Appendix N

Underkeel Clearance Study

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Port of Corpus Christi Authority Channel Deepening Project

Underkeel Clearance Study

October 04 2021 | 13242.102.R1.RevA

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Port of Corpus Christi Authority Channel Deepening Project

Underkeel Clearance Study

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13242.102.R1.RevA

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Revision	Date	Status	Comments	Prepared	Reviewed	Approved
A	10/04/2021	Draft	For Client Review	WvdM	SG	LW

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Executive Summary

Freese & Nichols, Inc. (FNI) has engaged W.F. Baird & Associates Ltd. to provide coastal engineering and modeling services for the proposed Corpus Christi Channel Deepening project. The project will comprise deepening of the Outer and Approach Channels to 77 ft, and the Jetty Channel and seaward-most portion of the Corpus Christi Ship Channel to 75 ft. The channel will be used by vessels including laden VLCC's at a maximum draft of 68 ft departing from the planned Axis and Harbor Island terminals. A dynamic underkeel clearance (UKC) assessment as described in this report was part of these studies developed for the purposes of assessing project adequacy for the Environmental Impact Statement. The study included an analysis of measured water levels, assessments of modeled currents and waves, and modeling of vessel squat and wave response.

Vessels departing from the Axis terminal would accelerate to a speed of 6-8 knots (kn) in between the jetties. Speeds for departure from the closer Harbor Island terminal would be slightly less. Cruising speeds in the Approach and Outer channels are expected to be in the range of 8-10 kn. Maximum significant wave height for vessel departures was adopted as 10-12 ft, limited by disembarking of the pilot after the channel transit as reported by the Aransas Corpus Christi Pilots Association (ACCPA). Most common wave conditions are from SSE with peak periods of 7-9 s.

Maximum vessel squat was estimated to be 2.7 ft in the Jetty Channel at 6.5 kn speed over ground and against a 1.9 kn flood tide current. However, the maximum flood tide current occurs close to high tide. Ebb tide currents that are maximum around low tide limit the squat to 1.1 ft in the Jetty Channel. Squat at low tide with small current effects in the Approach and Outer Channels at 9 kn speed over ground was estimated at 2.3 ft. The resulting maneuverability margin (safety clearance, not including wave response) with a 10% annual probability (1 in 10 year) low water level condition has a minimum value of 4.7 ft in the Jetty Channel. This is greater than the recommended margin of 3.4 ft suggested by PIANC and greater than the required 2 ft safety clearance by USACE. It is recommended that departure speed profiles be analyzed after the planned navigation simulations and squat re-assessed based on these speed profiles if greater speeds are expected.

The minimum safety clearance for the design operational wave conditions was calculated at 4.5 ft in the Jetty Channel and 5.2 ft in the Approach and Outer Channels, which is compliant with the 2 ft safety clearance criterion established by USACE. Wave response in the Outer Channel increases considerably in longer swells for peak periods greater than 13 s, resulting in 1.9 ft of safety clearance, slightly outside of the USACE criterion. However, peak periods greater than 13 s have only occurred offshore of Corpus Christi infrequently including during hurricanes Katrina, Rita and Ike based on the 1980-2014 wave WIS hindcast of the area. It is recommended that port closure policies be checked for extreme hurricane scenarios to verify whether vessels would depart under extreme wave conditions with large peak periods.

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1. Introduction

1.1 Project Background

W.F. Baird & Associates Ltd. (Baird) was engaged by Freese & Nichols, Inc. (FNI) to provide coastal engineering and modeling services for the Corpus Christi Ship Channel Deepening Project (CDP). The project is the proposed deepening of the Offshore Channel to a nominal depth of 77 ft (Segments 1 and 2 in Figure 1.1), and the Entrance Channel and seaward-most portion of the Corpus Christi Ship Channel to 75 ft (Segments 3 to 6 in Figure 6.1). The channel will service the planned Harbor Island and Axis terminals with laden vessels, including very large crude carriers (VLCC's), departing from these terminals.

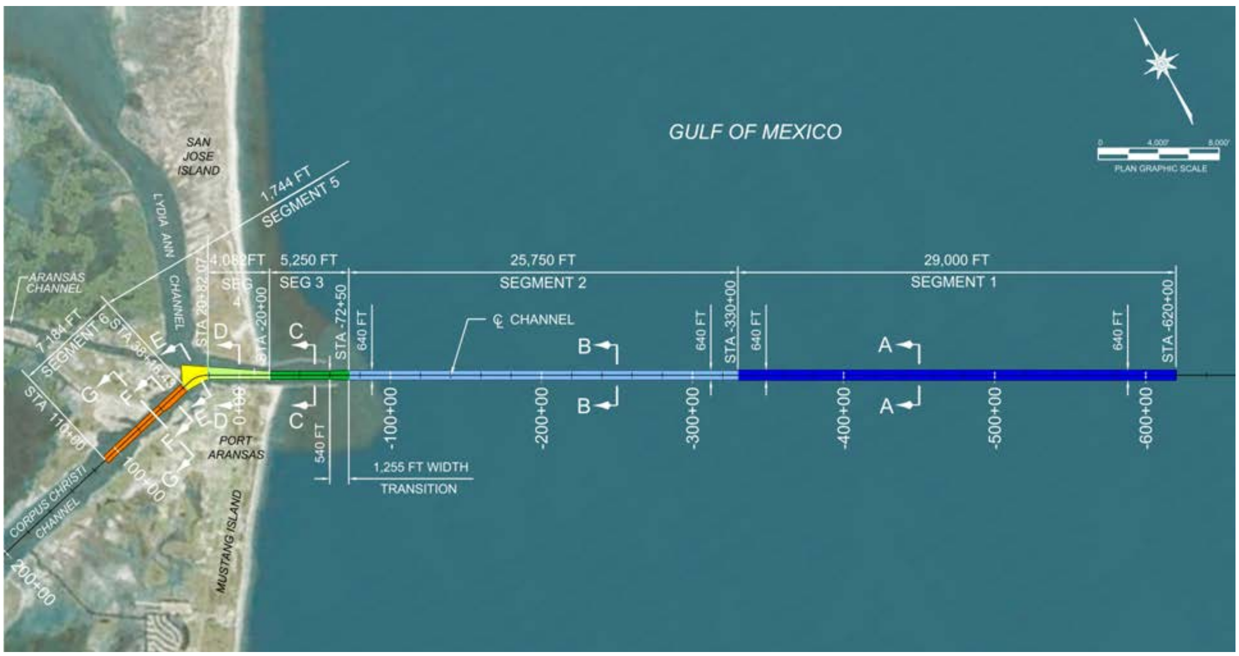

Figure 1.1: Dredging plan for the Corpus Christi Ship Channel Deepening Project

Baird's services include the following tasks:

- Vessel wake analysis
- Dynamic underkeel clearance (UKC) study
- Propeller scour study
- Tidal and hydrodynamic modeling
- Storm surge analysis
- Sediment transport modeling

The dynamic underkeel clearance study is addressed in this Report.

1.2 Study Objectives

The dredged depths for all channel segments have been proposed by the Port of Corpus Christi for the channel design. The objective of the UKC study is to verify adequacy these channel depths using analysis of water levels and the results of wave, hydrodynamic and vessel response modeling. The results of the vessel squat modeling may also be used as input to the planned navigation simulations.

1.3 Report Outline

This report provides a brief description of the numerical model that is used to determine vessel squat and wave response in Section 2. Input data to the UKC assessment are considered in Sections 3 and 4, with channel dimensions, vessel dimensions and vessel speed in Section 3, and water levels, currents and waves in Section 4. UKC criteria are described in Section 5 as set by USACE and adopted in this study. The study results are provided in Sections 6 and 7, with Section 6 focusing on squat and Section 7 considering the wave response and resulting safety clearance between the keel and the channel bed. Conclusions are provided in Section 8.

2. Vessel Response Numerical Model Description

2.1.1 General

Historically, squat was analyzed using squat formulas based on the results of a wide range of physical model test data. Numerical modeling of squat has become more widespread in the last decades with increased computer power. The advantage of numerical modeling is that the model can be better set-up for specific hull shapes, as well as channel geometries and local currents. Nevertheless, calibration and tuning to measurements remains important to account for limitations in the model.

The most common types of numerical models for squat predictions are (in order of complexity):

- slender body models,
- panel models,
- Computational Fluid Dynamics (CFD) models.

Slender body models compute the potential flow around the hull assuming that the vessel length is much greater than its width and draft. Limitations of these models exist when applied to relatively wide ships and for irregular shaped channel banks.

Panel models approximate the submerged vessel hull and channel geometry by a large number of flat quadrilateral panels. Similar to slender body models, the method is based on potential flow, but including 3D effects of both the vessel and channel geometry. The main limitation of panel models is that turbulent flow and propeller wash near the stern are not represented.

CFD models are potentially most accurate as it includes modeling of turbulent flows with the inclusion of propeller wash. However, it is difficult to generate and modify specific hull shapes and computationally demanding. Use of CFD models for squat predictions is at the moment mostly used in the research sphere.

2.1.2 Wavescat Model

Baird's in-house numerical model for squat and wave response "Wavescat" is a panel model. As such, it includes and can be easily set-up for various 3D hull shapes. Hull shapes of ships are usually provided as "body plans" describing the outline of the hull at several cross-sections along the ship from stern to bow. The body plan is transformed into a 3D panel mesh for input in Wavescat. An example of the body plan and hull mesh for a VLCC at 68 ft draft in Wavescat as used in this study is shown in Figure 2.1.

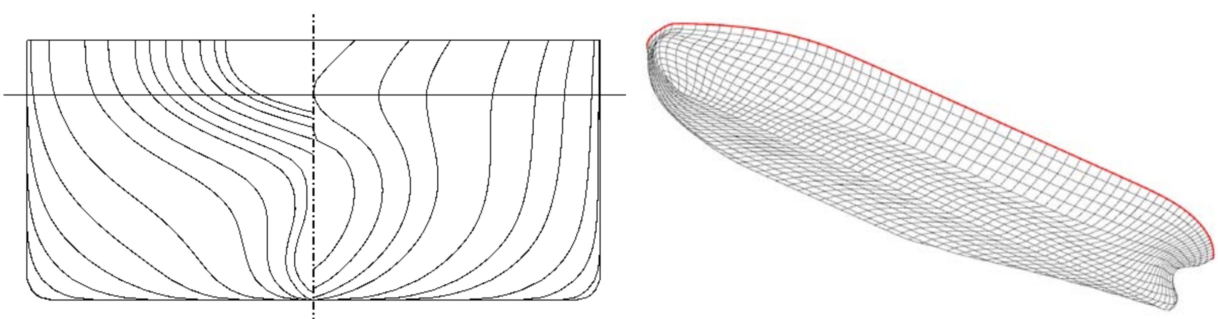

Figure 2.1: Body plan (left) and Wavescat hull mesh (right) for a VLCC

Wacescat is a 3D potential flow and diffraction model based on the free surface Green function. Aside from the hull mesh, panels can be placed on bathymetric features such as channel banks to model bank suction effects on maneuvering forces and squat. The channel bed is assumed horizontal elsewhere. The vessel speed in the model is the speed through water.

Model results include (relevant components for this study in bold):

- **squat,**
- **wave Response Amplitude Operators (RAO's),**
- wave forces,
- drift forces,
- hydrodynamic coefficients (added mass and damping).

The squat result is a midship squat and dynamic trim angle. The squat at bow and stern can be obtained from these two values. The vessel response to a certain sea state can be obtained from the RAO's in 6 degrees of freedom and wave spectrum for all wave frequencies and directions. The sinkage of keel points (bow, stern, port and starboard sides) can be obtained from the response in heave, roll and pitch at the center of gravity.

3. Physical Data Overview

3.1 Vessel Dimensions

The design vessel for the project is a 306k DWT VLCC laden to a draft of 68 ft. The vessel dimensions used in the UKC modelling are in accordance with the data of the vessel used during the navigation simulations provided in Table 1.

Table 3.1: Dimensions of VLCC at 68 ft draft

Designation	(m)	(ft)
Length Over All	332.00	1089.2
Width	58.00	190.3
Draft (Scantling)	22.50	73.8
Draft (Modeled)	20.73	68.0
Deadweight (at Scantling Draft)	306,200 MT	337,500 ST
Displacement (at Modeled Draft)	321,000 MT	353,800 ST

3.2 Channel Dimensions

The assessment of squat and wave response in the channel was done for four channel segments, the Harbor Island Transition Flare (HITF), Jetty Channel, Approach Channel and Outer Channel. These are channel segments 1-4 in Figure 1.1, ordered outward from the port, i.e. in the departing sailing direction. The channel dimensions as provided in the Project Description (Port Corpus Christi, 2019) are given in Table 3.2. The stated bed level that is assumed in the modeling and analysis is the authorized bed level. The channel will be dredged deeper to accommodate sedimentation that is expected to occur up to the guaranteed bed level before subsequent maintenance dredging occurs (i.e,, advanced maintenance dredging).

Table 3.2: Channel Depth and Width for the considered channel sections

Seg.	Name	Length (ft)	Bed Width (ft)	Depth (ft MLLW)	Side Slopes (V:H)
4	Harbor Island Transition Flare	4,082	540*	−75	1:3
3	Jetty Channel	5,250	540	−75	1:3
2	Approach Channel	25,750	640	−77	1:10
1	Outer Channel	29,000	540	−77	1:10

* Minimum width – channel widens to the Harbor Island turning basin

The actual channel in between the jetties is wider due to scour that has occurred on the southern side of the channel. The channel profiles used for the squat modelling presented here are the “typical sections” provided in the Project Description and shown in Figure 3.1 for the Jetty Channel. The section for the Harbor Island Transition Flare was narrowed to a 540 ft bed width representing a section on the eastern side of this segment.

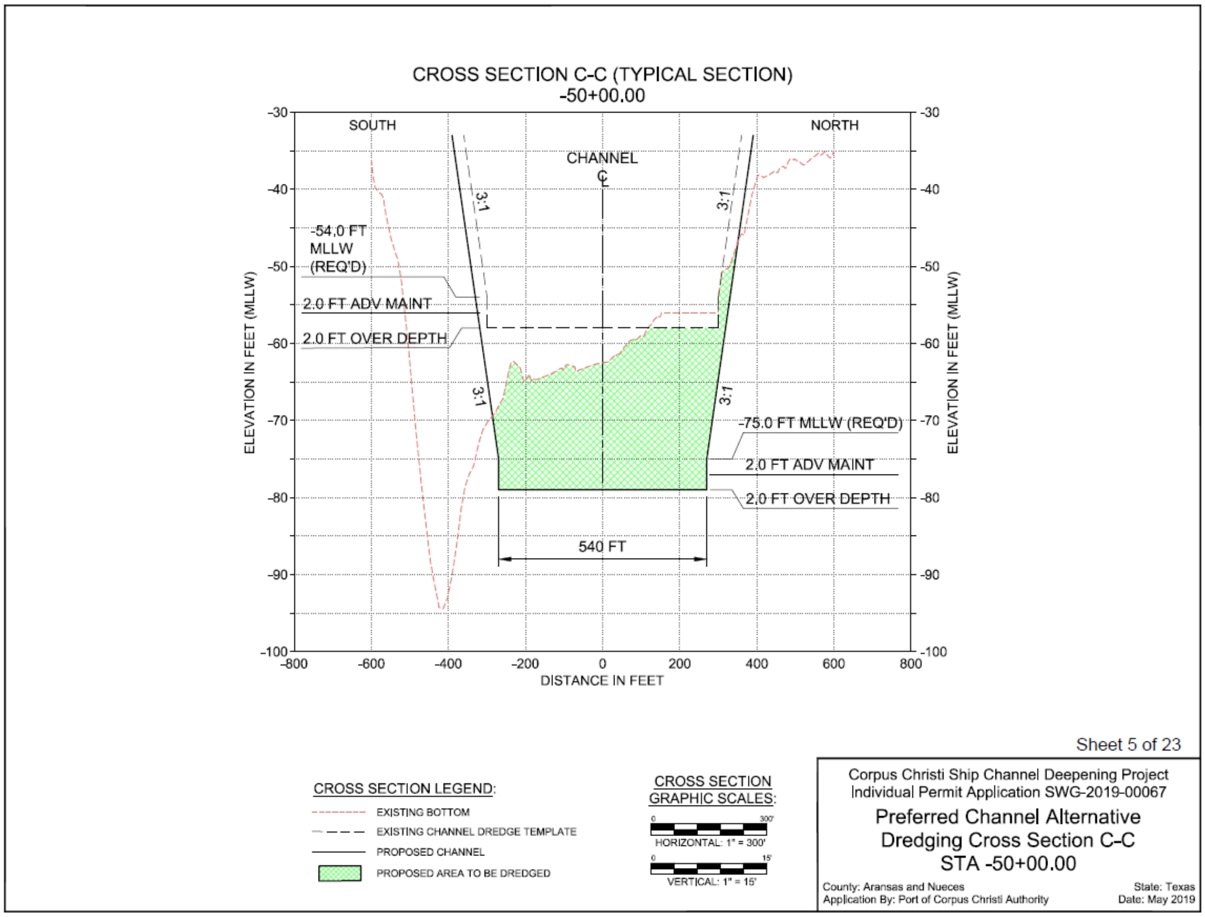

Figure 3.1: Typical channel cross-section in between the jetties (Port Corpus Christi, 2019)

3.3 Vessel Speed

3.3.1 Navigation Simulations

Navigation simulations were conducted as part of the project for the Harbor Island (SCI, 2019; WST & MITAGS-PMI, 2020) and Axis terminals (SCI, 2020). Several departure runs were conducted in these studies with the VLCC at 70 ft draft, sailing from the Harbor Island or Axis terminals to sea following the channel between the jetties. Speed profile data are provided for some of these runs and are summarized in Table 3.3.

The speed in between the jetties is generally around 9 kn but can be larger in an ebb tide when the vessel accelerates faster. Flood tide conditions are governing for speed through water (i.e., against an opposing current) which is most relevant to this study. The vessel continues accelerating in the approach channel.

Table 3.3: Summary of navigation simulation results in between the jetties with vessel speed over ground from the run data and estimates of current speed and vessel speed through water between the jetties

Facility	Terminal	Run #	Current		Speed between Jetties (kn)		Speed (kn)
			Condition	Speed (kn)	Over Ground	Through Water	Approach Ch.
SCI	Harbor Island	9	Flood	2	7.9	9.9	11.6
SCI	Harbor Island	11_2	Flood	2	9.2	11.2	-
SCI	Harbor Island	14	Ebb	2	12.0	10.0	-
SCI	Axis	10	Flood	2	9.6	11.6	-
WST	Harbor Island	13	Ebb	1	9.1	8.1	9.3
WST	Harbor Island	14	Flood	1	9.4	10.4	12.0
WST	Harbor Island	15	Ebb	2	10.6	8.6	12.0

3.3.2 AIS Analysis

Automatic Identification System (AIS) data of 50 VLCC departures from the terminal at Ingleside were also analyzed to verify vessel speeds during existing operations. Since these are historic departures the maximum draft would be 45 ft. The departure tracks are shown in Figure 3.2. The analyzed stretch of the tracks is from the bend in the channel at Harbor Island beyond the end of the existing channel up to a distance of 8.1 nm away from the bend, marked with a red line in Figure 3.2.

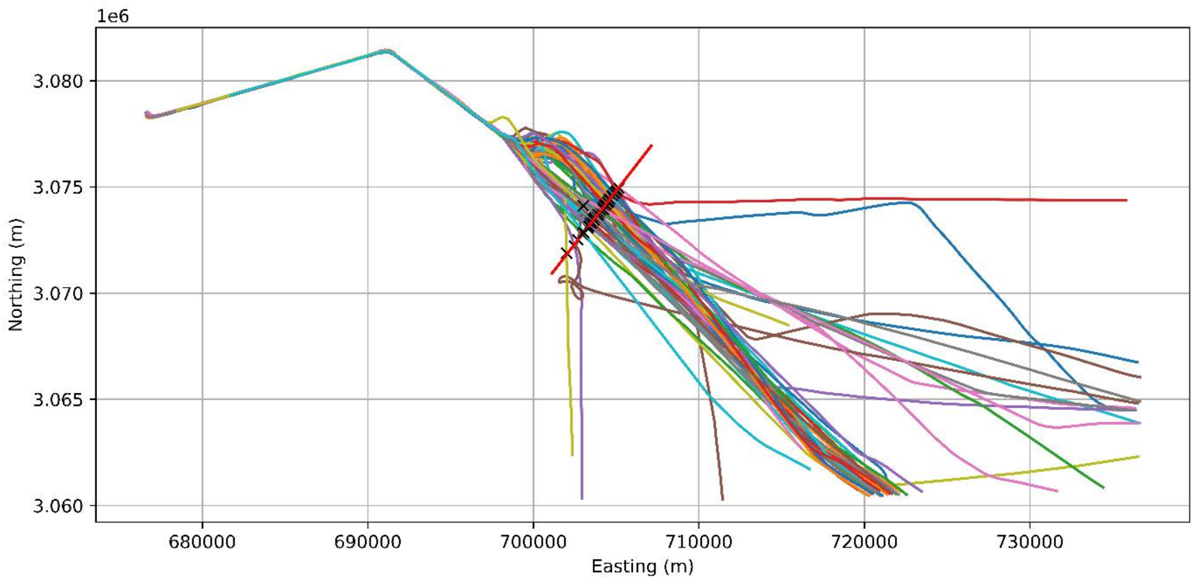

Figure 3.2: Tracks of 50 departures in the AIS data from the Ingleside terminal to sea; 8.1 nm distance away from the bend at Harbor Island marked in red

The speed profiles of the departures are plotted in Figure 3.3 according to the percentiles in the dataset. The head of the jetties are located approx. 1.4 nm away from the bend. The vessels reach a speed of 9-10 kn on average at the end of the jetties and continue to accelerate to an average speed of 11 kn before the end of the existing channel. The drop in speed after the end of the channel is assumed to be to allow a safe drop-off of the pilot to the pilot boat.

The speed in the Jetty Channel is affected by currents. This was analyzed by estimating the speed through water for the 50 AIS transits using the measured current data at Aransas Pass in the Jetty Channel. The results are summarized in Table 3.4. The probability distribution of the speed through water is narrower (more confined) than the distribution of the speed over ground, meaning that the speed over ground is lower in flood currents and higher in ebb currents. However, the difference is not fully due to current speeds. The difference in vessel speed is approx. 0.5 kn, while the current speeds are 1-2 kn. Hence, the variability in speed over ground is more due to other effects than due to current speeds and the speed through water is usually larger in flood currents.

Table 3.4: Probability distribution of speed over ground, speed through water and current velocity (positive for flood currents) in the Jetty Channel

Percentile	Speed over Ground (kn)	Speed through Water (kn)	Current Vel. (kn)
10	7.0	7.5	−1.8
20	7.5	8.0	−1.1
50	9.1	9.2	+0.4
80	10.4	10.1	+1.6
90	10.8	10.5	+2.1

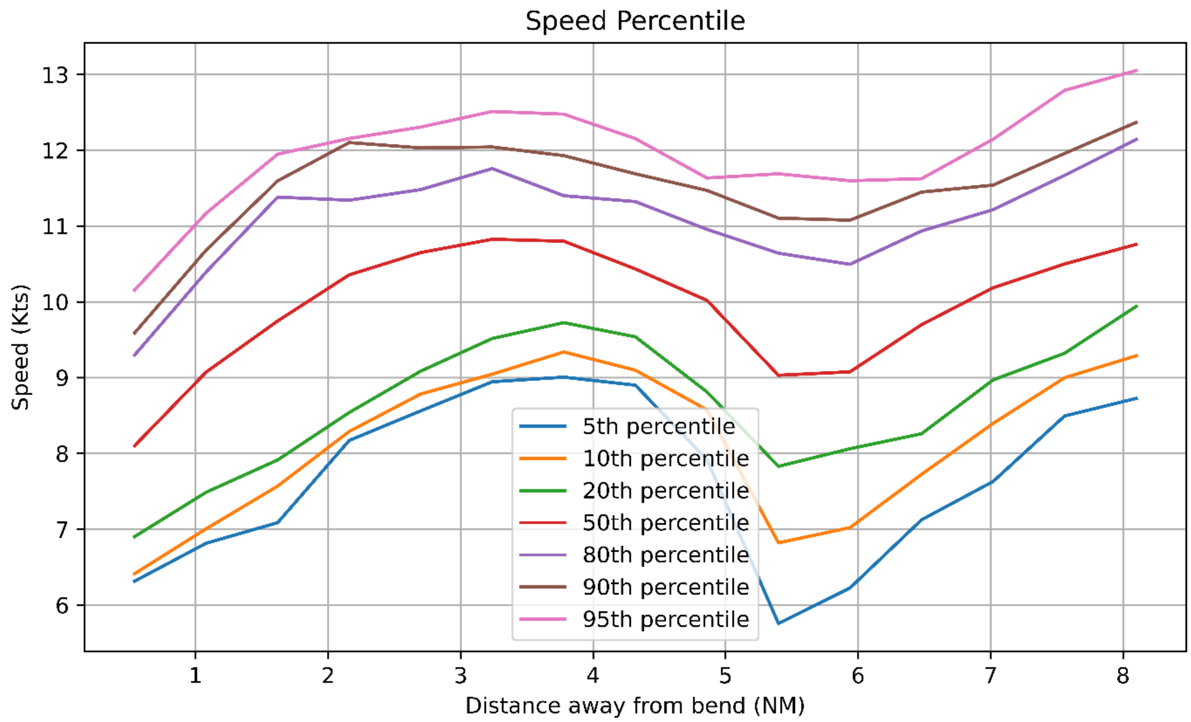

Figure 3.3: Percentile plot of speed profiles from the 50 VLCC departures in the AIS data from the bend near Harbor Island out to sea

3.3.3 Discussion

The vessel speeds observed in the navigation simulations and AIS data agree reasonably well. The vessel reaches a speed of about 9 kn in between the jetties and accelerates to a speed of about 11 kn further down the approach channel. However, based on knowledge and experience of the pilots, it is expected that VLCC's laden to a draft of 68 ft will accelerate much slower than the present vessels at 45 ft draft. Expected speeds over ground in the Jetty Channel are 6-8 kn when departing from the Axis Terminal and 5-7 kn when departing from the Harbor Island terminal. Cruising speeds in the Approach and Outer Channels would also be lower than the existing fleet with a speed of 8-10 kn expected.

Based on the assessment of speed through water from the AIS data, it is estimated that vessels will sail approx. 0.5 kn slower over ground in flood currents and 0.5 kn faster in ebb currents, compared to departures around slack tide with no currents present.

4. Metocean Conditions

4.1 Water Levels

Measured water level data are available from the Port Aransas (8775237) and Aransas Pass (8775241) stations. The Port Aransas station is located opposite the planned Axis terminal and the Aransas Pass station is located on the north slopes of the Jetty Channel. Near-continuous records are available from both stations from January 2017 through May 2021. The Mean Lower Low Water (MLLW) datums relative to NAVD88 at both stations are:

- Port Aransas: −0.15 ft
- Aransas Pass: −0.59 ft

The water levels are influenced by a combination of tidal and meteorological effects. Tides are dominated by a diurnal signal with a range in the order of 1-2 ft. Meteorological effects are in the same order of magnitude. The tides were removed from the records by taking a moving average over a period of 25 hours to analyze the meteorological effects. The time series of these averaged water levels for the Aransas Pass station are given in Figure 4.1. Water levels are usually lowest in January with another episode of low water levels in July and August. The monthly average water levels are given in Table 4.1.

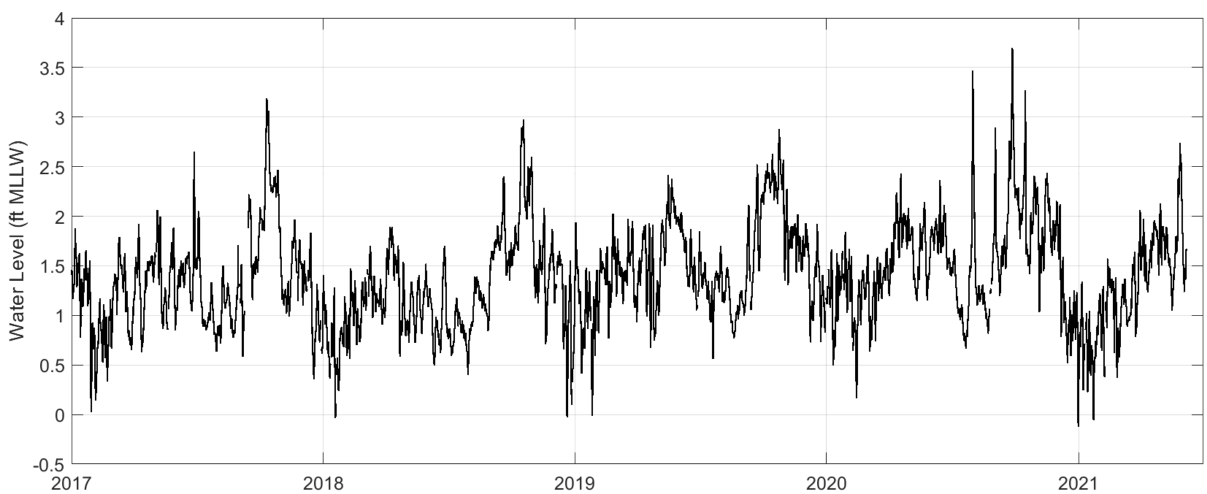

Figure 4.1: Measured water levels at Aransas Pass with tides removed

Table 4.1: Monthly average water levels (ft MLLW)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Port Aransas	0.81	0.81	1.02	1.32	1.41	1.29	0.94	1.00	1.58	1.98	1.49	1.02
Aransas Pass	0.99	1.07	1.27	1.52	1.54	1.45	1.12	1.16	1.73	2.22	1.62	1.15

Extreme low water levels were estimated from the five yearly lowest water levels in the measurements. A Gumbel fit was applied to provide estimates for different return periods provided in Table 4.2. The instantaneous water levels were obtained from the raw water level records, i.e. including tidal and meteorological effects. The mean-tide water levels were obtained from the records with the tides removed.

Table 4.2: Extreme low water levels (ft MLLW) obtained from the measured wave data from 2017-2021

Return Period (Years)		1	2	5	10	20
Instantaneous Water Level	Port Aransas	−1.00	−1.11	−1.27	−1.38	−1.50
	Aransas Pass	−1.08	−1.22	−1.41	−1.55	−1.69
Mean-tide Water Level	Port Aransas	−0.18	−0.24	−0.32	−0.39	−0.45
	Aransas Pass	+0.04	−0.02	−0.09	−0.15	−0.21

4.2 Currents

The current conditions along the channel were taken from the results of hydrodynamic modeling using the hydrodynamic model developed for this project for the sedimentation analysis (reported separately) which is forced on the offshore boundaries by the HYCOM model (Chassignet et al., 2007). A period of 19 days was modeled, January 5-23, 2020, to cover at least one spring-neap cycle. The resulting time series of water levels and current velocities for the Jetty Channel are provided in Figure 4.2. The plotted current velocities are the longitudinal current velocities (along the channel), positive for inward flowing (flood tide) currents. The peak of flood tide currents occurs close to high tide and the peak of ebb tide currents occurs close to low tide. This has a positive effect on the UKC of departing ships as the peak flood currents that enhance squat occur at higher water levels.

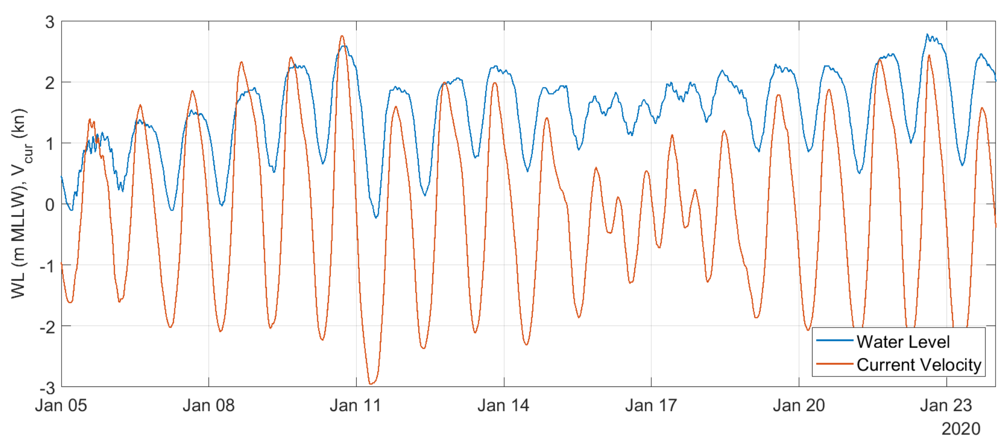

Figure 4.2: Modeled water levels and longitudinal current velocities in the Jetty Channel; outward flowing (ebb) currents negative, inward flowing (flood) currents positive

Three tide conditions were selected for the UKC assessment from January 7. This tide cycle was selected as an average spring tide condition with a relatively low low water. The three conditions are defined as follows:

- Ebb tide – Ebb currents coinciding with the minimum water level
- Slack tide – instance between low and high water closest to the moment when the current direction changes

- Flood tide – strongest flood current (occurring close to high tide)

The ebb and flood tide longitudinal current speeds along the channel are presented in Figure 4.3. The water level and current velocities at the four channel segments are given in Table 4.3 and Table 4.4, respectively.

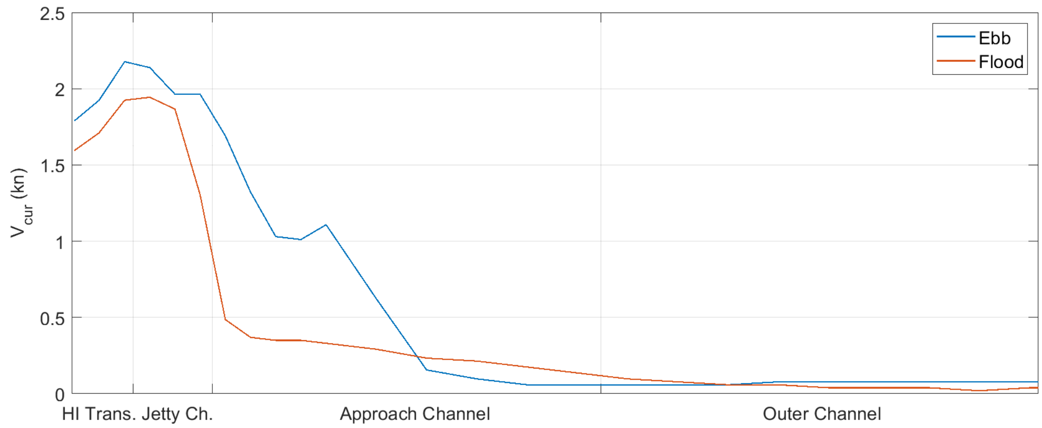

Figure 4.3: Longitudinal Current speeds along the channel at the considered ebb and flood conditions

Table 4.3: Water levels relative to mean tide (ft) for the three considered tide conditions

	HI Transition	Jetty Channel	Approach Channel	Outer Channel
Ebb	−1.05	−1.02	−0.98	−0.95
Slack	+0.07	+0.10	+0.13	+0.16
Flood	+0.56	+0.59	+0.82	+0.82

Table 4.4: Longitudinal current velocities; outward flowing (ebb) currents negative, inward flowing (flood) currents positive

	HI Transition	Jetty Channel	Approach Channel	Outer Channel
Ebb	−2.17	−1.96	−0.08	+0.01
Slack	−0.03	−0.04	+0.03	+0.05
Flood	+1.92	+1.86	+0.19	+0.02

4.3 Wave Conditions

The wave conditions along the Port of Corpus Christi channel were determined using near-shore wave transformation modelling for specific offshore wave conditions. A set of design and operational offshore wave conditions is provided in this Section from analysis of the 35-year (1980-2014) WIS model (Hubertz, 1992) hindcast data at 30 m water depth. These conditions were used as input for wave transformation modeling.

4.3.1 Extreme Wave Conditions

WIS hindcast data are available from Station 73040 (27.75° N, 96.8° W) at 30 m water depth. Significant wave height (H_{m0}) is less than 6 ft for approx. 90% of the time. Larger wave conditions with H_{m0} greater than 10 ft occur in advance of landfall of hurricanes during the hurricane season (June through October) and during strong cold fronts in the fall and winter (November through March). A list of 107 storms with peak significant wave heights greater than 10 ft was compiled from the 35-year hindcast. 25 storms occurred during the hurricane season and 82 storms outside the hurricane season. However, the largest wave events coincide with hurricanes.

Vessels will not depart from Port Corpus Christi in very large wave conditions, particularly due to constraints with pilot disembarking in open water after departure. Largest wave heights for departure are typically 10-12 ft as indicated by the pilots. It is further expected that departures will not occur in severe wind conditions. It is expected that vessels will not depart in gale force winds with a 34 kn wind speed or higher. These assumptions were verified using a list of historic channel closures from mid-2016 until the end of 2019. The closure periods are overlayed on the wave height and wind speed time series from offshore WIS hindcast data (2015-2019 extended dataset). Many closures occur for wave heights less than 10 ft and wind speeds less than 34 kn. However, there are four occurrences of wave heights of 10-12 ft when the channel was open (in Nov. and Dec. 2016, Oct. 2017 and Dec. 2018), and similarly several occurrences of wind speeds close to 34 kn.

The storm list was developed to include the peak of the storm for storms with H_{m0} of 10-12 ft and wind speeds less than 34 kn, and a time before or after the peak for storms with H_{m0} greater than 12 ft or wind speed greater than 34 kn. A scatter plot of peak period and mean wave direction for all storms is provided in Figure 4.4. Most events are outside the hurricane season with a SSE wave direction and peak period of 8 s. Some NE events also occurred, mainly outside the hurricane season, and longer-period events occurred in conjunction with hurricanes. Three events with peak periods close to 16 s are interesting outliers as these would result in a significantly larger response for departing ships. The three events were caused by the well-known hurricanes Katrina, Rita and Ike, all of which had landfall locations considerably north and east of Port Aransas. Data for these three hurricanes are indicated in Table 4.5. Hurricane Harvey is not in the list as it occurred after the end of the WIS data in 2014.

Table 4.5: Summary data for three hurricanes causing long swells with T_p > 15 s; hurricane Saffir-Simpson category, minimum pressure and maximum sustained wind speed are the data at the peak in the Gulf of Mexico; wave height and period data are at the peak of the event at the Corpus Christi WIS wave hindcast location

Date	Name	Cat.	Landfall	Press. (mbar)	Wind Spd. (kn)	H_{m0} (ft)	T_p (s)
Aug 29, 2005	Katrina	5	Louisiana	902	150	11.8	16.3
Sep 23, 2005	Rita	5	Louisiana	895	155	11.7	15.4
Sep 12, 2008	Ike	2	Texas	950	95	11.8	15.9

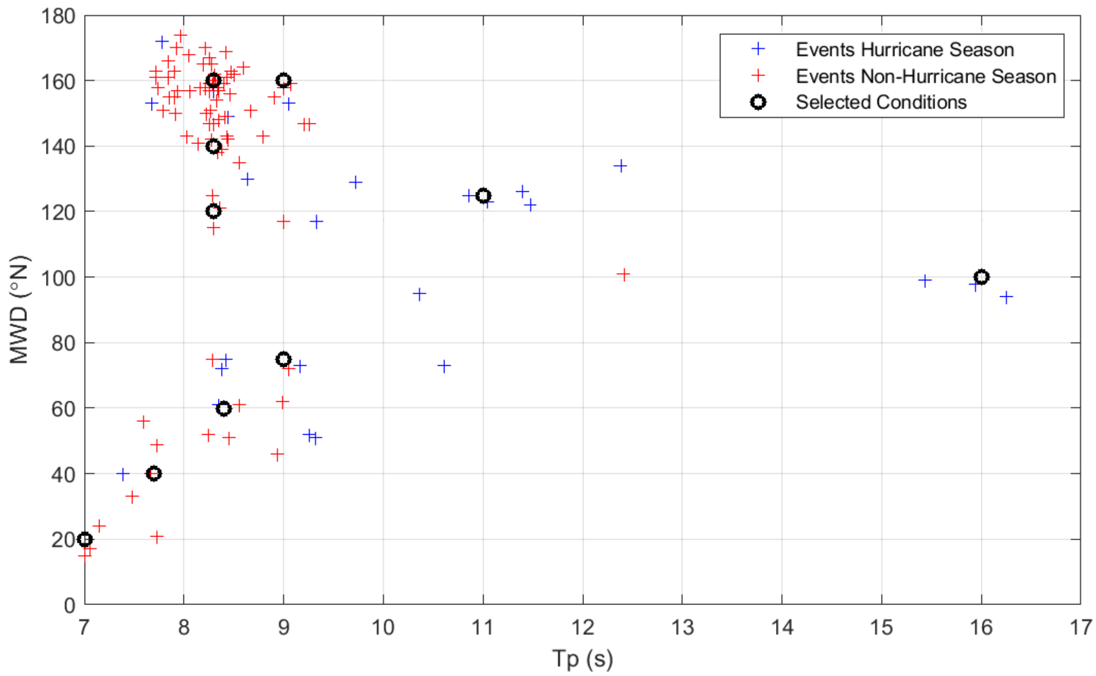

Figure 4.4: Scatter plot of mean wave direction against peak period for all storms with H_{m0} of 10-12 ft and wind speed < 34 kn from the 1980-2014 WIS hindcast at Station 73040

Table 4.6: Wave parameters for the ten selected conditions for input in the wave transformation modelling at 30 m water depth; sensitivity conditions are shaded

#	H_{m0} (ft)	T_p (s)	MWD (°N)	Spreading (°)	γ_0
1	12	7.0	20	30	2
2	12	7.7	40	30	2
3	12	8.4	60	30	2
4	12	9.0	75	30	2
5	12	8.3	120	25	1
6	12	8.3	140	25	1
7	12	8.3	160	25	1
8	12	9.0	160	25	1
9	12	11.0	125	30	1
10	12	16.0	100	10	3

Ten wave conditions were selected for input in the underkeel clearance modelling and as such for input in the near-shore wave transformation modeling. These wave conditions are highlighted as circles in Figure 4.4 and the wave parameters are given in Table 4.6. These wave conditions cover most relevant storms in the hindcast. Although the hurricane cases do not represent day-to-day operational conditions, they were used as sensitivity analyses for the model.

The significant wave height was chosen at the upper-bound of the 10-12 ft threshold for pilot disembarking. The peak period and mean wave direction were selected from the scatter plot. The conditions with peak periods of 7-9 s are considered as design operational events, while the longer-period conditions are added for sensitivity. Directional spreading was estimated from the average spreading in the related storm events and the JONSWAP peak enhancement factor γ_0 was estimated from the ratio between the peak and mean period (Tm01). The SSE events are generally more developed with a spectral shape close to Pierson-Moskowitz, while the longer-period events are due to swells from distant hurricanes with narrower spectra.

4.3.2 Operational Wave Conditions

Less extreme operational wave conditions are considered for UKC modelling combined with extreme low water levels. From the assessment of extreme low water levels, it appeared that there is no or no strong relationship between wave conditions and low water levels. Therefore, less extreme operational wave conditions will be considered than the extreme wave conditions for departure.

The occurrence of wave height against peak period for the entire 35-year WIS hindcast data is given in Table 4.7. The peak period is less than 8 s for approx. 93% of the time. The most probable peak period increases slightly for larger wave heights.

Table 4.7: Occurrence table of significant wave height against peak period from the 1980-2014 WIS hindcast

	Wave Period (s)											
Wave Height (m)	2.00-3.00	3.00-4.00	4.00-5.00	5.00-6.00	6.00-7.00	7.00-8.00	8.00-9.00	9.00-10.00	10.00+	Total	C(%)	Maximum Period (s)
0.00-0.30	0.14	0.70	1.07	0.33	0.43	0.35	0.29	0.18	0.11	3.61	100.00	16.03
0.30-0.61	0.21	2.34	6.98	5.44	1.62	0.59	0.27	0.08	0.07	17.59	96.39	18.68
0.61-0.91	0.00	1.31	7.69	9.11	5.78	1.69	0.41	0.08	0.05	26.13	78.80	16.96
0.91-1.22		0.17	3.70	7.93	5.81	2.57	0.76	0.17	0.09	21.20	52.68	16.39
1.22-1.52		0.02	1.01	5.20	4.73	2.34	0.87	0.29	0.08	14.54	31.47	15.35
1.52-1.83		0.00	0.28	1.69	3.61	1.58	0.52	0.19	0.10	7.95	16.93	16.48
1.83-2.13			0.05	0.51	2.06	1.27	0.46	0.12	0.08	4.56	8.98	15.20
2.13-2.44			0.00	0.19	0.75	0.90	0.30	0.07	0.06	2.28	4.42	15.27
2.44-2.74				0.05	0.19	0.54	0.22	0.05	0.06	1.11	2.14	15.87
2.74-3.05				0.00	0.05	0.24	0.18	0.04	0.03	0.54	1.04	16.16
3.05-3.35					0.01	0.06	0.14	0.03	0.02	0.27	0.49	16.41
3.35-3.66					0.00	0.01	0.07	0.02	0.01	0.12	0.23	16.59
3.66+					0.00	0.00	0.02	0.02	0.06	0.11	0.11	17.30
Totals	0.36	4.54	20.78	30.45	25.04	12.17	4.50	1.34	0.82	100.00		

Based on the occurrence table in Table 4.7, ten operational wave conditions were selected as input conditions for wave transformation modeling as shown in Table 3. Eight wave conditions are for wave heights of 2-9 ft combined with the median occurrence peak period with each wave height. The last two conditions for longer swell events that occur infrequently but may lead to larger vessel response and will be used for a sensitivity analysis in the UKC assessment.

Table 4.8: Wave parameters for the ten selected conditions for input in the wave transformation modelling at 30 m water depth; sensitivity conditions are shaded

#	Exceeedance	H_{m0} (ft)	T_p (s)	MWD (°N)	Spreading (°)	γ_0
11	79%	2	5.0	130	25	1.2
12	53%	3	5.5	130	25	1.2
13	31%	4	6.0	140	25	1.2
14	17%	5	6.4	140	25	1.2
15	9%	6	6.7	140	25	1.2
16	4%	7	7.0	150	25	1.2
17	2%	8	7.3	150	25	1.2
18	1%	9	7.6	150	25	1.2
19	-	5	8.5	110	25	1.0
20	-	6	10.0	90	20	1.0

4.3.3 Wave Modeling Results

Significant wave height and mean wave direction were extracted from the wave transformation model results along the channel centerline. The significant wave height along the channel for four of the prominent wave conditions is presented in Figure 4.5. The wave height along the channel declines more rapidly along the Outer and Approach channels for the longer-period events (9 and 10) than the for the events with more common peak periods, as the longer swells refract more away on the channel side slopes. Moreover, a wave direction more in line with the channel orientation enhances this refraction effect.

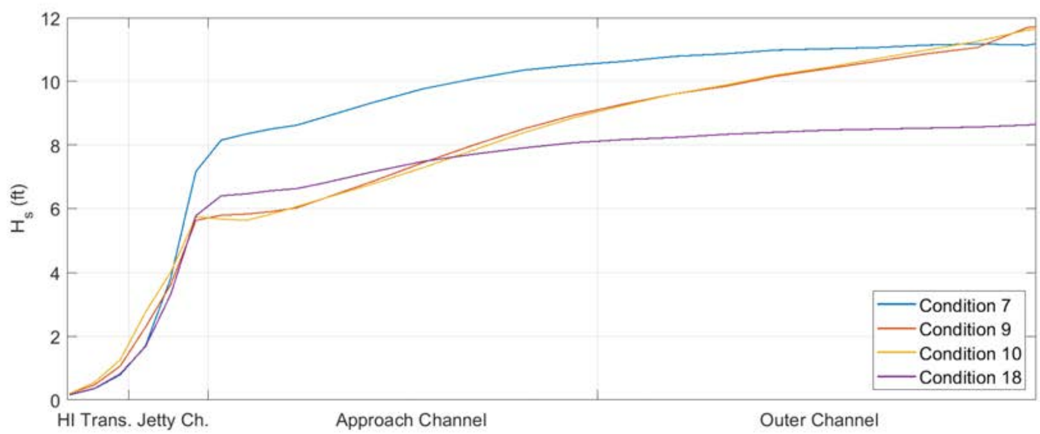

Figure 4.5: Significant wave height along the channel for three extreme wave conditions (7, 9 and 10) and one operational wave condition (18)

Wave modeling results for input to the UKC calculations were obtained from characteristic locations in the four channel segments:

- Harbor Island Transition Flare: STA −2,000 ft
- Jetty Channel: STA −6,000 ft
- Approach Channel: STA −25,000 ft
- Outer Channel: STA −55,000 ft

The significant wave height and mean wave directions at these locations are given in Table 4.9.

Table 4.9: Significant wave height and mean wave direction for all wave conditions; sensitivity conditions are shaded

Cond.	Sign. Wave Height (ft)				Mean Wave Dir. (°N)			
#	HITF	Jetty Ch.	Appr. Ch.	Outer Ch.	HITF	Jetty Ch.	Appr. Ch.	Outer Ch.
Extreme Wave Conditions								
1	1.1	3.1	3.8	4.7	113	87	70	55
2	1.9	5.3	6.2	7.0	113	96	82	67
3	2.4	6.8	8.4	9.2	113	96	90	79
4	2.6	7.1	9.2	10.4	113	99	95	88
5	2.1	6.2	9.1	11.2	116	118	121	121
6	1.5	6.0	9.5	11.2	121	136	142	140
7	1.1	6.3	10.1	11.1	128	144	153	156
8	1.0	5.9	9.8	11.1	128	143	152	156
9	1.5	5.1	8.0	10.9	117	124	128	126
10	1.8	5.3	7.8	11.0	115	106	107	106
Operational Wave Conditions								
11	0.8	1.7	2.0	2.0	116	127	130	130
12	1.0	2.4	3.0	3.0	116	127	130	130
13	1.0	2.9	3.8	3.9	119	136	140	140
14	1.1	3.4	4.7	4.9	119	136	140	140
15	1.1	3.9	5.5	5.8	120	136	141	140
16	1.0	4.4	6.4	6.7	124	142	149	149
17	1.1	4.8	7.2	7.6	124	142	149	149
18	1.1	5.1	7.9	8.5	124	141	149	149
19	1.0	2.7	4.0	4.7	115	110	112	111
20	1.2	3.3	4.7	5.5	114	102	100	97

5. Underkeel Clearance Criteria

The design of the Corpus Christi channel is recommended to be in accordance with USACE (2006) guidelines. The water level, draft, UKC and bed level components in the depth design of the navigation channel are shown in Figure 5.1 and defined as follows:

- Water level: indicated at Mean Lower Low Water (MLLW) but chosen at more extreme low waters in combination with operational wave conditions for the Corpus Christi channel due to the effect of seasonal and meteorological conditions on the water levels.
- Draft of the design ship: 68 ft.
- Effect of freshwater: ignored here as the draft is determined prior to departure in water with the same. density as in the channel.
- Wave response: according to wave response modeling for the selected wave conditions.
- Squat: according to vessel squat modelling.
- Safety clearance: USACE (2006) recommends a minimum of 2 ft clearance for regular sandy or silty channel bed types as present in the Corpus Christi channel.
- Authorized channel level: according to the channel design parameters listed in Table 3.2.
- Advance maintenance: 2 ft according to the Project Description (Port Corpus Christi, 2019).
- Dredging tolerance: 2 ft according to the Project Description (Port Corpus Christi, 2019).

PIANC (2014) also provides a recommendation for a maneuverability margin, which is defined as the clearance between the lowest point of the keel including effects from squat and heeling and the maneuverability bed level (equal to the authorized channel level here). A clearance of at least 5% of the draft is recommended for maneuverability, i.e. 3.4 feet for the VLCC at 68 feet draft. Heeling is ignored as this is negligibly small for laden VLCC's that are very stable and have relatively small windage areas.

It is assessed here that the design of the Corpus Christi channel is required to be in accordance with USACE (2006) guidelines, while accordance with PIANC (2014) guidelines would be recommended.

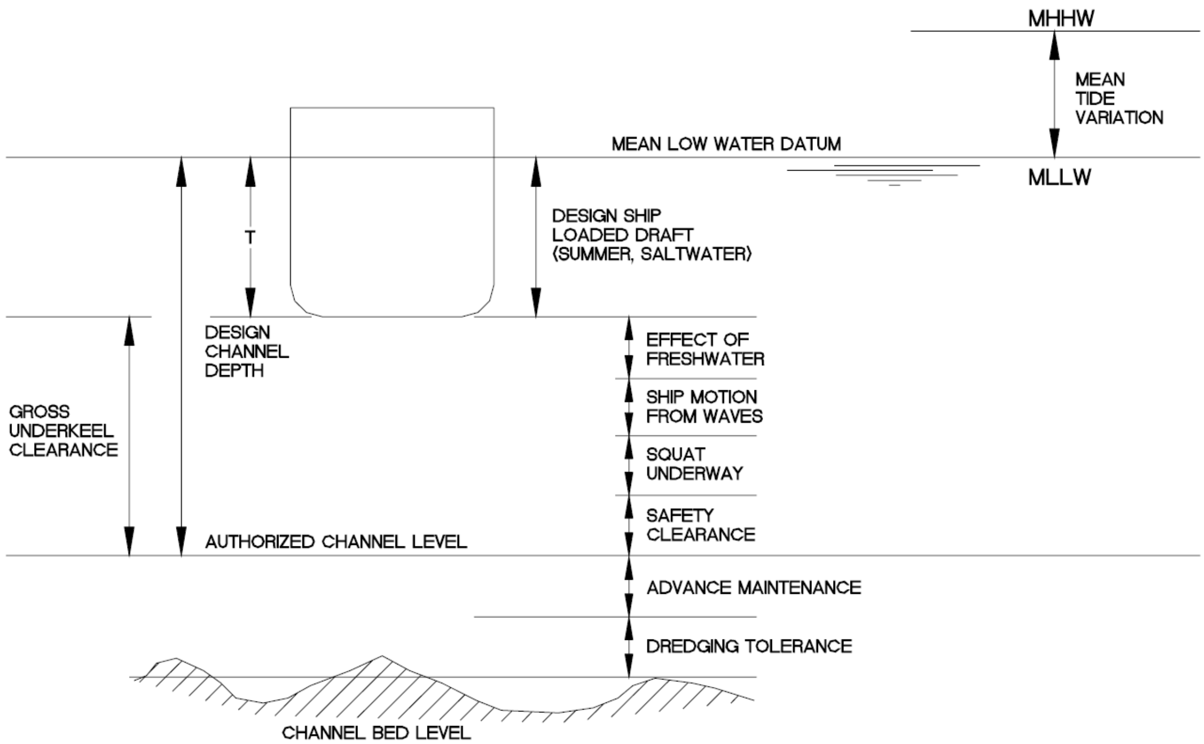

Figure 5.1: Channel depth allowances (source: USACE, 2006)

6. Squat and Maneuverability Margin

Squat was modeled in Wavescat for four channel segments. The water level was adopted at MLLW for ebb currents, +1 ft MLLW during slack tide and +2 ft MLLW for flood currents. The bed level is uniform at −77 ft MLLW in the approach channel and −75 ft MLLW between the jetties. Squat is related to the vessel speed through water with the current speeds according to Table 4.4. The resulting maximum (bow) squat is provided in Figure 6.1 for the Jetty and Outer Channels. The squat is largest in the Jetty Channel due to the effects of a confined channel and a strong counter current. The channel side slopes are included as arrays of panels to model the confined flow effects on squat.

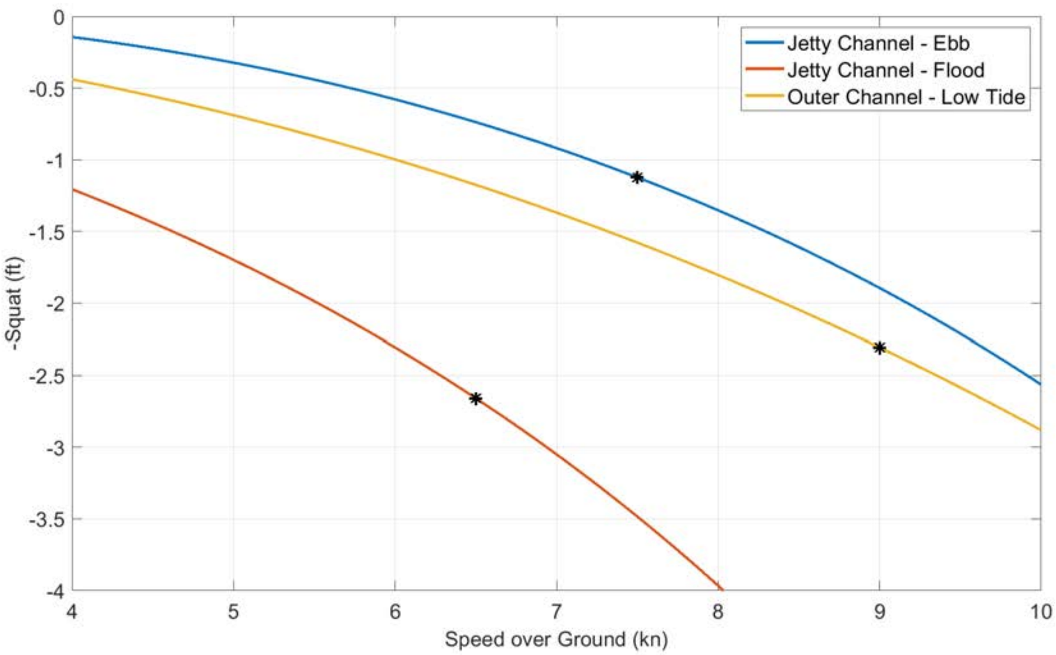

Figure 6.1: Modeled squat in the Jetty and Outer Channels; values used in the UKC assessment indicated with asterisks (*)

The modeled squat for the projected range of vessel speeds is provided in Table 6.1. For validation of the modelling, squat formula results were also determined for the Approach and Outer Channels according to the ICORELS formula (as recommended for the estimation of squat in USACE (2006), albeit with a different reference):

$$z_{squat} = 2.4\frac{\nabla}{L^2}\frac{F_h^2}{\sqrt{1-F_h^2}}$$

where z_{squat} is the sinkage at the bow, ∇ is the volume displacement, L is the length between perpendiculars and F_h is the depth-related Froude number. Water level was assumed at MLLW and ignoring the effects of currents in the ICORELS results. The modeled results agree well with the ICORELS results for low water (ebb). The small difference may be due to the fact that the ICORELS formula was derived more conservatively to be also applicable to fuller shaped tanker hulls with cylindrical bows compared to the more streamlined bulbous bow shape of the modelled VLCC.

Table 6.1: Squat (ft) in the four channel segments for different speeds over ground and at ebb (low water), slack tide (mid-tide) and flood (high water) conditions; note that considered speeds in the HI Transition Flare and Jetty Channel are 0.5 kn higher during ebb and 0.5 kn lower during flood; estimates using the ICORELS formula at low water are added for reference

Segment	HI Transition Fl.			Jetty Channel			Approach Channel			Outer Channel		
Speed (kn)	5	6	7	6	7	8	8	9	10	8	9	10
Ebb	0.3	0.5	0.7	0.7	1.1	1.6	1.8	2.3	2.9	1.8	2.3	2.9
Slack	0.6	0.9	1.3	1.3	1.8	2.4	1.8	2.3	2.9	1.8	2.3	2.8
Flood	1.0	1.4	1.9	2.0	2.7	3.5	1.9	2.4	2.9	1.7	2.2	2.8
ICORELS	-	-	-	-	-	-	*1.9*	*2.4*	*3.0*	*1.9*	*2.4*	*3.0*

The maneuverability margin, i.e. a safety clearance ignoring wave response, is defined according to the following assumptions:

- Water level according to 10 year return period estimate of the lowest mean tide level at Aransas Pass (−0.15 ft MLLW) and tidal variation according to the ebb, slack and flood tide levels of the reference tide.
- Vessel draft at 68 ft
- Squat according to mid-range speed estimates in Table 6.1.
- Channel depth at authorized bed level (75 ft and 77 ft)

The resulting maneuverability margins are given in Table 6.2. The results are compliant both with the 2 ft safety clearance (USACE, 2006) and the 3.4 ft maneuverability margin (PIANC, 2014) criteria. The ebb tide (low water) condition is governing in all four channel segments, although the flood tide conditions is close in the Jetty Channel due to the enhancement of squat in a counter current.

It is recommended that departure speed profiles be analyzed after the planned navigation simulations and squat reassessed based on any updates to the speed profiles. This will determine whether the transition between the deeper dredged Approach Channel (77 ft) and the Jetty Channel (75 ft) is at the most optimal location.

Table 6.2: Maneuverability Margin Results

	HITF	Jetty Ch.	Approach Ch.	Outer Ch.
Ebb	5.3	4.7	5.5	5.6
Slack	6.0	5.1	6.6	6.7
Flood	6.0	4.8	7.3	7.4

7. Wave Response and Safety Clearance

The wave response allowance was calculated for the 20 wave conditions and at the four channel segments. The resulting wave response allowance is listed in Table 7.1.

The Safety clearance was calculated using the following assumptions:

- Mean water levels according to:
  - Non-hurricane season extreme wave conditions 1-8 according to mean water level in January at Aransas Pass: +0.99 ft MLLW
  - Hurricane season extreme wave conditions 9 and 10 according to mean water level in July-August at Aransas Pass: +1.14 ft MLLW
  - Operational wave conditions 11-20 according to 10 year return period extreme mean water level at Aransas Pass: −0.15 ft MLLW
- Ebb tide (low water) condition for tidal water level variation and current condition
- Vessel draft at 68 ft
- Squat according to mid-range speed estimates in Table 6.1
- Channel depth at authorized bed level (75 ft and 77 ft)

The safety clearance results are also included in Table 7.1. The long-swell extreme condition 10 is governing for all segments except in the HITF where waves have diminished. The safety clearance is marginally non-compliant in the Outer Channel for this condition. Operational wave condition 18 (1% exceedance) combined with an extreme 10 year return period water level is governing between the design conditions. The safety clearance is compliant for this condition.

Wave response is relatively small for all except the 16 s swell condition, such that an extreme low water level combined with an operational wave condition is governing for the safety clearance except for this condition. Wave response increases beyond a peak period of 11 s (Condition 9) causing this.

It is recommended that port closure policies be checked for extreme hurricane scenarios to verify whether vessels would depart under extreme wave conditions with peak periods of 12 s or greater.

Table 7.1: Wave response and safety clearance results (ft); sensitivity (not-design) conditions are shaded grey; values less than the 2 ft criterion are highlighted in orange.

Cond.	Wave Response				Safety Clearance			
#	HITF	Jetty Ch.	Appr. Ch.	Outer Ch.	HITF	Jetty Ch.	Appr. Ch.	Outer Ch.
1	0.02	0.10	0.26	0.45	6.4	5.7	6.4	6.3
2	0.05	0.21	0.47	0.77	6.4	5.6	6.2	5.9
3	0.10	0.39	0.72	1.07	6.4	5.4	6.0	5.6
4	0.15	0.53	0.91	1.27	6.3	5.3	5.8	5.4
5	0.07	0.19	0.31	0.39	6.4	5.6	6.4	6.3
6	0.05	0.22	0.48	0.55	6.4	5.6	6.2	6.2
7	0.04	0.28	0.72	0.89	6.4	5.5	5.9	5.8
8	0.05	0.38	0.99	1.25	6.4	5.4	5.7	5.5
9	0.21	0.70	1.36	1.83	6.4	5.3	5.5	5.1
10	0.65	2.13	3.47	5.03	6.0	3.8	3.4	**1.9**
11	0.00	0.00	0.01	0.01	5.3	4.6	5.5	5.6
12	0.00	0.01	0.01	0.01	5.3	4.6	5.5	5.6
13	0.01	0.02	0.04	0.04	5.3	4.6	5.5	5.5
14	0.01	0.03	0.06	0.06	5.3	4.6	5.5	5.5
15	0.01	0.05	0.09	0.10	5.3	4.6	5.4	5.5
16	0.01	0.08	0.18	0.19	5.3	4.6	5.3	5.4
17	0.02	0.11	0.24	0.26	5.3	4.5	5.3	5.3
18	0.02	0.14	0.32	0.35	5.3	4.5	5.2	5.2
19	0.04	0.10	0.17	0.20	5.3	4.5	5.4	5.4
20	0.08	0.24	0.42	0.53	5.2	4.4	5.1	5.0
Minimum Over All					5.2	3.8	3.4	**1.9**
Minimum Design Conditions					5.3	4.5	5.2	5.2

8. Conclusions

Baird has conducted an underkeel clearance (UKC) study as part of the modeling services for the Corpus Christi Channel Deepening project. The project will comprise deepening of the Outer and Approach Channels to 77 ft, and the Jetty Channel and seaward-most portion of the Corpus Christi Ship Channel to 75 ft. The channel will be used by laden VLCC's at a maximum draft of 68 ft departing from the planned Axis and Harbor Island terminals.

The UKC study consisted of the following tasks:

- Assessment of vessel speeds in the channel
- Analysis of measured water levels with focus on extreme and operational low water levels
- Assessment of tidal current velocities from hydrodynamic modeling results
- Assessment of wave conditions from wave hindcast data and wave transformation modeling results
- Modeling and assessment of squat for selected vessel speeds and current conditions
- Modeling and assessment of response of the vessel in waves for selected wave conditions

The vessel speed is expected to be in the range of 6-8 kn in between the jetties and the vessel would accelerate to a cruising speed of 8-10 kn in the Approach and Outer channels. This is slower than current practice as it is expected that the VLCC's at a larger draft are more sluggish and will not reach the same cruising speed due to additional drag effects. It is recommended that departure speed profiles be analyzed after the planned navigation simulations and squat assessed based on these speed profiles.

The design water level was assessed from a mean level from measured data at Aransas Pass as a 10 year return period lowest level at −0.15 ft MLLW and a regular spring tide low water at −1.02 ft relative to mean tide in the Jetty Channel. Ebb current velocities peak close to low tide and cause a reduction of the vessel squat. Maximum flood currents that enhance squat occur close to high tide. The resulting maneuverability margin (safety clearance, not including wave response) has a minimum of 4.7 ft in the Jetty Channel. This is greater than the recommended margin of 3.4 ft suggested by PIANC (2014) and greater than the required 2 ft safety clearance by USACE (2006).

Maximum significant wave height for vessel departures was chosen at 10-12 ft limited by disembarking of the pilot after the channel transit. These events occur mostly due to winter depressions but can also be associated with swells from advancing hurricanes. Most common conditions are from SSE with peak periods of 7-9 s, and were selected as design wave events. Maximum wave response allowance is limited to 1.3 ft in the Outer Channel due to the relatively small wave period and since the vessel is advancing against the waves.

The minimum safety clearance for the design wave conditions was calculated at 4.5 ft in the Jetty Channel and 5.2 ft in the Approach and Outer Channels, which is compliant with the 2 ft safety clearance criterion by USACE (2006). Wave response in the Outer Channel increases considerably in longer swells with peak periods greater than 11 s. Swells with periods close to 16 s have only occurred offshore of Corpus Christi in the 1980-2014 wave hindcast associated with hurricanes Katrina, Rita and Ike. A safety clearance of 1.9 ft was calculated in the Outer Channel for a departure at low tide in such a long-period swell condition with a significant wave height of 12 ft and 16 s peak period. It is recommended that port closure policies be checked for extreme hurricane scenarios to verify whether vessels could depart under extreme wave conditions with peak periods of 12 s or greater.

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Appendix A

Historic Channel Closures

Plots of significant wave height and wind speed with historic channel closures highlighted in red. Wave and wind data obtained from the WIS hindcast Station 73040 offshore of Corpus Christi (27.75° N, 96.8° W) at 30 m water depth.

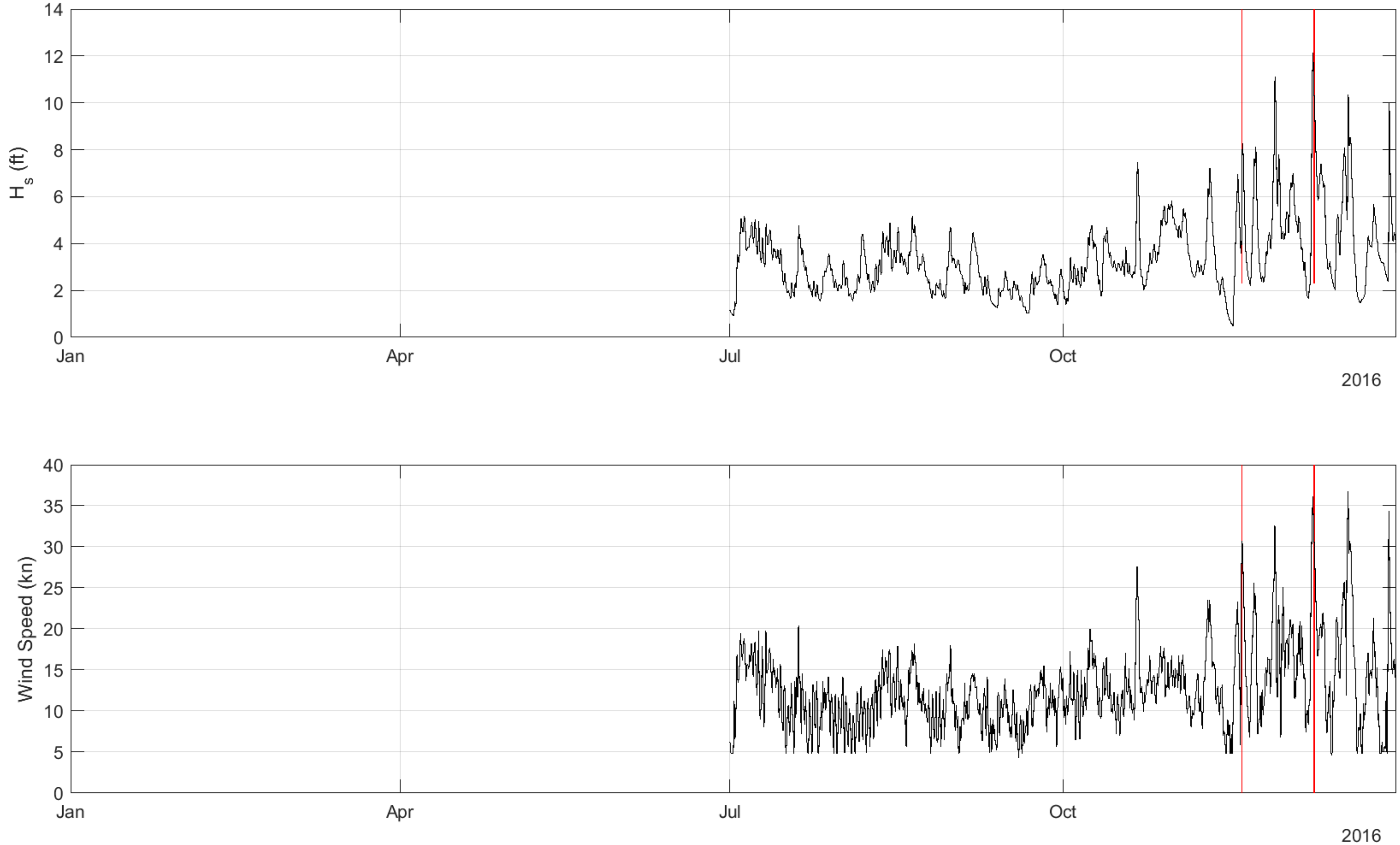

Figure A.1: Significant wave height and wind speed for 2016 with channel closures highlighted in red

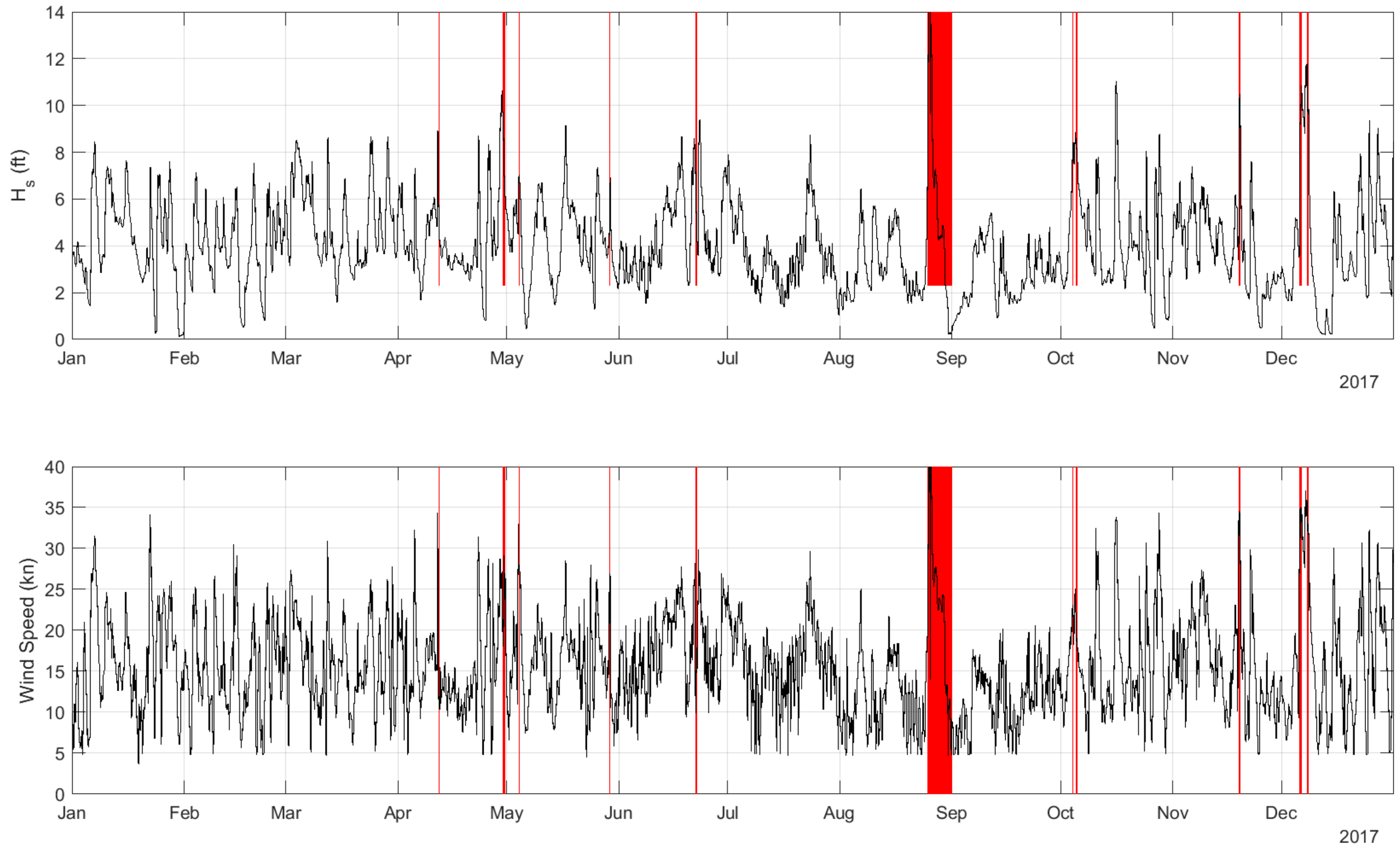

Figure A.2: Significant wave height and wind speed for 2017 with channel closures highlighted in red

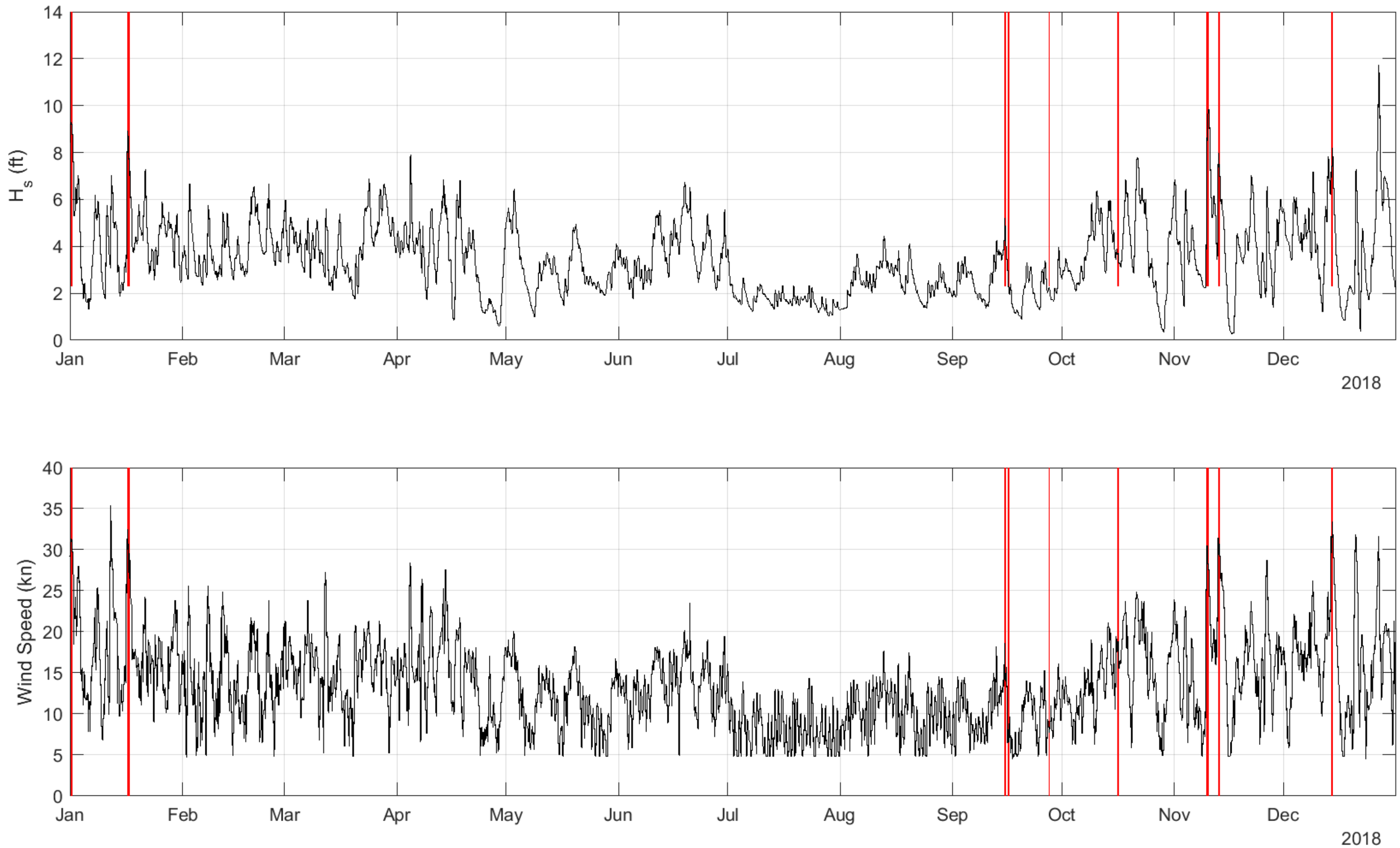

Figure A.3: Significant wave height and wind speed for 2018 with channel closures highlighted in red

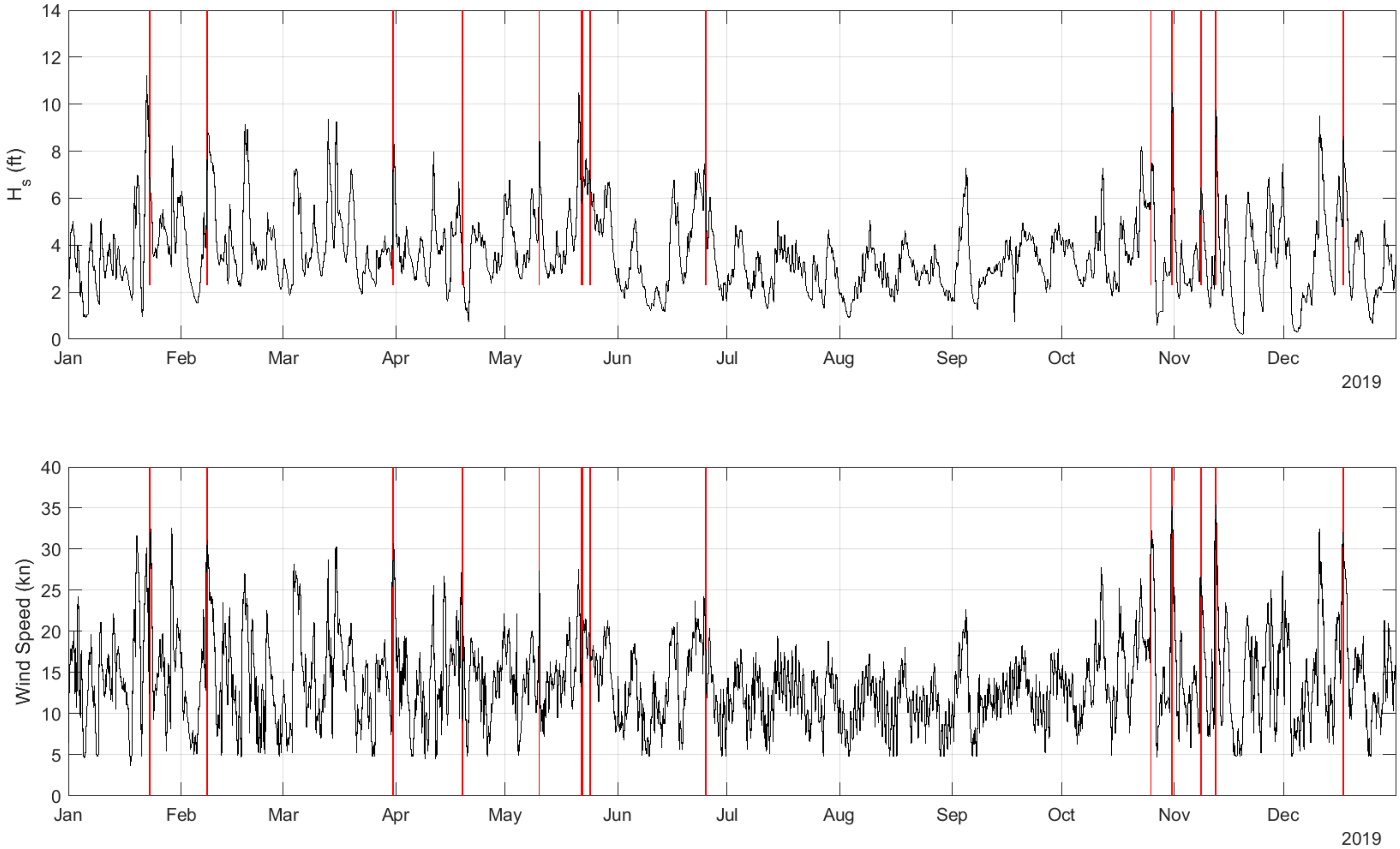

Figure A.4: Significant wave height and wind speed for 2019 with channel closures highlighted in red