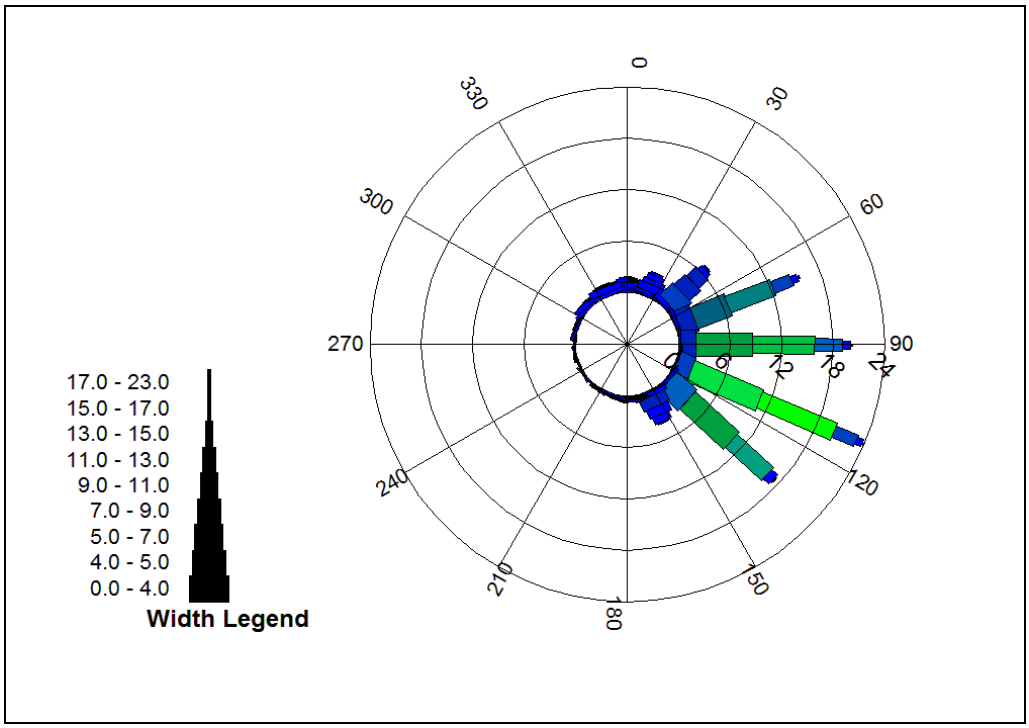

Figure 11. WIS199 wave period rose, 1980 to 1999, h=62.3 ft, 306,815 points, all cases (WIS199_allyrs_rose_tp.bmp).

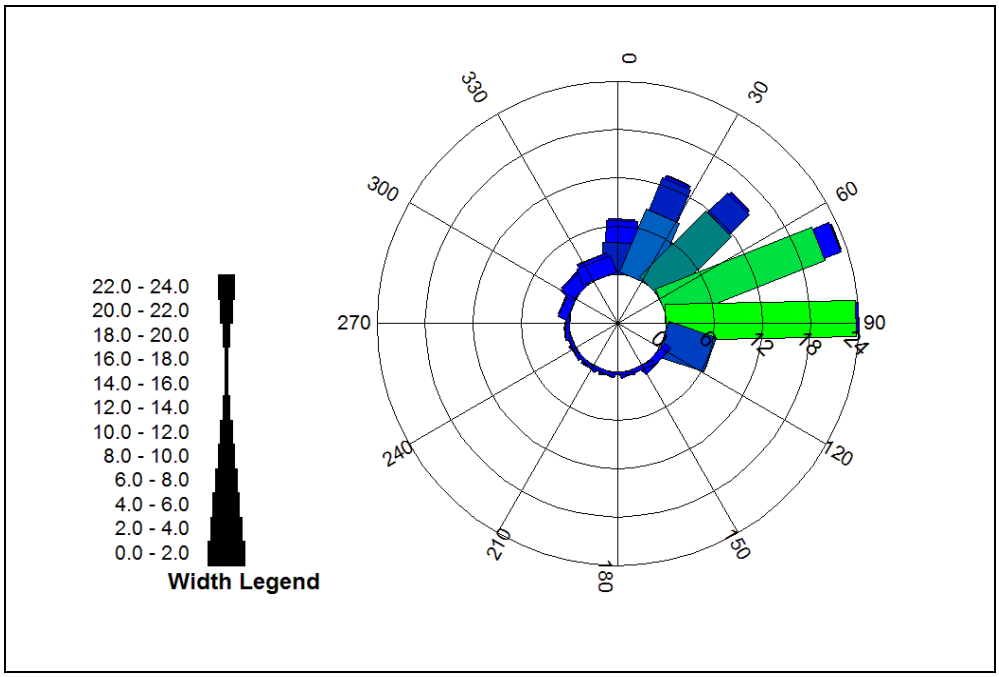

Figure 12. Norfolk 32nd Gage wave height rose, 2006 to 2016, 81,461 points, all cases (wavsum32_allyrs_rose_hs.bmp).

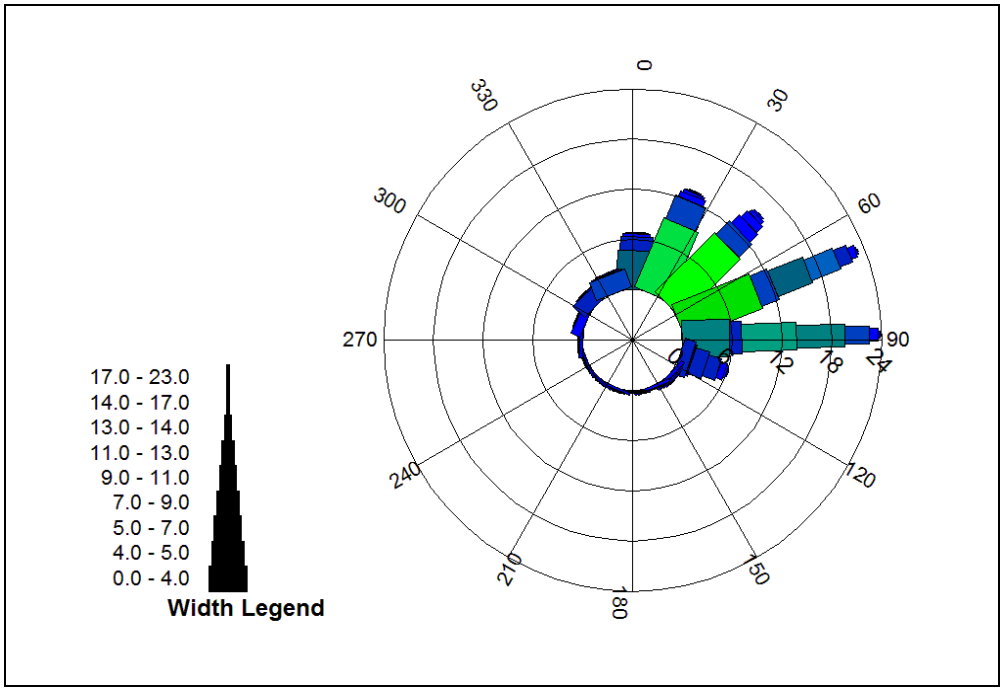

Figure 13. Norfolk 32 Gage wave period rose, 2006 to 2016, 81,461 points, all cases (wavsum32_allyrs_rose_hs.bmp).

Review of WIS 197 and WIS 199 data indicates close comparisons of wave climates; therefore WIS199 was chosen for the offshore boundary conditions given its location nearest to where the Norfolk Harbor navigation channel daylights. Furthermore, review of the City of Norfolk 32 gage data indicates that wave height events driven by northerly storm winds within the bay tend to have shorter wave periods and occur much less frequently then the sea and swell waves entering the bay from offshore directions of approximately 60 to 100 degrees North (i.e., from the east).

DIRECTION-LIMITED WAVES: Direction bands are in 22.5 deg increments encompassing waves from 60 deg to 132 deg, which is equivalent to ±50 deg on either side of shore normal to the southern and northern shores adjacent to the inlet. Waves approaching the coast from directions outside this arc are not a significant consideration because they will be refracted greatly and reduced in height before reaching the navigation channel at the inlet. The total number of observations for the entire 34-year hindcast dataset is 306,815. The limited dataset has 69.1 percent of these observations, or 212,056 observations. Table 2 summarizes the lower, upper, and mid-point direction band limits for the four 22.5-deg direction bands. The number of observations and the percent of the limited and total dataset are also listed for each band.

Table 2. Band limits based on direction-limited waves.

Band No.	Direction Band Limits, deg			No. Observations	Percent	
	Lower	Upper	Middle		Limited	Total
Direction-limited waves						
1	56.3	78.8	67.5	44,163	20.8%	14.4%
2	78.8	101.3	90.0	63,504	29.9%	20.7%
3	101.3	123.8	112.5	75,145	35.4%	24.5%
4	123.8	146.3	135.0	29,244	13.8%	9.5%
Top 3-5% wave heights and direction-limited waves						
1	56.3	78.8	67.5	1670	38.4%	0.54%
2	78.8	101.3	90.0	1487	34.2%	0.49%
3	101.3	123.8	112.5	916	21.1%	0.30%
4	123.8	146.3	135.0	237	6.28%	0.09%

Notes:

1. Direction bands were 22.5 deg wide.
2. Total number of observations = 306,815.
3. Total number of observations within direction band limits = 212,056 or 69.1 percent of total.
4. Total number of observations within top 3-5% wave heights and direction band limits = 4,346 or 1.4% of total.

Figure 14 is a percent occurrence histogram of wave direction, period, and height for the direction limited data-set. Figure 15 is the equivalent number of occurrence histogram. Direction bands are in 22.5 deg increments from 0 to 360 deg. As before the numbers on top of the bars are the percentages or number of occurrences and the numbers on the bottom of the bars are the mean values. The total number of points for this dataset is 212,056. The most common wave direction, with 35.4 percent (75,145) of the cases, is between 101.3 and 123.8 deg, with a mean of 112.9 deg. The overall mean wave direction is 99.2 deg. Wave periods range from 1 to 23 sec, with variable band limits. The most commonly occurring wave period band, with 37.4 percent (79,265) of the cases, is from 9 to 11 sec, with a mean of 9.9 sec. The overall mean wave period is 9.4 sec. Significant wave heights range from 0 to 21.4 ft, with variable band limits. The most common wave height, with 49.2 percent (104,284) of the cases, is from 2 to 4 ft, with a mean of 2.9 ft. The overall mean wave height is 3.7 ft. The largest significant wave height is 21.4 ft, with corresponding peak period of 16.1 sec and wave direction of 112.5 deg. However, as noted previously this is a rare occurrence.

Figure 16 is a rose of H_s that illustrates the percentage of waves coming from different directions. Figure 17 is a similar rose for T_p. The length of the radial bars indicates the percentage from that particular wave direction. As before, the thicker bars represent smaller H_s or T_p bands. The lowest bands are shown nearest the center of the rose. The radial bars become narrower toward the outer end of each bar, indicating increasing wave heights or periods.

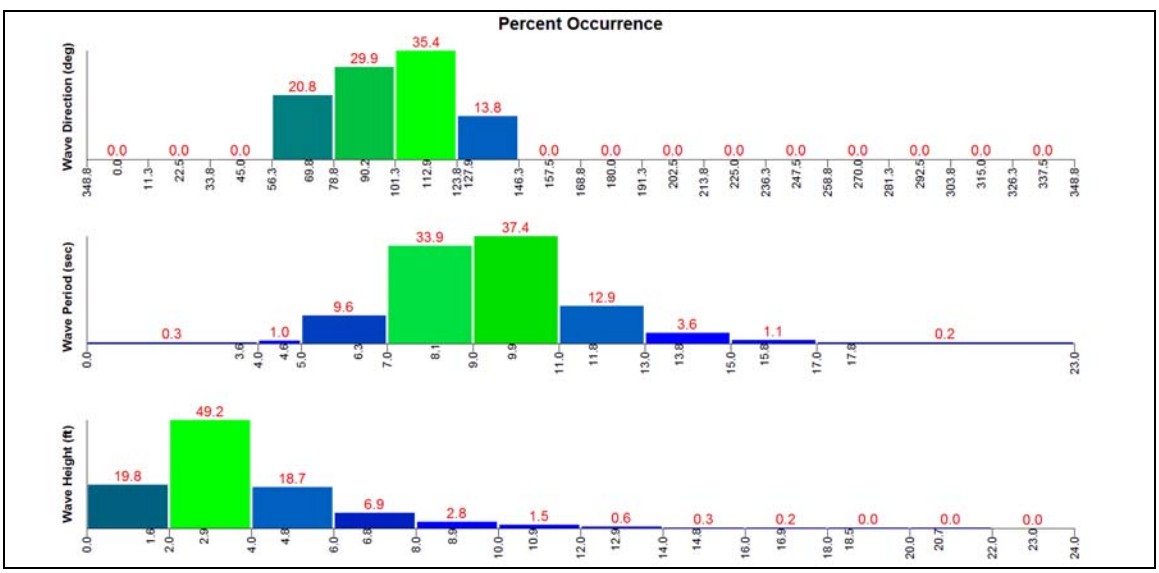

Figure 14. WIS199 percent occurrence histogram of wave direction, period, and height, 1980 to 2014, h = 62.3 ft, 212,056 points, direction limited cases, (WIS199_allyrs_dir_histogram%.bmp).

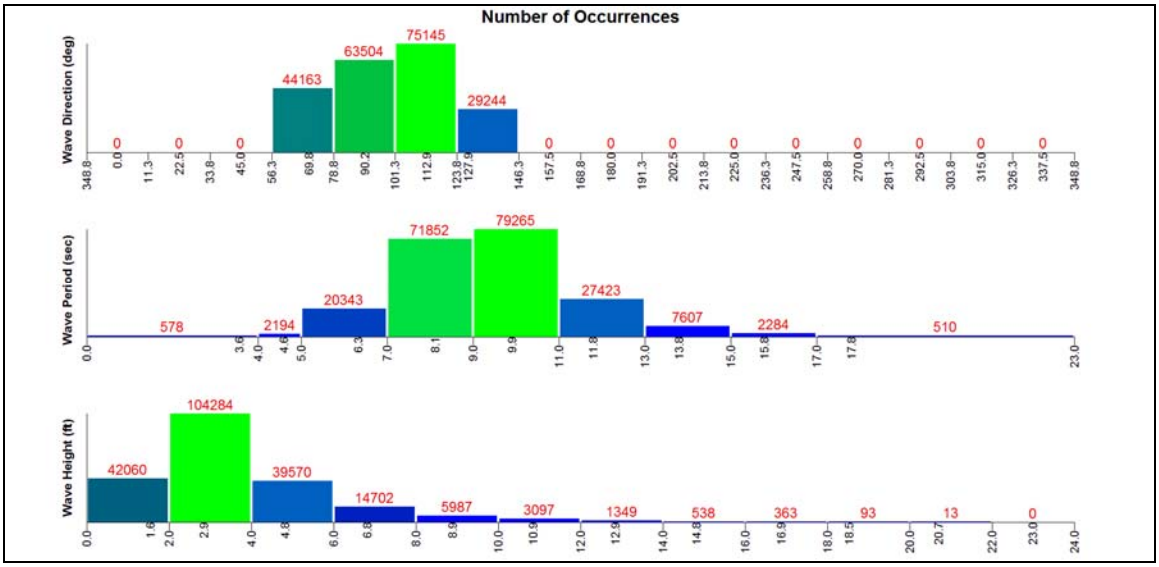

Figure 15. WIS199 number of occurrences histogram of wave direction, period, and height, 1980 to 2014, h = 62.3 ft, 212,056 points, direction limited cases, (WIS199_allyrs_dir_histogramnum.bmp).

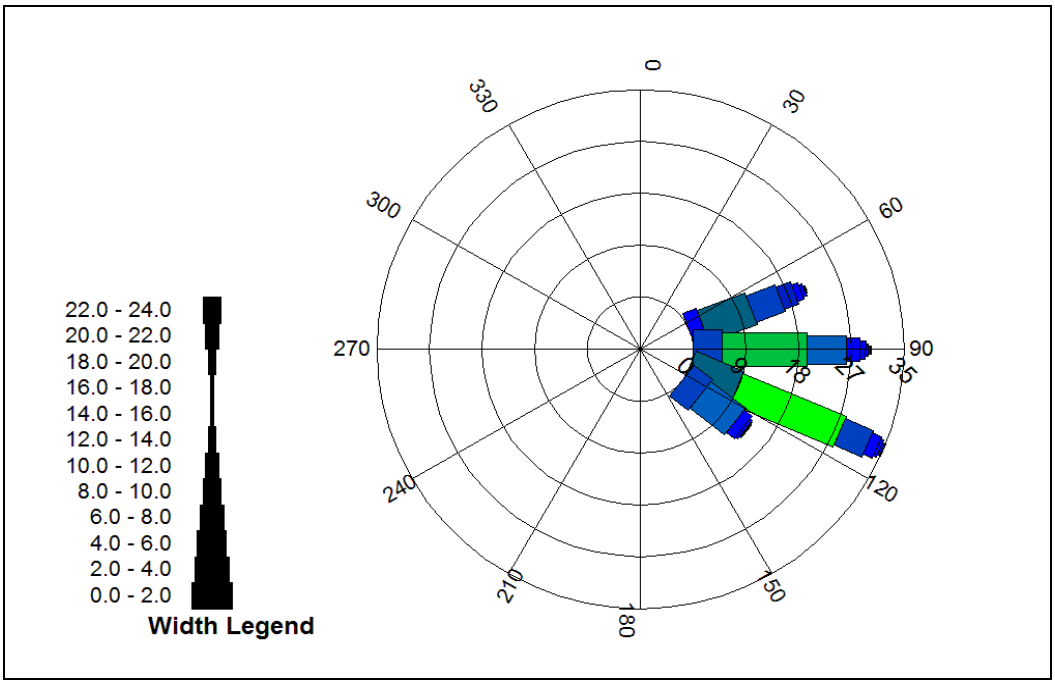

Figure 16. WIS199 wave height rose, 1980 to 2014, h=62.3 ft, 212,056 points, direction limited cases, (WIS199_allyrs_dir_rose_hs.bmp).

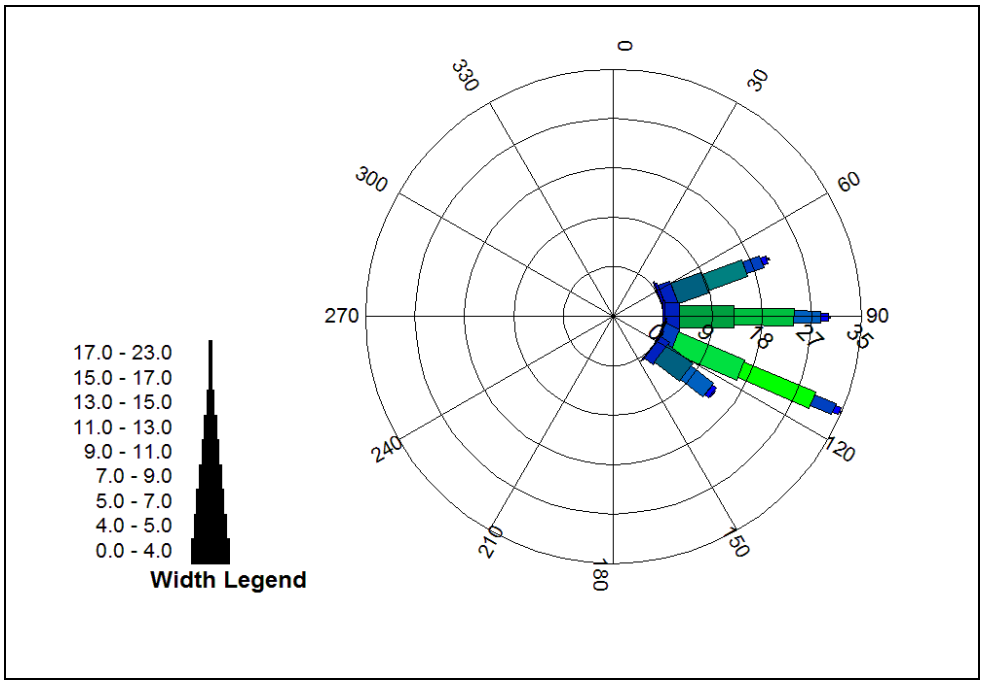

Figure 17. WIS199 wave period rose, 1980 to 2014, h=62.3 ft, 212,056 points, direction limited cases, (WIS199_allyrs_dir_rose_tp.bmp).

TOP 3 TO 5 PERCENT WAVE HEIGHTS: Mean H_s, mean T_p, and mean θ_p were calculated based on a further reduced dataset of the top 3 to 5 percent wave heights. The limited dataset has 1.4 percent of these observations, or 4,346 observations. Table 2 also lists the lower, upper, and mid-point direction band limits for the six 22.5-deg direction bands in this subset of waves. Again, the number of observations and the percent of the limited and total dataset are also listed for each band.

Figure 18 is a percent occurrence histogram of wave direction, period, and height for the top 3 to 5% dataset. Figure 19 is the equivalent number of occurrence histogram for the top 3 to 5% dataset. Direction bands are in 22.5 deg increments from 0 to 360 deg. As before, the numbers on top of the bars are the percentages or number of occurrences and the numbers on the bottom of the bars are the mean values. The total number of points for this dataset is 4,346. The most common wave direction, with 38.4 percent (1,670) of the cases, is between 56.3 and 78.8 deg, with a mean of 70.5 deg. The overall mean wave direction is 88.9 deg. Wave periods range from 1 to 23 sec, with variable band limits. The most commonly occurring wave period band, with 43.3 percent (1,881) of the cases, is from 9 to 11 sec, with a mean of 10.1 sec. The overall mean wave period is 11.1 sec. Significant wave heights range from 8.2 to 9.6 ft, with 2-ft band limits. The most common wave height, with 100 percent (4,346) of the cases, is from 8 to 10 ft, with a mean of 8.9 ft. The overall mean wave height is 8.9 ft. The largest significant wave height is 9.6ft, with corresponding peak period of 10.0 sec and wave direction of 70.5 deg.

Figure 20 is a rose of H_s that illustrates the percentage of waves coming from different directions for the top 3 to 5% dataset. Figure 21 is a similar rose for T_p. As before, the length of the radial bars indicates the percentage from that particular wave direction. Thicker bars represent smaller H_s or T_p bands. The lowest bands are shown nearest the center of the rose. The radial bars become narrower toward the outer end of each bar, indicating increasing wave heights or periods.

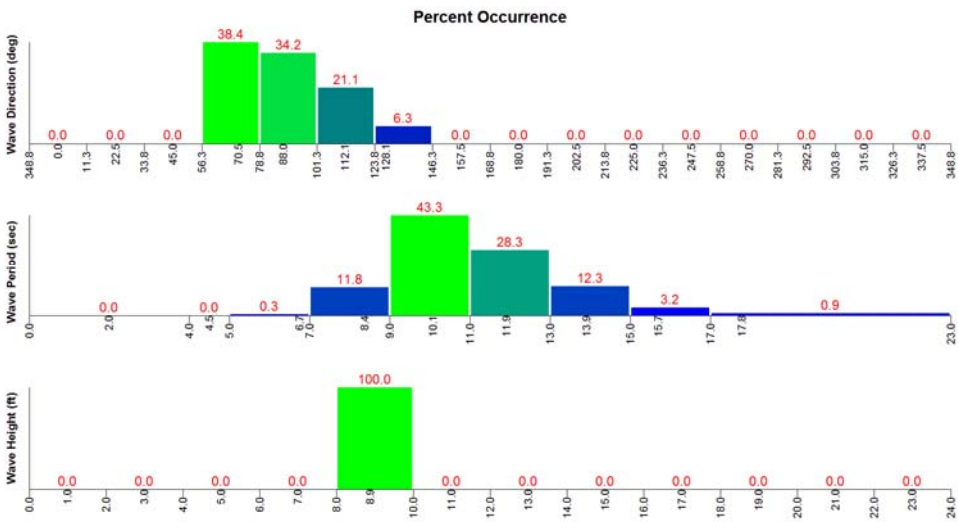

Figure 18. WIS199 percent occurrence histogram of wave direction, period, and height, 1980 to 2014, h = 62.3 ft, 4,346 points, direction limited cases, top 3 to 5 % highest wave heights (WIS199_allyrs_dir_3to5%_histogram%.bmp).

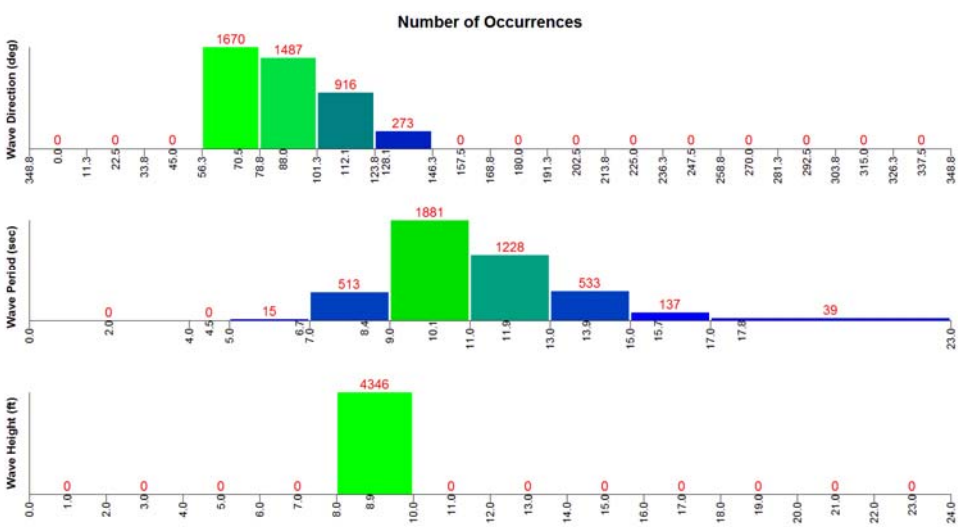

Figure 19. WIS199 number of occurrences histogram of wave direction, period, and height, 1980 to 2014, h = 62.3 ft, 4,346 points, direction limited cases, top 3 to 5 % highest wave heights (WIS199_allyrs_dir_3to5%_histogramnum.bmp).

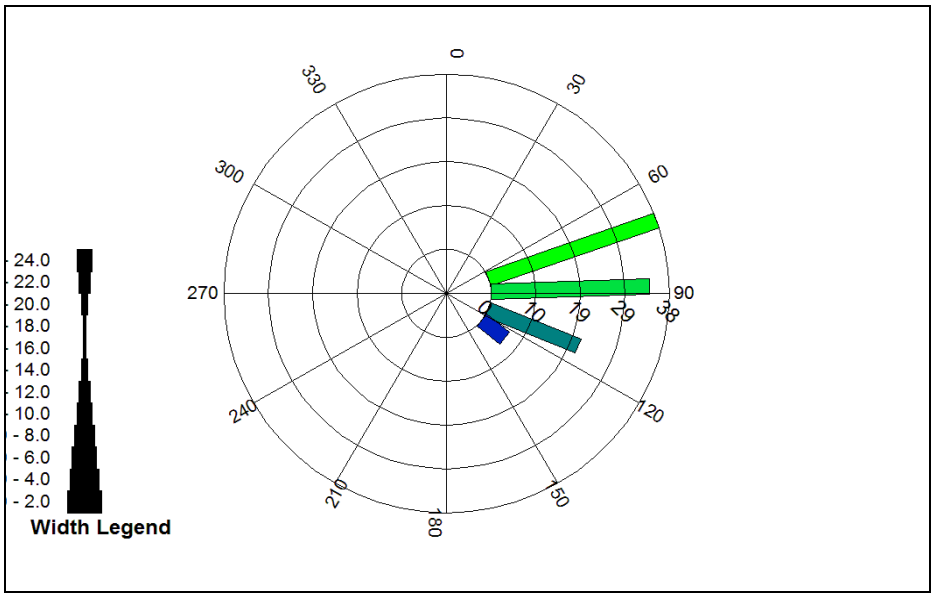

Figure 20. WIS199 wave height rose, 1980 to 2014, h=62.3ft, 4,346 points, direction limited cases, top 3 to 5 % highest wave heights (WIS199_allyrs_dir_3to5%_rose_hs.bmp).

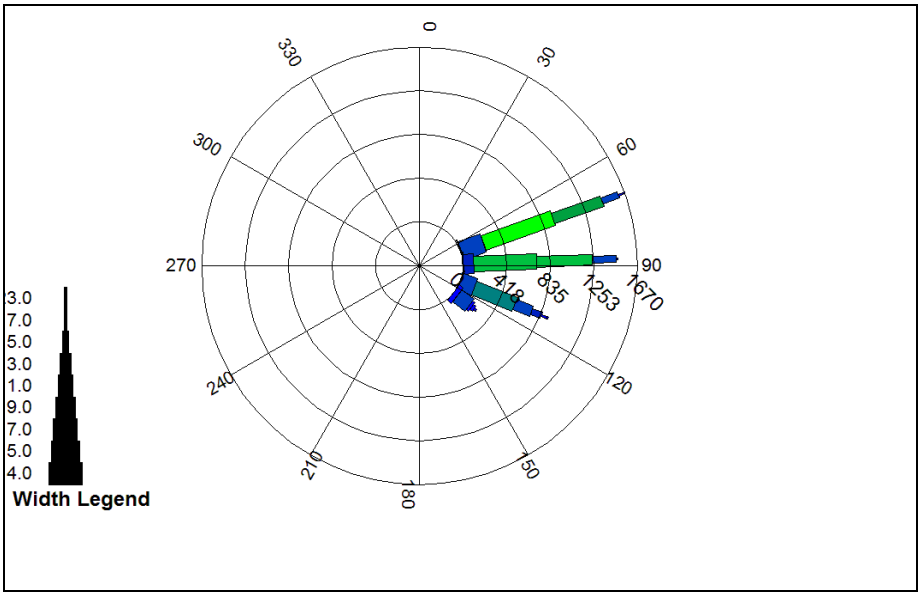

Figure 21. WIS199 wave period rose, 1980 to 2014, h=62.3 ft, 4,346 points, direction limited cases, top 3 to 5 % highest wave heights (WIS199_allyrs_dir_3to5%_rose_tp.bmp).

JOINT PROBABILITY DISTRIBUTIONS: The next step in the wave processing is to separate the data into joint probability or percent occurrence tables of T_p vs. H_s for the set of direction bands for the direction limited and 3 to 5% datasets. The T_p vs. H_s percent occurrence figures for each of the four direction bands in the direction-limited cases are contained in the Appendix in Figures A1-A8. Figures A9-A16 in the Appendix are the corresponding plots for the top 3 to 5 percent wave height cases. There are two

figures for each direction band: a percent occurrence in the band and corresponding number of occurrences.

From the joint probability distributions, wave parameter statistics were gathered for generating empirical directional wave spectra on the offshore boundary of the STWAVE grid. Table 4 lists the wave parameters for the 49 different combinations of T_p, H_s, and θ_p that were obtained for development of "multipliers" for adjusting the wave height as the wave transforms from deep to shallow water along the Atlantic Ocean and Thimble Shoal Channels. Table 4 combines the significant wave height from the direction limited cases and the top 3 to 5% cases with wave direction and period bins with greater than 106 occurrences or 0.05 percent of the 212,056 points of the direction limited dataset. Wave bins outside of this were removed as they would not be expected to result in significant vessel motion and/or represent rare events on both low and high ends of the dataset.

STWAVE MODEL SIMULATIONS: The Steady-state Spectral WAVE model (STWAVE) (Massey et al. 2011), which was designed to simulate wave transformation and propagation in nearshore regions, was applied to provide these needed estimates of nearshore wave transformation along the channel.

MODEL SETUP: A Cartesian STWAVE grid covering the entire extent of the Norfolk Harbor Channel and the surrounding area was created in order to effectively model the wave conditions in that region (see Figure 22). The grid has a resolution of 50 m and was comprised of 1311 cells in the cross-shore direction (I) and 609 cells in the alongshore direction (J). The offshore boundary of the grid was aligned with the location of WIS station 199, which provided offshore wave forcing as well as local wind forcing for the STWAVE domain. The projection used for the grid was the State Plane Coordinate System Virginia South (FIPS 4502). Grid properties of the STWAVE domain are provided in Table 3.

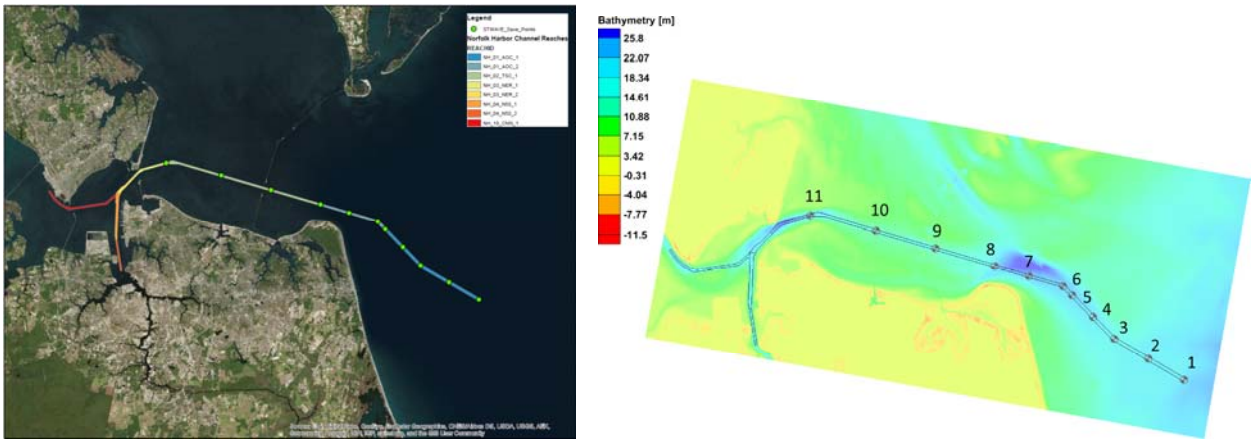

Figure 22. The location of the Norfolk Entrance Channel in the Norfolk Harbor (left); the extent of the STWAVE grid used to model the area (right), with bathymetry and CADET savepoints indicated.

Table 3. STWAVE Grid Properties.

Projection	Grid Origin (x,y) (m)	Azimuth (deg)	Δx/Δy(m)	Number of Cells	
				I	J
State Plane 4502	(3750292.6,1081480.6)	169.8	50.0	1311	609

Initial bathymetry for the STWAVE grid (Figure 1) was found by interpolating depths from the North Atlantic Coast Comprehensive Study's ADvanced CIRculation model (ADCIRC) mesh (Cialone et al. 2015). The VDatum tool, developed by NOAA, was used to convert the bathymetry of the ADCIRC mesh from Mean Sea Level to Mean Lower Low Water. To better resolve the channel bathymetry, the water depth within the channel was updated to its maintenance depth of 15.2 m (50 ft). Those areas of the channel that were already deeper than the required 15.2 m were left at their original interpolated depths. Bottom friction values for the STWAVE grid were found by interpolating Manning n values from the same ADCIRC mesh.

Simulations were conducted using the full-plane mode of the STWAVE model to allow for wave generation in a full 360-degree plane. The input spectra from WIS station 199 were set as constant along the offshore boundary of the STWAVE domain. The spectra were represented by 32 frequency bands, ranging from 0.025 Hz to 0.335 Hz. A total of 72 angle bands were used for the simulations, ranging from an angle of 0 deg to 355 deg with respect to the x-axis. Angle resolution was 5 degrees.

A total of 49 wave conditions with varying significant wave heights (H_s), peak periods (T_p), wave directions (Dir), and wind speeds (Winspd) and directions (Windir) were

modeled (Table 4). Each of these cases were modeled with a non-adjusted water level as well as an adjusted water level of 0.61 m (2 ft), resulting in 98 simulations. The modeled conditions do not represent extreme storm conditions, as a ship would be unlikely to be traversing the harbor under such circumstances; rather, they represent both mid-range and high non-storm wave conditions. Although an analysis of each case for all eleven savepoints is beyond the scope of this report, extreme or otherwise significant results are examined in the next section.

Table 4. Wind and Wave Conditions for Each STWAVE Case.

ID	H_s (ft)	T_p (s)	Dir (deg)	Winspd (knt)	Windir (deg)	H_s (m)	Winspd (m/s)
1	4.8	6.2	67.5	29.2	36.3	1.46	15.02
2	4.8	8.2	67.5	23.3	43.6	1.46	11.99
3	4.8	10.0	67.5	17.4	142.25	1.46	8.95
4	4.8	11.8	67.5	25.4	187.5	1.46	13.07
5	4.8	13.8	67.5	23.4	266	1.46	12.04
6	4.8	15.8	67.5	16.7	316	1.46	8.59
7	4.8	18.0	67.5	8.9	39.0	1.46	4.58
8	4.8	6.3	90.0	23	107	1.46	11.83
9	4.8	8.1	90.0	16.7	203.7	1.46	8.59
10	4.8	9.9	90.0	15.8	158.7	1.46	8.13
11	4.8	11.8	90.0	20.8	236.3	1.46	10.70
12	4.8	13.8	90.0	22.3	191	1.46	11.47
13	4.8	15.8	90.0	17.2	121.5	1.46	8.85
14	4.8	6.4	112.5	28.2	145	1.46	14.51
15	4.8	8.1	112.5	21.2	236.5	1.46	10.91
16	4.8	9.9	112.5	25	304	1.46	12.86
17	4.8	11.8	112.5	19.3	272.6	1.46	9.93
18	4.8	13.8	112.5	19.6	95	1.46	10.08
19	4.8	15.8	112.5	12.6	266	1.46	6.48
20	4.8	6.4	135.0	27.5	200.5	1.46	14.15
21	4.8	8.0	135.0	15.1	169	1.46	7.77
22	4.8	9.9	135.0	18	246	1.46	9.26
23	4.8	11.7	135.0	22.3	212	1.46	11.47
24	4.8	13.8	135.0	29.5	247	1.46	15.18
25	8.9	8.4	67.5	31.5	103.5	2.71	16.20
26	8.9	10.2	67.5	31.5	103.5	2.71	16.20
27	8.9	11.8	67.5	31.5	103.5	2.71	16.20
28	8.9	14.1	67.5	31.5	103.5	2.71	16.20
29	8.9	15.3	67.5	31.5	103.5	2.71	16.20
30	8.9	6.6	90	25.2	140	2.71	12.96

ID	H_s (ft)	T_p (s)	Dir (deg)	Winspd (knt)	Windir (deg)	H_s (m)	Winspd (m/s)
31	8.9	8.4	90	25.2	140	2.71	12.96
32	8.9	10.1	90	25.2	140	2.71	12.96
33	8.9	11.9	90	25.2	140	2.71	12.96
34	8.9	13.7	90	25.2	140	2.71	12.96
35	8.9	16.1	90	25.2	140	2.71	12.96
36	8.9	19.9	90	25.2	140	2.71	12.96
37	8.9	6.6	112.5	27.2	167	2.71	13.99
38	8.9	8.4	112.5	27.2	167	2.71	13.99
39	8.9	10.1	112.5	27.2	167	2.71	13.99
40	8.9	11.9	112.5	27.2	167	2.71	13.99
41	8.9	13.7	112.5	27.2	167	2.71	13.99
42	8.9	16.1	112.5	27.2	167	2.71	13.99
43	8.9	19.9	112.5	27.2	167	2.71	13.99
44	8.9	8.5	135	32.4	179	2.71	16.67
45	8.9	9.9	135	32.4	179	2.71	16.67
46	8.9	12.4	135	32.4	179	2.71	16.67
47	8.9	14	135	32.4	179	2.71	16.67
48	8.9	15.6	135	32.4	179	2.71	16.67
49	8.9	18.3	135	32.4	179	2.71	16.67

ANALYSIS: Overall, the wave heights at each of the savepoints in the channel were noticeably larger for cases with a larger offshore wave height, but were not significantly different for the adjusted water level cases versus the non-adjusted cases. Figure 23 shows the significant wave height (in meters) for the non-adjusted water level cases that resulted in the lowest and highest average significant wave height considering all the savepoint locations. The wave heights (H_s), mean (T_m) and peak wave periods (T_p), and wave directions with reference to STWAVE (WaveDirSTW) and meteorological (WaveDirMet) conventions for each of these points are listed in Table 6.

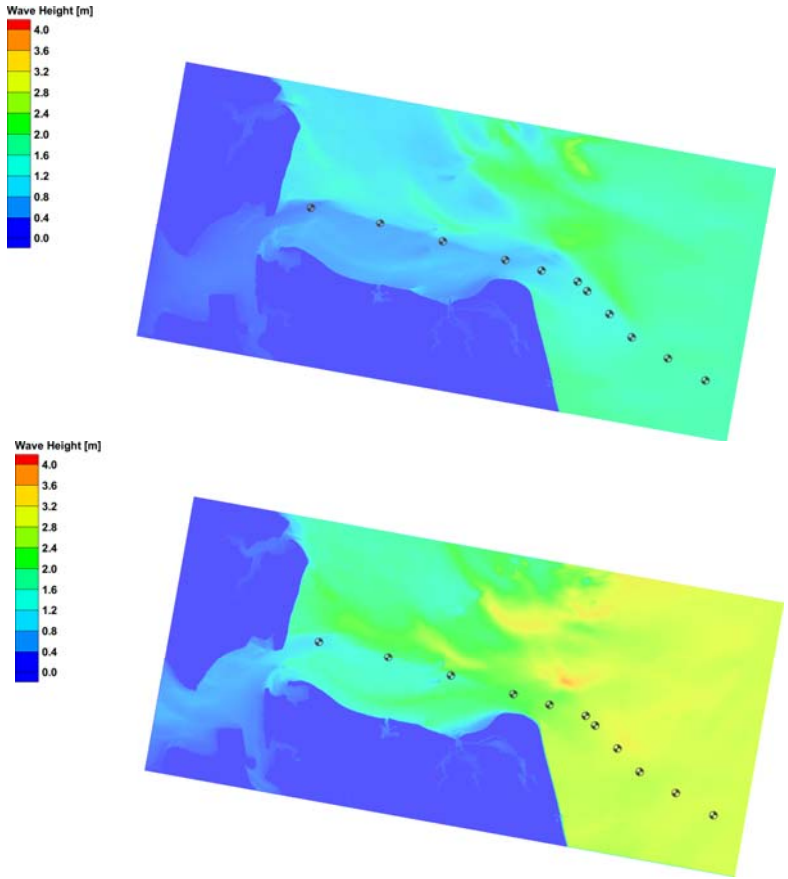

Figure 23. Significant wave height results (m) for Case 19 (top) and Case 25 (bottom), which had the lowest and highest average Hs values, respectively, at the savepoints amongst the non-adjusted cases.

Both cases exhibited the same basic trends with respect to wave height. The savepoints located closest to the mouth of the harbor had the largest wave heights, which generally decreased as waves propagated towards the shoreline. The region between Savepoints 1 and 2 saw a slight wave height increase for both water level cases. Savepoint 2 and Savepoint 4 had the largest wave height for the lowest average wave height case (Case 19) and the highest average wave height case (Case 25), respectively. The smallest significant wave height for both cases was seen at Savepoint 11.

Table 5. Savepoint Data for Non-Adjusted Cases 19 and 25.

	Case 19					Case 25				
Savepoint ID	H_s (m)	T_m (s)	WaveDirSTW	T_p (s)	WaveDirMet	H_s (m)	T_m (s)	WaveDirSTW	T_p (s)	WaveDirMet
1	1.44	13.9	346.4	15.4	-246.2	2.69	7.5	27.2	8.3	73.0
2	1.51	14.0	349.2	15.4	-249.0	2.71	7.3	24.7	8.3	75.5
3	1.3	13.8	341.8	15.4	-241.6	2.64	7.2	18.7	8.3	81.5
4	1.19	13.5	344.9	15.4	-244.7	2.77	7.4	20.8	8.3	79.4
5	1.16	13.5	351.8	15.4	-251.6	2.65	7.3	16.8	8.3	83.4
6	1.11	13.5	353.2	15.4	-253	2.58	7.2	14.5	8.3	85.7
7	0.85	13.0	2.9	15.4	97.3	2.28	6.9	17.3	8.3	82.9
8	0.54	11.2	24.6	15.4	75.6	2.01	6.6	16.1	8.3	84.1
9	0.51	11.8	46.3	15.4	53.9	1.48	6.0	10.2	8.3	90.0
10	0.52	11.6	24.2	15.4	76.0	1.41	5.9	7.1	8.3	93.1
11	0.30	8.1	228.2	15.4	-128.0	0.96	5.0	357.3	3.9	-257.1

Figure 24 and Table 6 show the STWAVE results for the cases with the lowest and highest average wave heights at the channel savepoints for the adjusted water level scenario. Overall, the results showed trends very similar to those of the non-adjusted cases. The lowest and highest averages cases did not have significant wave height differences compared to the non-adjusted water level simulations. As before, wave height generally decreased along the channel after seeing a small increase between the first two CADET savepoints. Savepoint 11 had the smallest wave heights for both cases, while Savepoints 2 and 4 had the largest heights for the lowest (Case 19) and highest (Case 25) average cases, respectively. The wind and wave input values that produced these two cases were the same as those used for the lowest and highest average wave height cases in the non-adjusted water level scenario.

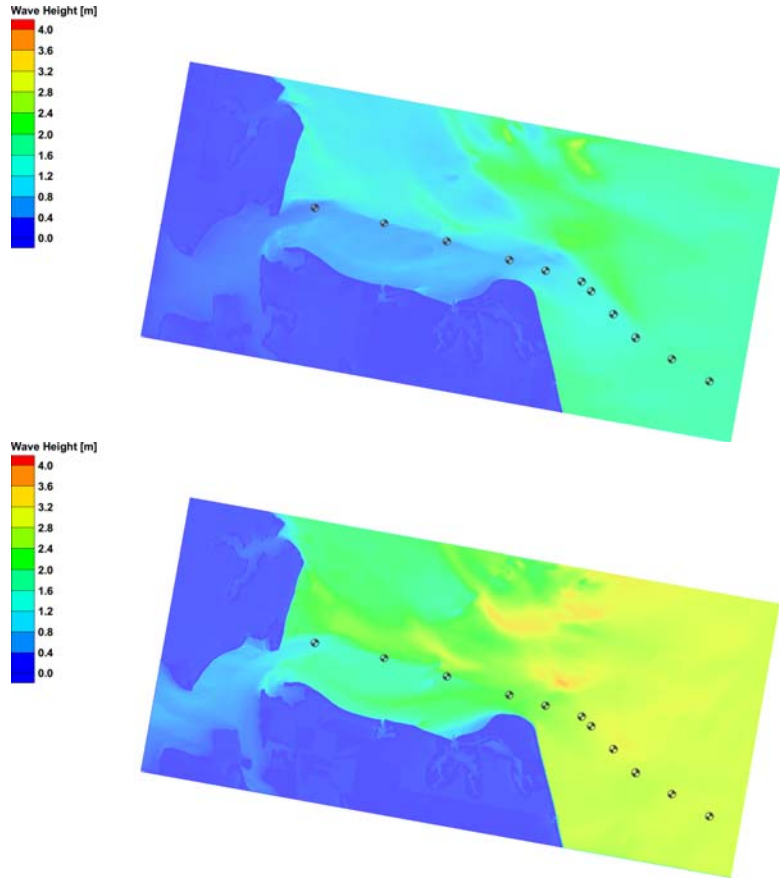

Figure 24. Significant wave height results (m) for Case 19 (top) and Case 25 (bottom), which had the lowest and highest average Hs values, respectively, at the savepoints for the adjusted water level cases.

Table 6. Savepoint Data for Adjusted Cases 19 and 25.

	Case 19					Case 25				
Savepoint ID	H_s (m)	T_m (s)	WaveDirSTW	T_p (s)	WaveDirMet	H_s (m)	T_m (s)	WaveDirSTW	T_p (s)	WaveDirMet
1	1.44	13.9	346.4	15.4	-246.2	2.70	7.5	27.4	8.3	72.8
2	1.51	14.0	349.1	15.4	-248.9	2.71	7.3	24.9	8.3	75.3
3	1.31	13.8	342.0	15.4	-241.8	2.66	7.2	19.3	8.3	80.9
4	1.2	13.5	345.1	15.4	-244.9	2.78	7.4	21.3	8.3	78.9
5	1.18	13.5	351.6	15.4	-251.4	2.67	7.3	17.5	8.3	82.7
6	1.13	13.5	352.9	15.4	-252.7	2.61	7.2	15.4	8.3	84.8
7	0.87	13.0	2.4	15.4	97.8	2.33	7.0	18.0	8.3	82.2
8	0.56	11.3	24.3	15.4	75.9	2.10	6.7	18.0	8.3	82.2
9	0.53	12.1	46.4	15.4	53.8	1.64	6.2	14.2	8.3	86.0
10	0.54	11.8	23.6	15.4	76.6	1.59	6.2	11.0	8.3	89.2
11	0.32	8.4	321.3	15.4	-221.1	1.12	5.3	2.5	8.3	97.7

To compare the wave height outputs for each of the CADET savepoints, the average wave height at each location were calculated across simulations of similar water level and offshore wave height conditions (Table 7). Savepoint 2 had the highest average wave height for all cases, and the wave height almost always decreased along the channel. It should also be noted that the average wave heights for each location did not differ drastically between adjusted and non-adjusted cases with the same offshore wave forcing, particularly at points closest to the harbor entrance. However, as expected, large differences were seen between cases with initial wave heights of 1.46 m and those with initial heights of 2.71 m. This indicates that the increased offshore wave height had a significant effect on wave heights estimates along the channel.

Table 7. Average Significant Wave Heights of Savepoints.

	All Non-adjusted Cases (Hs_0 = 1 .46 m)	All Adjusted Cases (Hs_0 = 1.46 m)	All Non-adjusted Cases (Hs_0 = 2.71 m)	All Adjusted Cases (Hs_0 = 2.71 m)
Savepoint ID	Avg. H_s (m)	Avg. H_s (m)	Avg. H_s (m)	Avg. H_s (m)
1	1.53	1.53	2.71	2.72
2	1.56	1.56	2.78	2.78
3	1.46	1.47	2.55	2.56
4	1.44	1.46	2.45	2.48
5	1.39	1.41	2.35	2.38
6	1.35	1.37	2.27	2.30
7	1.12	1.15	1.84	1.89
8	0.92	0.95	1.30	1.35
9	0.80	0.85	1.07	1.15
10	0.81	0.86	1.06	1.16
11	0.57	0.62	0.77	0.84

CONCLUSION: The results shown above detail the estimated wave conditions produced by the STWAVE model in Norfolk Harbor. The values indicate that wave heights across both water level cases were largest in the easternmost portions of the Norfolk Harbor Channel, with heights decreasing along the channel as waves propagated toward shore. Cases with significantly larger offshore wave heights were observed to have noticeably greater wave heights at each savepoint location. Comparisons between cases that had the same wind and wave input conditions but were conducted with and without a 0.61 m (2 ft) water level adjustment showed that while the adjusted cases tended to have slightly higher wave height values in the channel, the differences were typically small.

REFERENCES: Cialone, M.A., T.C. Massey, M.E. Anderson, A.S. Grzegorzewski, R.E. Jensen, A. Cialone, D.J. Mark, K.C. Pevey, B.L. Gunkel, T.O. McAlpin, N.C. Nadal-Caraballo, J.A. Melby, and J.J. Ratcliff. *North Atlantic Coast Comprehensive Study (NACCS) Coastal Storm Model Simulations: Waves and Water Levels*. ERDC/CHL TR-15-14. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Massey, T.C., M.E. Anderson, J.M. Smith, J. Gomez, and R. Jones. 2011. *STWAVE: Steady-state spectral wave model user's manual for STWAVE, Version 6.0*. ERDC/CHL SR-11-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

ADDITIONAL INFORMATION: This letter report was prepared by Elizabeth Godsey (Elizabeth.S.Godsey@usace.army.mil) of the Mobile District, U.S. Army Corps of Engineers and Margaret Owensby (Margaret.B.Owensby@erdc.dren.mil) and Mary Bryant (Mary.Bryant@usace.army.mil) of the Coastal Hydraulics Laboratory of the U.S. Army Corps Engineer Research and Development Center.

APPENDIX

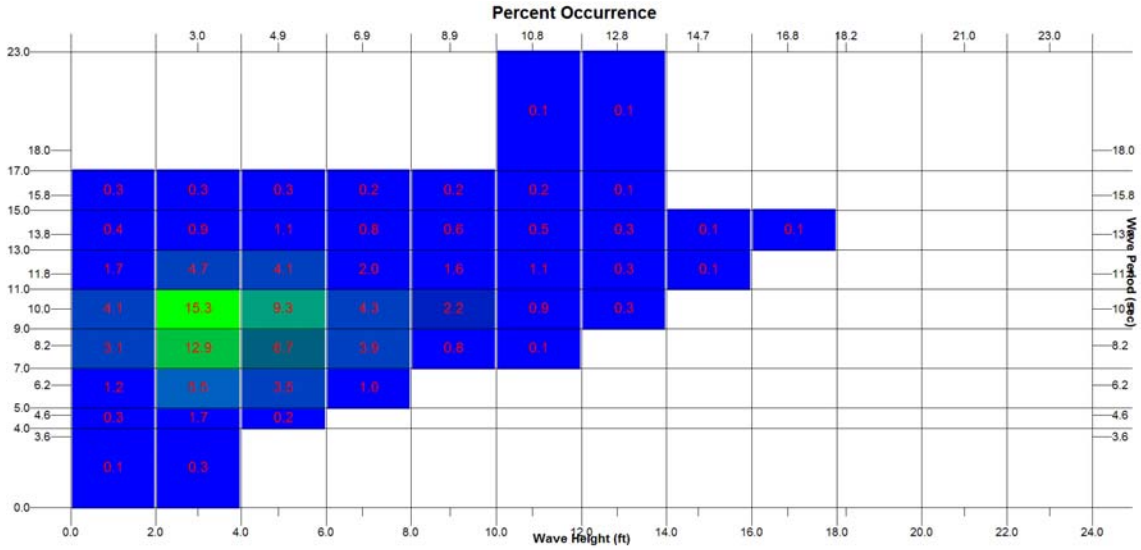

Figure A1. WIS199 percent occurrence table, Tp vs. Hs, θp=67.5 deg, direction limited cases, (WIS199_allyrs_dir_block%_tpvshs_dir67.5.bmp).

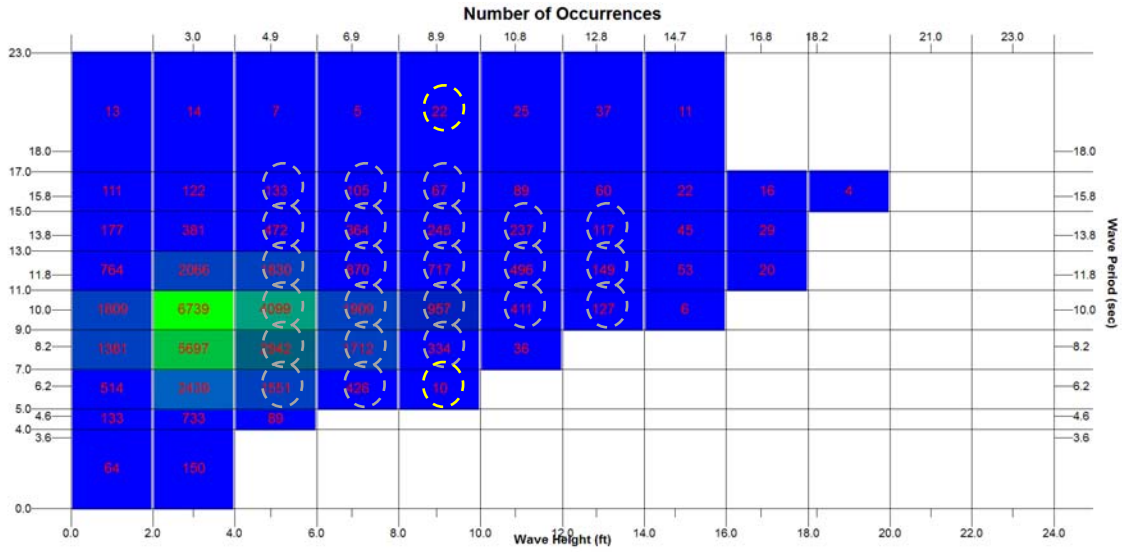

Figure A2. WIS199 number of occurrences table, Tp vs. Hs, θp=67.5 deg, direction limited cases, (WIS199_allyrs_dir_blocknum_tpvshs_dir67.5.bmp)

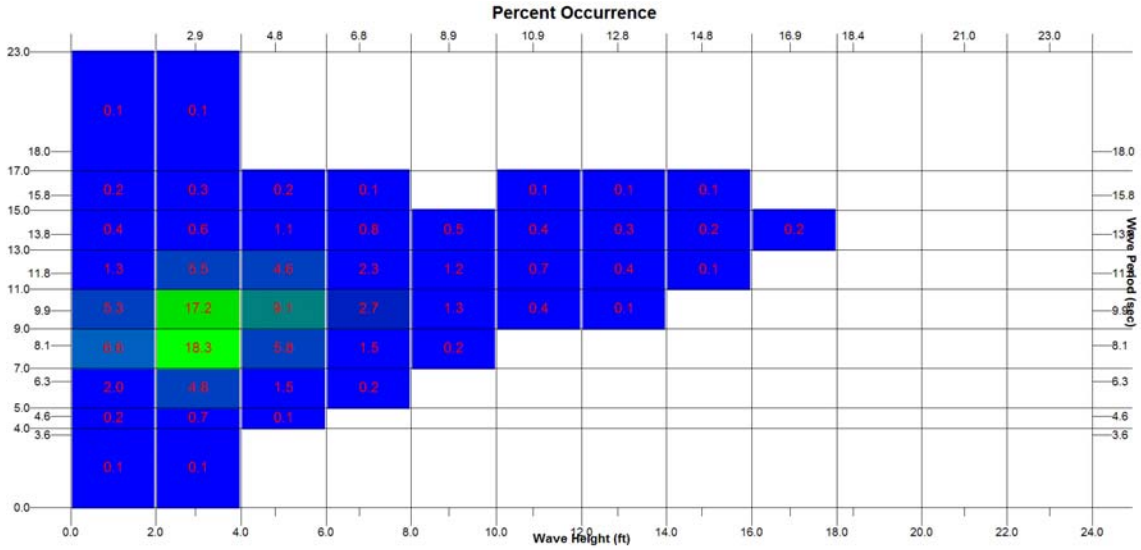

Figure A3. WIS199 percent occurrence table, Tp vs. Hs, θp=90.0 deg, direction limited cases, (WIS199_allyrs_dir_block%_tpvshs_dir90.0.bmp).

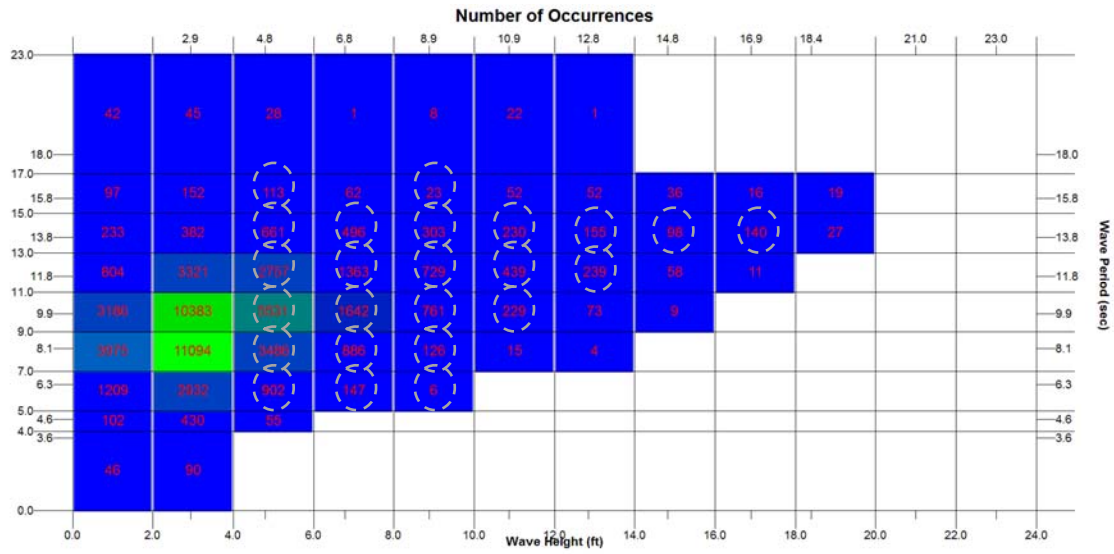

Figure A4. WIS199 number of occurrences table, Tp vs. Hs, θp=90.0 deg, direction limited cases, (WIS199_allyrs_dir_blocknum_tpvshs_dir90.0.bmp)

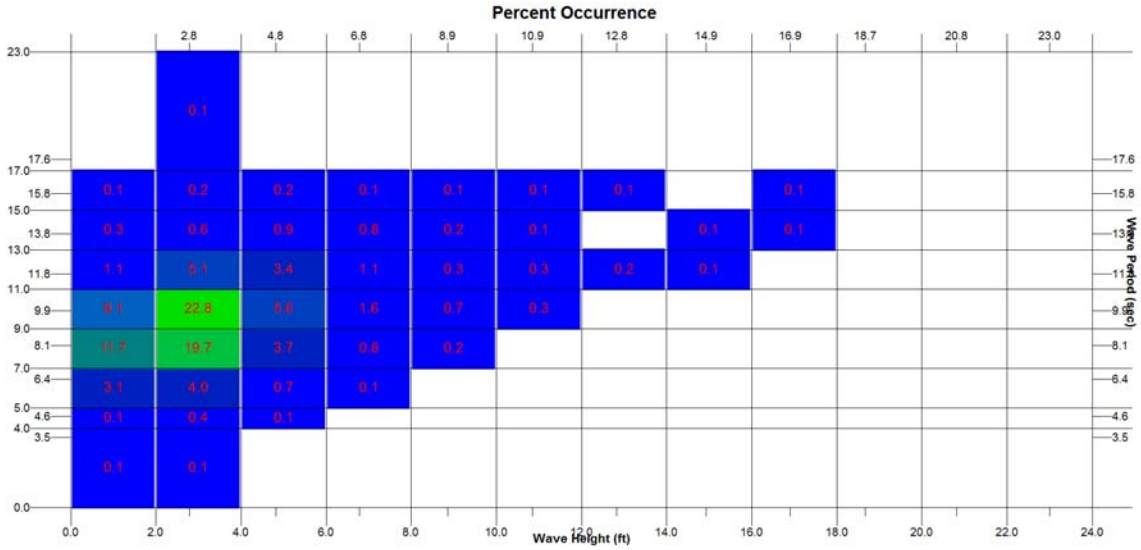

Figure A5. WIS199 percent occurrence table, Tp vs. Hs, θp=112.5 deg, direction limited cases, (WIS199_allyrs_dir_block%_tpvshs_dir112.5.bmp).

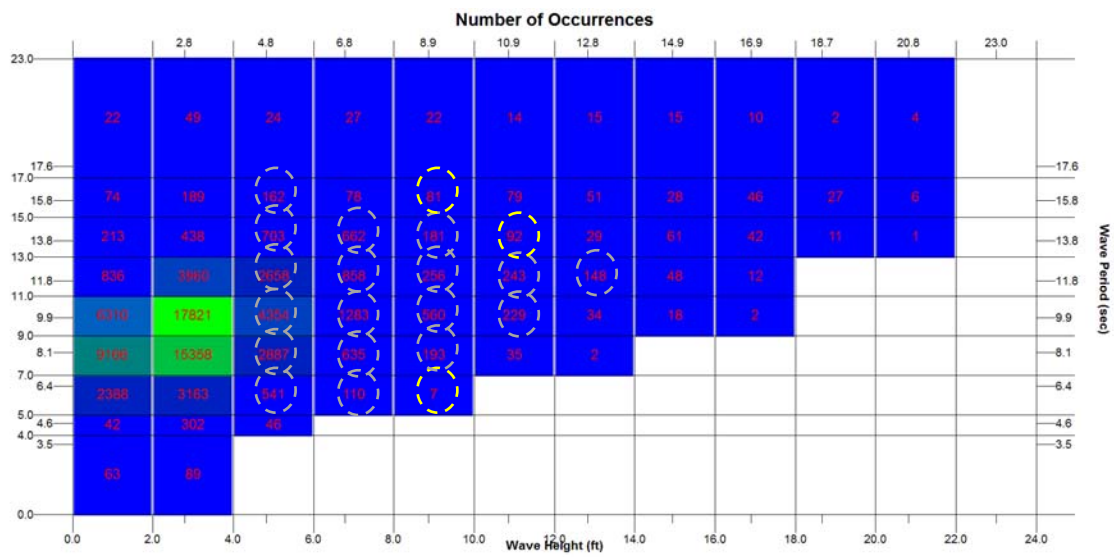

Figure A6. WIS199 number of occurrences table, Tp vs. Hs, θp=112.5 deg, direction limited cases, (WIS199_allyrs_dir_blocknum_tpvshs_dir112.5.bmp)

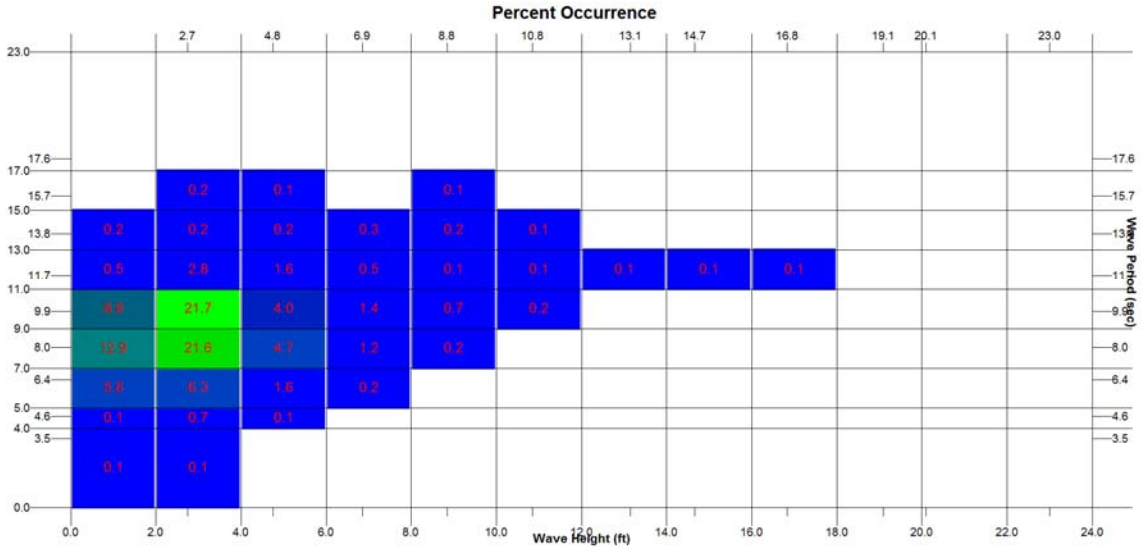

Figure A7. WIS199 percent occurrence table, Tp vs. Hs, θp=135.0 deg, direction limited cases, (WIS199_allyrs_dir_block%_tpvshs_dir135.0.bmp).

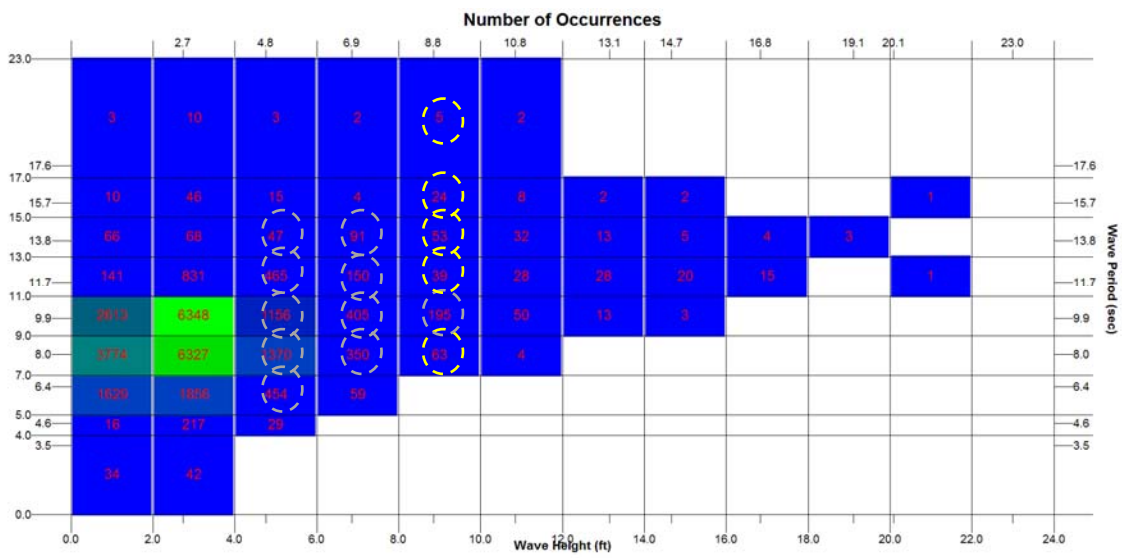

Figure A8. WIS199 number of occurrences table, Tp vs. Hs, θp=135.0 deg, direction limited cases, (WIS199_allyrs_dir_blocknum_tpvshs_dir135.0.bmp)

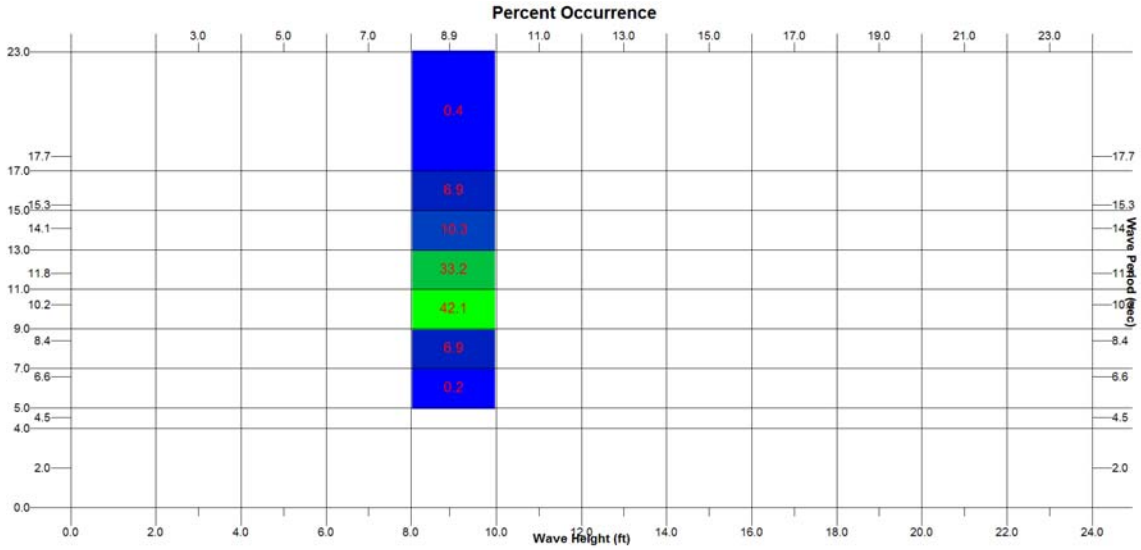

Figure A9. WIS199 percent occurrence table, Tp vs. Hs, θp=67.5 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_block%_tpvshs_dir67.5.bmp).

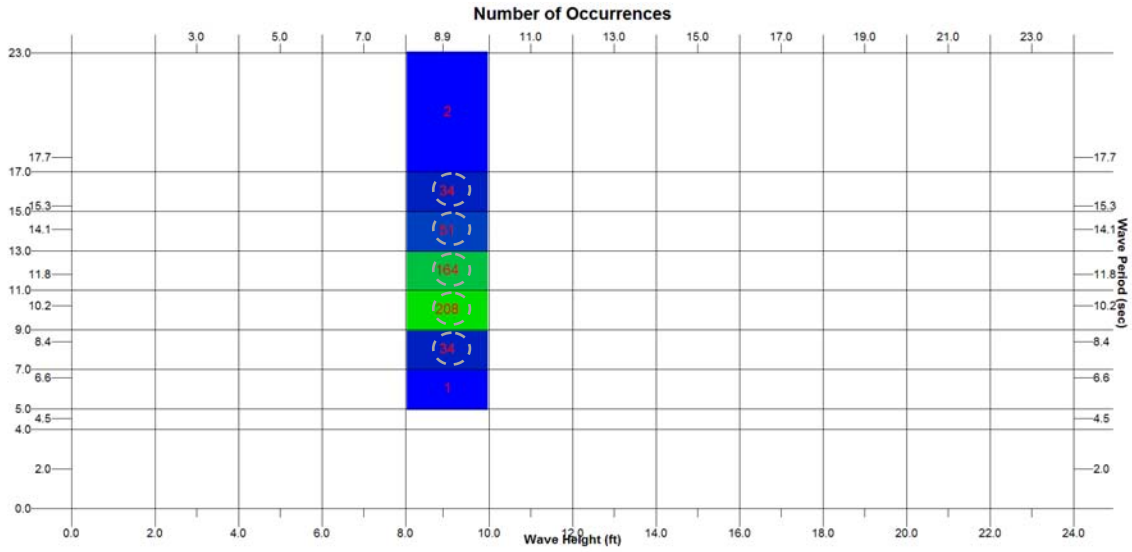

Figure A10. WIS199 number of occurrences table, Tp vs. Hs, θp=67.5 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_blocknum_tpvshs_dir67.5.bmp)

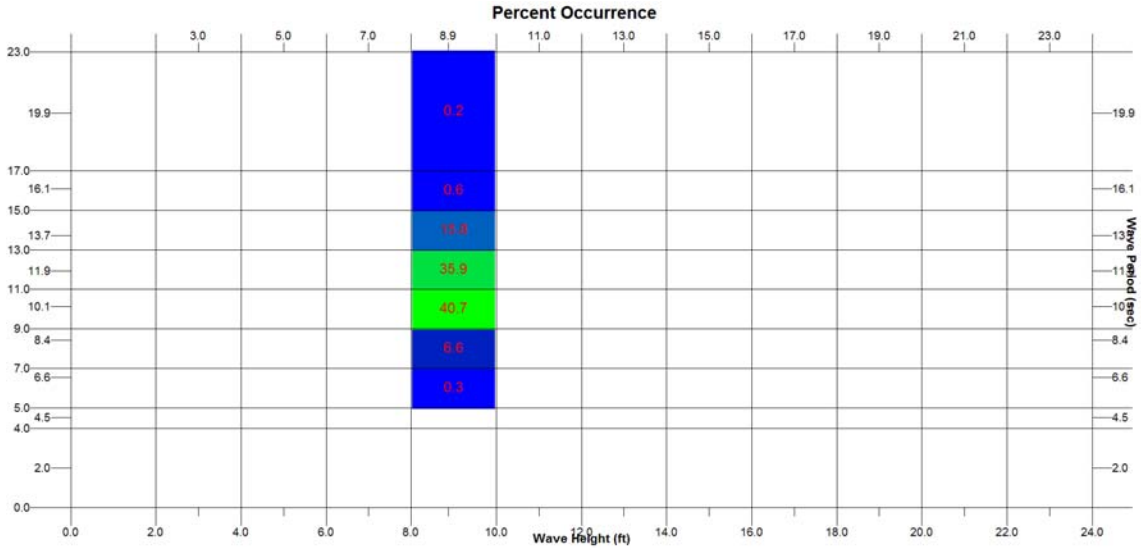

Figure A11. WIS199 percent occurrence table, Tp vs. Hs, θp=90.0 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_block%_tpvshs_dir90.0.bmp).

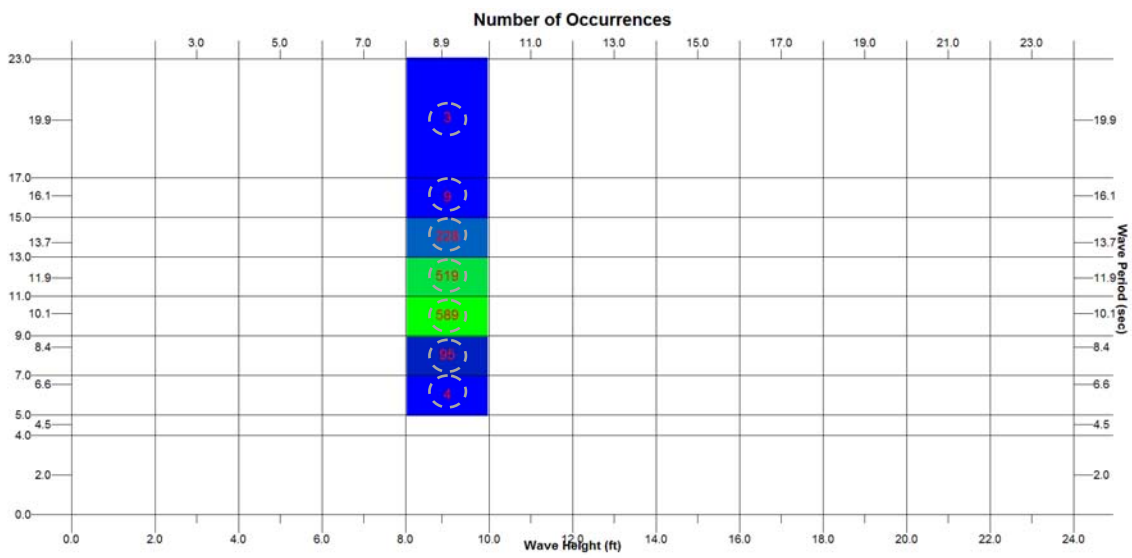

Figure A12. WIS199 number of occurrences table, Tp vs. Hs, θp=90.0 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_blocknum_tpvshs_dir90.0.bmp)

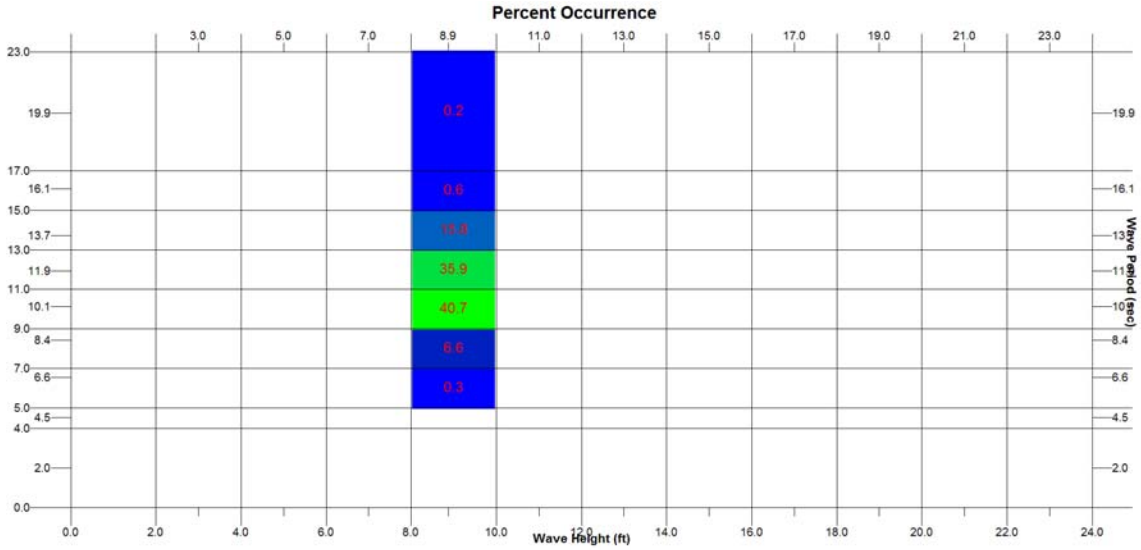

Figure A13. WIS199 percent occurrence table, Tp vs. Hs, θp=112.5 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_block%_tpvshs_dir112.5.bmp).

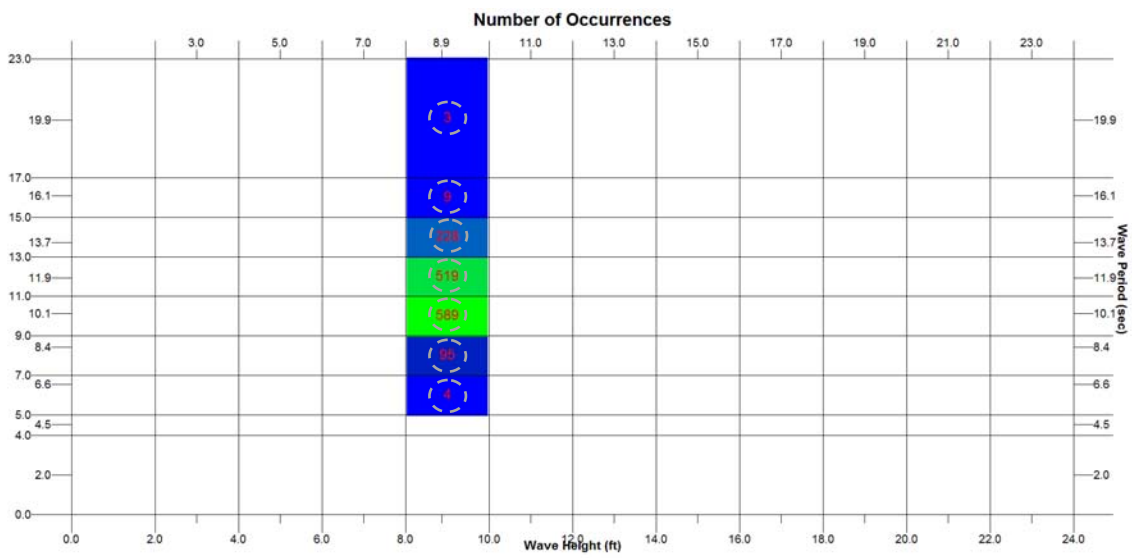

Figure A14. WIS199 number of occurrences table, Tp vs. Hs, θp=112.5 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_blocknum_tpvshs_dir112.5.bmp)

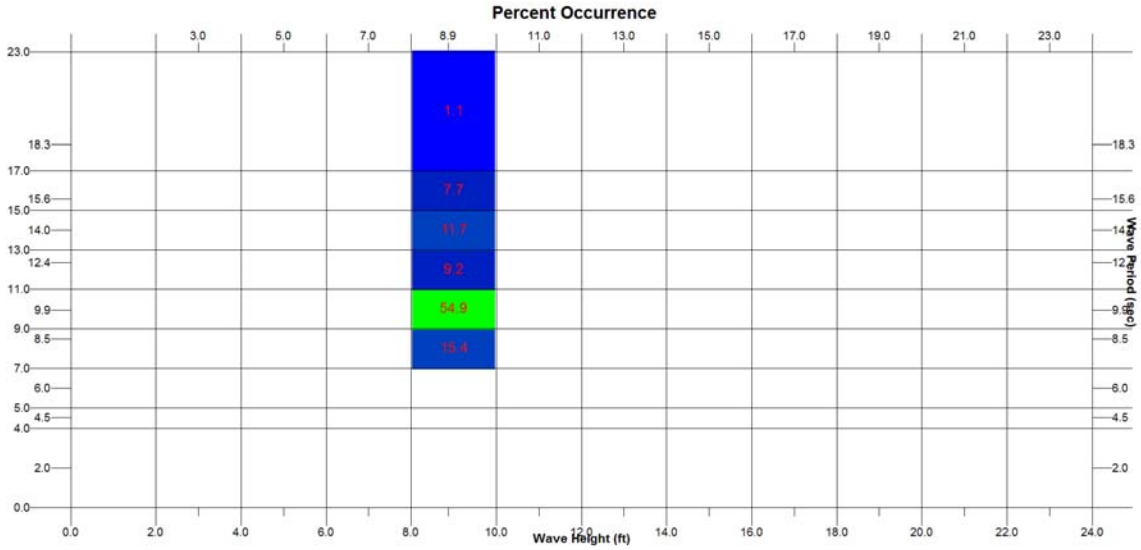

Figure A15. WIS199 percent occurrence table, Tp vs. Hs, θp=135.0 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_block%_tpvshs_dir135.0.bmp).

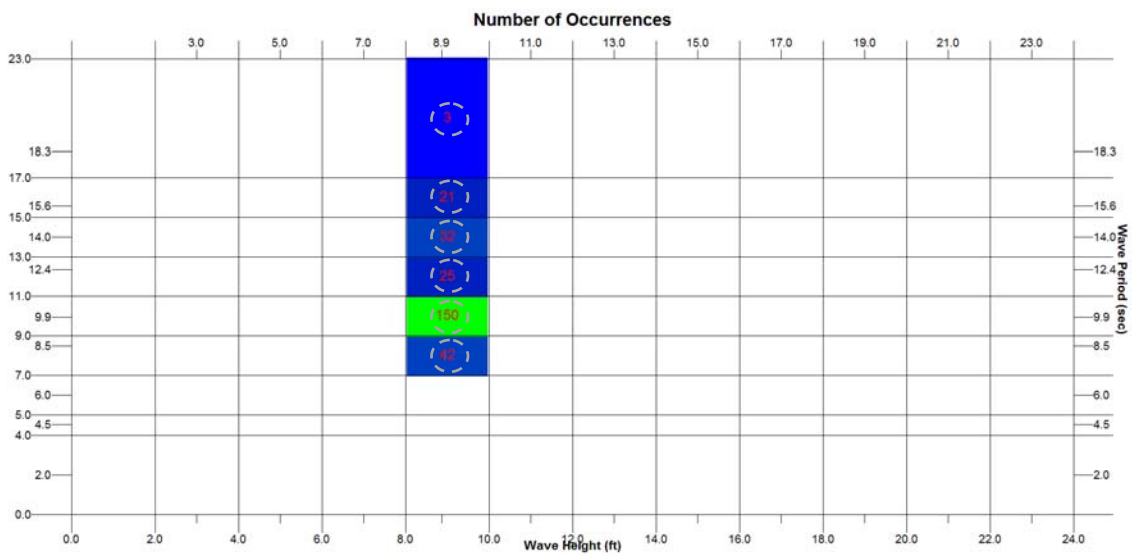

Figure A16. WIS199 number of occurrences table, Tp vs. Hs, θp=135.0 deg, direction limited cases, top 3-5% wave heights, (WIS199_allyrs_dir_3to5_blocknum_tpvshs_dir135.0.bmp)

Engineering Appendix D: Sedimentation Study

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11/11/2016

Memorandum

Revision	Date	By	Reviewed By	Comment
1	7/20/2016	R Mathew	R Canizares	Initial Draft, for DQC
2	9/29/2016	R Mathew	B Joyner, I Brotman	Updated w/ TSC Meeting Areas & AOC maintenance dredging rate
3, Final	11/11/2016	R Mathew	I Brotman	Updated w/ District DQC comments

Subject: **Desktop Assessment of Future Sedimentation Rates**
Norfolk Harbor and Channels Deepening, Virginia and Elizabeth River and *Southern Branch of the Elizabeth River, Virginia Navigation Improvements* General Reevaluation Reports

1. Introduction

The navigation channels leading into Norfolk Harbor from the Chesapeake Bay and the Atlantic Ocean, along with the channels within Norfolk Harbor and the Southern Branch of the Elizabeth River are currently the subject of two feasibility studies (General Reevaluation Reports) for deepening and navigation improvements. As part of the impact assessments associated with the proposed deepening projects, a desktop analysis has been conducted for a first-order estimate of the maintenance dredging rate to be expected in the navigation channels following deepening. Since the periodic maintenance dredging primarily includes sediments deposited on top of the native sediment surface within the channel (the native sediment surface is the sediment strata exposed following the deepening of the channel), the maintenance dredging rate can be considered to be the same as the sedimentation rate. Therefore the terms maintenance dredging rate and sedimentation rate are used interchangeably in the remainder of this document. The following provides an overview of the study area, followed by an overview of the approach for estimating the future sedimentation rate, the data used, and the results of this desktop analysis.

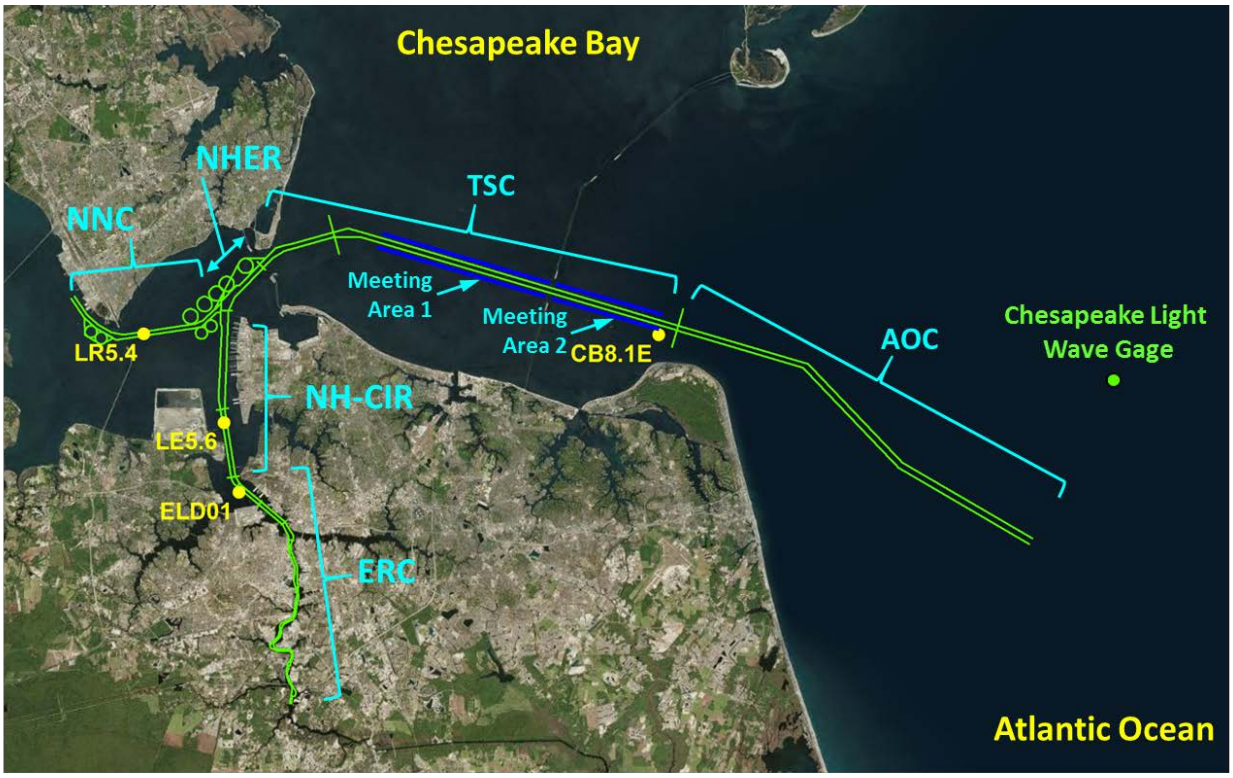
2. Study Area

Figure 1 shows a map with the layout of the navigation channel in the vicinity of Norfolk Harbor. Discrete portions of the navigation channel relevant to the analysis presented here are also identified in this map. For purposes of this study, the estimates of sedimentation rates have been developed separately for the following zones:

- Elizabeth River Channel (ERC)
- Norfolk Harbor and Craney Island Reaches (NH-CIR)
- Norfolk Harbor Entrance Reach (NHER)
- Newport News Channel (NNC)

- Thimble Shoals Channel (TSC)
- Atlantic Ocean Channel (AOC)

The channel segments (as designated by the US Army Corps) comprising these zones as well as the current and proposed channel dimensions are shown in Table 1. Current channel depths (as constructed) range from about 35' in the Elizabeth River to 52' in the Atlantic Ocean Channel. Natural channel depths (i.e. depth in the cross-section outside the channel) range from about 15' in the Elizabeth River to 44' in the Atlantic Ocean Channel. In other words, the channel bottom in the Elizabeth River is currently about 20' deeper than the areas outside the channel. In comparison, the channel bottom in the Atlantic Ocean Channel is currently only 8'-10' deeper than the adjacent seafloor outside the channel. This has implications for the estimated future sedimentation rate as discussed subsequently in this memorandum. In addition to the deepening of the navigation channels, within the Thimble Shoals Channel (TSC), two meeting areas are also under consideration. Each of the meeting areas include an additional 200 feet of bottom width on either side of the channel. Therefore, the analysis of future sedimentation rates in zone TSC includes estimates with and without these meeting areas.



AOC – Atlantic Ocean Channel
TSC – Thimble Shoals Channel
ERC – Elizabeth River Channel
NH-CIR – Norfolk Harbor and Craney Island Reaches
NHER – Norfolk Harbor Entrance Reach
NNC – Newport News Channel

Water Quality Data Locations
Wave Gage

Figure 1. Site map showing the layout of the navigation channel in Norfolk Harbor and Elizabeth River along with locations of various data referenced in this analysis.

Table 1. Current and proposed dimensions of the various channel segments in Norfolk Harbor and Elizabeth River.

Zone	Channel Segment	Length (ft)	Design Side Slopes (H toV)	Natural Depth[1] (ft)	Bottom Width[2] (ft)	USACE Maintained Channel Depth (ft)	Estimated Approximate Current Top Width[3] (ft)	Proposed Channel Depth (ft)	Estimated Approximate Proposed Top Width[4] (ft)
ERC	Elizabeth River Reach	15840	3 to 1	23	750	40	852	47	894
ERC	Lower Reach	10560	3 to 1	32	450	40	498	47	540
ERC	Middle Reach	5280	3 to 1	26.5	375	40	456	47	498
ERC	Upper Reach A	12672	3 to 1	25	375	35	435	42	477
ERC	Upper Reach B	3168	3 to 1	18	300	35	402	37	414
ERC	Upper Reach C	7920	3 to 1	15	250	35	370	37	382
NH-CIR	Craney Island Reach	15840	3 to 1	15	800	50	1010	58	1058
NH-CIR	Norfolk Harbor Reach	21120	3 to 1	20	1200	50	1380	58	1428
NHER	Norfolk Harbor Entrance Reach	10560	3 to 1	27	1220	50	1358	58	1406
NNC	Newport News Channel	28512	3 to 1	22	800	50	968	58	1016
TSC	Thimble Shoals Channel	68640	3 to 1	40	1000	50	1060	58	1108
TSC	Meeting Area 1[5]	36457	3 to 1	40	1400	50	1060	58	1508
TSC	Meeting Area 2[5]	21266	3 to 1	40	1400	50	1060	58	1508
AOC	Atlantic Ocean Channel	52800	3 to 1	44	1300	52	1348	61	1402

[1] Natural depth refers to the depth of the seabed outside the channel. In other words, the depth of the seabed before construction of the channels.
[2] With the exception of the two Meeting Areas, width listed indicates the current width. For the two Meeting Areas, with listed is the future width.
[3] Since the navigation channel is constructed with a side slope of 3 to 1, width is larger at the top of the channel than at the bottom.
[4] The width at the top of the channel increases from current conditions because of the increase in channel depth which causes a widening of the channel up to the top to maintain a side slope of 3 to 1.
[5] Meeting Areas 1 & 2 both include an 200 feet of additional bottom width on either side of the channel

In addition to the channel segments described here, anchorage areas adjacent to the Norfolk Harbor Entrance Reach (zone NHER), and Newport News Channel (zone NNC) are also proposed to be deepened. These areas are also shown in Figure 1, apparent as circular areas adjacent to the channel in zones NHER and NNC. However, this memorandum does not include estimates of future maintenance dredging in the anchorage areas because (1) the methods used for estimating maintenance dredging in the channel segments are not suitable for the circular planform geometry of these areas, and (2) as described subsequently, the maintenance dredging in the anchorage areas is relatively small compared to the channel segments.

3. Methods to Estimate Future Sedimentation Rate

Future sedimentation rates within the study area have been estimated by analytical and empirical methods. As described subsequently, two different analytical methods were used in different parts of the study area, mainly driven by the physical processes considered responsible for sedimentation. The analytical approaches follow the basin sedimentation approach of Eysink and the channel sedimentation approach of Van Rijn. The approach chosen for a given zone is a function of the physical processes expected to dominate sediment transport in that zone. Table 2 lists the physical processes expected to be responsible for sedimentation in each zone, and the resulting analytical approach used. Both approaches are implemented as spreadsheet-based tools applied for a representative tidal condition. In addition, specifically for the TSC zone, future sedimentation rates have also been estimated using the Volume of Cut empirical approach described in Van Rijn. Each of these approaches is described briefly. All three methods were first applied to and calibrated to reproduce the ongoing sedimentation rate (i.e., the current maintenance dredging rate). Subsequently, the calibrated method for each zone was applied to estimate the future sedimentation rate in that zone. This is further described in the following sections.

Table 2. Physical processes expected to influence sedimentation and the analytical approach used to estimate future sedimentation rate for various zones.

Zone	Analytical Approach	Physical Processes Expected to Influence Sedimentation
ERC	Eysink	Tidal infilling and density (salinity) driven circulation
NH-CIR	Eysink	Tidal infilling and density (salinity) driven circulation
NHER	Van Rijn	Tidal currents
NNC	Van Rijn	Tidal currents
TSC	Van Rijn	Tidal currents and waves
TSC w/ Meeting Areas	Van Rijn	Tidal currents and waves
AOC	Van Rijn	Tidal currents and waves

3.1 Basin Sedimentation Method

The harbor basin sedimentation approach of Eysink and Vermaas (1983) and Eysink (1989) has been used to calculate sedimentation in the ERC and NH-CIR zones. This method is applicable

to enclosed or semi-enclosed basins or tidal channels. Briefly, it involves the calculation of the water exchange between the basin and adjacent marine environment due to the vertical gradient in density (salinity) within the basin, due to tidal inflow and outflow, and due to horizontal eddies generated by horizontal gradients in currents at the mouth of the basin. The latter two processes are depicted in Figure 2. The exchange of water between the basin and surrounding waters when associated with a suspended sediment concentration (SSC) provides a sediment load entering the basin per tidal cycle. Due to lower flow velocities within the basin, a fraction of this total sediment influx can deposit in the basin, with the deposition flux calculated based on the trapping efficiency of the system which is a function of the settling velocity of the suspended sediments, and other basin-specific parameters such as the total water depth and residence time within the basin. Thus, the outflowing water (during the ebb tide), will be associated with a lower SSC compared to the inflowing water. The net difference in SSC reflects the sedimentation in the basin during that tidal cycle.

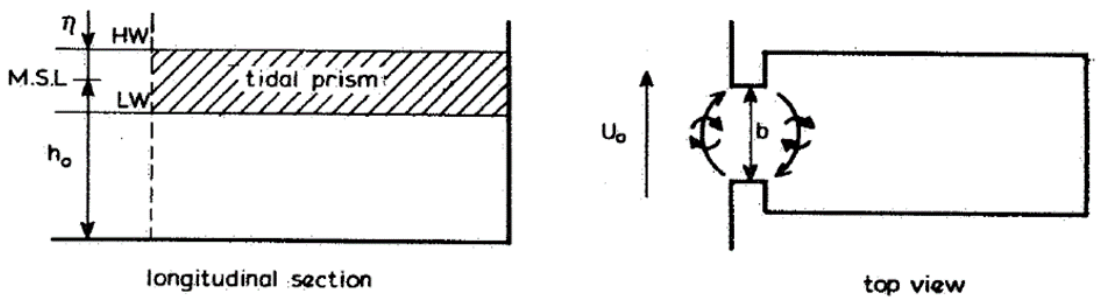


Figure 2. Schematic of volume exchange for tidal basins: tidal exchange (left) and horizontal eddy filling (right). Adapted from Eysink and Vermaas (1983).

The method requires information on the geometry of the channel (length, width, and depth), tidal range, density (salinity) gradient, SSC, currents just outside the basin, and settling velocity. This approach was used for the ERC zone (only tidal exchange and salinity-driven circulation active), and for the NH-CIR zone (tidal exchange, salinity-driven circulation, and horizontal eddies active). The basin geometries were defined using the information presented in Table 1; the remaining inputs were derived using a combination of empirical data and numerical model results as described subsequently. Note that in addition to sediments originating from the marine source, zones ERC and NH-CIR are also expected to include sediments originating from the freshwater inflow to the Elizabeth River. The effect of the sediment loadings from the two sources is integrated into the SSC used as an input to this methods. As described subsequently, the SSC is defined on the basis of measured data at appropriate locations for both zones.

3.2 Channel Sedimentation Method

The channel sedimentation approach of Van Rijn (2013) has been used to calculate sedimentation in the NHER, NNC, TSC, and AOC zones. This method is applicable to navigation channels cutting through coastal zones and wide basins. Briefly, this approach involves the calculation of the change in flow velocity within the channel (due to the larger water depth relative to areas outside the channel), and therefore the reduction in sediment transport capacity within the channel. The plan view on the upper panel of Figure 3 shows a schematic of flow (from the bottom left to upper right of the panel) over a channel oriented at an arbitrary angle relative to the direction of tidal currents. The reduction in flow velocity within the channel is calculated using basic equations of motion and continuity. In addition to a reduction in velocity within the channel, the currents also experience refraction (a change in direction). The velocity component perpendicular to the channel experiences a reduction in magnitude that is inversely proportional to the local water depth, while the velocity component parallel to the channel may increase in

magnitude due to a reduction of bottom friction. As a result, the streamlines show a refraction-type pattern in the channel (see Figure 3). Associated with SSC, the sediment load entering the channel is calculated, and using the trapping efficiency of the channel (a function of the flow velocity, settling velocity, and channel geometry), the sediment deposition rate is calculated. In addition to deposition associated with advection (i.e. the horizontal transport of suspended sediment with the tidal currents), wave-driven sediment mobilization from the seafloor adjacent to the channel and potential deposition within the channel can also be calculated.

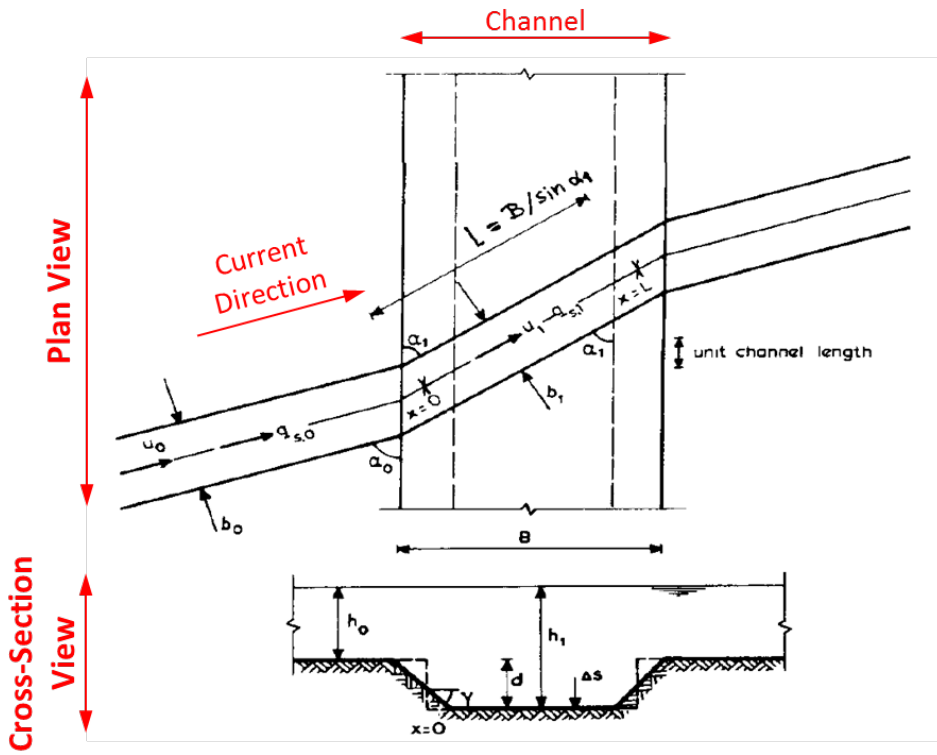


Figure 3. Schematic of flow over a channel oriented at an arbitrary angle relative to the tidal current direction. Adapted from Van Rijn (2013).

The application of the Van Rijn method for calculating sediment deposition due to advection and waves requires information on water depth and currents (over the entire tidal cycle), orientation of the channel relative to tidal current direction, SSC, channel geometry, water depths outside the channel, wave characteristics (height and period), particle size characteristics for the sediments in the bed, and settling velocity. This approach was used for NHER and NNC zones (only considering advection, especially due to the predominantly fine sediments depositing in this zone), and for the TSC and AOC zones (considering advection of fine sediments and wave-driven sand transport which are considered to represent the majority of the sediments currently depositing in this zone as described subsequently in this memorandum). The channel geometries were defined using the information presented in Table 1; the remaining inputs were derived using a combination of empirical data and numerical model results as described subsequently.

3.3 Volume of Cut Method

In addition to the analytical approaches described above, the future sedimentation rate was also estimated using an empirical approach, namely the Volume of Cut approach (Van Rijn, 2013). According to this approach, the volume of sediment deposited in the channel is related to the

volume of sediment that was removed beyond the natural depth (i.e. the volume of cut) to create a channel of given dimensions or to expand an existing channel. For instance, in the example shown in Figure 3, the volume of cut is the cross-sectional area of the channel below the surrounding seafloor, i.e. with depth *d* and associated bottom-width, top-width, and length. Accordingly, this is expressed as:

$$V_d = \gamma V_{Cut} \tag{1}$$

where, V_d is the volume of sediment deposited in the channel on an annual basis, V_{Cut} is the volume of cut, and γ is the proportionality factor.

This approach has been applied to the TSC zone as an additional check on the results of the analytical approach. V_d is set equal to the reported current annual average maintenance dredging rate in this zone, and V_{Cut} is calculated using the channel geometry and seafloor depths given in Table 1. The proportionality term γ is first calculated using the current channel geometry and the current reported maintenance dredging rate. The future maintenance dredging rate is subsequently estimated using the calculated value of γ and the future channel geometry, i.e., the value of V_{Cut} for the future geometry.

4. Data

The application of the analytical and empirical methods described in the preceding section requires information on various physical parameters and processes relevant for sediment transport in the study area. Furthermore, the choice of analytical approach to be applied for a given zone depends upon the physical characteristics of the zone as well as an understanding of the physical processes responsible for sedimentation in that zone. This conceptual understanding of sediment transport dynamics in the study area and the inputs and parameters necessary for the various approaches for estimating future sedimentation rates in the study area were derived from a number of sources as described below.

4.1 Sediment Substrate

Information on the sediment substrate was obtained from the dredged materials characterization study performed by Fugro (2016a, and 2016b). These reports were reviewed to develop a qualitative understanding of the sediments depositing within the various zones and thus guide the representation of various processes within the analytical methods (eg. only currents, or currents and waves). Based on data presentations of the fine sediment content (fraction smaller than 63 μm) in the surficial sediments of the zones relevant to this analysis, the depositing sediments within these zones were classified as either predominantly fine grained or sandy (for purposes of this analysis, depositing sediments were considered to be the sediment strata located at depths shallower than the authorized channel depth for given zone). Accordingly, the sediments within zones ERC, NH-CIR, NHER, and NNC were considered to be predominantly fine sediments. Based on presentations of cross-sections showing the sediment stratigraphy as well as grain size distribution, the depositing sediments within zone AOC were found to be predominantly sandy, with only about 20% fines content. Based on presentations of cross-sections showing the sediment stratigraphy, the depositing sediments within zone TSC were found to be more variable, with predominantly sandy sediments east of the Chesapeake Bay Bridge Tunnel, and fine sediments to the west. Due to the lack of data on grain size distribution in the depositing sediments, the average fines content over the zone TSC was assumed as 40%. Since typical tidal currents within the TSC and AOC zones are not strong enough to result in appreciable suspended sand transport, the presence of significant sandy sediments in zones TSC and AOC suggests that wave-driven sediment transport in the offshore zone may be the likely mechanism

responsible for sediment transport and accumulation within the navigation channel in these zones. Therefore, wave-driven sediment transport was included as a transport process in zones TSC and AOC for the Van Rijn channel sedimentation approach described in Section 3.2. Table 3 lists the composition of the depositing sediments assumed for purposes of this analysis.

Table 3. Composition of sediments depositing in various zones

Zone	Composition of Depositing Sediments
ERC	Predominantly fine (100%; smaller than 63 μm)
NH-CIR	Predominantly fine (100%; smaller than 63 μm)
NHER	Predominantly fine (100%; smaller than 63 μm)
NNC	Predominantly fine (100%; smaller than 63 μm)
TSC	Mix of fine sediments (40%) and sands (60%; greater than 63 μm)
AOC	Predominantly sand (80%) with 20% fine sediment

In addition to the information on sediment substrate, the data on sediment grain size distribution presented in Fugro (2016a) was also used to develop inputs on the median diameter D_{50}, and the D_{90} (the diameter corresponding to the 90th percentile passing), both of which are required for the calculation of wave-driven sediment transport. The D_{50} was thus determined as 200 μm and the D_{90} as 1000 μm. Both analytical approaches also require information on the sediment dry bulk density. The formulations calculate the sediment accumulation in terms of mass over a given time period. The mass accumulation rate is converted to a volumetric sediment accumulation rate using the dry bulk density. This was assumed (based on representative values for similar sediments at other sites) to be 31 lb/ft^3 for the fine sediments depositing in zones ERC, NH-CIR, NHER, and NNC and 75 lb/ft^3 for the predominantly sandy sediments depositing in zone AOC. The sediments in zone TSC were assigned an intermediate dry density of 47 lb/ft^3.

4.2 Water Quality Data

Information on the average SSC within all the zones and the vertical salinity gradient near the downstream ends of zones ERC and NH-CIR was obtained from the water quality database maintained by the Chesapeake Bay Program (http://www.chesapeakebay.net). Figure 1 shows the locations where relevant data were obtained for purposes of this study. Data collected over 1989-2016 were retrieved for this purpose; sample size was on the order of several hundred at each location. SSC was calculated as an average of the entire dataset, with average SSC of 14 mg/L for zone ERC (station ELD01), 21 mg/L for zone NH-CIR (station LE5.6), 19 mg/L for zones NHER and NNC (station LE5.4), and 20 mg/L for zones TSC and AOC (station CB8.1). The vertical salinity gradient required for the application of the basin sedimentation approach was calculated as an average of surface measurements and of bottom measurements as 16 PSU and 18 PSU, respectively at station ELD01, and 16 PSU and 25 PSU at station LE5.6.

4.3 Tidal Current and Water Depth Data

Information on the tidal water depths, tidal range, and tidal currents in the study area were obtained from an existing regional-scale numerical hydrodynamic model of Chesapeake Bay developed by Moffatt & Nichol and used for several marine infrastructure and coastal projects in and around Chesapeake Bay. Figure 4 shows the peak flood and ebb tidal depth-average currents calculated by the model. Maximum currents range between 1-2 ft/s in the vicinity of the navigation channels. Currents were characterized at several locations in the vicinity of the channel in zones NHER, NNC, TSC, and AOC. The average tidal currents over the tidal cycle during a representative tide was specified as an hourly input to the channel sedimentation approach. In addition, Figure 4 also shows the tidal currents oriented at an angle of approximately 10° relative to the channel in most of the study area. This was also an input parameter for the channel sedimentation calculations. Similarly, water level variations over a typical tidal cycle were extracted from the numerical model and used as an input in the channel sedimentation approach. The tidal range associated with a typical tidal cycle was also extracted from the numerical model and used as an input in the basin sedimentation approach.

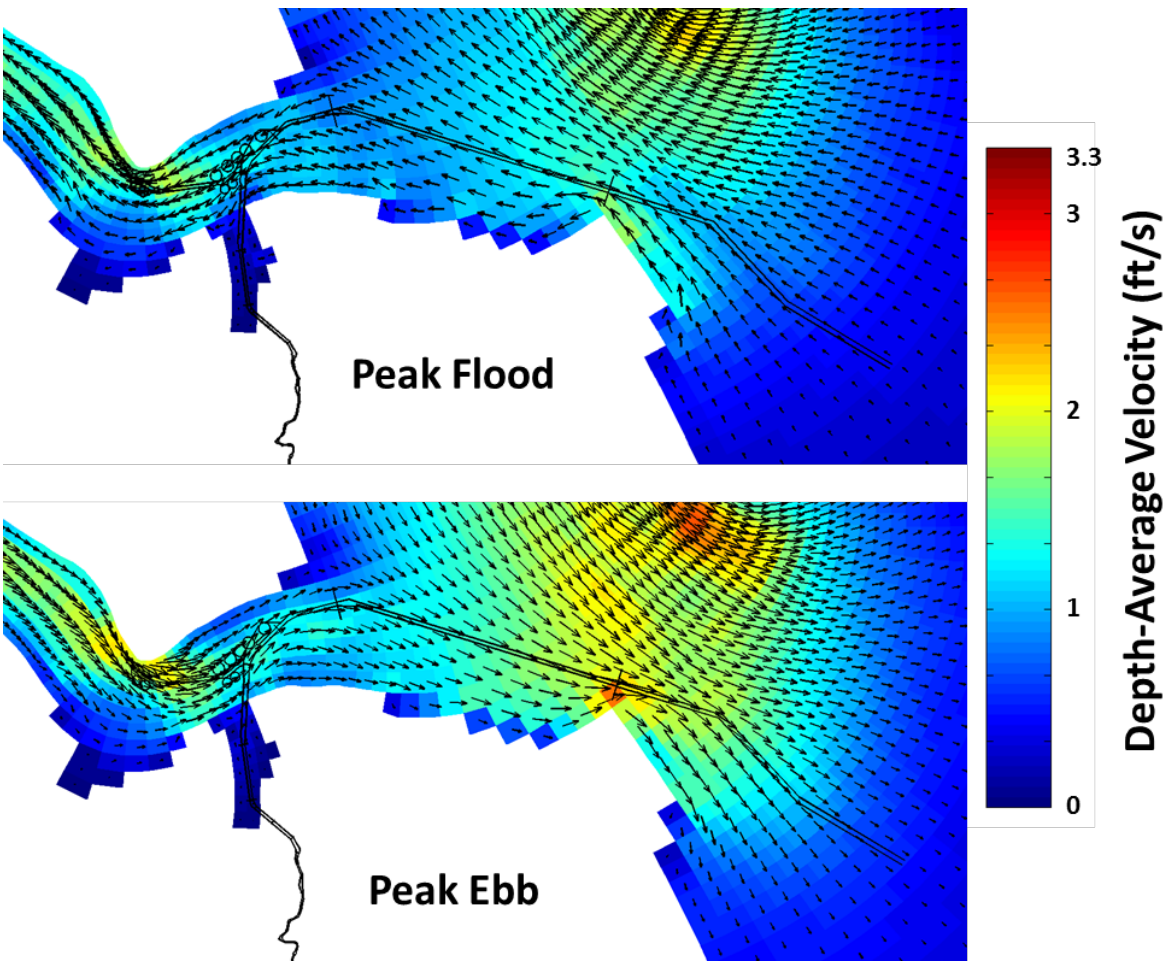


Figure 4. Snapshot of peak flood and peak ebb tidal currents in the study area.

4.3 Wave Data

Information on the wave climate in the vicinity of the navigation channels in zone AOC was determined using measurements from the NOAA wave gage located at the Chesapeake Light

station about 5 miles east of the navigation channel as shown in Figure 1. Figure 5 shows a cumulative probability distribution of the significant wave heights recorded at the Chesapeake Light station over 1984-2004 (http://www.ndbc.noaa.gov/station_page.php?station=chlv2). In addition, wave measurements over 2008-2016 at an adjacent location, Cape Henry, (http://www.ndbc.noaa.gov/station_page.php?station=44099) about 100 feet away were examined. Comparison of wave heights over the two periods suggested that the long-term wave climate was relatively similar. Therefore the measurements at the Chesapeake Light station over 1984-2004 were used for the analyses presented here.

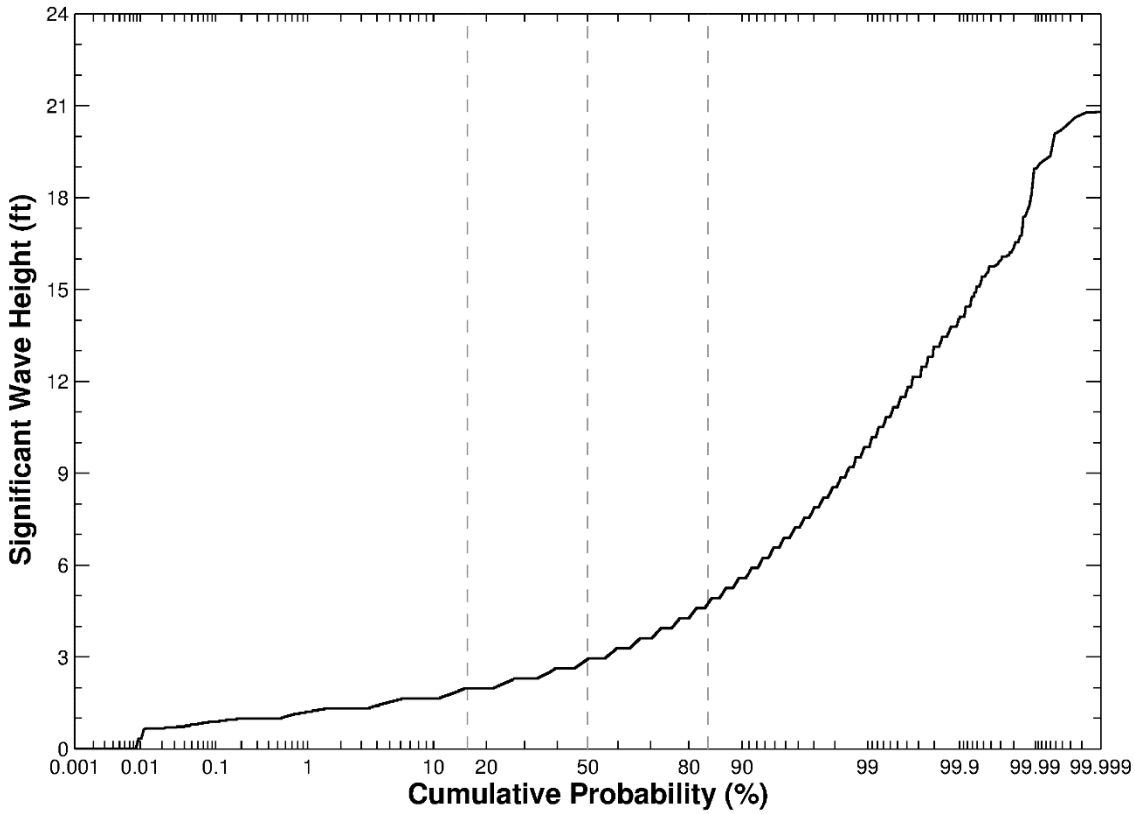


Figure 5. Cumulative probability distribution of significant wave height measured at the Chesapeake Light station over 1984-2004.

As seen in Figure 5, historical wave data at the Chesapeake Light location shows significant wave heights in excess of 18 ft occasionally, with wave periods of up to 20 s. In reality, some of these larger wave heights can be expected to be attenuated with distance into Chesapeake Bay and towards the shore, leading to more spatially variable wave characteristics. In other words, wave-driven sediment (mainly sand) transport is expected to decrease in magnitude with distance into Chesapeake Bay. This is also consistent with the observation of sediment stratigraphy and grain size distribution in the depositing sediments in zones AOC and TSC, which show predominantly sandy sediments depositing in zone AOC and towards the eastern end of zone TSC, and finer sediments depositing towards the western end of zone TSC. However, the precise definition of the wave climate within the study area is beyond the scope of this desktop exercise. Rather, the wave climate measured at the Chesapeake Light station has been taken as indicative of the wave characteristics within zone AOC. Since similar information is lacking in zone TSC, the wave data from the Chesapeake Light station is applied to zone TSC, with a calibration parameter in the analytical formulations adjusted to reproduce the reported maintenance dredging rates.

It is a well-accepted that sediment transport rate is a non-linear function of the wave height and period. Therefore, the probability distribution in Figure 5 has been discretized into various wave height conditions (along with corresponding wave periods) and associated with corresponding frequency of occurrence. The average wave height (and associated frequency of occurrence and wave period) was calculated over 0.8 ft intervals. The channel sedimentation calculation was then performed for each of these discretized wave conditions, and the sedimentation rate for the individual wave conditions scaled by the corresponding frequency of occurrence. The integrated sedimentation rate over each of these discrete wave events is then taken to be the annualized estimate of sediment (sand) deposition driven by waves.

4.5 Maintenance Dredging Data

In order to calibrate the various methods described in Section 3, available historical dredging records were reviewed. Historic maintenance dredging records were provided by the USACE for the period 1980 to 2014. During this period, the channels were deepened (e.g. Norfolk Harbor Channels were deepened to -50-ft MLW in the 2005 – 2006 timeframe). However, there was no clear indication of an increase in maintenance dredging due to the deepened channels. We note that through informal discussions with USACE personnel it has been suggested that factors such as the following have contributed to what appears to be a decrease in maintenance dredging rate:

- Budget constraints within the USACE have shifted maintenance from a proactive program of advanced maintenance to a more reactive operation focused on correcting deficiencies as they are identified.
- Evolving environmental policies may have contributed to reduced sediment transport and resultant accumulation within the channels.
- Continued trends toward vessels with deeper drafts approaching the limit of the channel, combined with higher vessel traffic may be generating a “self-maintaining” effect as the prop wash of transiting vessels prevents accumulation of sediment within the high-traffic regions.

The available maintenance dredging records were used to develop an estimate of the annual sedimentation rate within the navigation channels in the study area. Historical (from 1980 onwards) and recent data were examined; however, only the post-50’ deepening records were used within the TSC, AOC, NH-CIR, NHER, and NNC zones. Within zone ERC, all available data were used since the 50’ deepening project did not extend to this zone.

Figure 6 shows the current annualized maintenance dredging rate by channel segment based on the afore-mentioned dredging records from the USACE. The dredging rate reported for Norfolk Harbor, Sewells Point to Lamberts Bend represents the dredging within zones NHE and the Norfolk Harbor and Craney Island channels (located in zone NH-CIR). However, the dredging records do not distinguish between these individual channel segments. Therefore, the dredging rate reported for Norfolk Harbor, Sewells Point to Lamberts Bend was apportioned to the Norfolk Harbor Entrance channel and the channels in zone NH-CIR based on the individual segment lengths.

Figure 7 shows the resulting dredging rates, calculated (existing) for the individual zones examined in this study. Note that the dredging rate reported for the anchorage areas in Norfolk Harbor is only about 5,000 cy/year, an order of magnitude smaller than the next higher dredging rate, reported for zone ERC as 53,000 cy/year. Given this relatively insignificant dredging rate, the sedimentation rate calculations have therefore not been performed for the anchorage areas.

In addition, the reported dredging volumes within zone AOC also include some borrow projects. However, the current dredging volume associated with ongoing sedimentation in this zone cannot be separated from the dredging volume associated with the borrow activities (without significant effort in obtaining and reviewing the pre- and post-dredge bathymetric surveys, dredging design documents, etc., as available). Therefore, although this total dredging volume in zone AOC is included in Figure 6 and Figure 7, it is not used in the remainder of the analysis described in this memorandum. The maintenance dredging rate for the remaining zones was considered to be representative of the current sedimentation rate and used in the sedimentation rate calculations as described in the next section. Therefore, the terms maintenance dredging rate and sedimentation rate are used interchangeably in this memorandum.

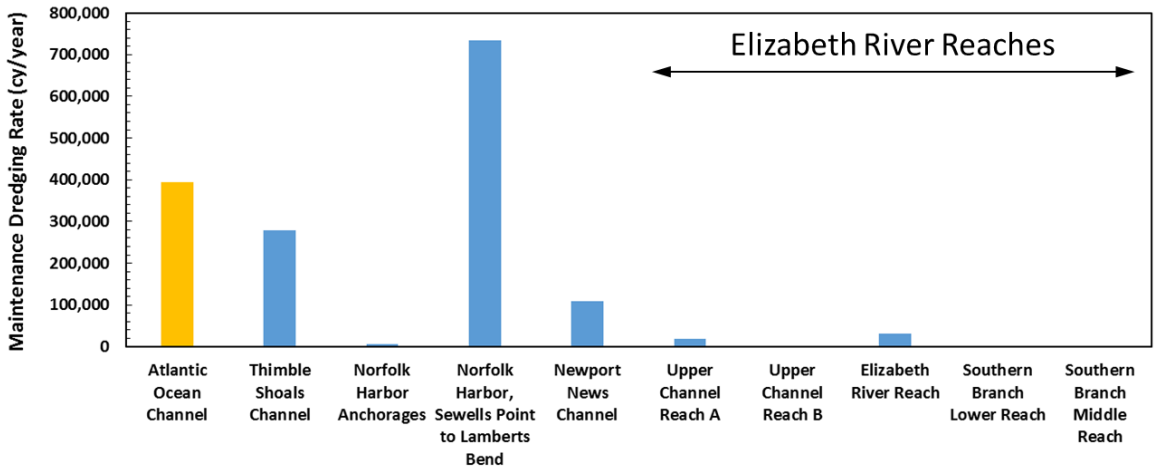


Figure 6. Current maintenance dredging rates for the various channel segments in the study area based on dredging records from the USACE. Note that AOC dredging data also includes removal associated with borrow activities.

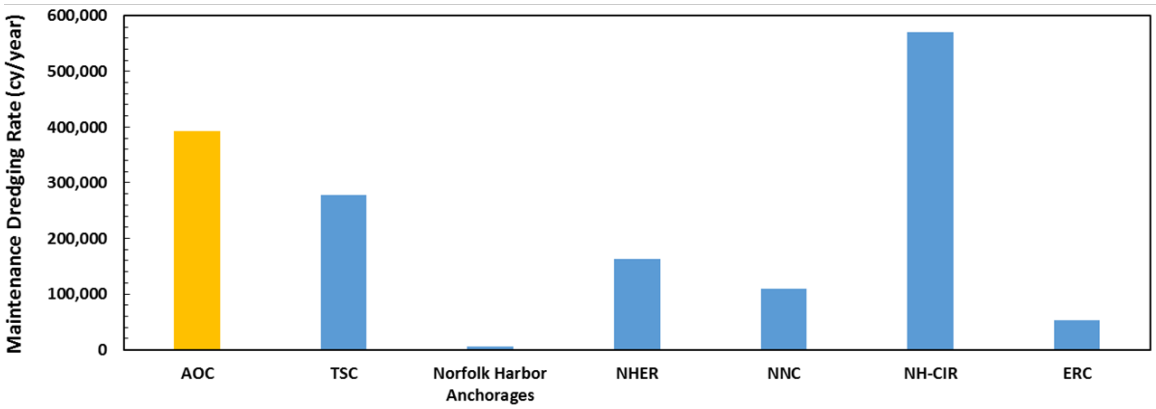


Figure 7. Current maintenance dredging rates for the zones used for sedimentation calculations based on dredging records from the USACE. Note that AOC dredging data also includes removal associated with borrow activities.

5. Results

Information on the physical processes, physical parameters, and channel geometry described in the preceding sections were used to develop and parameterize the basin and channel sedimentation approaches described previously. Based on the observations of the depositing

sediments in the various zones, only fine sediment transport and accumulation was considered in zones ERC, NH-CIR, NHER, and NNC. The sediments accumulating in zones TSC and AOC was considered to be a mix of fine sediments and sands (about 20% fines in AOC and 40% in TSC), and the transport of both sediment types was considered for these zones. Sand accumulation was assumed to be associated only with waves, and fine sediment accumulation was assumed to be associated only with tidal currents, i.e. advection.

The calculations were first performed for current conditions using the current channel geometry, and the effective settling velocity of the sediments optimized to reproduce the reported current maintenance dredging rates. The settling velocity was varied only for the fine sediments in the various zones. In zone TSC, the settling velocity of the fine sediments was adjusted such that the calculated sediment accumulation represented about 40% of the reported current maintenance dredging rate, consistent with the approximate fines content of the depositing sediments. The remainder of the sediment accumulation consists of sands; a calibration parameter which scales the sedimentation rate in the channel sedimentation calculation was adjusted to reproduce the reported accumulation rate for sand in this zone. Physically, this represents the effects of wave attenuation with distance from the wave gage location towards zone TSC. Within zone AOC, due to the uncertainty in the actual sedimentation rate as mentioned previously, the current sedimentation rate was estimated by a direct application of the channel sedimentation approach without the afore-mentioned tuning parameter. In other words, the data measured at the wave gage location was considered to be representative of the wave climate in the vicinity of zone AOC. The sand accumulation in zone AOC was thus estimated and the fines accumulation estimated by adjusting the settling velocity such that fine sediments accounted for 20% of the total estimated sedimentation due to sands plus fines.

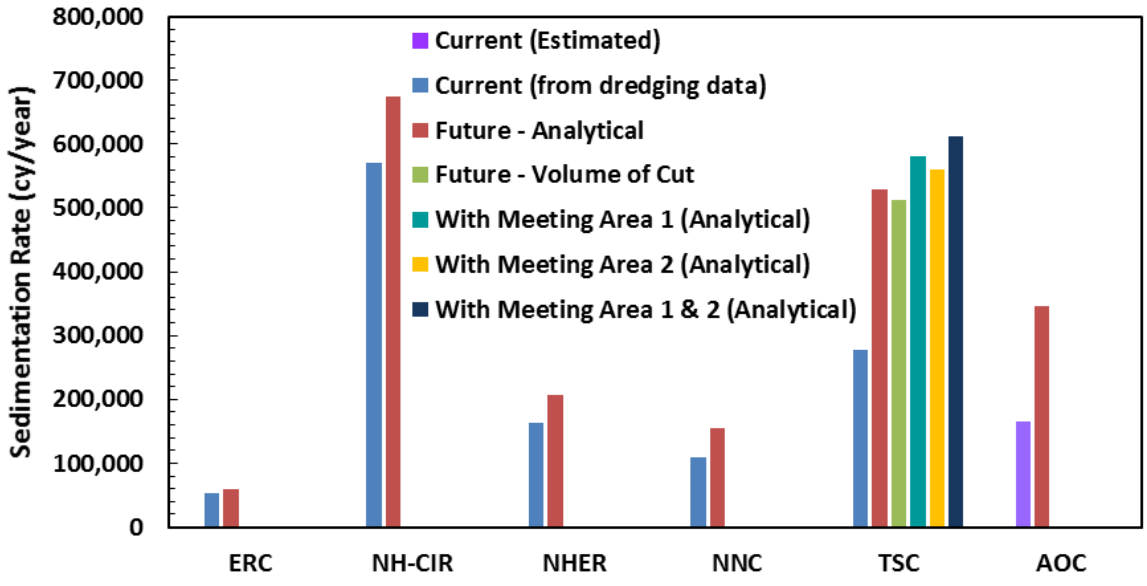


Figure 8. Current and estimated future sedimentation (maintenance dredging) rates using analytical and empirical approaches.

Following optimization to reproduce/estimate the current maintenance dredging rates, the settling velocity and other inputs were used to estimate the future sedimentation rates in the various zones using the future channel geometry. Figure 8 shows the resulting estimated future sedimentation rates (same as maintenance dredging rates) using the analytical approaches compared to the current maintenance dredging rates. The relative increase in the estimated future maintenance

dredging rates (compared to current conditions) is shown in Figure 9. Table 4 summarizes the results presented in Figure 8 and Figure 9.

For zone TSC, the calculations were performed for a base channel configuration (which does not include either meeting area), with Meeting Area 1, with Meeting Area 2, and with Meeting Area 1 & 2.The relative increase in the maintenance dredging rate ranges from a low of 11% in zone ER to 120% in zone TSC (with Meeting Areas 1 & 2). In four of the six zones (ERC, NH-CIR, NHER, and NNC), the increase in sedimentation rate is less than 42%. Converting the volumetric sedimentation rates into an average bed accretion rate over each of the zones results in somewhat smaller increases under future conditions – 7% for ERC, 16% for NH-CIR, 24% for NHER, and 39% for NNC. The bed accretion rates may be considered to be more relevant to issues such as limiting depths for navigation, and the frequency of maintenance dredging. The additional sedimentation in these areas is due to changes in sediment trapping efficiency, additional water exchange (due to salinity gradients and horizontal eddies) in the case of ERC and NH-CIR, and partly due to the increased cross-sectional area of the channel under future conditions (since the top width of the channel is a function of the channel depth for given side slope). Note that the assumption of additional water exchange driven by the salinity gradient is consistent with the results of the interim hydrodynamic model (Zhang et al., 2016) which shows increased salinity (which implies additional water exchange) in the Elizabeth River under future conditions (with deepened navigation channels) as compared to existing conditions.

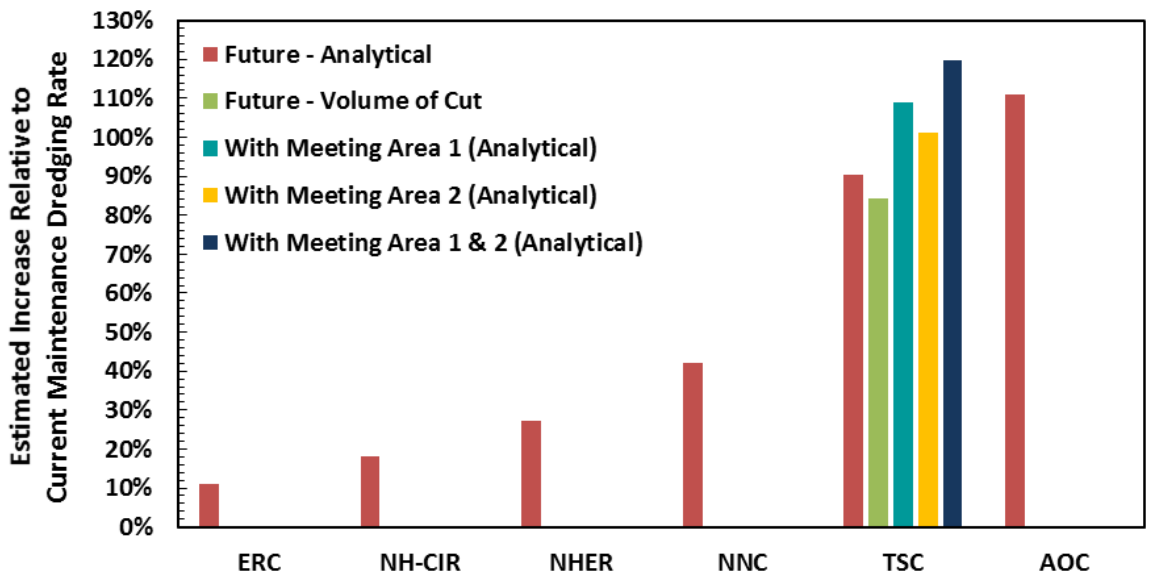


Figure 9. Relative increase in estimated future maintenance dredging rate relative to current conditions using analytical and empirical approaches.

In comparison to the zones within Norfolk Harbor and the Elizabeth River, zones TSC and AOC show significantly larger sedimentation rates (up to 120% higher than current conditions). In order to provide another line of evidence in this regard, the future sedimentation rate for zone TSC (for the base channel configuration without either meeting area) was also estimated following the volume of cut approach described previously. Terms V_d and V_{Cut} in Eq. (1) were determined using the current maintenance dredging rate and the current channel geometry. The proportionality term γ was calculated using Eq. (1). The future estimated maintenance dredging rate was then calculated using the calculated value for γ and the future channel geometry. These estimates are also included in Figure 8, Figure 9, and Table 4.

Table 4. Current and estimated future maintenance dredging rates and the relative increase from current rates using the analytical and empirical approaches. Estimated current maintenance dredging rate indicated by an asterisk.

Zone	Maintenance Dredging Rate (cy/yr)			Relative Increase (%)	
	Current[6]	Future - Analytical[7]	Future – Empirical[7]	Future - Analytical	Future - Empirical
ERC	53,152	59,063	-	11%	-
NH-CIR	570,601	674,762	-	18%	-
NHER	163,029	207,192	-	27%	-
NNC	109,624	155,922	-	42%	-
TSC	278,135	529,182	512,308	90%	84%
TSC w/ Meeting Area 1	278,135	581,337	-	109%	-
TSC w/ Meeting Area 2	278,135	559,717	-	101%	-
TSC w/ Meeting Areas 1 & 2	278,135	611,344	-	120%	-
AOC	164,359*	346,506	-	111%	-

The results from the empirical approach are very similar to the results from the analytical approach for zone TSC with the estimated future maintenance dredging rate 84% higher than current maintenance dredging rate – in comparison, the analytical approach estimates a 90% increase. The reason why both the analytical and empirical approaches predict a significantly larger sedimentation rate is likely related to the current and proposed channel depths in relation to the natural channel depths in this zone. Review of the channel geometries in Table 1 shows that compared to the natural channel depth of 40’ in this zone, the current channel is only 10’ below the surrounding seafloor. Following the proposed deepening, the channel bottom will be located between 18’ below the surrounding seafloor. This represents roughly a doubling of the channel depth relative to the adjacent seafloor compared to current conditions. The volume of cut approach, which gives maintenance dredging rates that scale with the depth of the channel bottom relative to the adjacent seafloor (i.e., the volume of the dredge cut), accordingly calculates a near-doubling of the maintenance dredging rates from current conditions. From a physical standpoint, compared to current conditions, the near-doubling of the channel bottom relative to the adjacent seafloor causes a significant decrease in sediment transport capacity (due to both tidal currents and waves), thereby increasing the trapping efficiency of the channel, and thus

[6] Based on maintenance dredging records provided by the USACE except for zone AOC which is an estimate for the reasons described in the text.
[7] Estimates developed using the proposed future channel geometry as shown in Table 1.

increasing the maintenance dredging estimates with the future channel geometry in the analytical approach.

The volume of cut approach provides an additional line of evidence and an empirical check on the results of the analytical approach in zones TSC. It should be noted that barring zone AOC, none of the other zones exhibit a similar magnitude of increase in the channel depths relative to the natural depths. The increase in channel depth relative to natural depths ranges from 25% to about 40% for the other zones. As a consequence, sediment trapping efficiency, and therefore sedimentation rates are not estimated to increase as dramatically for the other zones.

6. Summary

The future maintenance dredging rates within the navigation channels in and around Norfolk Harbor have been estimated in a desktop study using a combination of analytical and empirical approaches. The analyses make use of the channel geometries, information on the physical forcings, and the physical parameters responsible for sediment transport and deposition in the study area. Data from a number of sources was utilized as part of this analysis. The performance of the analytical approaches was constrained by the reported current maintenance dredging rates; this provides a measure of confidence in the projected future maintenance dredging rates. The analytical approaches calculate increases in maintenance dredging rates (on volumetric basis) of less than 42% within Norfolk Harbor and Elizabeth River. The largest increase in estimated maintenance dredging rate is in the Thimble Shoals and Atlantic Ocean channels, primarily driven by a large future increase in channel depth relative to the adjacent seafloor depths. The results of the analytical approach for these channels are also comparable to an empirical approach, namely the volume of cut approach.

The desktop analysis presented in this memorandum represents a first-order estimate of the future sedimentation rates. A number of caveats and limitations are inherent in the results from such an approach. Some of these caveats and limitations include, in no particular order:

- The analyses rely on a limited study/understanding of sediment dynamics and transport in the study area.
- The analyses do not explicitly consider any spatial variation in the wave climate within the study area.
- The analyses are based on limited information on the sediment substrate within the study area which provides source material for the sands deposited in the navigation channel in zones TSC and AOC. In particular, the analytical solutions assume an equilibrium condition or an unlimited supply of sediments available for deposition in the navigation channels.
- The application of the analytical approach within zone TSC relied on an assumption of the fines content in the depositing sediments in this zone.
- The analytical approaches are based on limited calibration/validation (only to historical maintenance dredging rates). More sophisticated approaches for estimating future sedimentation rates would involve numerical modeling tools, which would be calibrated/validated against various metrics such as water levels, wave characteristics, currents, salinity, SSC, sediment fluxes, and bathymetric changes in addition to historical maintenance dredging rates. The extensive calibration/validation involved with such tools would provide more confidence in the future estimates of sedimentation rate than the results of the desktop study presented here.

Resolving these limitations will involve a much larger level of effort in various aspects – data collection and analysis, numerical model development (hydrodynamics, waves, and sediment transport), and model application. Although such studies have been performed at other sites around the world in a similar context, the level of effort involved is likely to be orders of magnitude larger than involved in this desktop study. However, such a study would provide more confidence in the estimates of future sedimentation rates, and can provide a better spatial and temporal resolution of the sedimentation patterns.

7. References

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Engineering Appendix E:

DMMP

Norfolk Harbor Navigation Improvements– Dredged Material Placement Plan

1 Introduction

USACE policy (ER 1105-2-100 section 3-2b(8) Dredged Material Management Plans) states the following:

> *Dredged material management planning for all Federal harbor projects is conducted by the Corps to ensure that maintenance dredging activities are performed in an environmentally acceptable manner, use sound engineering techniques, are economically warranted, and that sufficient confined disposal facilities are available for at least the next 20 years. These plans address dredging needs, disposal capabilities, capacities of disposal areas, environmental compliance requirements, potential for beneficial usage of dredged material and indicators of continued economic justification. The Dredged Material Management Plans shall be updated periodically to identify any potentially changed conditions*

A Preliminary Assessment conducted as a part of this Norfolk Harbor Channel Improvement Project concluded that there was sufficient disposal capacity for a 20-year period and identified the least cost disposal plan (Technical Memorandum dated 25Jul16). The Preliminary Assessment evaluated placement alternatives for each channel segment and identified the least cost placement site and any beneficial use opportunities for that material. Each placement site identified in the Preliminary Assessment, including beneficial use sites, has completed the requirements of the National Environmental Policy Act (NEPA) of 1969, which evaluated the potential environmental consequences dredged material placement at each site.

The existing DMMP for the Federal navigation projects at Hampton Roads is based on three placement areas: the Craney Island Dredged Material Management Area (CIDMMA), the Dam Neck Ocean Dredged Material Disposal Site (ODMDS), and the Norfolk ODMDS. Three USACE Erosion Control and Hurricane Protection projects, the USACE Craney Island Eastward Expansion project, and one Chesapeake Bay Bridge and Tunnel Authority project have completed NEPA documents and could accept dredged material for beneficial use[1]

This Dredged Material Placement Plan (DMPP) is organized as follows:

- Chapter 2: Characteristics of material dredged from each channel segment;
- Chapter 3: Placement area site characteristics and material requirements (including beneficial use sites);
- Chapter 4: Historical quantities and placement locations for maintenance and construction material;

[1] Norfolk Harbor and Channel Deepening Study Beneficial Reuse Sites Overview, Technical Letter #013. 08 Jun 2016.

- Chapter 5: Dredging and placement projections for 20 years
- Chapter 6: Identification of the least cost plan (the Federal standard).

On 4 August 2016, a Vertical Team Meeting was held on this project to discuss the Dredged Material Management Plan (DMMP). The meeting was conducted as a webinar and the attached PowerPoint presentation was used to facilitate the discussion. The DMMP was to be presented in the GRR/EAs as component to support the Plan Formulation Appendix. The Vertical Team concurred with the PDT's way forward on the DMMP for this study.

2 Sediment Characteristics

The sediments within the navigation channels, meeting areas, and Anchorage F are briefly discussed below. A detailed discussion of project sediments is contained in the Geotechnical attachment to the Engineering Appendix. Planning reaches (Table 1) identify the grouping of channel reaches used for plan formulation.

Table 1: Navigation Channel Dimensions

Planning Reach	Channel Reaches	Channel Depth (ft)		Channel Width (ft)		Length (miles)
		Authorized	Constructed	Authorized	Constructed	
Atlantic Ocean Channel to Lamberts Bend (Segment 1)	Atlantic Ocean Channel	57	52	1,300	1,300	10.0
	Thimble Shoal Channel	55	50	1,000	1,000	13.0
	Norfolk Harbor Entrance Reach	55	50	1,500	1,000-1,4000	2.0
	Norfolk Harbor Reach	55	50	850-1,200	850-1,200	4.0
	Craney Island Reach	55	50	800	800	3.0
Norfolk Harbor Entrance Reach to Newport News (Segment 2)	Newport News Channel	55	50	800	800	5.4

2.1 Atlantic Ocean Channel

Material to be dredged in the Atlantic Ocean Channel (AOC) consists predominately of sandy materials. The AOC has been used as a borrow source for sandy material for the City of Virginia Beach’s Big Beach project as well as for dike construction for the Craney Island Eastward Expansion.

2.2 Thimble Shoal Channel

Material to be dredged from the Thimble Shoal Channel (TSC) can be described as predominately sandy on the east side of the Chesapeake Bay Bridge Tunnel (CBBT), and predominately fines (silts and clays) with some sand on the west side of the CBBT. Material from the east side has been used in beneficial use projects including beach renourishment for the City of Norfolk's beaches and several Navy projects. Material from the east side also has been placed at the Dam Neck Ocean Dredged Material Disposal Site (ODMDS) when beneficial use opportunities were not available. Material west of the CBBT is typically not suitable for beneficial use and has historically been deposited in the Dam Neck ODMDS.

2.3 Norfolk Harbor Entrance Reach, Norfolk Harbor Reach, Craney Island Reach, Norfolk Harbor Anchorages, Sewells Point Anchorages

Material to be dredged from the remaining Segment 1 channels (Norfolk Harbor Entrance Reach, Norfolk Harbor Reach, Craney Island Reach, Norfolk Harbor Anchorages, Sewells Point Anchorages) consist predominately of fines (silts and clays) with some sands. This material is typically not suitable for beneficial use. Historically all maintenance and deepening material have been hydraulically dredged and placed into CIDMMA. Any sand settled out in CIDMMA is reclaimed (to the extent possible) for dike maintenance.

2.4 Newport News Channel

Material to be dredged from the Newport News Channel consists predominately of fines (silts and clays) with intermixed areas of sand lenses. Historically all maintenance and deepening material have been hydraulically dredged and placed into CIDMMA. Any sand settled out in CIDMMA is reclaimed (to the extent possible) for dike maintenance.

3 Placement Areas

There are three dredged material placement areas that have historically served and continue to serve the Norfolk Harbor Channels project:

- Craney Island Dredged Material Management Area (CIDMMA);
- Dam Neck Offshore Dredged Material Disposal Site (ODMDS); and
- Norfolk ODMDS

In addition to the three established placement areas, the Craney Island Eastward Expansion (CIEE), which was authorized by Congress in 2007, will be available to supplement the confined placement available at CIDMMA.

Four beneficial use sites, three historical and one new, are also available for suitable material from the Atlantic Ocean Channel and the Thimble Shoal Channel. Based on projected dredged material volumes and available capacity at existing placement areas, no additional placement areas are required.

3.1 Craney Island Dredged Material Management Area (CIDMMA)

CIDMMA is approximately two miles square with existing ground elevations within the cells varying from approximately +32 to +40 feet MLLW. CIDMMA receives dredged material which is pumped hydraulically into the cells. Dredged material is typically pumped in over the east dike. This is evidenced by the large sand mounds observed at the influent points where these heavier sand particles quickly settle out of the dredge slurry. Existing external dikes range in elevation from +35 to +45 feet MLLW.

CIDMMA is currently operated using the guidance from the existing DMMP prepared in 1981. The 1981 DMMP estimated that, over its operating life, CIDMMA would be able to accept over 250 MCY of dredged material (since it began operation in 1957), a significant increase over the original capacity estimate of 96 MCY.

The existing DMMP is based on the current configuration of CIDMMA, which is divided into three cells: South Cell (734 acres for storage), Center Cell (766 acres for storage) and North Cell (689 acres for storage). Currently Norfolk District rotates each of the three cells as necessary to allow adequate drying before dredged material is again pumped into the cell. The District also typically caps the volume of dredged material that can be pumped into an individual cell at no more than 5 MCY annually. Monthly inflows are typically limited to 650,000 CY.

The Norfolk District currently has an annual earthwork/grading contract to maintain and raise the perimeter and division dikes. Under this contract, approximately 750,000 CY of granular material is excavated and placed on the dikes annually. The material is borrowed from the eastern side of CIDMMA using conventional excavation equipment and hauled using off-road trucks to the required location. Existing dikes are continually maintained to compensate for consolidation settlement of the marine clay foundation beneath the dikes, and the need to maintain adequate freeboard on the dikes.

Each cell has two spillboxes along the west dike. Spillboxes are operated by the dredging contractor pumping into the cell. The dredging contractor is responsible for ensuring effluent being released from CIDMMA is clarified water. The contractor verifies by sampling the effluent total suspended solids (TSS). The target or goal is to release only clarified water from the spillboxes, with the daily average effluent TSS concentration of 500 mg/l as an upper action limit. Typically measured effluent TSS values are 100 mg/L or less.

As determined in the Craney Island Eastward Expansion Feasibility Report (USACE, 2006), capacity of CIDMMA is defined as when the dikes can no longer be raised. The CIEE Feasibility Report determined the maximum height of +50 feet MLLW without additional modifications to the subsurface or geometry.

CIDMMA capacity is regularly increased to meet short-term inflow projections by raising the height of the dikes. Dike heights currently range from 36 to 40 feet above MLLW. Under current conditions, the dikes are capable of being raised to elevation 50 feet, allowing for an interior fill height of 47 feet. With the dikes at 50 feet, the CIDMMA foundation is anticipated to have reached its bearing capacity (USACE, 2006).

The CIEE Feasibility Report estimated that CIDMMA would achieve its full capacity in 2025, which includes acceptance of 177 mcy from 2000 to 2025. Actual inflow from 2000 – 2015 are 65 mcy, indicating that remaining capacity is 52 mcy. This remaining capacity estimate is currently being revised with updated fill level and dike elevations.

At such time when CIDMMA is no longer available, Norfolk Harbor dredged material will be disposed of at the U.S. Environmental Protection Agency (USEPA) designated ocean disposal site (Norfolk Ocean Dredged Material Disposal Site), located approximately 35 miles from CIDMMA and 17 miles east of the mouth of the Chesapeake Bay.

3.2 Norfolk Ocean Dredged Material Disposal Site (ODMDS)

The Norfolk Ocean Disposal Site (NODS) is a 42,600-acre area, with an estimated total capacity of 1,300 MCY. The site is delineated by a circle with a radius of 4 nautical miles centered at 36 degrees, 59 minutes north latitude, and 75 degrees, 39 minutes west longitude. Water depth at the site ranges from 43 to 85 feet. NODS was developed, in part, to receive material after CIDMMA had achieved its capacity:

> *If in the future the Craney Island Dredged Material Management Area (Norfolk, Virginia) is no longer available, suitable material currently placed in the Craney Island DMMA could be placed in the ODMDS. (NODS Site Management Plan, February 2009)*

The Norfolk Ocean Disposal site is permitted to receive both coarse and fine grained materials that meet the Environmental Protection Agency's (EPA) requirements for ocean disposal. The site has been used since 1979. The current Site Management and Monitoring Plan (SMMP) is dated February 2009 and will be in effect until 2019.

Material dredged for placement at NODS will most likely be dredging via hopper dredged, although mechanical dredging with material transported to the site using bottom dump scows may be used. Placement will be performed and monitored in accordance with the Norfolk District's SMMP.

3.3 Dam Neck Ocean Dredged Material Disposal Site (ODMDS)

The Dam Neck ODMDS has an area of about 9-square nautical miles with a water depth averaging about 40 feet. The Dam Neck ODMDS is currently designed and managed to hold approximately 50 million cubic yards of dredged material. The Dam Neck SMMP states that future evaluation and management could increase this quantity.

No specific disposal method is required for this site. Disposal may be by hopper dredge, dump scow, or by pipeline discharge. There are no seasonal restrictions to the placement of dredged material within the Dam Neck ODMDS. Approximately 1.2 million cubic yards (CYS) of material from the three Federal navigation channels will be placed in the site every 2 years.

Material dredged for placement at Dam Neck will most likely be dredging via hopper dredge, although mechanical dredging with material transported to the site using bottom dump scows

may be used. Placement will be performed and monitored in accordance with the Norfolk District's Site Management and Monitoring Plan.

3.4 Craney Island Eastward Expansion

The CIEE Southeast Cell is currently under construction, with its completion dependent on Federal funding. If available at the time of the proposed deepening, the cells could be considered as a placement area. The CIEE project expands existing CIDMMA to the east by constructing a new, approximate 522-acre, placement area. The CIEE area will be a total of approximately 8,500-ft x 2,500-ft. The cell will be subdivided with a cross dike to form the Southeast Cell and the Northeast Cell. With the proposed filling to elevation +18 feet MLLW, the Southeast Cell and Northeast Cell have a neat volume capacity of 6.7 and 12.7 MCY respectively. This is the volume within the cell, and does not include bulking of the dredged material.

CIEE will effectively provide an additional cell to CIDMMA. After the cell is completed (confined) filling with material from both the proposed deepening and maintenance dredging can occur. Hydraulic filling will be similar to existing CIDMMA operations, by the use of a hydraulic pipeline cutterhead dredge.

Approximately 4.8 mcy of sand is required to complete the construction the three cross dikes, and portions of the main dike, as part of the CIEE project. About 1.5 million cubic yards of sand will be required for each of the three cross dikes. The construction of the south and center cross dikes will be a component of the south east cell dike construction. In addition, some (i.e., the lower portion) or all of the north cross dike will be completed during the south east cell construction.

Sands mined from the Atlantic Ocean Channel or Thimble Shoal Channel (or both) that is placed using hydraulic techniques is anticipated to be the primary method of construction of the cross dikes. Material from the ocean channels will be delivered to site by hopper dredges and placed hydraulically. In the lower elevations (deeper water), the material may be bottom dumped while in the higher placement elevations, the hopper will pump the sand slurry through a pipeline and discharge at the location and elevation desired, as is done for beach nourishment projects. A spill barge will be used to help control the placement of the material and minimize turbidity.

Sand from upland sources will likely be transported to the site via barges and placed through a tremie pipe (from a spill barge) to the required location.

3.5 Beneficial Use Sites

Three USACE Erosion Control and Hurricane Protection projects, the USACE Craney Island Eastward Expansion project, and one Chesapeake Bay Bridge and Tunnel Authority project have completed NEPA documents and could accept dredged material for beneficial use.

Beach nourishment materials should be similar in geological make-up to the existing sediments of the native beach materials. Nourishment materials should have a low percentage of fine-grained sediments. The goal for typical local beach nourishment (Cities of Norfolk and Virginia Beach) material is a D50 grain size of greater than 0.2mm. Suitable materials will have no more than 5 percent fines by weight.

Table1: NHC Deepening Project Potential Beneficial Use Sites

Project:	Description	NEPA/Permit Reference	Estimated Volume Needs
Big Beach	USACE/City of Virginia Beach federally authorized hurricane protection project	Beach Erosion Control and Hurricane Protection Main Report and Supplemental EIS 1984 USACE	2 MCYs Estimated every 7 years
Sandbridge	USACE/City of Virginia Beach federally authorized hurricane protection project	Sandbridge Beach, VA Erosion Control and Hurricane Protection EA 2009 USACE; 2012 BOEM	1.75 MCYs Estimated every 5 years
Willoughby Norfolk	USACE/City of Norfolk federally authorized hurricane protection project	Willoughby Spit and Vicinity Norfolk Virginia Beach Erosion and Hurricane Protection Project, EIS 1983 USACE	1.2MCYs Estimated every 5 years
CIEE	USACE/VPA federally authorized expansion to CIDMMA	Final Environmental Impact Statement and Finding of No Significant Impact, dated Jan 2006 – EA Supp FONSI dated 11/10/2009	4 MCY
CBBT	CBBT Authority permitted parallel TSC tunnel project – material of expand portal islands 1 and 2	Final Environmental Assessment and Finding of No Significant Impact, dated 7/31/15	1.75 MCY

The Chesapeake Bay Bridge and Tunnel (CBBT) District, in cooperation with the Federal Highway Administration (FHWA), is in the process on bidding the parallel Thimble Shoal Tunnel. This construction will require the expansion of the two portal islands on either side of the TSC. One consideration documented in the projects Final EA and FONSI is borrowing sandy material from the TSC or AOC for expanded the portal islands (2015, FHWA). Dependent on the schedule of the proposal deepening project sandy material can be beneficially reused for the portal islands. The CBBT estimates the volume of sandy material required is 1.75 MCY (Add reference).

4 Historical Placement

The placement of material dredged from the Norfolk Harbor Channels depends on the characteristics of the dredged material and the cost of dredging and placement. Material dredged from the Atlantic Ocean Channel and the Thimble Shoal Channel east of the Chesapeake Bay Bridge Tunnel is typically suitable for ocean placement and is placed at the Dam Neck ODMDS,

which is the lowest cost placement area for this material. Material dredged from Norfolk Harbor Channels west of the Chesapeake Bay Bridge Tunnel are typically not suitable for ocean placement and are placed in CIDMMA, which is the least cost placement area for this material. Table 2 presents the historical placement of material dredged from the Norfolk Harbor Channels.

Table 2: Norfolk Harbor Channels Dredged Material Volumes and Placement Locations (1980 – 2015)

	CIDMMA	Dam Neck	NODS	Total
1980	1,087,166			1,087,166
1981	2,238,076	818,270		3,056,346
1982	2,832,414	853,214		3,685,628
1983	2,451,377			2,451,377
1984	3,109,514			3,109,514
1985	251,987			251,987
1986	529,325			529,325
1988	624,764			624,764
1989	905,069	275,135		1,180,204
1991	931,755	146,400		1,078,155
1992	1,136,614			1,136,614
1993	1,506,997	340,000		1,846,997
1994	1,194,942			1,194,942
1995	2,354,330			2,354,330
1996	985,782	282,431		1,268,213
1998	1,071,373			1,071,373
1999	1,155,578			1,155,578
2000	816,448	1,901,077		2,717,525
2001	1,135,130			1,135,130
2002	1,042,895			1,042,895
2003	872,509	135,655		1,008,164
2005	852,894		1,496,645	2,349,539
2006	618,633	466,403		1,085,036
2007	1,235,826			1,235,826
2008	438,316			438,316
2009	1,251,047	750,000		2,001,047
2011	1,304,329	451,202		1,755,531
2012	1,632,949			1,632,949
2013	54,981	1,113,744		1,168,725
2014	1,098,544			1,098,544
Grand Total	**36,721,564**	**7,533,531**	**1,496,645**	**45,751,740**

5 Projected Future Dredged Material Volumes

5.1 Construction Material

Table 3 presents the new work dredged material volumes for authorized (WRDA 1986) 55-foot Norfolk Harbor Channel project as an example of potential dredged material quantities and placement locations. These volumes will be revised upon final selection of the recommended plan. In total, for the authorized 55-foot project approximately 26 mcy of new work material would be placed at the Dam Neck ODMDS and approximately 9 mcy of new work material would be placed in CIDMMA.

Table 3: Example of Potential New Work Volumes (-55 ft MLLW)

Reach	Controlling Depth, ft MLW	Actual Depth	Comments	Volume, MCY	Placement Area
Atlantic Ocean Channel	59	-61	59' Reqd + 2' Allowable Overdepth	6.5	Dam Neck
Thimble Shoal Channel	56	-58	56' Reqd + 2' Allowable Overdepth	8.2	Dam Neck
TSC Meeting Area #1	56	-58	56' Reqd + 2' Allowable Overdepth	8.7	Dam Neck
TSC Meeting Area #2	56	-58	56' Reqd + 2' Allowable Overdepth	2.6	Dam Neck
Norfolk Harbor Sewells Point to Lamberts Bend	55	-58	55' Reqd + 1' Adv Maint +2' Allowable Overdepth	6.1	CIDMMA
Channel to Newport News	55	-57	55' Reqd + 2' Allowable Overdepth	2.4	CIDMMA
Anchorage F	55	-58	55' Reqd + 1' Adv Maint +2' Allowable Overdepth	0.6	CIDMMA
Total				35.1	

5.2 Maintenance Material

As an example of potential future maintenance volumes, Table 4 presents estimated maintenance volumes for the authorized -55-foot Norfolk Harbor Channel project. The available maintenance dredging records were used to develop an estimate of the annual sedimentation rate within the navigation channels in the study area. Historical (from 1980 onwards) and recent data were examined and used for developing the sedimentation rate (see Engineering Appendix Section 5 Future Maintenance Quantities) and future annualized maintenance dredging quantities.

Table 4: Example of Potential Annualized Maintenance Volumes (-55MLLW)

Segment/Channel	Controlling Depth + Overdredge (feet, MLLW)	Current Annualized Dredge Volume (CY)	Proposed Annualized Maintenance Volume (CY)	% Increase Over Without-Project Conditions
1 / Atlantic Ocean Channel	60	164,400	303,800	85%
1 / Thimble Shoal Channel	57	325,600	486,600	49%
1 / Norfolk Harbor Entrance Reach	57	163,000	199,000	22%
1 / Norfolk Harbor Craney Island Reach	57	570,600	648,000	14%
2 / Newport News Channel	57	109,600	133,500	22%
Total		**1,333,200**	**1,770,900**	**33%**

6 Identification of the Least Costs Plan

The primary planning objective of a DMMP is to identify the Federal Standard, or the base plan, which is the least costly disposal plan consistent with sound engineering practice that meets all Federal environmental standards and meets placement needs for the 20-year planning horizon (Planners Guidance Notebook, USACE, 2000).

Figure 1 presents the locations of potential dredged material disposal sites relative to the federal channels. Distances to CIDMMA for the inner harbor channels are relatively short, with pumping distances ranging from 30,000 to 43,000 feet. Haul distances to the offshore disposal sites and beneficial use sites are considerably longer. Average one-way haul distances to the Dam Neck Offshore Disposal Site include:

- Atlantic Ocean Channel: 9 miles;
- Thimble Shoal Channel East: 17 miles
- Thimble Shoal Channel West: 26 miles;

- Meeting Area 1 (west): 25 miles; and
- Meeting Area 2 (east): 17 miles.

Table 5 presents a comparative cost assessment for each channel reach and for each potential placement site. Costs per cubic yard and total costs include all mobilization, dredging, material testing, and placement costs. Construction quantities are based on the assumption of a controlling depth equal to authorized depths in each reach and three feet of overdepth dredging in the Atlantic Ocean channels and two feet of overdepth dredging in all other reaches.

Big Beach (City of Virginia Beach) is used as the potential beneficial use placement site for the Atlantic Ocean Channel due to it being the closest site (and therefore least cost of other beneficial use sites considered). Willoughby (City of Norfolk) is used as the potential beneficial use placement site for Thimble shoal Channel east of the Chesapeake Bay Bridge Tunnel because it is the closest site (and therefore least cost of other beneficial use sites considered). Other sites, including Sandbridge, CBBT and the CIEE have longer hauls from the AOC and would have higher unit costs than shown in Table 5. Unit costs for beneficial reuse site include dredging, hauling, pump-out and upland crew.

As an illustration of the base plan (least cost plan), Table 6 is based on the assumption that each channel is dredged to its currently authorized depth, with three feet of over depth dredging in the Atlantic Ocean Channel and two feet of overdepth dredging in all other channels. Dredge quantities include maintenance material above the existing maintained depths. In the least cost plan, dredged material from the inner channels is placed at CIDMMA and material from the Thimble Shoal Channel and Atlantic Ocean Channel are placed at the Dam Neck ODMDS.

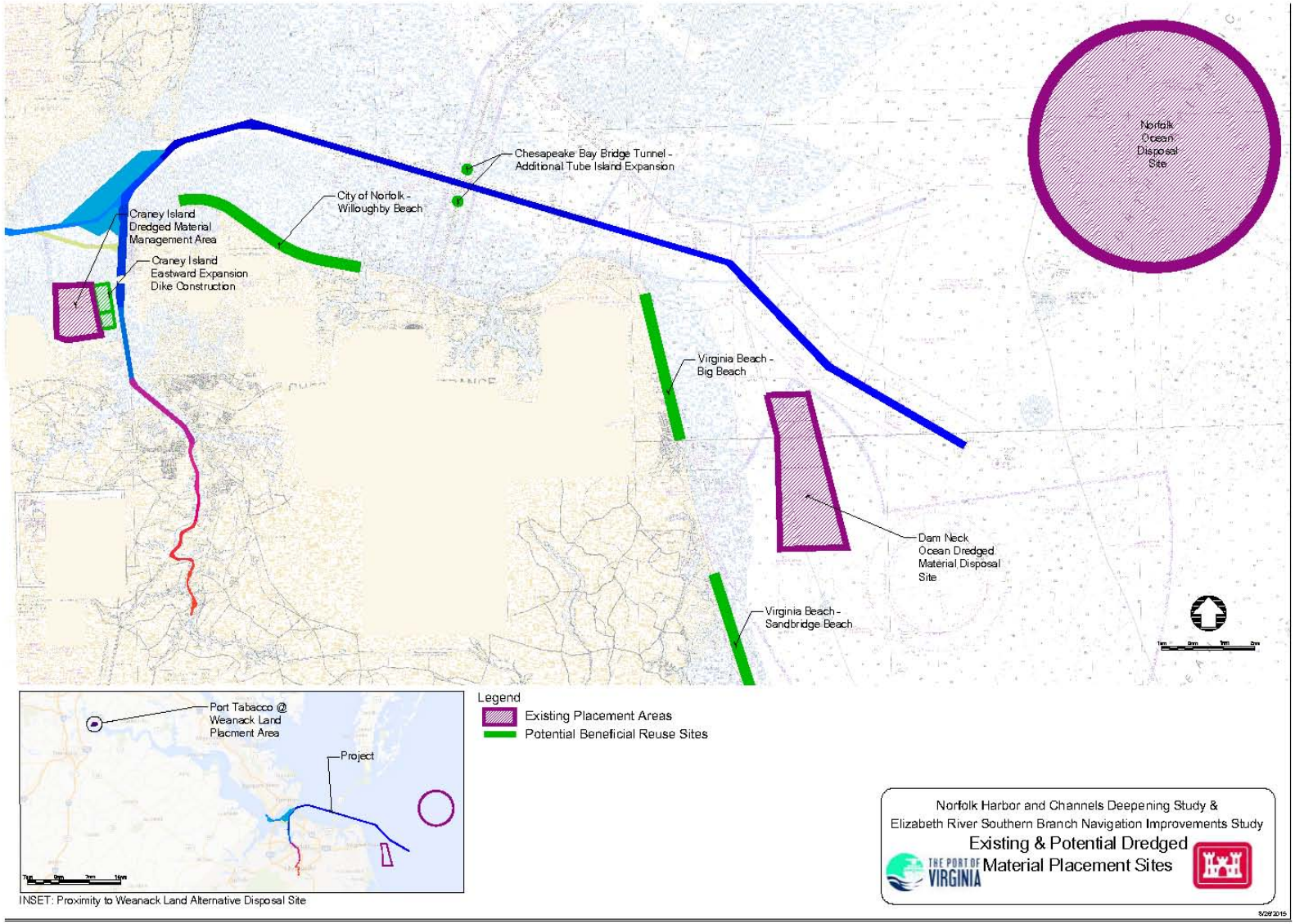

Figure 1: Dredged Material Placement Sites

Table 5: Lowest Unit Cost Placement Site by Channel Reach

Reach	Quantity (cy)	CIDMMA	Dam Neck ODMDS	Norfolk ODMDS	Big Beach**	Willo-ughby**
Atlantic Ocean Channel	6,489,167	xx	$5.37	xx	$7.99	xx
Thimble Shoal Channel East	1,426,752	xx	$7.82	xx	xx	$9.36
Thimble Shoal Channel West	6,807,585	xx	$11.84	xx	xx	xx
Norfolk Harbor Sewells Point to Lambert's Bend	6,100,666	$4.22	xx	xx	xx	xx
Channel to Newport News	2,400,730	$8.86	xx	xx	xx	xx
Sewells Point Anchorage F	653,168	$8.42	xx	xx	xx	xx
TSC Meeting Area #1	8,690,139	xx	$10.87	xx	xx	xx
TSC Meeting Area #2	2,623,737	xx	$7.36	xx	xx	$8.19

Quantity calculations are for authorized depths.

Table 6: Lowest Total Cost Placement Site by Channel Reach

			Least Cost Plan		Beneficial Use Plan	
Reach	Placement Area	Quantity	Unit Cost	Total Cost	Unit Cost	Total Cost
Atlantic Ocean Channel	Dam Neck	6,489,167	$5.37	$34,847,000	$7.99	$51,848,000
Thimble Shoal Channel East	Dam Neck	1,426,752	$7.82	$11,157,000	$9.36	$13,354,000
Thimble Shoal Channel West	Dam Neck	6,807,585	$11.84	$80,602,000	xx	xx
Norfolk Harbor Sewells Point to Lambert's Bend	CIDMMA	6,100,666	$4.22	$25,745,000	xx	xx
Channel to Newport News	CIDMMA	2,400,730	$8.86	$21,270,000	xx	xx
Sewells Point Anchorage F	CIDMMA	653,168	$8.42	$5,500,000	xx	xx
TSC Meeting Area #1	Dam Neck	8,690,139	$10.87	$94,462,000	xx	xx
TSC Meeting Area #2	Dam Neck	2,623,737	$7.36	$19,311,000	$8.19	$21,488,000

*Note that only a portion of the material from these reaches may be suitable for placement at CIDMMA

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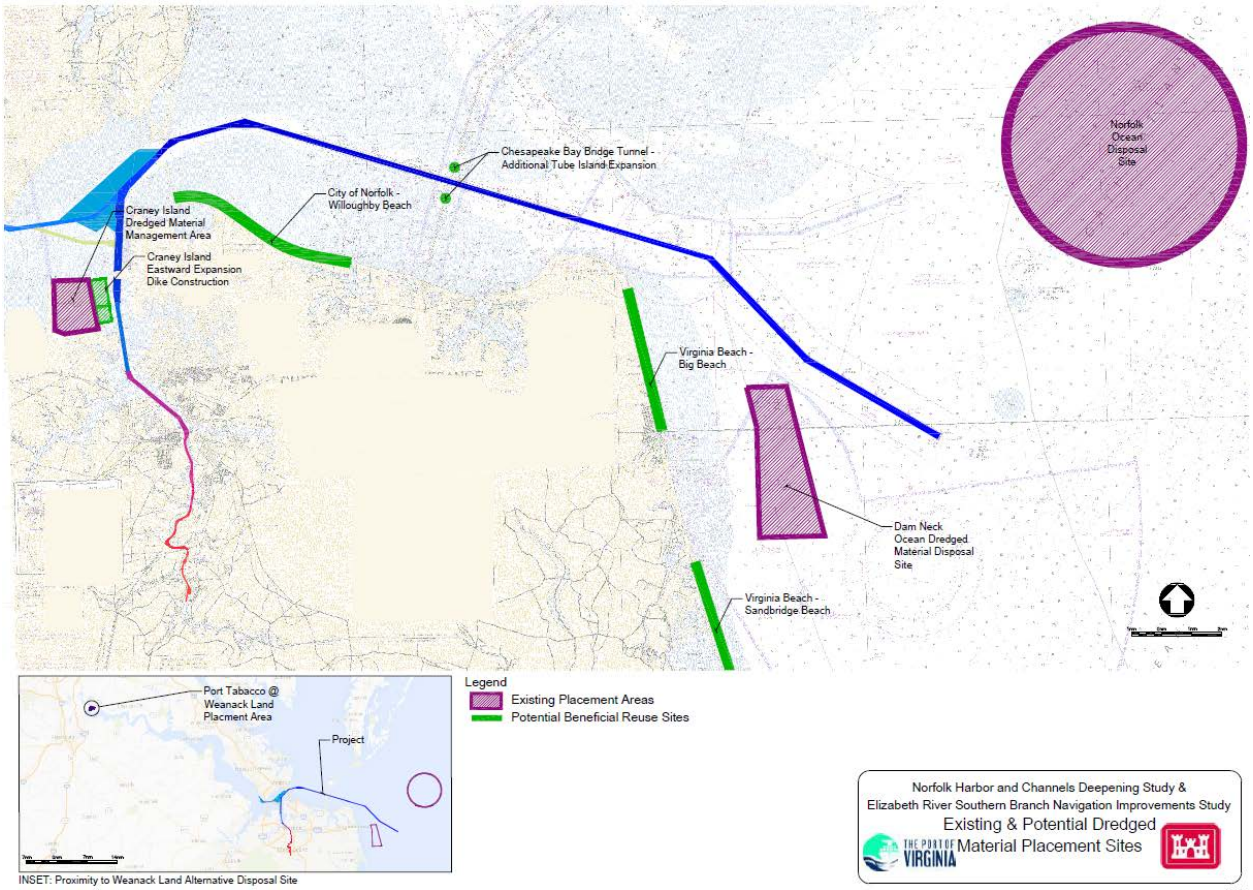
USACE (2009), Site Management and Monitoring Plan for the Dam Neck Ocean Disposal Site (DNODS), February 2009.

USACE (2009), Site Management and Monitoring Plan for the Norfolk Ocean Disposal Site (NODS), February 2009.



INSET: Proximity to Weanack Land Alternative Disposal Site

CENAO-PM-C 24 August 2016

MEMORANDUM FOR RECORD

THRU: Douglas Stamper, Project Manager, Programs and Civil Works Branch

Mr. Richard Klein, Chief, Programs and Civil Works Branch

Ms. Susan Conner, Chief, Planning and Policy Branch

FOR: Office Files

SUBJECT: Norfolk Harbor and Channels and Elizabeth River Southern Branch Deepening Projects

1. On 4 August 2016, a Vertical Team Meeting was held on the subject projects to discuss the Dredged Material Management Plan (DMMP) for each of the ongoing general reevaluation studies. The meeting was conducted as a webinar and the attached PowerPoint presentation was used to facilitate the discussion. The following individuals participated in the meeting:

- Norfolk District: Doug Stamper, Susan Conner, Kristen Scheler, Richard Harr, Rachel Haug, Alicia Logalbo, Richard Klein, Robert Pruhs, Mike Anderson,
- VPA: Jeff Florin, Ira Brotman, Mike McGarry
- DDNPCX: Idris Dobbs, Todd Nettles, Eric Bush, Daniel Small, Kim Otto,
- NAD: Naomi Fraenkel
- HQUSACE (OWPR): Jeremy LaDart

2. The purpose of the meeting was to meet the following goals:

- Ensure that the DMMPs being developed for both studies meet the DMMP requirements for feasibility-level studies (**See Slide 2**);
    - Provides for 20 years of placement capacity
    - Establishes a base plan (least cost placement plan)
    - Assesses potential for beneficial use
    - Demonstrates economic justification
    - Provides agency review and consultation
    - Provides public involvement
    - Demonstrates consistency with environmental requirements

- Demonstrate that continuing the current dredged material management practices will fulfill the DDMP requirements; and

- Obtain Vertical Team (NAD, DDNPCX, and HQUSACE) concurrence.

3. The following paragraphs present the major points of discussion focused on the meeting goals presented in paragraph 2.

a. Provides for 20 years of Placement Capacity. The location of the Norfolk Harbor and Channels Deepening Project and the Elizabeth River Southern Branch Navigation Improvements Project are show on **Slide 3** and the projected quantities for construction and 20-year maintenance for each project are shown on **Slide 4**.

Although no complete and approved DMMP currently exists for each of the two projects, all of the information, as presented, currently exists and additional calculations are being done to assure 20+ years of capacity for each project. The needed capacity currently exists (**See Slide 5**) at a combination of the three existing placement areas (**See Slide 6**) consisting of the Dam Neck Ocean Dredged Material Disposal Site (ODMDS), the Norfolk ODMDA, and the Craney Island Dredged Material Management Area (CIDMMA). Specific information, including estimated total capacity, was presented on **Slides 7, 8, and 9**, respectively.

b. Establishes a Base Plan (Least Cost Placement Plan). The PDT has established the following Least Cost (Base) Dredged Material Placement Plan for each project, as follows;

- Norfolk Harbor and Channels Deepening (**See Slides 10 and 11**): Plan consists of using the ODMDSs for the Thimble Shoal and Atlantic Ocean Channels and the CICMMA for the Norfolk Harbor Channel; and

- Elizabeth River Southern Branch Navigation Improvements (**See Slides 12**): Plan consists of using the CIDMMA for the suitable material and several potential upland sites for the material unsuitable for placement at CIDMMA (**See Slide 17**). One potential site, Port Tobacco at Weanak (**See Slides 17 and 18**), has proven to be a successful dredged material handling site and transfer area to the Charles City County Landfill.

c. Assesses Potential for Beneficial Use**.** Beneficial Use Opportunities (**Slides 14 and 15**)

- Big Beach, Sandbridge, Willoughby, CIEE, and CBBT
- To be addressed in more detail during PED Phase
- Based on Sponsor need, timing, and incremental costs

d. Demonstrates Economic Justification, Provides Agency Review and Consultation, Provides Public Involvement, and Demonstrates Consistency with Environmental Requirements. As indicated on **Slide 19**, dredged material placement is a component of the GRR/EA for each project. The DDMPs will be presented in the GRR/EAs as components of the Plan Formulation

Appendix for both studies which will ensure that economic justification, agency review and consultation, public involvement, and environmental consistency determination will be addressed for each project.

e. Demonstrate that continuing current dredged material management practices fulfills DMMP requirements. Continued management of CIDMMA and ODMDS sites using our existing proven successful practices will ensure long-term capacity for the project. As will be outlined in the DMMP.

4. Comments provided by the Vertical Team:

- Although the DMMP accounts for 20 years, please note that the economics for the plan formulation must account for 50 years of disposal. RESPONSE: Understood

- Please note that the eastward expansion of Craney Island has a different cost-share (86/14) than most projects. RESPONSE: noted

- Question on ocean disposal permitting now and in the future. RESPONSE: The Ocean Disposal Sites are permitted though 2019 (needs to be confirmed) and the PDT is confident that these sites will continue to be approved for use in the future (needs to be confirmed by Robert Pruhs).

- Ensure that PDT looks at beneficial use sites. RESPONSE: Although that is not the base plan, it will be mentioned in both the DMMP and the NEPA document for both studies that beneficial use opportunities exist and those will be evaluated in the future based on needs and timing.

- PDT needs to verify and document that the least cost that was originally established is still the least cost plan today. RESPONSE: Concur and PDT will document this.

5. In summary (Slide 20), both DMMPs meet all requirements from ER 1105-2-110 and continues existing dredged material management practices. The DDMPs will be presented in the GRR/EAs as components of the Plan Formulation Appendix for both studies. The Vertical Team concurred with the PDT's way forward on the DMMP for both studies.

Prepared with notes provided by Susan Conner, Chief, Planning and Policy Branch, and Douglas Stamper, Project Manager, Programs and Civil Works Branch.

Robert N. Pretlow, Jr., PE, PMP
Project Manager
Programs and Civil Works Branch
USACE, Norfolk District

ATTACHMENT

Dredged Material Placement Plan for the

Norfolk Harbor and Channels Deepening Project

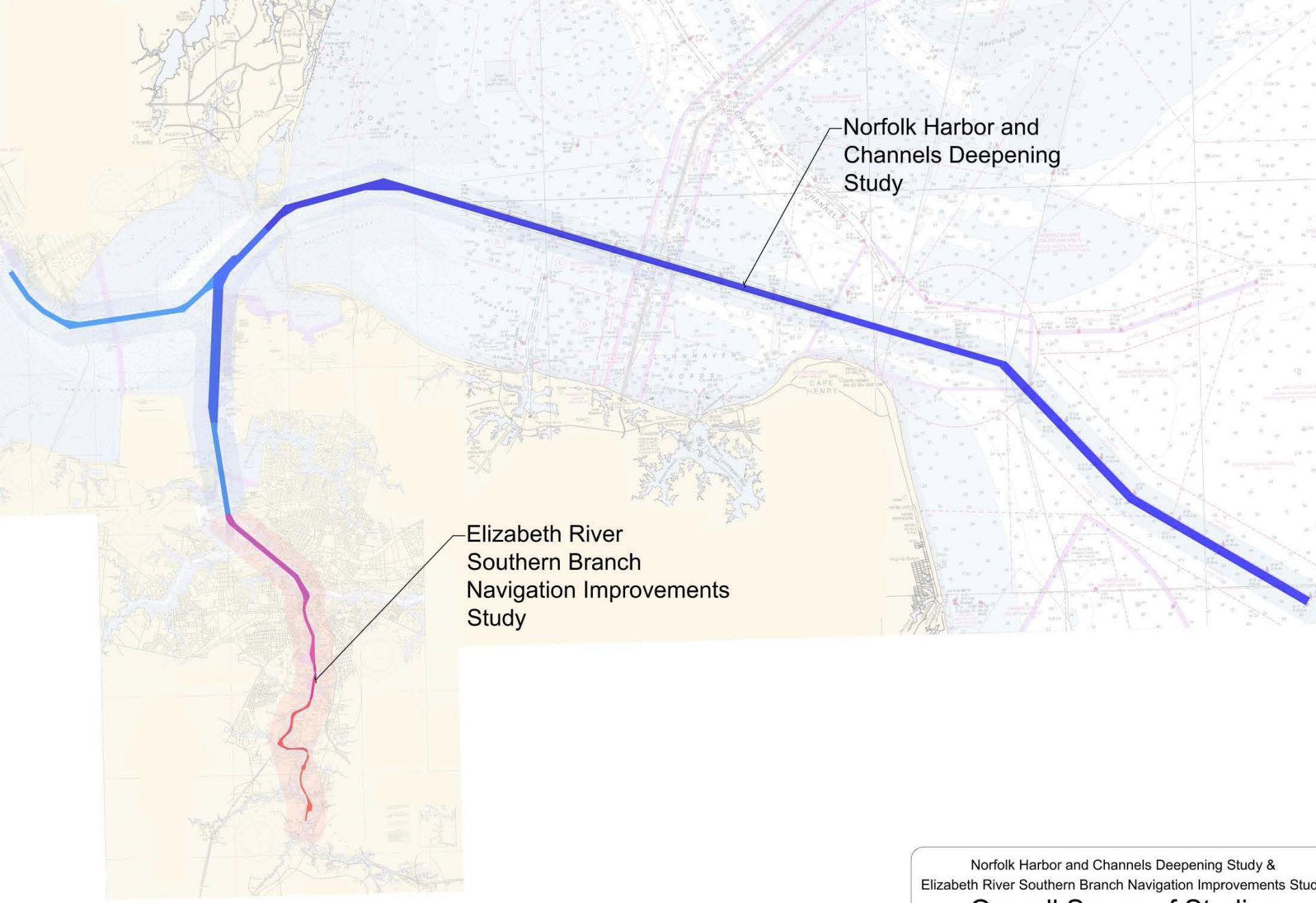
And

Elizabeth River and Southern Branch Navigation Improvements Project
General Reevaluation Studies

28 July 2016

Meeting Objectives

- Demonstrate that the DMMP for NH & ERSB
  - Provides for 20-years of placement capacity
  - Establishes a base plan (least cost placement plan)
  - Assesses potential for beneficial use
  - Demonstrates economic justification
  - Provides agency review and consultation
  - Provides public involvement
  - Demonstrates consistency with environmental requirements
- Demonstrate that continuing current dredged material management practices fulfills DMMP requirements



Norfolk Harbor and Channels Deepening Study &
Elizabeth River Southern Branch Navigation Improvements Stud

Overall Scope of Studies

Projected Quantities

- Norfolk Harbor
  - Construction: 35 MCY *(2/3rds to Offshore)*
  - Annual maintenance: 1.5 MCY to 2 MCY
  - 20-year total: 65 MCY to 75 MCY
    - *Offshore: 45 MCY*
    - *CIDMMA: 22 MCY*
- Eliz. River and So. Branch
  - Construction: 1.7 MCY
  - Annual maintenance: 60,000 CY
  - 20-year total: 2.5 MCY
    - Upland: 1 MCY
    - CIDMMA: 2 MCY

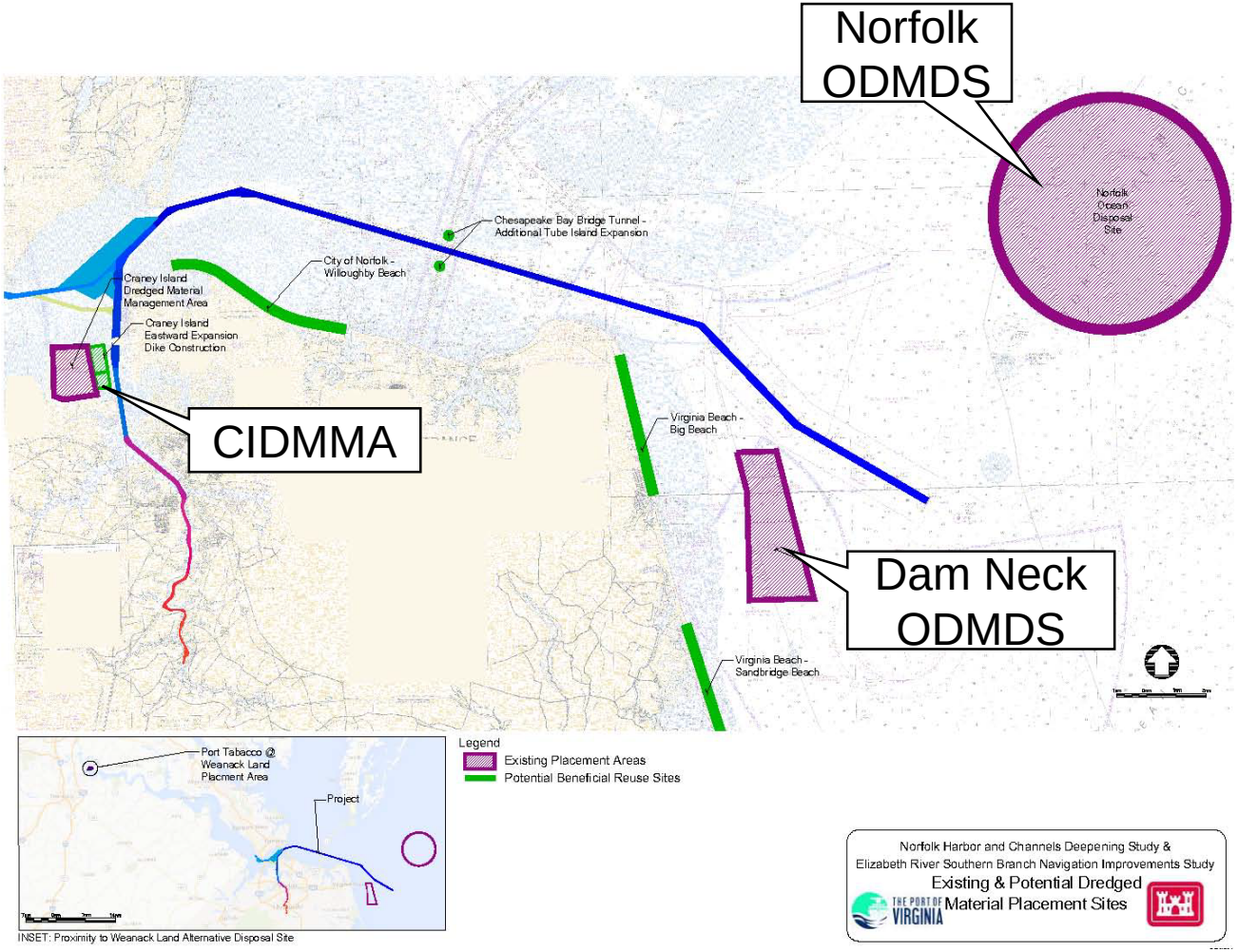
Capacity Availability

- DMMP Based on 3 Established and Operating Placement Areas
  1. Dam Neck ODMDS
     - Initiated in 1970’s current SMMP 2009 - 2019
  2. Norfolk ODMDS
     - Initiated in 1970’s current SMMP 2009 - 2019
  3. CIDMMA
     - Feasibility Study & NEPA 1981
     - In continuous use since 1981

Placement Areas

DMMP Exist.
At Each:

- Dam Neck
- Norfolk
- CIDMMA



Dam Neck Ocean Dredged Material Disposal Site (ODMDS)

- ~9-square Nautical Miles
- Water Depth ~40 feet
- Designed for Min 50 MCY
- SMMP allows for possible capacity expansion
- No Time of Year Restrictions

Norfolk Ocean Dredged Material Disposal Site (ODMDS)

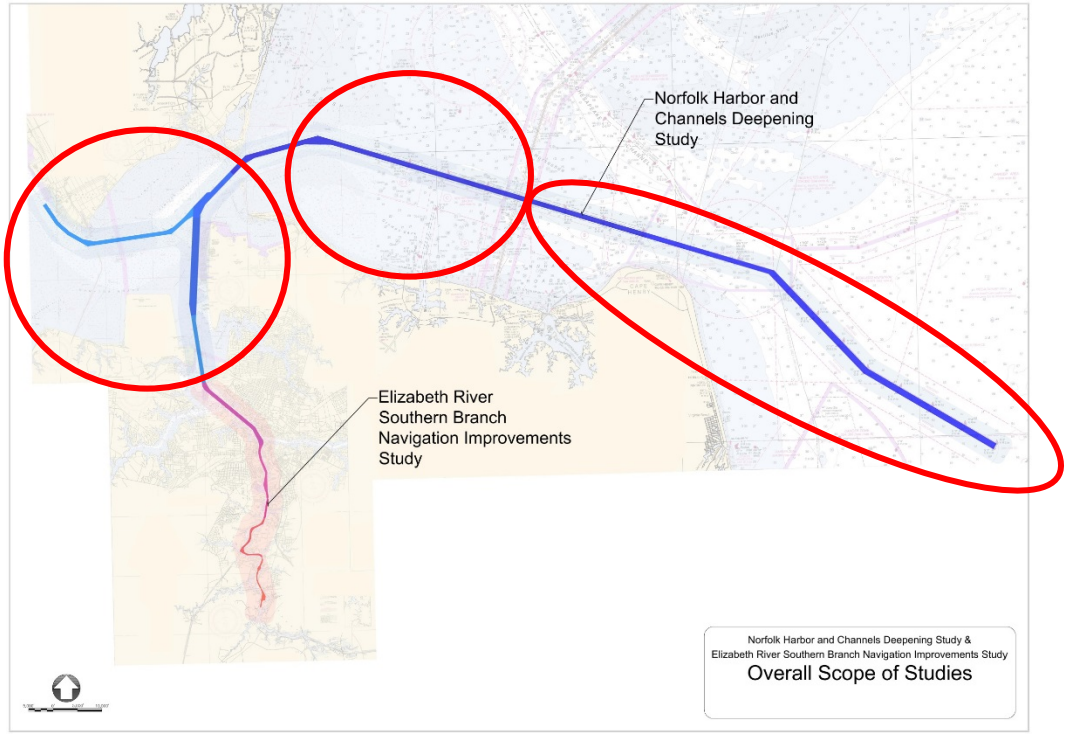
- Estimated total capacity of 1,300 MCY.
- Circle With a Radius of 4 NM (50 square NM)
- Water Depth ~43 to 85 feet
- Designed for Post-CIDMMA

Craney Island Dredged Material Management Area Capacity

- CIDMMA, Feas Report:
  - Feas Report, Capacity ~117 MCY (2000 to 2025)
  - Actual Inflows 2000 to 2015 ~65 MCY
  - Therefore, 117 MCY – 65 MCY = 52 MCY Capacity
  - Needs to be validated
- CIEE:
  - Adds 43 MCY to CIDMMA capacity
  - CIEE Acts as CIDMMA's 4th Cell
  - SE Cell Scheduled for early 2020
- Total CIDMMA & CIEE capacity = >95MCY

Norfolk Harbor – Least Cost Plan

- Ocean Channels: TSC and AOC
  - Offshore Disposal
- Norfolk Harbor Reaches
  - CIDMMA



“55-foot” NHC – Least Cost Plan

Reach	Nominal Depth	Actual Depth	Comments	Volume, MCY	Placement Area
Atlantic Ocean Channel	55	-60	57' Reqd + 3' Allowable Overdepth	6.5	Dam Neck
Thimble Shoal Channel	55	-57	55' Reqd + 2' Allowable Overdepth	8.2	Dam Neck
TSC Meeting Area #1	55	-57	55' Reqd + 2' Allowable Overdepth	8.7	Dam Neck
TSC Meeting Area #2	55	-57	55' Reqd + 2' Allowable Overdepth	2.6	Dam Neck
Norfolk Harbor Sewells Point to Lamberts Bend	55	-57	55' Reqd + 2' Allowable Overdepth	6.1	CIDMMA
Channel to Newport News	55	-57	55' Reqd + 2' Allowable Overdepth	2.4	CIDMMA
Anchorage F	55	-57	55' Reqd + 2' Allowable Overdepth	0.6	CIDMMA
Total				**35.2**	

Summary of New Work by Placement Area:

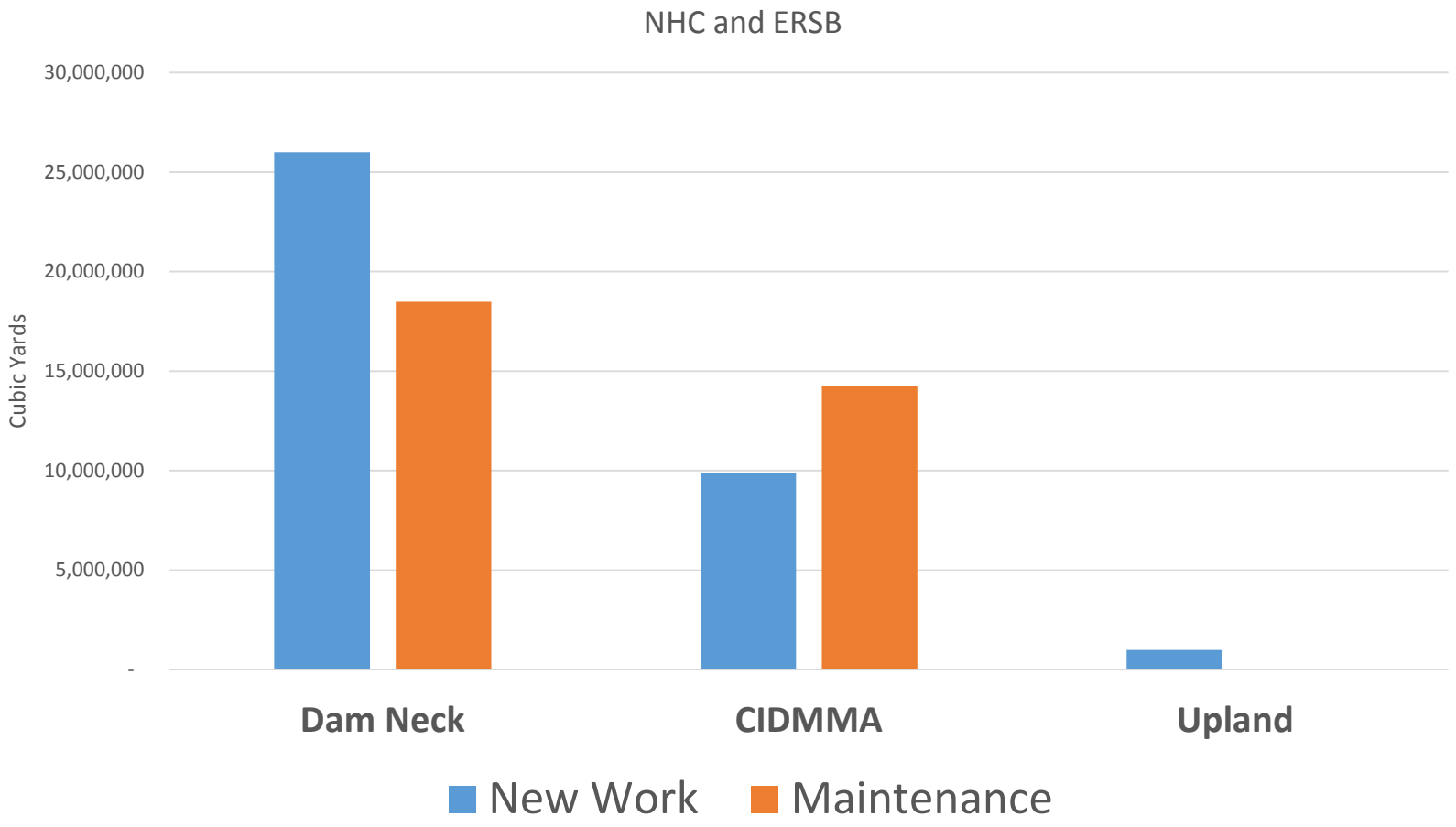
- Offshore: ~26MCY
- CIDMMA: ~9 MCY

ERSB – Least Cost

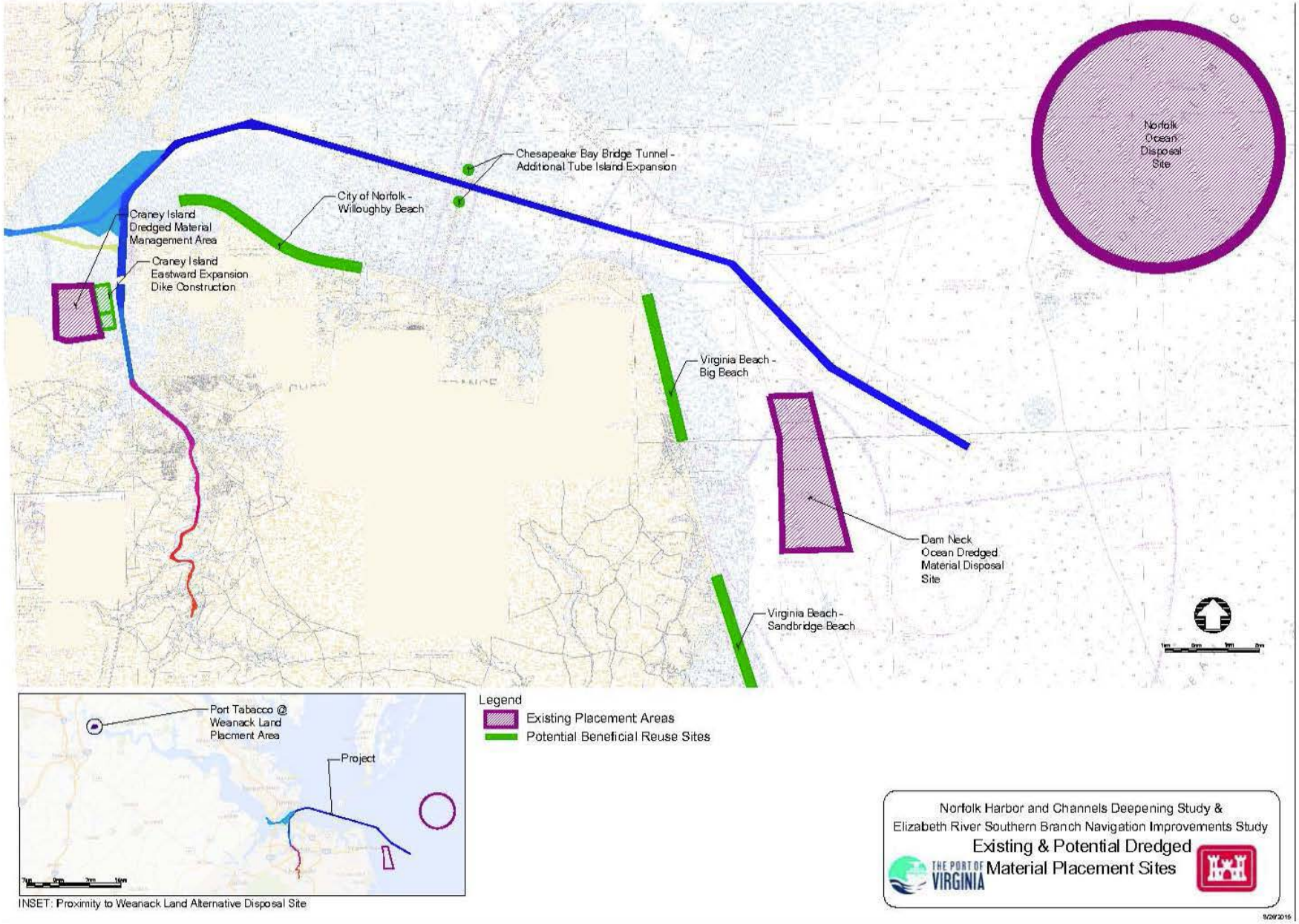
		Least Cost Plan		
Reach	**Quantity (CY)**	**Placement Area**	**Unit Cost**	**Total Cost**
Elizabeth River Reach (-45')	610,000	CIDMMA	$6.58	$7.7M
Lower Reach (-45')	90,000	CIDMMA	$11.66	$1.1M
Middle Reach (-40')	270,000	Port Tobacco /Landfill	$88.48	$23.9M
Upper Reach A (to -40)*	726,000	Port Tobacco /Landfill	$88.36	$64.2M
Upper Reach B (to -37)*	19,000	Port Tobacco /Landfill	$103.49	$2.0M

* No beneficiaries – dredging unlikely

New Work and
20-YR Maintenance Dredging Estimate



Beneficial Reuse Sites



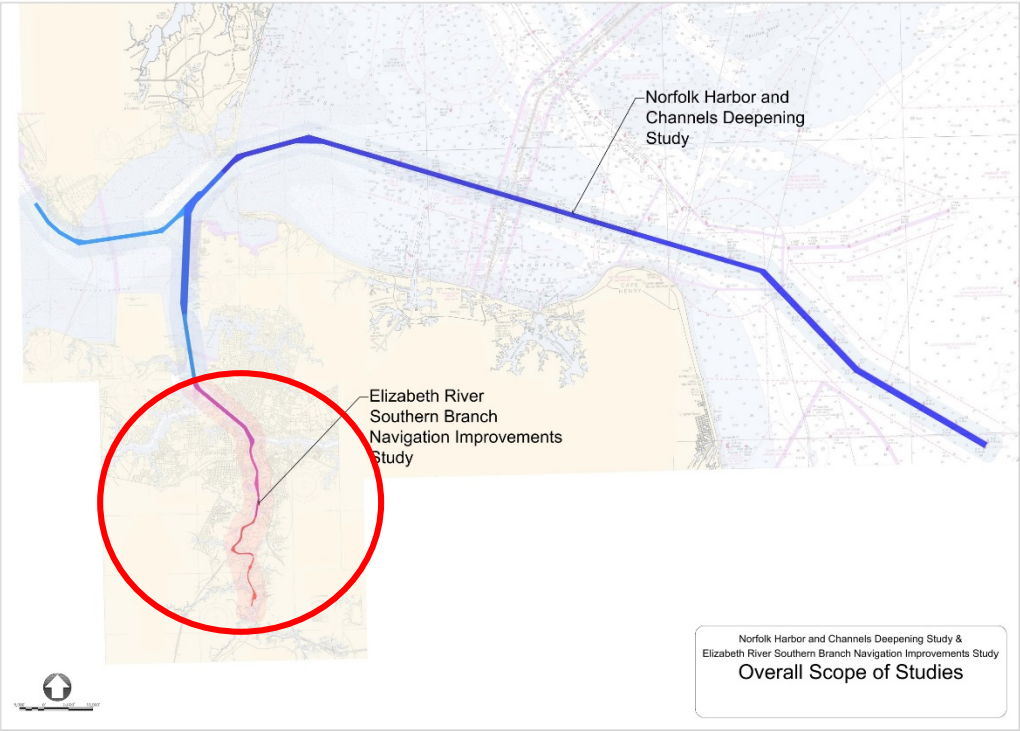
Beneficial Reuse Sites

- NEPA Compliant
- Limited to sandy areas, including TSC (East of CBBT), AOC and TSC Meeting Area #2
- No ERSB beneficial use

		Least Cost Plan			Beneficial Use Plan		
Reach	**Quantity**	**Placement Area**	**Unit Cost**	**Total Cost**		**Unit Cost**	**Total Cost**
Atlantic Ocean Channel	6.5 MCY	Dam Neck	$5.37	$36.7M	Big Beach	$7.99	$57.6M
Thimble Shoal Channel East	1.4 MCY	Dam Neck	$7.82	$12.1M	Willoughby	$9.36	$15.3M
TSC Meeting Area #2	2.6 MCY	Dam Neck	$7.36	$20.2M	Willoughby	$8.19	$23.4M

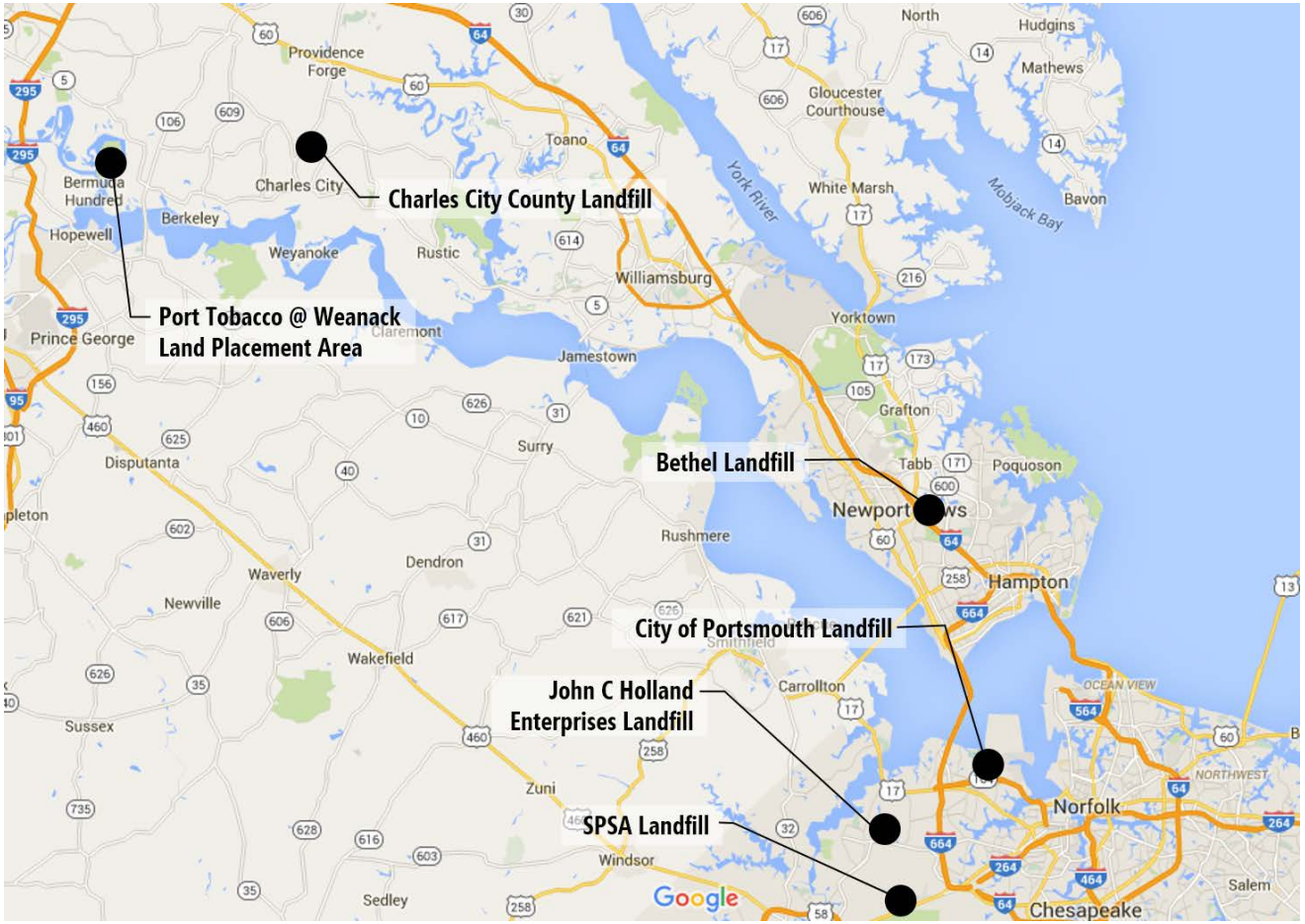
ERSB – Some Material Unsuitable for CIDMMA

- Southern Branch
  - CIDMMA
  - Upland



Upland Sites
Material Unsuitable for CIDMMA

- Southern Branch



Port Tobacco @ Weanak

- Successful track record of handling dredged material on site and transfer to Charles City County Landfill
- Current capacity to receive ~1MCY
- Expansion capacity to ~2MCY (authorized under existing permits)

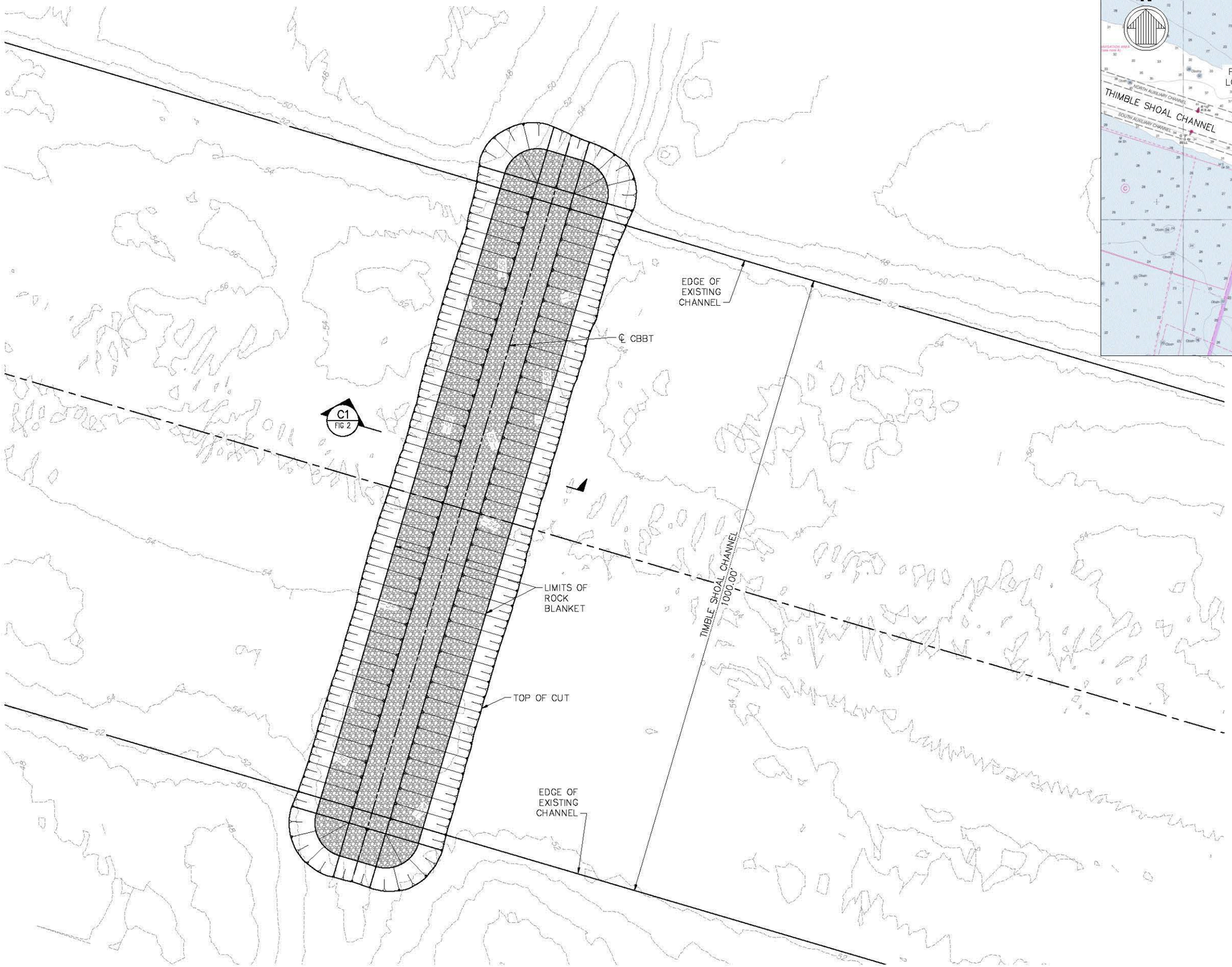
Dredged Material Placement is a Component of the GRR/EA

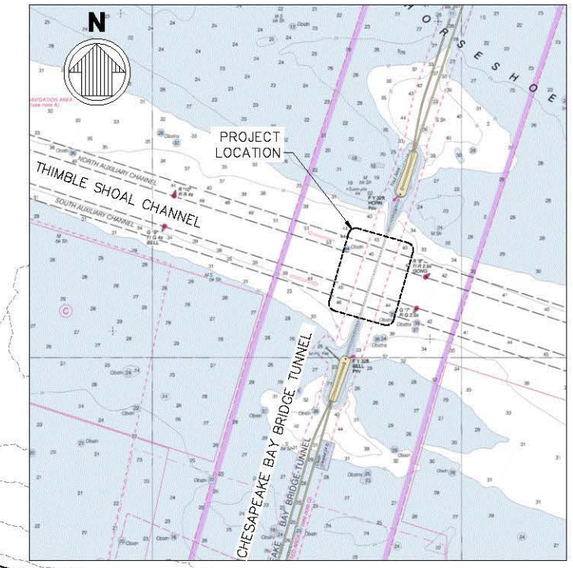
- Included in economic justification
- Included in agency review & consultation
- Included in public involvement
- Included in the environmental consistency determination

DMMP Summary

- DMMP meets all requirements from ER 1105-2-110
  - Section 3.2b(8), and
  - Appendix E Section E-15
- Will be presented in the GRR/EA as a component of the Plan Formulation Appendix
- Continues existing dredged material management practices

Engineering Appendix F:
CBBT Concept





LOCATION PLAN
SCALE: NONE

CONCEPT FOR NORFOLK HARBOR AND CHANNEL DEEPENING STUDY

DRAWING SCALES SHOWN BASED ON AN ANSI D DRAWING

SEAL

CONCEPT
NOT TO BE USED FOR CONSTRUCTION

Mark	Description	Date	Appr.

Designed by:
Date: SEPT. 2016
Rev.
Dwn by: BA
Ckd by: IB
A/E Project No. 8885-01
Reviewed by: IB
Drawing code:
Submitted by: MOFFATT & NICHOL
Drawing Scale: GRAPHIC
Plot scale: 1:1

Plans Prepared For
U.S. ARMY ENGINEER DIVISION
CORPS OF ENGINEERS - NORFOLK DISTRICT
& THE VIRGINIA PORT AUTHORITY

Plans Prepared By
MOFFATT & NICHOL
800 WORLD TRADE CENTER
NORFOLK, VA 23510

CHESAPEAKE BAY BRIDGE TUNNEL
THIMBLE SHOAL DREDGING
NORFOLK, VIRGINIA

PLAN - ROCK BLANKET

Sheet Reference Number:
FIG 1
Sheet 1 of 2

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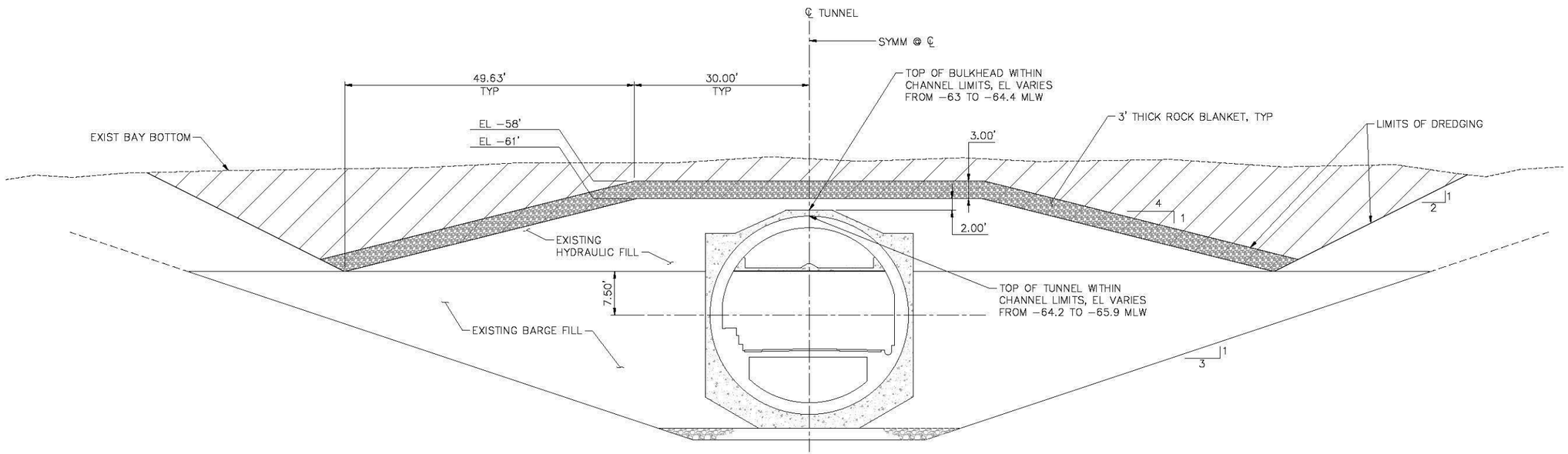

C1 FIG 1 TYPICAL SECTION
SCALE: 1"=10'-0"

CONCEPT FOR NORFOLK HARBOR AND CHANNEL DEEPENING STUDY

10' 0' 10' 20'
SCALE: 1"=10'

DRAWING SCALES SHOWN BASED ON AN ANSI D DRAWING

SEAL

CONCEPT
NOT TO BE USED FOR CONSTRUCTION

Work	Description	Date	Appr

Designed by:
Date: SEPT. 2016
Rev.
Dwn by: BA
Chkd by: IB
A/E Project No. 8885-01
Reviewed by: IB
Drawing code:
Submitted by: MOFFATT & NICHOL
Drawing Scale: GRAPHIC
Plot scale: 1:1

Plans Prepared For
U.S. ARMY ENGINEER DIVISION
CORPS OF ENGINEERS, NORFOLK DISTRICT
& THE VIRGINIA PORT AUTHORITY

Plans Prepared By
MOFFATT & NICHOL
800 WORLD TRADE CENTER
NORFOLK, VA 23510

CHESAPEAKE BAY BRIDGE TUNNEL THIMBLE SHOAL DREDGING NORFOLK, VIRGINIA

CBBT TYPICAL SECTION WITH ROCK BLANKET

Sheet Reference Number:
FIG 2
Sheet 2 of 2

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