NOWDRC Agreement #103

Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry:

Maneuvering Simulation to Indicate Operational Limits Technical Report

Milestone Number 3.4 (Rev 0)

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Abstract

This report provides a technical analysis of data collected from a series of *maritime navigation mission simulations* in a Full Mission Ship Simulator of the type used to train tug operators. The maneuvers analyzed were planned and revised by tug operators and the performance and limitations were judged by experienced captains after performing each maneuver. The significant wave height (Hs), wave period (Tp) and wave field directionality selected for the study are based on analysis of measured environmental conditions at the project site. The weather conditions used in the simulation were actual wave spectrum data modeling the wave energy from the most active direction and frequency bins.

The Cargo Feeder System (CFS) examined is a tight-line operation consisting of a lead tug, a barge loaded with the components of one (1) wind turbine generator (WTG) and a support tug.

Each *maritime navigation mission simulation* sequence is time consuming, and a wide range of cases were examined with a broad array of variables. **Therefore, the results should be considered to provide an indication of operational limits, not statistically significant results, or generalized guidelines**.

Keywords

Feeder barge, tight-line operation, wind turbine generator installation, wind installation vessel, stow plan, maritime navigation maneuvering simulation, ship simulator

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Acronyms and Abbreviations

CES	Crowley Engineering Services
CF	Cargo Feeder (prefix to identify tug or barge that is part of CFS)
CFS	Cargo Feeder System (including tug, barge, and support vessel, if required)
CFV	Cargo Feeder Vessel (any vessel or assembly that deliver WTG components offshore)
CGS	Crowley Government Services
CMS	Crowley Marine Services
DNV GL	Det Norske Veritas / Germanischer Lloyd
DOF	degrees of freedom
ft	feet
Hs	significant wave height
IEA	International Energy Agency
kJ	kilojoules
kWh	kilowatt hours
m/s	meters per second
MW	megawatts
MWS	marine warranty survey
N	newtons
NOWRDC	The National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
OCMI	Officer in Charge, Marine Inspection
OEM	Original Equipment Manufacturer
RAO	Response Amplitude Operator
TBD	to be determined
Tp	wave period, peak
W	watts
WDT	weather downtime
WTIV	Wind Turbine Installation Vessel
WTG	Wind Turbine Generator

1 Executive Summary

1.1 Overview

Wind Turbine Installation Vessels (WTIV) are high value, high day-rate equipment whose primary role is installing wind turbine generators on site. Only one Jones Act-compliant WTIV is under currently under construction. Using WTIVs to ferry equipment to the installation site may not be cost effective if that operation can be conducted by a fleet of low-cost cargo feeder vessels (CFV). This frees up the WTIVs to remain on site and continually erect wind generators.

The overall study examines WTIV feeder system feasibility using a minimally modified deck cargo barge accompanied by the appropriate tugs. The analysis includes:

- Dynamic Motions Analysis – under tow and alongside the WTIV
- Maneuvering Simulation – bringing barge to standoff zone and to make “soft landing”
- WTIV/Feeder Weather Down Time (WDT) Simulation – based on motions and maneuvering

This report covers the *Maritime Navigation Mission Simulation* and documents the simulations performed in a Full Mission Ship Simulator of the type used to train tug operators and the findings. Each *maritime navigation mission simulation* sequence is time consuming, and a wide range of cases were examined with a broad array of variables. **Therefore, the results should be considered to provide an indication of operational limits, not statistically significant results. Also, due to sensitivity of the simulation results to the modeling of the vessel load conditions and environmental data, none of the results presented in this document should be generalized to other vessel types or environmental conditions.**

The load conditions evaluated are described in Reference 6.1 #1. The method used to model the metocean data is summarized in Appendix B.

The weather conditions used in this study are from measured wave spectrum, modeling the wave energy from the 20 most energetic bins of wave spectrum. The significant wave height (Hs), wave period (Tp) and wave field directionality selected for this study are based on the measured sea condition at the project site.

1.2 Summary of Findings

The sample size is large for a simulation of this type; however, it is not large enough to provide statistically significant results or to calculate a reliable variance. The results should only be considered to provide an **indication of operational limits**.

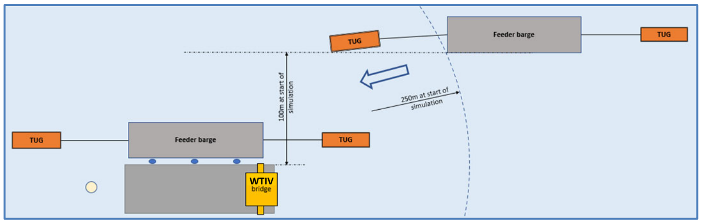


Figure 1 - Approach Maneuver (M4)

The simulation indicated the approach maneuver (M4) can be performed in 25 knot winds and 1.5 m (Hs) waves when coming from the bow and, for weather coming from the beam, the wind limit is 20 knots but, due to time constraints, wave height limit was not determined. Wave and wind limits are as shown:

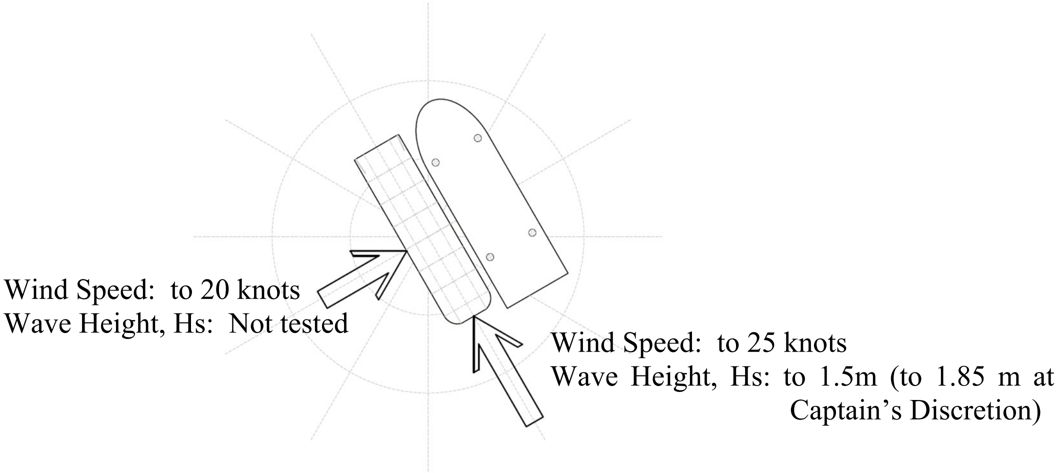


Figure 2 - WTIV Approach Limits

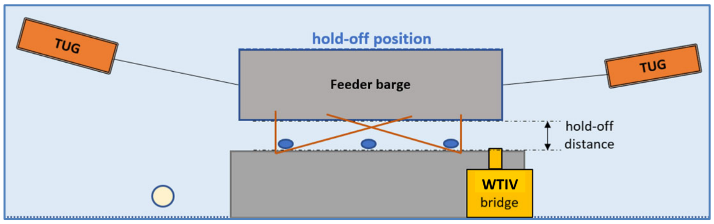


Figure 3 - Hold-Off Maneuver (M3)

The simulation indicated the hold-off maneuver (M3), with both breast and spring lines, can maintain a watch circle (box) of approximately 2.2 m x 1.8 m in environmental conditions like the M4 operational conditions.

This simulation was inconclusive about peak wave period limits.

2 Introduction

Europe presently has a total installed offshore wind capacity of 28.3 GW. That corresponds to 5,785 grid-connected wind turbines across 12 countries.[1] There are two projects totaling 42 MW in operation in the United States with an additional 35.3 GW in various stages of development.[2] The U.S. offshore wind industry is just transitioning from the pilot stage to utility-scale commercial development.

Fixed foundation offshore wind turbines are installed in water depths of up to about 160 ft (50 m). Wind Installation Vessels (WTIVs) are self-propelled with azimuthing thrusters, a ship-shaped hull, and a jack-up system to lift the hull out of the water providing a stable foundation for a very large crane. The first Jones Act-compliant vessel, the 472-ft (144 m) *WTIV CHARYBDIS,* is currently under construction at a cost of a half billion dollars[3] with a day rate assumed to be above a quarter of a million dollars. It is highly unlikely that there will be enough WTIVs available to meet the needs of all the projects in the pipeline due to the high cost of Jones Act-compliant WTIVs.

Foreign flag WTIVs may be used to install offshore wind turbine generators (WTGs) if they do not transport any cargo within the U.S. territorial sea (46 U.S. Code § 55102). Jones-Act qualified cargo vessels are available to transport cargo, and they have day rates several orders of magnitude less than WTIVs. In theory, a cargo feeder vessel (CFV) could improve the efficiency of a WTIV by eliminating the time spent traveling to and from port. The CFV would deliver cargo to the WTIV just-in-time for it to transload the cargo, install the WTG and move to the next installation site. CFVs may also be able to operate out of ports with restrictive bridge clearance or water depth limitations, thus offering more flexibility for marshalling site selection.

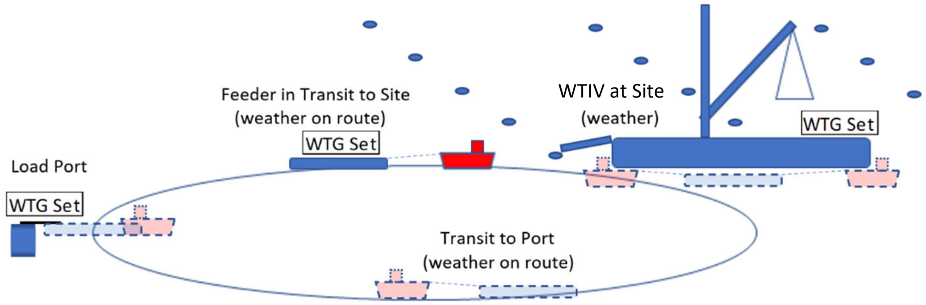


Figure 4 - WTIV with Feeder System

This study evaluates a cargo feeder system (CFS) comprised of a minimally modified deck cargo barge accompanied by the appropriate tugs in three key facets of the operation:

- Dynamic Motions Analysis – under tow and alongside the WTIV
- Maneuvering Simulation – bringing barge to standoff zone and to make "soft landing"
- WTIV/Feeder Weather Down Time (WDT) Simulation – based on motions and maneuvering

2.1 Background

Installation of an offshore wind farm is divided into several steps. One step includes preparing the field by installing foundations and electrical cables on the seabed. A monopile is the most common foundation. A monopile is a steel tube that is fixed to the seabed and extends up near the water surface. A transition piece is mounted on top of the monopile, and the WTG's tower, hub and blades are installed on that.

Another step is to install the wind turbine generators (WTG) on the foundations. When a wind installation vessel (WTIV) prepares to install a WTG on a pre-installed foundation, the WTIV must extend its legs to the sea floor and "jack-up" to lift the vessel out of the water forming a stable platform for the crane. Since there are cables running from shore to the wind farm site and between the foundations, WTIV must land its legs in specific locations. One of the options is generally aligned with the predominant wave direction to minimize roll as the WTIV prepares to jack up. Therefore, for this study, waves approaching the site from the predominant weather directions dominated the simulation cases.

2.2 Intent

The purpose of the *maritime navigation mission simulation* is to engage with Crowley's operations team to develop a detailed plan for CFS operation, and test and revise it to enable the operations team to optimize the plan. The simulation also enables the engineering team to better understand the challenges and limitations of the equipment. The CFS operations plan includes tow vessel selection, tow line arrangement, approach path, barge holding position for mooring or off-loading, communication, and control.

2.3 Objective

There have been many studies examining the barge motions and the relative motions between the WTIV and CFVs, but the details of the CFS' approach are less well understood. The goal of this study is to plan, review, test, improve and measure the performance and limitations, as judged by the captains, of a minimally modified deck cargo barge maneuvered by the appropriate tugs in a tightline configuration in the approach and positioning for cargo transload to a stationary WTIV. Data collected includes:

- Operations plan for two tugs and barge on tightline
- Preferred starting point and final approach path
- Captains' evaluation of operations for environmental conditions
- Operation duration
- Tug power requirements

2.4 Method

The engineering team worked with the *maritime navigation mission simulation* vendor of the type used to train mariners. These simulators generally use individual vessel models that permit operators to practice operating a particular vessel type (conventional tug, Voith Schneider or Z-drive tractor tug, articulated tug barge (ATB), etc) or practice operating in a particular location (harbor, channel, turning basin, etc.). The types of training performed in support of the offshore wind industry by the *maritime navigation mission simulator*[4] include:

- Navigation simulation allowing mariners to experience piloting through a wind farm.
- Validation simulation to assist in the selection of equipment during the feasibility stages.
- Vessel transit planning from construction staging area to wind farm.

In addition, training programs to support of the offshore wind industry that are under development include:

- Mariner Familiarization Training
- GWO Basic Safety Training

While *maritime navigation mission simulators* are generally used for mariner training or transit planning, the underlying program has motions prediction algorithms that replicate model vessel responses to environmental and tow or moor line forces. To do this study, the MITAGS and CES teams studied manuals and developed the barge and environmental models in a new way. Then a test matrix was developed to systematically test the limits for environmental conditions such as wind magnitude and direction, wave height and direction, and peak period using actual wave spectra so that the captains could optimize the planned maneuvers and they could judge the level of safety for each scenario.

The simulation was developed to model the barge in three load conditions including material attributes (hull form, weight distribution, ballast condition, tow and mooring line strength and elasticity, etc.), physical response characteristics (roll & pitch period and decay, wind and wave drift, hydrodynamic and aerodynamic drag coefficients, etc.), and environmental conditions (wave spectrums including significant wave height, Hs, period, Tp, and directionality). The tugs were selected from the simulator's vessel library and represent vessels of similar size and performance to those selected by the operations team. Information provided to set up the simulation and methods to tune and verify response characteristics are described in Appendix A. Analysis of environmental data and a description of the environmental conditions used for the study are described in Appendix B.

The operators performed test runs with various combinations of tug capabilities, tow and mooring line configurations, wind speeds and directions, and wave heights, periods, and directionality. After each run, the operators provided ideas for improvement and feedback to help establish operational limits and safety rating of the completed maneuver.

The simulator measured and reported vessel location, orientation, and dynamic response characteristics and recorded operator feedback for each test run. Results of the simulation are described in Section 3.1 and Reference 6.5 #8.

2.5 Overview of Report

The report is organized to provide progressively more detail regarding the goals, methods, assumptions, and findings. The maneuvers studied are presented in Figure 1, Figure 3, and Section 3.1.3. The findings are presented in Section 3.2. The details of the simulator configuration and validation are provided in Appendix A. Details about the Metocean data source, data processing and preparation for the simulator in Appendix B.

2.6 Maritime Navigation Simulator

The *maritime navigation mission simulator* used for this study is operated by MITAGS West. The simulator is the type that reproduces the bridge of a vessel with a visual display of the vessel, marine environment, and fixed structures to approximate actual conditions that are used to training ship pilots, shipmasters, and deck officers. Details about the simulator are provided in Section 3.1.5.

2.7 Limits of Study

2.7.1 Time Constraints

Each *maritime navigation mission simulation* sequence is run in real time with real vessel captains, so it is time consuming. The first runs gave the operators an opportunity to get familiar with the simulator, perform, review, and modify the maneuvers, try different tow wire materials and configurations, and validate the model. Once the preferred maneuvers were selected, a systematic program of sixty-two (62) runs were completed over a wide range of wind speeds and directions, wave heights and directions, and wave periods. For a simulation of this type, the sample size is large, however, it is not large enough to provide statistically significant results or to calculate a reliable variance. **The results should only be considered to provide an indication of operational limits at the study site**.

2.7.2 Software Constraints

The *maritime navigation mission simulator* software uses a ship motion mathematical model which includes motion equations and main forces calculated from ship dynamics equations, hull forces (hydrodynamics and aerodynamics) at deep water, rudder, propeller and thruster forces and engine dynamics equations. It is intended to reproduce vessel motions and hydrodynamic responses with enough accuracy to give an operator the general sense of 6-DOF motions including displacements, velocities, accelerations, and amplitudes.

The software does not use finite element analysis methods or boundary element strip theory. It does not use or calculate response amplitude operators (RAOs). It is intended to simulate general overall vessel motions, in response to vessel operator actions and reactions. The ship bridge graphical user interface (GUI) provides the visual, electronic and communication tools captains use to control their vessels. While not a perfect model of real-world motions, it is a good tool for planning, revising, practicing, and understanding a vessel operation prior to performing it in the real world.

This report demonstrates that experienced tug captains operating the appropriate tugs can maneuver a minimally modified deck cargo barge in a tightline configuration through the approach and positioning near an offshore stationary WTIV. The motion study, performed as part of this overall study, can provide details about the barge motions when located beside the offshore WTIV and will provide environmental limits for the "last meter" of the approach. Taken together, this report and the motions study can be used to determine if, in each weather condition, the barge can and should be brought alongside for mooring and cargo discharge.

3 Discussion

3.1 Methodology

3.1.1 Study Design: Goals & Planning

The goal of this study is to plan, review, test, improve and measure the performance and limitations, as judged by the captains, of a minimally modified deck cargo barge maneuvered by the appropriate tugs in a tightline configuration in the approach and positioning for cargo transload to a stationary WTIV.

Before the proposal for this study was issued, the engineering team met with the operations team to discuss the tug/barge configuration, maneuvers to be studied, and other considerations.

3.1.2 Barge Approach to WTIV

To maneuver a barge on a tightline, the tugs must be positioned to pull on the line to maneuver the barge and, ideally, be in position to move the barge away from the WTIV quickly in case of potential danger.

If the barge is being blown toward the WTIV, the tugs position themselves to slow the barge. If something goes wrong, they are in position to pull the barge away immediately.

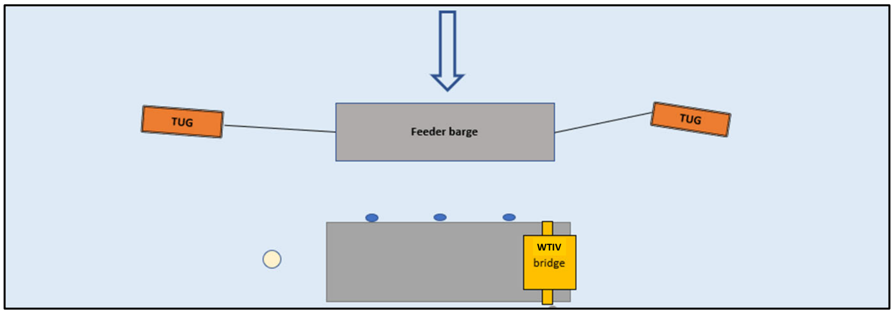


Figure 5 - Tug Positions with Wind Blowing Barge Toward WTIV

If the barge is being blown away from the WTIV, the tugs position themselves to pull the barge toward the WTIV. If something goes wrong, they must change positions before they can pull the barge away.

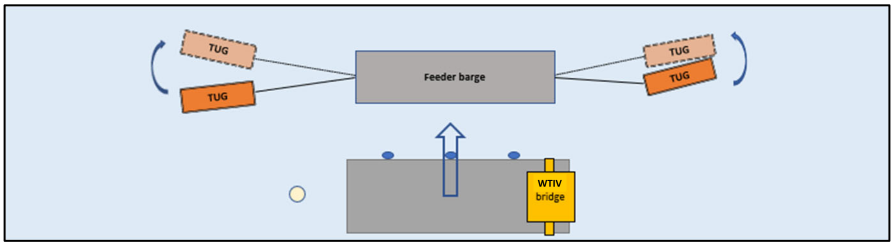


Figure 6 - Tug Positions with Wind Blowing Barge Off WTIV

Therefore, it is preferable to have the barge approach the WTIV so that it is being blown toward the WTIV.

3.1.3 Design of Experiment (DOE)

To develop the Request for Proposal, the team discussed the approach path and sequence of events with key stakeholders including Crowley operations and WTIV operators. The path was mapped from the 500m Safety Zone entry point, through the approach, mooring, offloading and departure then analyzed to determine the key maneuvers. The maneuvers identified for simulation were:

M1 - With both tugs made up, walk the barge from standoff zone 1 to standoff zone 2 and hold position.

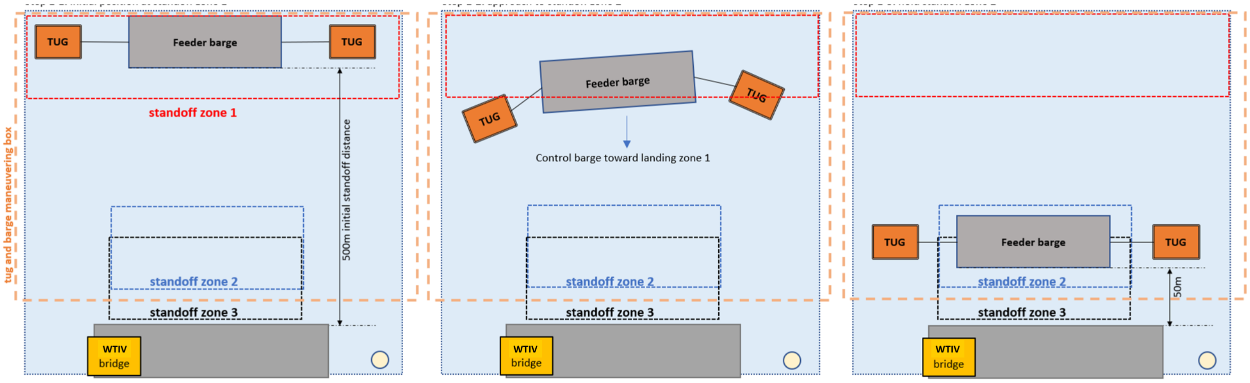


Figure 7 - Simulation Maneuver #1 (Initial Approach)

M2 - With both tugs made up, hold barge in standoff zone 2 while crew is transferred aboard, and breast lines are made up. WTIV winches bring Barge in while Tugs maintain longitudinal position and arrest speed for gentle landing.

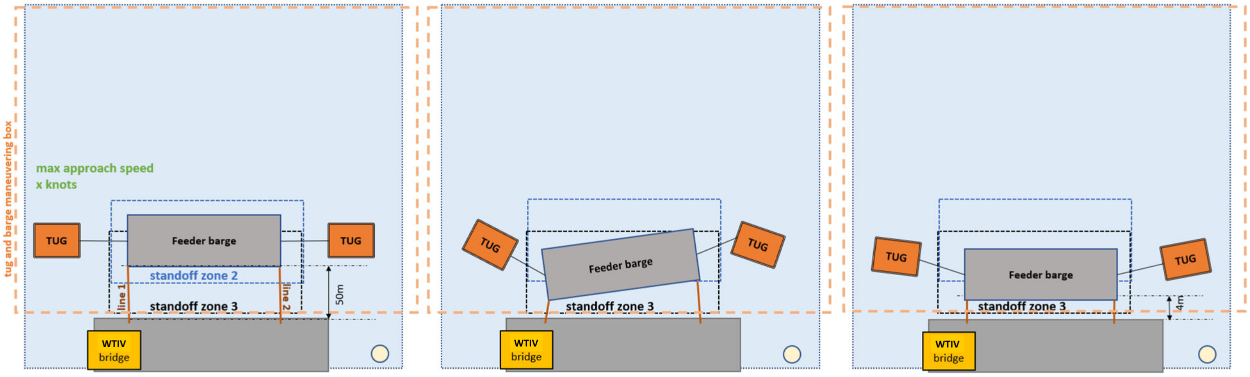


Figure 8 - Simulation Maneuver #2 (Controlled Landing)

Once the simulation crew started performing the controlled landing maneuvers, they quickly determined that spring lines were necessary to keep the vessel within a small watch circle. So, Maneuver #3 replaced Maneuver #2.

M3 - With both tugs tow lines and breast and spring mooring lines made up, pull tugs off WTIV and hold barge in place while cargo is off-loaded.

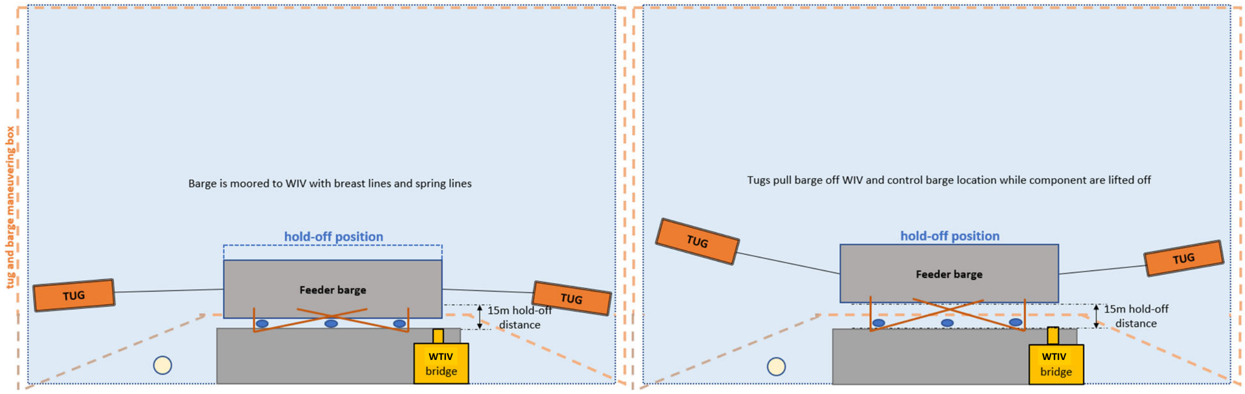
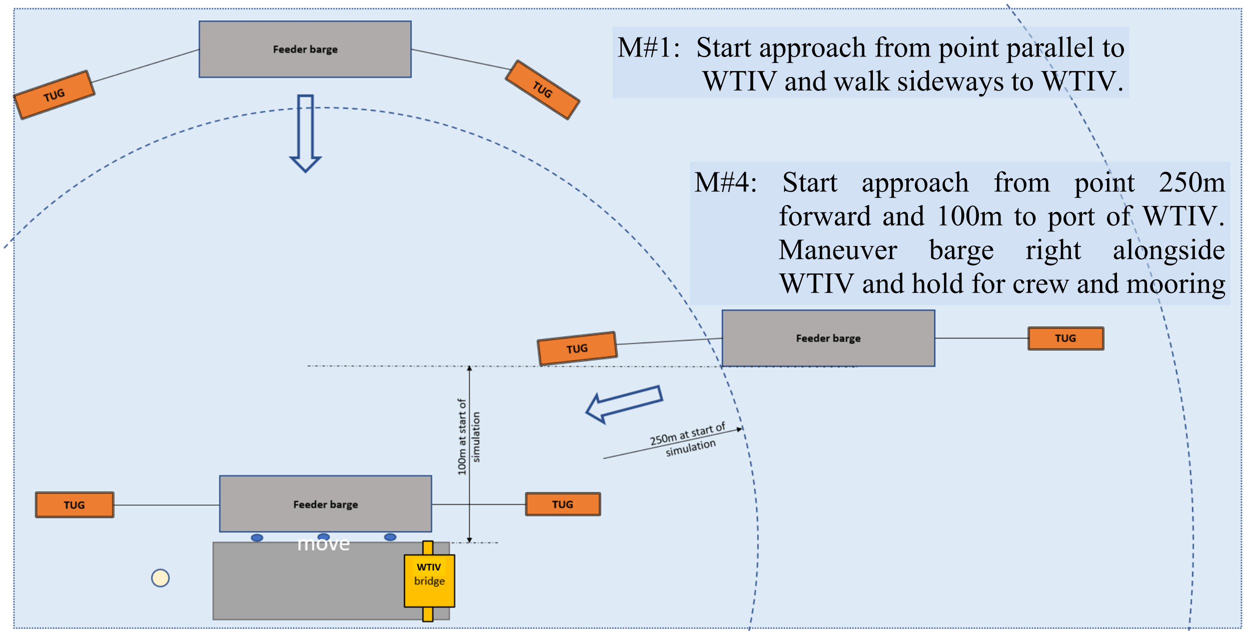


Figure 9 - Simulation Maneuver M3 (Hold for Pick)

Once the simulation crew started performing the approach maneuvers, almost immediately they determined that driving in from a point off the WTIV's starboard bow would be easier and safer than trying to walk the barge in from the side. They also had experience putting a barge alongside a jack-up and said it was much safer for the mooring crew to moor the vessel in that position. So, Maneuver #4 replaced Maneuver #1.



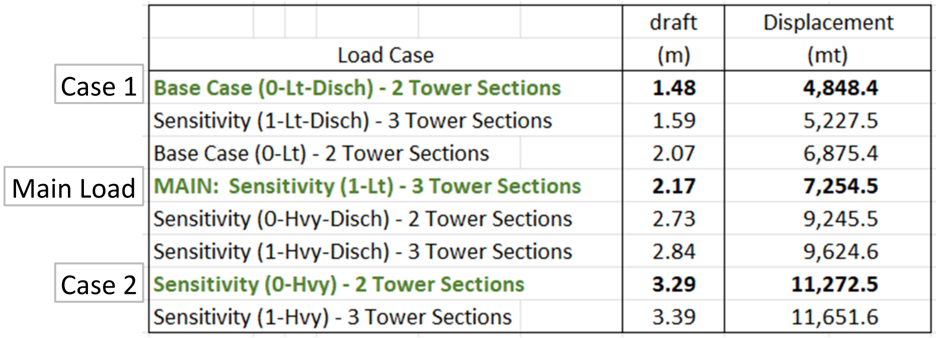
M#1: Start approach from point parallel to WTIV and walk sideways to WTIV.

M#4: Start approach from point 250m forward and 100m to port of WTIV. Maneuver barge right alongside WTIV and hold for crew and mooring

Figure 10 - Simulation Maneuver #4 (Revised Initial Approach)

3.1.4 Load Conditions

The overall study will examine four stow plan and ballast level combinations. When both the full cargo and post cargo discharge conditions are included, those four load conditions become eight and they become many more when all possible discharge combinations are included. Maritime navigation simulation is time consuming, so the main condition to test was the light ballast, three tower section case. The two sensitivity cases were the lightest and heaviest two tower section cases:



	Load Case	draft (m)	Displacement (mt)
Case 1	**Base Case (0-Lt-Disch) - 2 Tower Sections**	**1.48**	**4,848.4**
	Sensitivity (1-Lt-Disch) - 3 Tower Sections	1.59	5,227.5
	Base Case (0-Lt) - 2 Tower Sections	2.07	6,875.4
Main Load	**MAIN: Sensitivity (1-Lt) - 3 Tower Sections**	**2.17**	**7,254.5**
	Sensitivity (0-Hvy-Disch) - 2 Tower Sections	2.73	9,245.5
	Sensitivity (1-Hvy-Disch) - 3 Tower Sections	2.84	9,624.6
Case 2	**Sensitivity (0-Hvy) - 2 Tower Sections**	**3.29**	**11,272.5**
	Sensitivity (1-Hvy) - 3 Tower Sections	3.39	11,651.6

Figure 11 - Load Conditions Selected for Maritime Navigation Simulation

3.1.5 Maritime Navigation Simulation

3.1.5.1 Simulator

A *maritime navigation mission simulator* is the operator interface apparatus, computer hardware and software that reproduce the bridge of a vessel with a visual display of the vessel, marine environment, and fixed structures to approximate actual conditions. A mission simulation is a is a set of scenarios used for training, practicing, and evaluating performance of ship pilots, shipmasters, and deck officers.

The maritime navigation simulator used for this study is operated by MITAGS West. (See Reference 6.5.1.) MITAGS West has three bridge simulators. For this study, two bridge simulators were integrated into the same exercises. MITAGS' 300° Full-Mission Workboat Bridge Simulator was used to model the main long-haul tug. MITAGS' 300° Full-Mission Tug Bridge Simulator was used to model the assist tug. MITAGS' main simulation software is the Wärtsilä Full-Mission 360^{o} Shiphandling Simulator.

The core of the simulator is the mathematical modeling software. MITAGS' runs Wärtsilä Navi-Trainer Professional (NTPRO), version 5.40. The Wärtsilä software was written by Transas MIP LTd. Transas, established in 1990, was a global market leader in marine navigation, professional training, and simulation services. Wärtsilä purchased Transas in 2018.

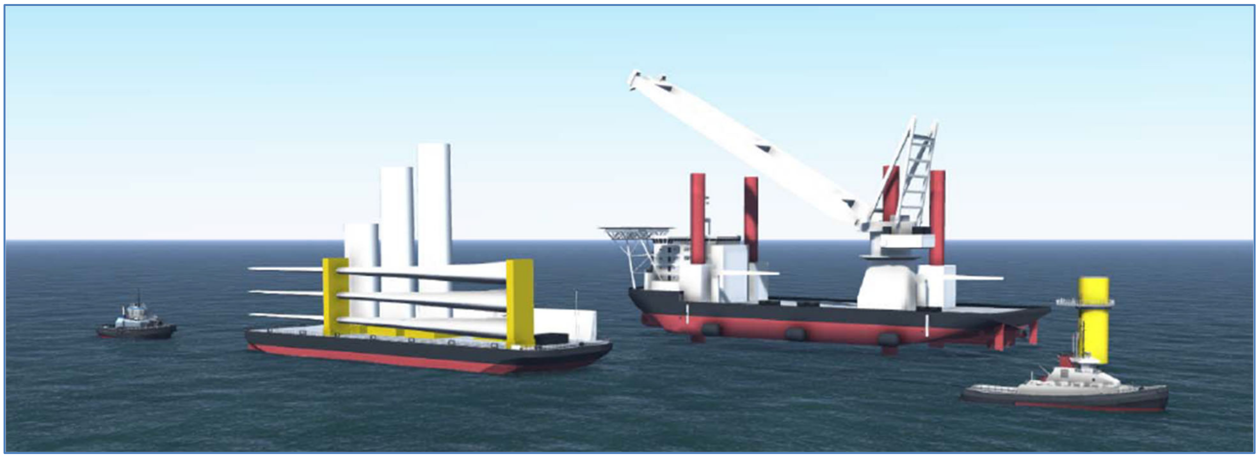


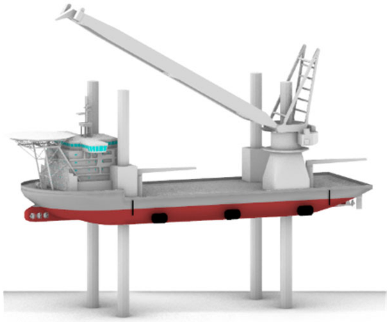
Figure 12 - MITAGS Navigation Simulation Models

3.1.5.2 Simulator Library

MITAGS' maintains a library of validated tug models with bollard pull ranging from twenty-six (26) to eighty (80) metric tons. MITAGS' fleet includes Z-drive and Voith Schneider Propeller (VSP) tugs which can be operated in the indirect mode. For this study, the tugs were selected from the MITAGS' library.

3.1.5.3 Simulator Input

MITAGS' created the WTIV as a fixed feature.



MITAGS created the barge model specifically for this study using Wartsila Virtual Shipyard II Software. The software is used to develop, edit, and document ship motion, engine, and propulsion models. (See Reference 6.5 #2.)

WTIV and barge dimensions and other details are provided in Appendix A.

3.1.5.4 Simulator Output

The simulation software records the location and orientation of each of the three vessels that comprise the cargo vessel system (lead tug, barge and support tug) at every minute throughout the simulation.

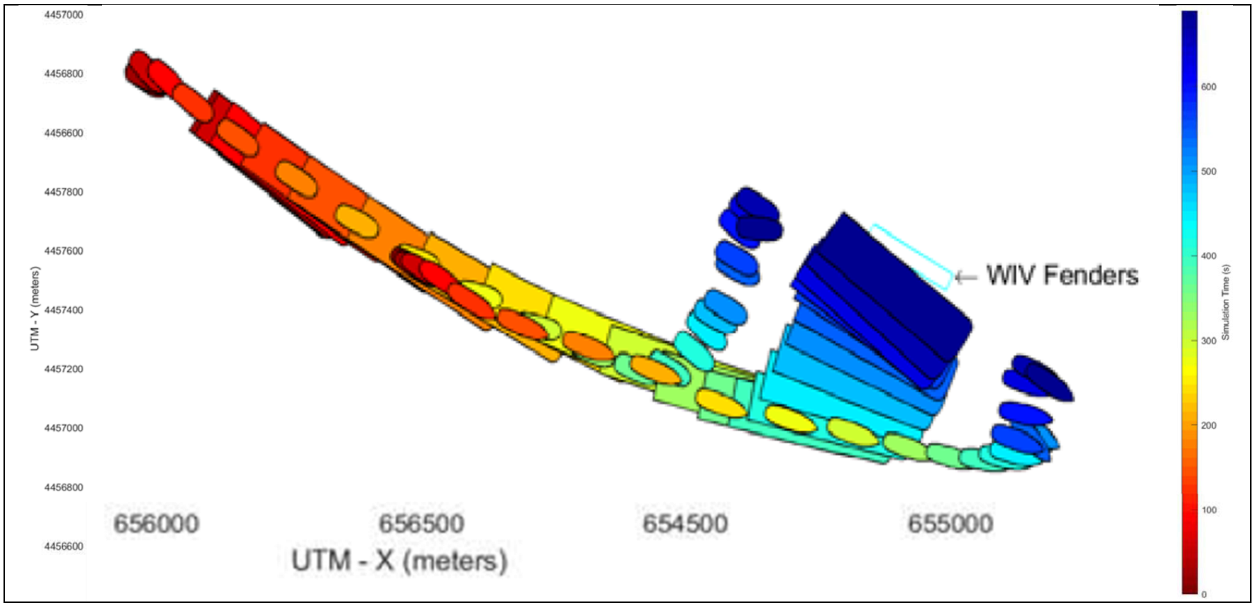
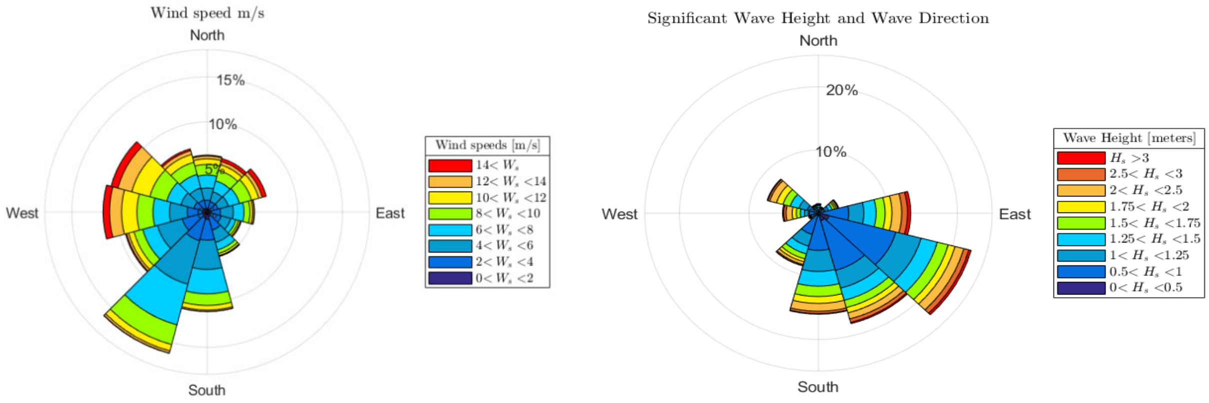


Figure 13 - Swept Path Simulator Output

The output also includes minute-by-minute logs of events, environmental and line forces, 6 DOF vessel position, attitude and velocity, ship dynamics (COG, SOG, rudder angle, engine speed, thruster power), towing and mooring line forces, traffic, vessel orientation and forces, and environmental conditions.

3.1.6 Metocean Data

For this study, the full 2D ocean wave spectra measured at the National Data Buoy Center (NDBC) Station 44025 was collected. The prevailing wave and wind cardinal direction and magnitude were determined from the measured data for the past 22 years (since 2000):



Wind from 210° dominates.

Waves from 120° dominate.

Figure 14 - Most Probable Wind and Wave Conditions

See Appendix B for more information.

3.2 Findings

As explained above, the sample size is not large enough to provide statistically significant results or to calculate a reliable variance. The results provide an **indication of operational limits**.

Unless mentioned otherwise, these findings are based on simulations of the M4 maneuver described in Section 3.1.3.

After each run in the *maritime navigation mission simulator,* the captains provided their opinion of the overall difficulty of the maneuver, overall difficulty of holding the barge in place and the overall safety of the operation. The captains used a 5-point scale with, 1 = Very Difficult or Unsafe, 3 = Average, and 5 = Not Difficult or Very Safe. The captains' safety evaluations were used to establish operational limits.

3.2.1 Barge Landing Velocity

Before using the captains' safety evaluations, their safety ratings were compared with the effective landing velocity to understand how the captains' appraisals were "calibrated". This comparison may also provide an indication of how realistic the maneuvering seemed to the captains. The environmental conditions for the test cases included in this section are:

- Average period of 8.23 s (range: 3.15 to 11.1 s)
- Average significant wave height of 1.56 m (range: 2.2 to 1.03 m)
- All coming in from 120-degree direction
- Wind is at 210-degree (perpendicular to barge), 20 knots or less
- Load cases: Main, C1, C2

Figure 15 provides the results of this analysis. The color zones are based on the average safety rating and amount of scatter observed in the safety evaluations. The green zone is the region with an average safety rating of 3 and above, with minimum scatter in the data. When data scatter becomes apparent, there is an inflection point. The yellow zone is defined as the region between the inflection point and the value with an average safety rating of 2.5. Finally, the red zone is defined for conditions with an average safety rating less than 2.5.

The plot of landing velocity and safety evaluation shows an inflection point at approximately 0.3 m/s and the average safety rating goes below 2.5 at 0.6 m/s:

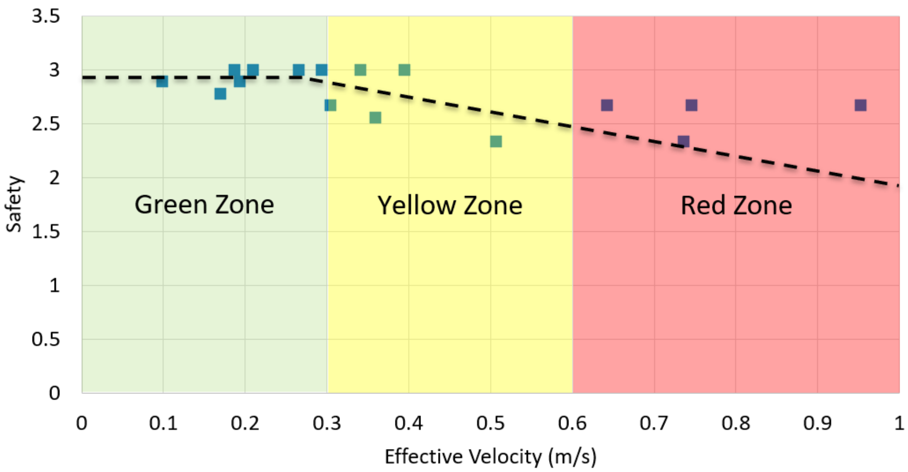


Figure 15 - Safety Level at Landing Velocities

This indicates that these operators rate the maneuvers with these landing velocities as follows:

Safe for Everyday Operations (Green Zone)	Landing Velocity < 0.3 m/s
May be Safe; Subject to Captain's Discretion (Yellow Zone)	Landing Velocity: 0.3 to 0.6 m/s
Likely Unsafe; Subject to Captain's Discretion (Red Zone)	Landing Velocity > 0.6 m/s

3.2.2 Barge Landing Force

When the barge lands against the WTIV, the forces applied to the WTIV are a function of barge displacement and landing velocity. The total barge displacement (or weight) includes the lightship weight of the barge, the weight of the cargo and the weight of the ballast. The ballast is used to control trim and heel and increase draft to minimize slamming. The risk of slamming can be minimized by weighing down the vessel, changing course and/or reducing the transit speed. To minimize the landing forces on the WTIV, the barge ballast load must be minimized as much as possible. The only weight item that can be reduced is ballast, therefore, the light ballast condition was selected as the main load condition examined in this study.

When this moving barge lands against a stationary WTIV, the landing energy is equivalent to Yokohama's "Berthing Energy". (See Reference 6.6 #1.) As shown below, for a constant "Berthing Energy", a barge with less displacement can land at a higher velocity – which means it can land in a higher sea state.

For the three load conditions studied (highlighted below), the landing kinetic energy or "Berthing Energy" is estimated below. (See Table 1.) The dashed line provides an example of a landing energy limit of 250 kJ.

		Berthing Energy "E" (kJ)									
	V (m/s) Displ (mt)	0.10	0.12	0.15	0.18	0.20	0.25	0.30	0.40	0.50	0.60
Case 1	4,848.4	26.5	38.1	59.6	85.8	105.9	165.5	238.4	423.8	662.1	953.5
	5,227.5	28.7	41.4	64.7	93.1	114.9	179.6	258.6	459.8	718.4	1,034.5
	6,875.4	38.8	55.9	87.3	125.8	155.3	242.6	349.3	621.0	970.4	1,397.4
Main	**7,254.5**	**41.2**	**59.3**	**92.7**	**133.5**	**164.8**	**257.5**	**370.8**	**659.2**	**1,030.0**	**1,483.2**
	9,245.5	54.1	77.9	121.8	175.4	216.5	338.3	487.1	866.0	1,353.1	1,948.5
	9,624.6	56.7	81.6	127.5	183.6	226.6	354.1	509.9	906.5	1,416.5	2,039.7
Case 2	11,272.5	68.0	97.9	152.9	220.2	271.8	424.7	611.6	1,087.3	1,698.9	2,446.4
	11,651.6	70.6	101.7	158.9	228.8	282.5	441.4	635.5	1,129.9	1,765.4	2,542.2

Table 1 - Landing Energy - Barge on WTIV - Simulation Cases

3.2.3 Wind Speed Limit in Predominant Wind Direction

The loaded feeder barge has a very high windage area. At the location used for this study, the dominant wind direction is perpendicular to the dominant wave direction. To understand the operational limits for wind, a series of runs were completed over a range of calm seas (Tp: 6.8 – 8.9 sec, Tp_{avg}= 8.3 sec; Hs: 0.8 – 1.4 m, Hs_{avg} = 1.1 m, coming from 120°) with varying wind speeds. The captains judged the wind limits to be:

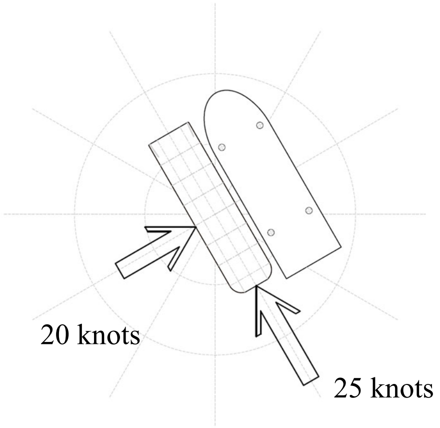


Figure 16 - Wind Speed Limits by Wind Direction

This indicates that these operators rate the maneuvers in these wind conditions as follows:

• Wind Limit for Beam Winds	Wind Speed ≤ 20 knots
• Wind Limit for Quartering Winds	Captain’s Discretion, in 20 to 25 knot range
• Wind Limit for Head Winds	Wind Speed ≤ 25 knots

Wind gusts do not lend themselves to study; operation in gusty conditions should be left to captain’s discretion.

3.2.4 Significant Wave Height Limit in Predominant Wave Direction

Once operational limits were established for wind, a systematic series of runs were completed over a range of significant wave heights with peak wave period in the dominant range (Tp: 7.6 – 9.0 sec, Tp_{avg}= 8.3 sec). Actual buoy wave spectra were used (as described in B.2.3.3.3 in Appendix B); however, to account for wind speed variation, the measured wind speed for the time step modeled was increased by 5.2 knots or to 20 knots, whichever is less. The wind speed increase was set at 5.2 knots which is equivalent to 1.5 times standard deviations for all wind over 20 years, at the buoy location. For waves in the dominant direction (coming from 120°), the significant wave height with peak wave period in the most dominant range:

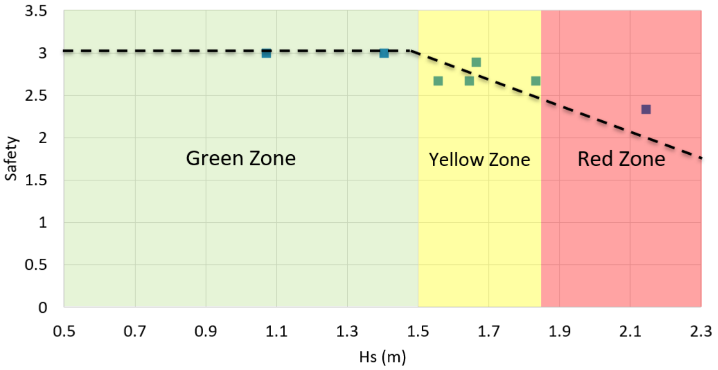


Figure 17 - Safety Levels at Various Wave Heights

This indicates that these operators rate the M4 maneuver (Section 3.1.3) in head seas with these significant wave heights (Hs) as follows:

- Safe for Everyday Operations (Green Zone)	Wave Height < 1.5 m
- May be Safe; Subject to Captain's Discretion (Yellow Zone)	Wave Height: 1.5 to 1.85 m
- Likely Unsafe; Subject to Captain's Discretion (Red Zone)	Wave Height > 1.85 m

3.2.5 Peak Wave Period Limit in Predominant Wave Direction

Once operational limits were established for wind and significant wave height, a systematic series of runs were completed over a range of peak wave periods with the significant wave heights in the dominant range (Hs: 1.0 – 1.7 m, Hs_{avg}= 1.4 m). Wind speeds were increased above the wind speed associated with the spectra selected as described in Section 3.2.4 above. The findings were inconclusive.

3.2.6 Significant Wave Height Limit, Sensitivity to Loading

Once the significant wave height limit for the main operating condition was determined, a systematic series of runs were completed in the lighter C1 condition and the heavier C2 condition. Load conditions are defined in Appendix A. A range of significant wave heights were selected with a peak wave period in the wider range (Tp: 4.7 – 11.1 sec, Tp_{avg}= 8.3 sec). Wind speeds were increased above the wind speed associated with the spectra selected as described in Section 3.2.4 above. For waves in the dominant direction (coming from 120°), the indicated significant wave height limit for three load conditions are:

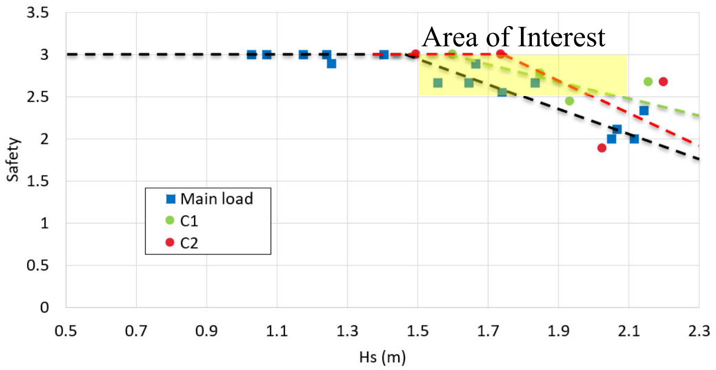


Figure 18 - Safety Levels at Various Wave Heights for 3 Load Cdns

As described in Section 3.2.1 above, the yellow zone is defined as the region between the inflection point for the Main Load test case and the average safety rating of 2.5.

These indications are based on a very small sample size; however, these operators suggest that the M4 maneuver in head seas with these significant wave heights (Hs) have similar or slightly higher levels of safety than the main load case. This seems to indicate that limits found for the main load condition may also apply to the other two load conditions observed in this study.

3.2.7 Significant Wave Height Limit, Assist Tug Sensitivity

Once the significant wave height limit for the main operating condition was determined, a systematic series of runs were completed with a tug with Voith Schneider Propeller (VSP) replacing the Z-Drive tug. The models used are described in Appendix A. A range of significant wave heights were selected with a peak wave period in the dominant range (Tp: 7.6 – 9.0 sec, Tp_{avg}= 8.3 sec). Wind speeds were increased above the wind speed associated with the spectra selected as described in Section 3.2.4 above. For waves in the dominant direction (coming from 120°), the indicated significant wave height limit for two tug types are:

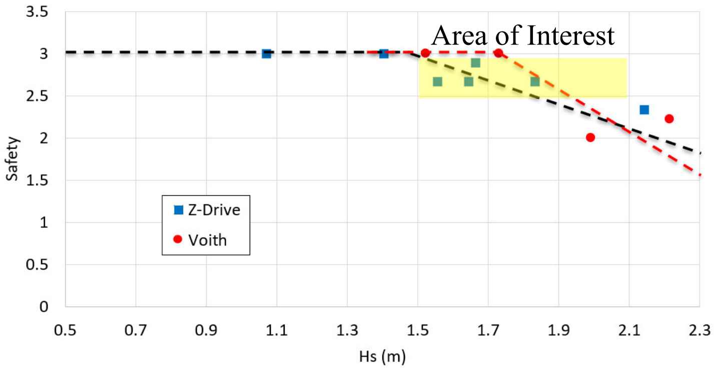


Figure 19 - Safety Levels at Various Wave Heights for Two Assist Tug Types

These indications are based on a very small sample size; however, these operators suggest that the M4 maneuver in head seas with these significant wave heights (Hs) with the Voith tug have similar or slightly higher levels of safety than the Z-Drive tug. This seems to indicate that limits found for the Z-Drive tug observed in the study may also be applied to a VSP tug.

3.2.8 Significant Wave Height Limit, ATB Sensitivity

Once the significant wave height limit for the main operating condition was determined, a systematic series of runs were completed with an Articulated Tug Barge (ATB) replacing the lead tug and barge. A Z-Drive tug assisted with the maneuver. A range of significant wave heights were selected with a peak wave period in the dominant range (Tp: 7.6 – 9.0 sec, Tp_{avg}= 8.3 sec). Wind speeds were increased above the wind speed associated with the spectra selected as described in Section 3.2.4 above. For waves in the dominant direction (coming from 120°), the indicated significant wave height limit for the two configurations are:

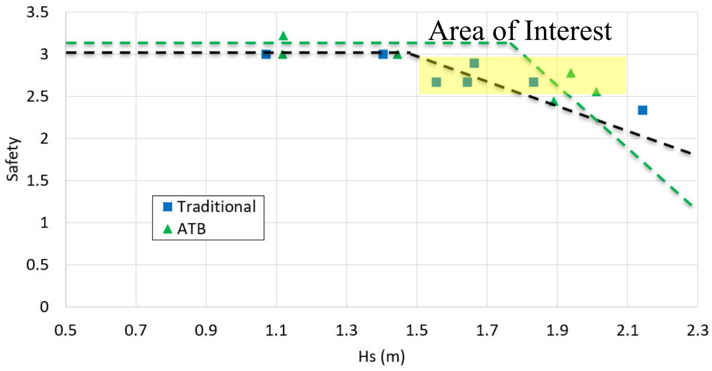


Figure 20 - Safety Levels at Various Wave Heights for Two CFS Configurations

These indications are based on a very small sample size; however, these operators suggest that the M4 maneuver in head seas with these significant wave heights (Hs) with the ATB have similar or slightly higher levels of safety when compared to the tightline (traditional) CFS configuration. This seems to indicate that limits found for the tightline CFS observed in the study may also apply to an ATB.

3.2.9 Tug Power Requirements

This section presents the dynamic responses from the tugboats. These responses include total bollard pull, engine power, maximum bow thruster force, and time of bow thruster use. The power requirements do not appear to correlate with wave height. An example of mean engine power (Hp) for Z-drive tugboat is presented below for different significant wave heights.

The dynamic responses of the tugboats are presented in Table 2. In this table, an average value is reported for engine power, bollard pull, and bow thruster power and duration.

	Lead Tug Conventional	Assist Tug Z-Drive
Average Bollard pull (tf)	30.9	30.7
Average Bow Thruster (tf)	6.6	N/A
Max Bow Thruster (tf)	11.5	N/A
Max Bow Thruster Duration (s)	400.0	N/A

Table 2 - Tug Power Requirements

3.2.10 Approach Maneuver Duration (Maneuver 4)

The approach maneuver consistently took 15 to 20 minutes from the 250-meter starting position. A thirty (30) minute window should be adequate for this maneuver from the 500-meter Safety Zone entry point.

3.2.11 Holding Station Off WTIV (Maneuver 3)

As for the other simulations, different environmental conditions were used to evaluate the feasibility of the stand-off maneuver (M3, see Section 3.1.3). Once the barge was pulled off the WTIV by the desired distance, the tugs held it in place. To evaluate the maneuver, statistics were run. The steady state region was defined as the time when the standard deviation of the distance was less than 5% as shown in Figure 21. The distance from WTIV was also plotted with one standard deviation to confirm the results by visual inspection as shown in Figure 22. The eastward-northward region of barge stability was measured to determine the watch circle achieved as shown in Figure 23.

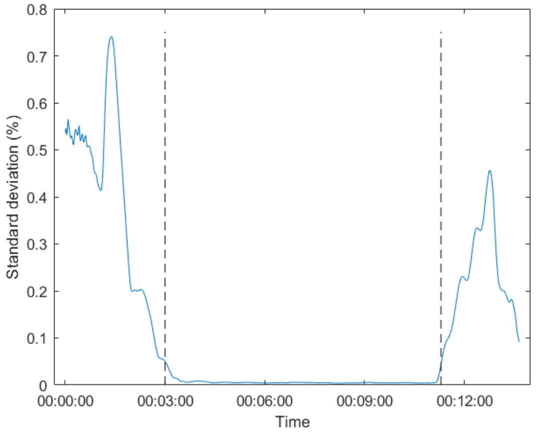


Figure 21 - Maneuver 3, Standard Deviation of Distance

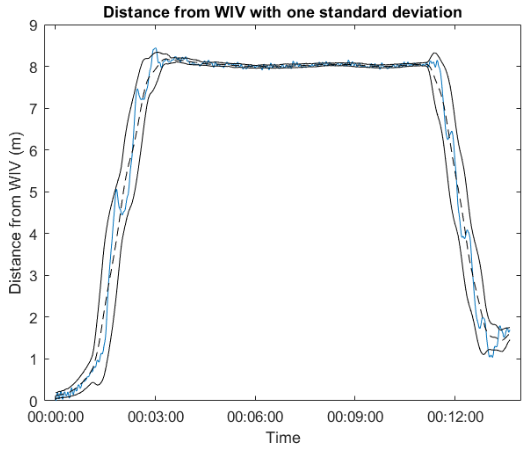


Figure 22 - Distance from WTIV (with 1 Standard Deviation)

M3 test cases were performed for:

- Tp: 5.8 – 8.3 sec, Tp_{avg}= 7.7 sec;
- Hs: 0.8 – 2.1 m, Hs_{avg} = 1.4 m,
- All waves coming from 120° +/- 20°
- Wind is at 210 degrees, 20 knots or less

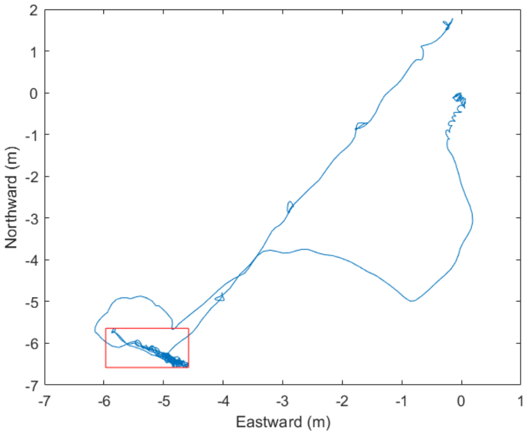
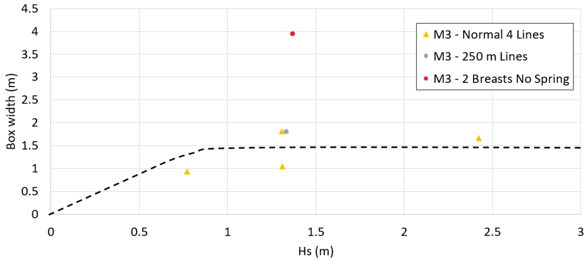


Figure 23 - Measurement of Watch Circle

This data set is small; use data with caution. This indicates tugs can maintain a watch circle (or box) of:



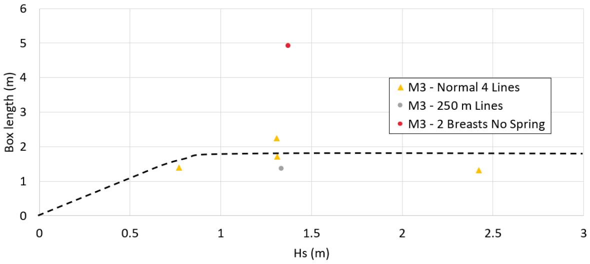


Figure 24 - Watch Circle (Box) Width for Hs

Figure 25 - Watch Circle (Box) Length for Hs

Other findings regarding the hold-off maneuver (M3):

- All tests were evaluated as safe by the operators.
- Captains expressed a preference for longer tow wires (250 m); however, only one case was tested.
- Captains expressed concern for 2 breast/no spring line case; single case tested indicates less control.

3.2.12 Hold-Off Maneuver Duration (Maneuver 3)

The team consistently held the barge off the WTIV for 10 minutes which was enough to determine that the barge was stable. With spring lines, it appears that the tugs can hold the barge off the WTIV in conditions at least as severe as the approach conditions.

4 Concluding Remarks

4.1 Intersection of Findings

The mission to deliver cargo to the WTIV and be broken into two broad activities: transporting the cargo into the vicinity of the WTIV and bringing the cargo vessel alongside the WTIV for transloading. This study demonstrates that a minimally modified deck cargo barge maneuvered by appropriate tugs with experienced captains can bring the cargo to the vicinity of the WTIV. Cargo vessels cannot respond quickly enough to respond to individual waves, but even if they were, this simulation does not model vessel motion response with enough accuracy to evaluate the moment it contacts the WTIV.

Whether the barge first order wave motions are benign enough to limit the landing energy of the barge into the WTIV fenders must be the subject of a different type of study.

4.2 Evaluation of Method

4.2.1 Simulation Method Challenges

An ideal simulator study would repeat a given scenario with the same variables at least forty time per independent variable to determine the % pass rate (or risk) with statistical significance. In a *maritime navigation mission simulator*, the number of times each scenario can be repeated depends on the number of simulations required to identify a limit and the stamina of the simulation crew. *Maritime navigation mission simulation* seems to be well suited to validating a mission plan and training crew but developing operational limits with confidence statistics should be done in a way that is less human capital intensive. Due to these limitations, performing enough repetitions to run statistics is probably impossible.

4.2.2 Simulation Method Strengths

In developing the request for proposal for this work, the engineering and operations teams met together to plan the equipment, tow and mooring plans and approach and hold-off maneuvers. During the meetings there was a good exchange of ideas, but the meetings were brief and one of many responsibilities in the day of each team member. In contrast, the time in the simulator was spread over two weeks and the team members were all engaged and focused on the simulation process, debriefings and exchange of ideas and challenges. In addition to being an opportunity to develop the CFS plan consisting of tow vessel selection, tow line arrangement, approach path, barge holding position for mooring or off-loading, communication, and control, it became an opportunity for team members to develop relationships across disciplines and get a feel for the challenges the others face.

5 Areas for Further Study

5.1 Align with Motions Study

Once the barge motions report is complete, review barge motions predictions to identify barge motions in weather conditions operators found to permit safe operations and compare to weather conditions operators found unsafe. Examine boundary conditions to understand if operational limits can be developed from barge motions.

5.2 Evaluate Landing Motions

The tug captains may be able to bring the barge alongside the WTIV, but first order barge motions might be such that the barge impact forces are too large to safely land the barge.

Once the barge motions report is complete, review barge sway, yaw, and roll motions to identify wind magnitude or direction, wave magnitude, period, or direction to determine landing or "last meter" operational limits.

5.3 Consider Additional Simulation

5.3.1 Model Development

Further validate the physics model for each hull.

5.3.2 Study Limits for Other Wave Directions

If wave directionality limits cannot be found by comparing motions in safe landings to those of marginal or unsafe landings, use "last meter" environmental limits to develop a test matrix for additional *maritime navigation mission simulation* runs to identify the limiting wave height for beam seas and quartering seas.

5.4 Compare CFS to WTIV Availability

To create an efficient system, the CFS and the WTIV should have similar performance limits. If the WTIV can install WTGs at the site, but the CFS cannot deliver them, the system efficiency is reduced. Conversely, if the CFS can deliver WTGs to the site, but the WTIV cannot install them, the system efficiency is also reduced.

Develop estimates of WTIV operational limits by:

- Requesting operational limits from a WTIV operator, or

- Using a free body diagram, make an estimate of the displacement of each WTG component during lifting for various wind speeds to estimate operational limits during lifting operations.

Perform an exceedance/non-exceedance study to understand the availability of the CFS and the WTIV and to understand the specific limit (wind magnitude or direction, wave magnitude, period, or direction) that are the most restrictive operational limits. Examine options and costs of methods to expand the operational window.

6 References

6.1 NOWDRC Agreement #103 Reports

1. Technical Validation of Existing U.S. Flagged Barges as a Feeder Solution for the U.S. Offshore Wind Industry: Barge, Cargo and WTIV Load Properties Technical Report, Milestone Number 1.3.

6.2 Barge Info

1. 400' x 105' x 26' Deck Cargo Barge, GENERAL ARRANGEMENT, Dwg 73-03, Rev B
2. Crowley Spec Sheet: 455 Series – 400' x 105' x 25'
   [applicable to Barges: 455-1 (Marty J), 455-3, 455-4, 455-5, 455-6, 455-7. 455-8, 455-9]
3. 213025-833-1, Weight Estimate
4. 213025-034-01, 15 MW NREL Reference Turbine Stow Plan, Base Case – Two Tower Sections
5. 213025-034-02, 15 MW NREL Reference Turbine Stow Plan, Sens. Case 1 – Three Tower Sections
6. 213025-034-03, 15 MW NREL Reference Turbine Stow Towing & Mooring Arrangement
7. General HydroStatics (GHS) model: (21-11-29) 213025-455.gf

6.3 Tug Info

1. Crowley Spec Sheet: Ocean Class Tugs [applicable to DP1 Ocean Wind & Ocean Wave, and DP2 Ocean Sky & Ocean Sun]
2. Crowley Spec Sheet: Alert Class Tugs [applicable to Alert, Attentive & Aware which are outfitted with azimuthing drives (z-drive)/controllable pitch (CP) propellers]

6.4 Wind Turbine Generator Info

1. IEA Wind TCP Task 37, Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report, March 2020

6.5 Simulator Info

1. Simulation Capabilities and Facilities Guide, Maritime Institute of Technology and Graduate Studies (MITAGS), July 2021 https://www.mitags.org/simulation-capabilities-facilities-guide/
2. Wärtsilä Virtual Shipyard software https://www.wartsila.com/voyage/simulation-and-training/virtual-shipyard
3. Wärtsilä Simulation and Training Solutions https://www.wartsila.com/docs/default-source/product-files/optimise/simulation-and-training/simulation-and-training-solutions-brochure.pdf?sfvrsn=4df0d044_2
4. Wärtsilä Navigational Simulators, Navi-Trainer Professional 5000
   https://www.wartsila.com/docs/default-source/product-files/optimise/simulation-and-training/navigational-simulators-brochure.pdf?sfvrsn=aa87cf44_4

5. Wärtsilä Navi-Trainer Professional 5000 Instructor Manual, (Version 5.20, June 2011 & Version 5.35, October 2014)
6. Wärtsilä Description of Ship Motion Mathematical Modeling, SMM Version: 2.221.1744.0, Version 02.14
7. Transas Description of Ship Motion Mathematical Model, Version 02.12, Issue Date: June 2015
8. Crowley Simulation Study of Wind Installation Vessel (WTIV) For Empire Wind - February 22 to March 8, 2022, by the Maritime Institute of Technology and Graduate Studies (MITAGS), Issued April 19, 2022

6.6 Fender Design Info

1. Yokohama Pneumatic Fender ISO 17357-1: 2014 PIANC: 2002, Catalog No. FDL-2019-9

6.7 Endnotes

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[1] https://windeurope.org/intelligence-platform/

[2] https://www.energy.gov/eere/wind/wind-market-reports-2021-edition#offshore

[3] https://news.dominionenergy.com/2021-06-01-Dominion-Energy,-rsted-and-Eversource-Reach-Deal-on-Contract-to-Charter-Offshore-Wind-Turbine-Installation-Vessel

[4] https://www.mitags.org/offshore-wind-research/

Appendix A. Configuration Input to Simulator

A.1 Wind Farm Site

A1.1 Geographic Location for Study

The site assumed for the Crowley/NOWRDC Study is Empire Wind:

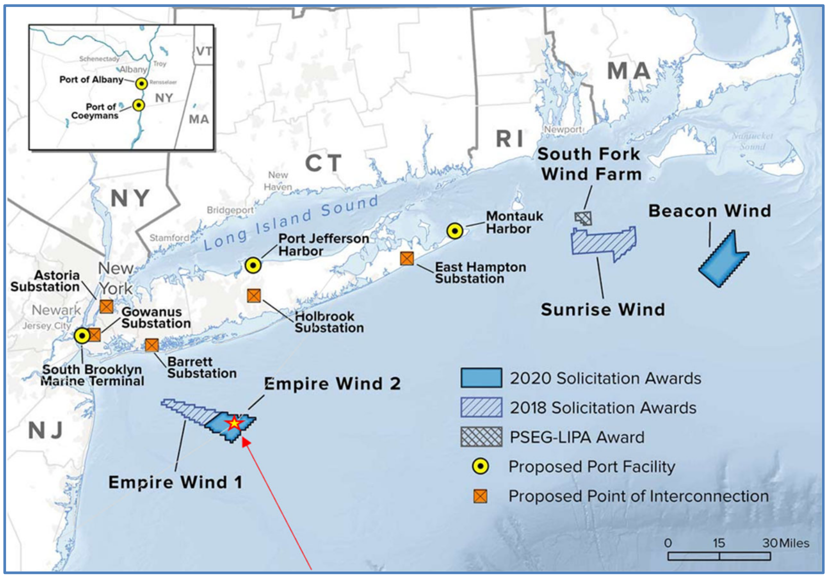


Figure 26 - Empire Wind Study Site

Buoy data used for this study is: Station 44025 (LLNR 830) – LONG ISLAND – 30 NM South of Islip, NY located at 40.251 N 73.164 W (40°15’3” N 73°9’52” W)

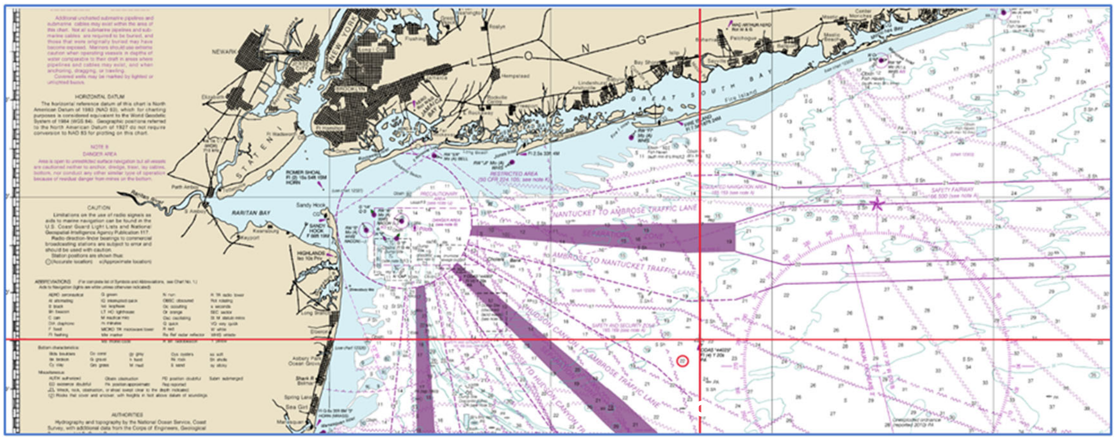


Figure 27 - Chart 12300 - Nantucket Shoals to Five Fathom Bank – Approaches to New York

The simulation is done assuming “deep water”; therefore, water depth and bottom contours are immaterial. Mean drift, tides or other long swells that might affect this assumption were not included in this study.

A.1.2 Dominant Wind/Wind Direction

The climatology analysis is included in Appendix B. The prevailing waves and wind are shown below.

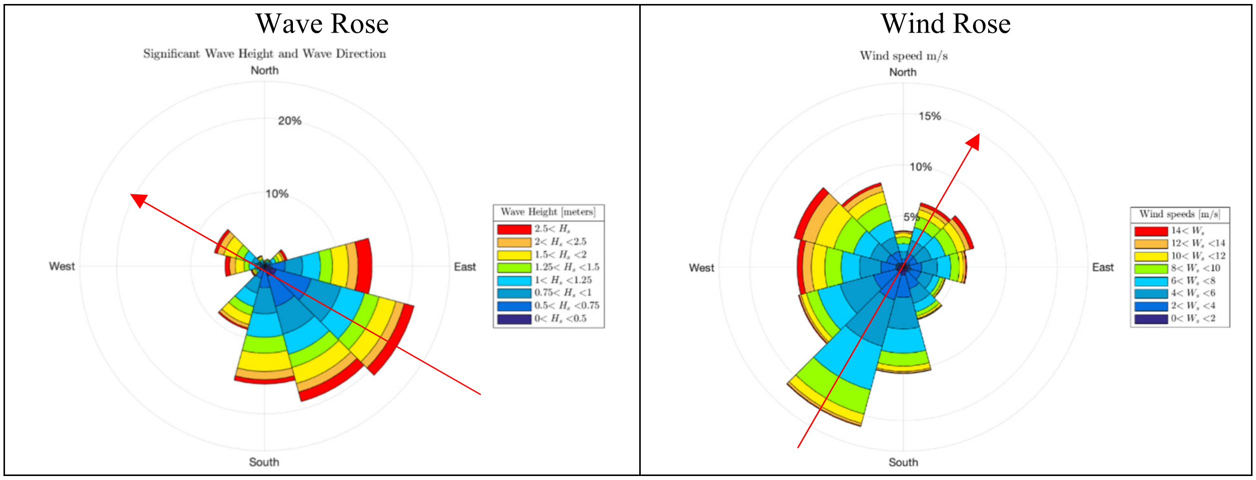
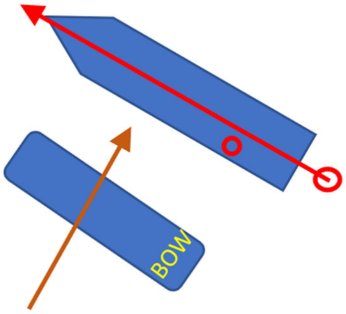


Figure 28 - Dominant Wave and Wind Direction.

For this Study, wave energy and wind are described by direction they are coming from.

A.1.3 WTIV Orientation

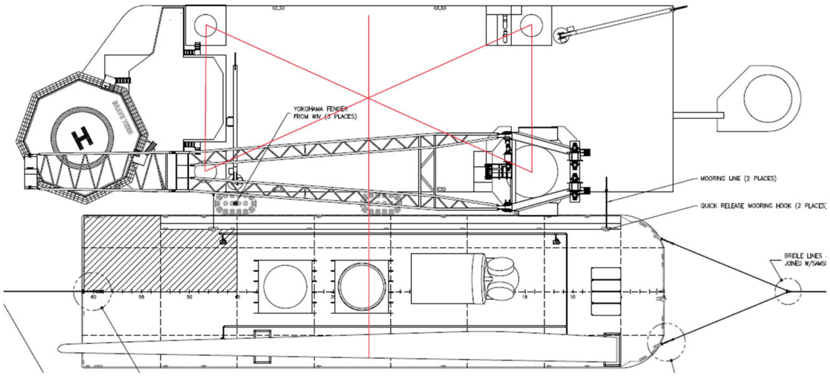


The WTIV alignment is selected based on the direction of the dominant wave energy. The barge will approach the side that the prevailing wind is coming from. The WTIV's crane is oriented toward the barge.

The dominant wave energy is from the southeast (120 deg). The prevailing wind is from the southwest (210 deg).

For operations, no other vessels will operate within a 500m safety zone. Therefore, the tugs will not meet any other vessels during the exercises.

A.1.4 WTIV Geometry



The generic WTIV is assumed to be 136 m x 44 m x 9.5 m (446 ft x 144 ft x 31 ft) with four (4) 4.5m (15 ft) legs. The WTIV is jacked up with a 3 m (10 ft) air gap, so the main deck is 12.5 m (41 ft) above the waterline. The WTIV is securely attached to the sea floor.

A.2 Cargo Feeder System: Barge

A.2.1 Crowley Barge 455 Stow Plan

To transport this cargo, the barge is assumed to be fitted with:

- A fender wall design was developed for 10.8 ft x 32.8 ft (3.3 m x 10 m) fenders centered 20.6 ft (6.3 m) above the CFV deck with a maximum allowable reaction load of 200 LT (203 MT),
- A ballast system for tanks 2P/S and 7 P/S with four (4) Goulds 3171 vertical sump pumps and associated piping,
- Sea fastenings/grillages for the WTG components, and
- An electrical system, mooring fittings and other outfit.

Cargo includes a nacelle, blades and tower with tower transported in two (2) or three (3) sections:

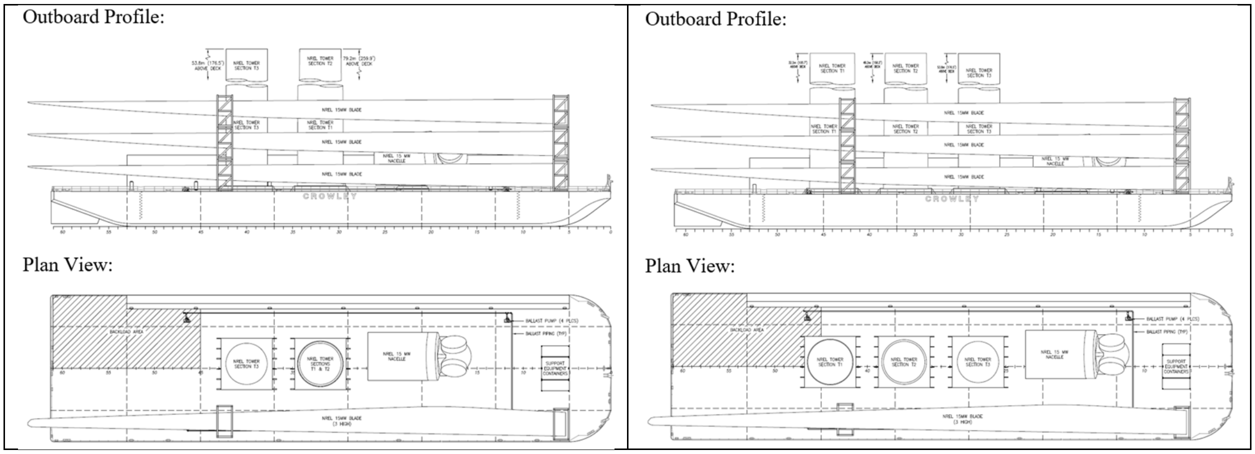


Figure 29 - Stow Plans with 2 or 3 Tower Sections

When ballasting the vessel, the load condition must provide adequate freeboard and stability and have a draft deep enough to reduce motions and slamming. Minimizing ballast reduces the overall displacement of the loaded barge, which is expected to make the barge easier for the tugs to maneuver. It will also impart a smaller contact load on the WTIV than it would if the CFV were more heavily ballasted. Therefore, for transporting one (1) NREL 15 MW Reference Wind Turbine Generator on Crowley 455 Series Barges, light and heavy cases will be studied:

- Base Case, Case 0-0 – Barge with Fender Wall and other outfit transporting two (2) Tower sections (T1/2, T3), Nacelle and Blades – minimum ballast (Draft 27% to 19% hull depth)
    - Sensitivity 0-1 – ballast to draft 43% to 36% hull depth
- Sensitivity, Case 1-0 – Barge with Fender Wall and other outfit transporting three (3) Tower sections (T3, T2, T1), Nacelle and Blades – minimum ballast (Draft 29% to 21% hull depth)
    - Sensitivity 1-1 – ballast to draft 45% to 37% hull depth

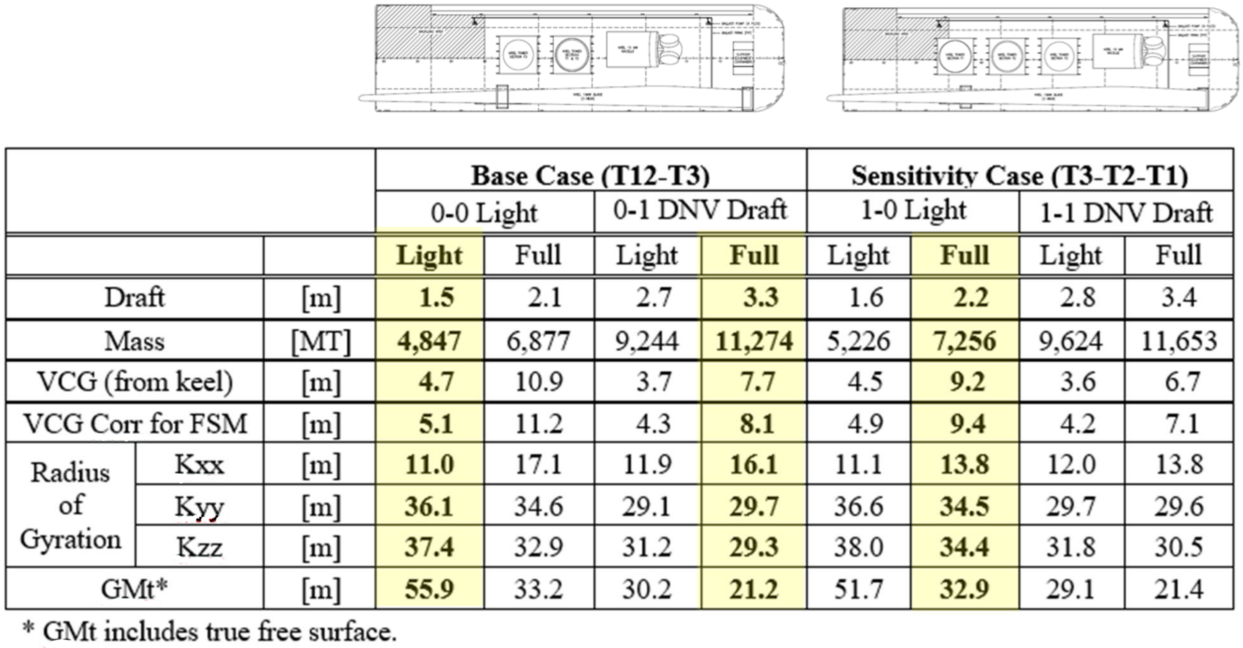
To cover the full range of displacement in the simulation, three load cases were modeled:

- Case 1, 0-Lt-Disch – two (2) sections, light (min) ballast, cargo discharged (Draft 19% hull depth)

- Main Load, 1-Lt-Full – three (3) sections, light (min) ballast, full cargo (Draft 29% hull depth)
- Case 2, 0-Hvy-Full – two (2) sections, heavy ballast, full cargo (Draft 43% hull depth)

A.2.2 Crowley Barge Load Conditions

To load conditions considered in the simulation cover a wide range of displacements. Conditions modeled are highlighted in yellow:



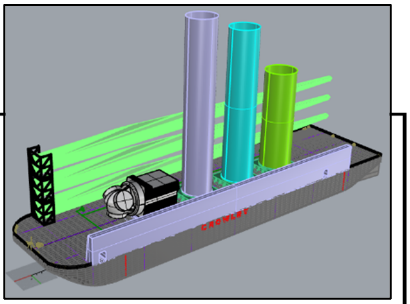
			Base Case (T12-T3)				Sensitivity Case (T3-T2-T1)			
			0-0 Light		0-1 DNV Draft		1-0 Light		1-1 DNV Draft	
			Light	Full	Light	**Full**	Light	**Full**	Light	Full
Draft		[m]	**1.5**	2.1	2.7	**3.3**	1.6	**2.2**	2.8	3.4
Mass		[MT]	**4,847**	6,877	9,244	**11,274**	5,226	**7,256**	9,624	11,653
VCG (from keel)		[m]	**4.7**	10.9	3.7	**7.7**	4.5	**9.2**	3.6	6.7
VCG Corr for FSM		[m]	**5.1**	11.2	4.3	**8.1**	4.9	**9.4**	4.2	7.1
Radius of Gyration	Kxx	[m]	**11.0**	17.1	11.9	**16.1**	11.1	**13.8**	12.0	13.8
	Kyy	[m]	**36.1**	34.6	29.1	**29.7**	36.6	**34.5**	29.7	29.6
	Kzz	[m]	**37.4**	32.9	31.2	**29.3**	38.0	**34.4**	31.8	30.5
GMt*		[m]	**55.9**	33.2	30.2	**21.2**	51.7	**32.9**	29.1	21.4

* GMt includes true free surface.

Figure 30 - Load Cases for Study

A.2.3 Crowley Barge 455 Characteristics

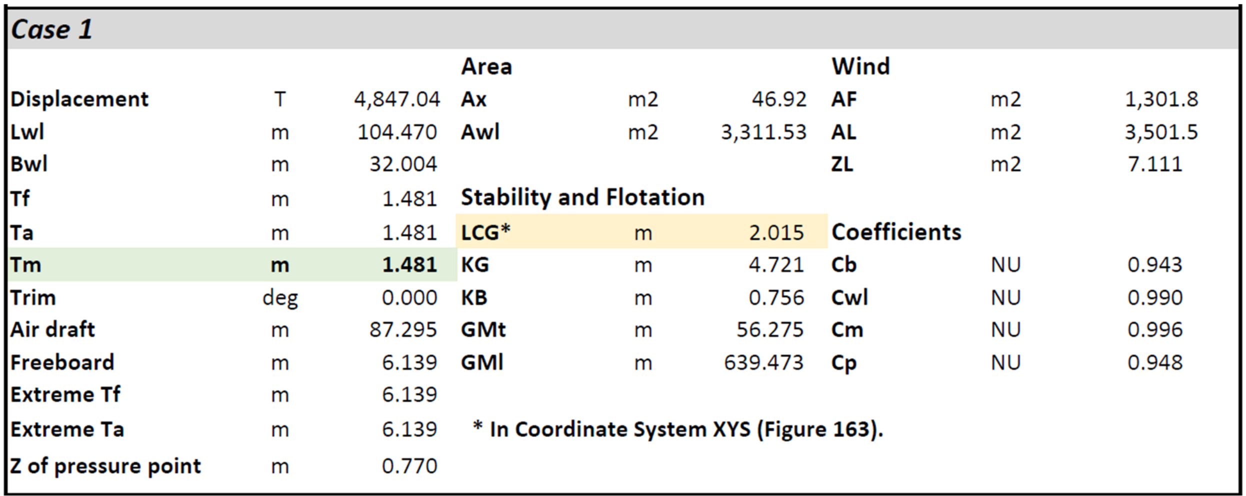
Barge 455 Input for Simulator



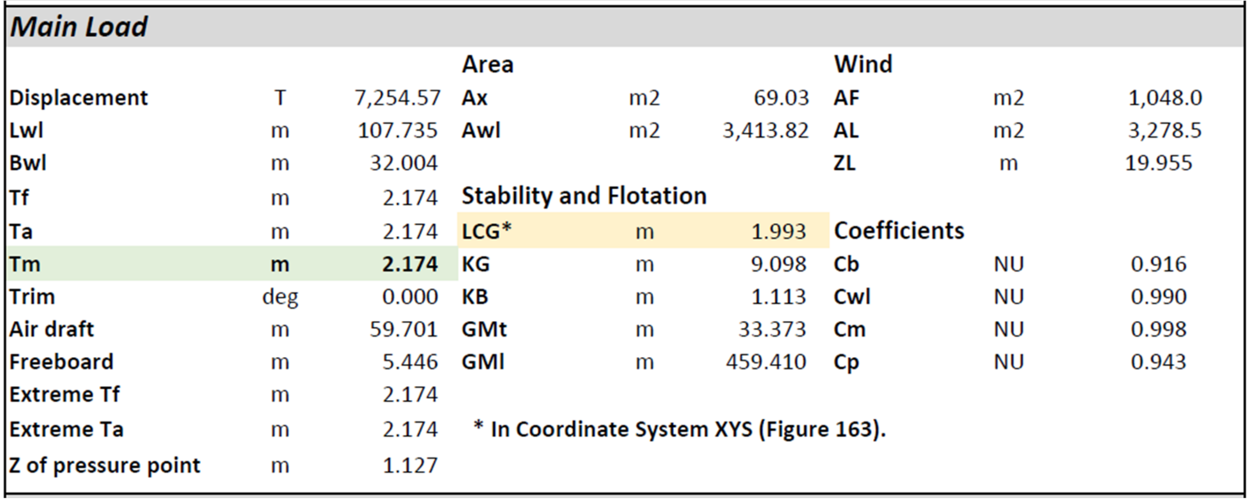
Constant Ship Elements (metric)

Deadweight	T	17,487.74	**Depth**	m	7.620
Loa	m	121.92	**Top Height**	m	87.295
Boa	m	32.00	**dTf**	m	5.837
Lpp	m	117.04	**dTa**	m	5.837
			dTm	m	5.837
			dTrim	deg	0.000

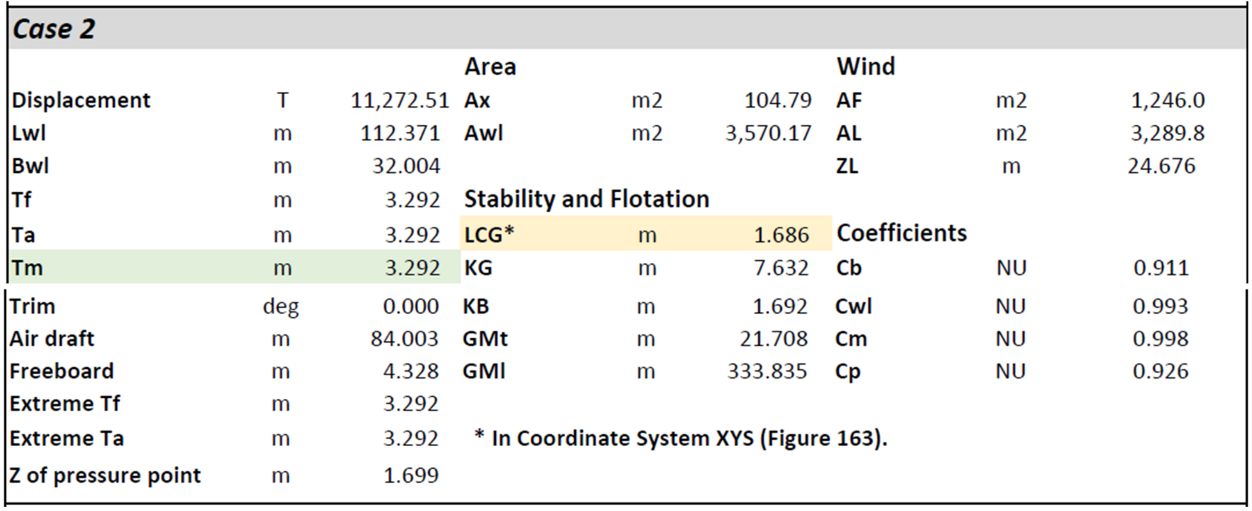
Barge 455 Input for Simulator



Case 1								
			Area			**Wind**		
Displacement	T	4,847.04	**Ax**	m2	46.92	**AF**	m2	1,301.8
Lwl	m	104.470	**Awl**	m2	3,311.53	**AL**	m2	3,501.5
Bwl	m	32.004				**ZL**	m2	7.111
Tf	m	1.481	**Stability and Flotation**					
Ta	m	1.481	**LCG***	m	2.015	**Coefficients**		
Tm	**m**	**1.481**	**KG**	m	4.721	**Cb**	NU	0.943
Trim	deg	0.000	**KB**	m	0.756	**Cwl**	NU	0.990
Air draft	m	87.295	**GMt**	m	56.275	**Cm**	NU	0.996
Freeboard	m	6.139	**GMl**	m	639.473	**Cp**	NU	0.948
Extreme Tf	m	6.139						
Extreme Ta	m	6.139	*** In Coordinate System XYS (Figure 163).**					
Z of pressure point	m	0.770						

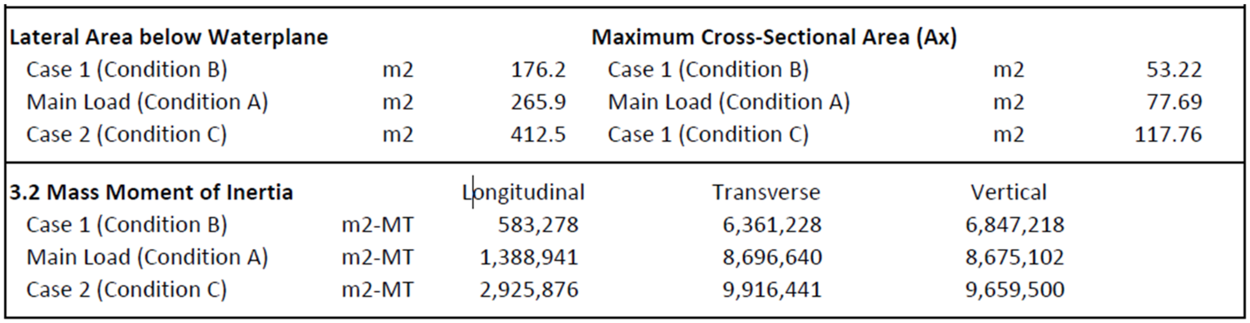


Main Load								
			Area			**Wind**		
Displacement	T	7,254.57	**Ax**	m2	69.03	**AF**	m2	1,048.0
Lwl	m	107.735	**Awl**	m2	3,413.82	**AL**	m2	3,278.5
Bwl	m	32.004				**ZL**	m	19.955
Tf	m	2.174	**Stability and Flotation**					
Ta	m	2.174	**LCG***	m	1.993	**Coefficients**		
Tm	**m**	**2.174**	**KG**	m	9.098	**Cb**	NU	0.916
Trim	deg	0.000	**KB**	m	1.113	**Cwl**	NU	0.990
Air draft	m	59.701	**GMt**	m	33.373	**Cm**	NU	0.998
Freeboard	m	5.446	**GMl**	m	459.410	**Cp**	NU	0.943
Extreme Tf	m	2.174						
Extreme Ta	m	2.174	*** In Coordinate System XYS (Figure 163).**					
Z of pressure point	m	1.127						



Case 2								
			Area			**Wind**		
Displacement	T	11,272.51	**Ax**	m2	104.79	**AF**	m2	1,246.0
Lwl	m	112.371	**Awl**	m2	3,570.17	**AL**	m2	3,289.8
Bwl	m	32.004				**ZL**	m	24.676
Tf	m	3.292	**Stability and Flotation**					
Ta	m	3.292	**LCG***	m	1.686	**Coefficients**		
Tm	m	3.292	**KG**	m	7.632	**Cb**	NU	0.911
Trim	deg	0.000	**KB**	m	1.692	**Cwl**	NU	0.993
Air draft	m	84.003	**GMt**	m	21.708	**Cm**	NU	0.998
Freeboard	m	4.328	**GMl**	m	333.835	**Cp**	NU	0.926
Extreme Tf	m	3.292						
Extreme Ta	m	3.292	*** In Coordinate System XYS (Figure 163).**					
Z of pressure point	m	1.699						

Barge 455 Input for Simulator



Lateral Area below Waterplane			Maximum Cross-Sectional Area (Ax)		
Case 1 (Condition B)	m2	176.2	Case 1 (Condition B)	m2	53.22
Main Load (Condition A)	m2	265.9	Main Load (Condition A)	m2	77.69
Case 2 (Condition C)	m2	412.5	Case 1 (Condition C)	m2	117.76

3.2 Mass Moment of Inertia		Longitudinal	Transverse	Vertical
Case 1 (Condition B)	m2-MT	583,278	6,361,228	6,847,218
Main Load (Condition A)	m2-MT	1,388,941	8,696,640	8,675,102
Case 2 (Condition C)	m2-MT	2,925,876	9,916,441	9,659,500

A.2.4 Navi-Trainer Professional (NTPro) Modeling

A.2.4.1 Coordinate System

The Virtual Shipyard model development software uses a left-hand rule coordinate system to set the position of ship model's devices such as propellers, rudders, etc. The origin of the coordinates XYZ is located in the point of intersection of the ship's central lateral plane, the midsection plane and the base plane. X-axis is directed forward, Y-axis is directed starboard and Z-axis is directed upward.

The mathematical modeling software (NTPro), uses and inverted left-hand rule. The origin of the coordinates XYZ is located in the center of gravity. X-axis is directed forward, Y-axis is directed starboard and Z-axis is directed downward.

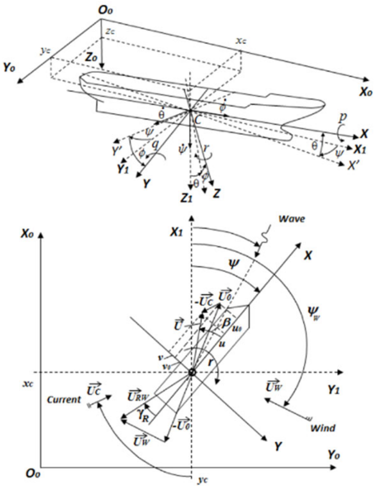


Figure 31 - NTPro Coordinates

A.2.4.2 Hydrodynamic Coefficients: Wave Induced Motions

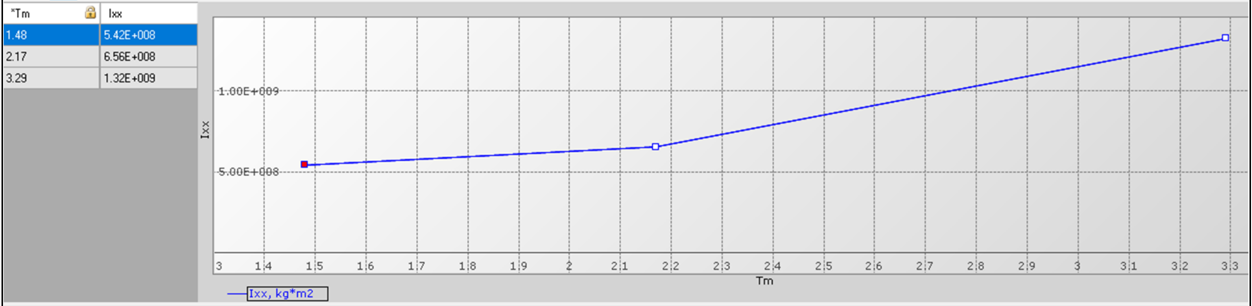
The mathematical modeling software, Wärtsilä Navi-Trainer Professional (NTPro) written by Transas uses dozens of equations to control various aspects of vessel motion and response characteristics. To model the 455 barge wave induced motions in each load condition, Response Amplitude Operators (RAOs) were computed using 3D panel radiation diffraction-based BEM code with Orcawave by Orcina. Orcaflex was used to compute pitch, roll, heave decay time signals. These signals and the mass moments of inertia computed to develop the RAOs were used to tune the NTPro model damping (rate of decay) and period.

A.2.4.2.1 Roll Damping

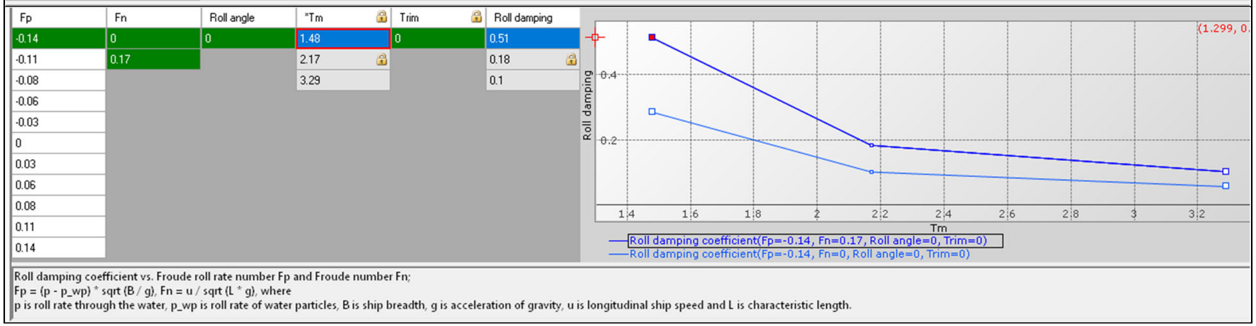
The upper graphs in each table show information developed in OrcaFlex. The lower graphs show restitution from an initial roll of 5° measured by MITAGS.

Damping Variable Settings for MITAGS Model

Roll Coefficients



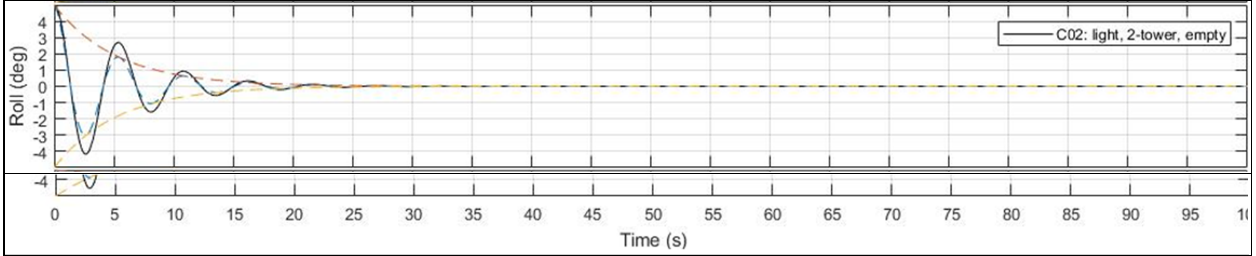
*Tm	Ixx
1.48	5.42E+008
2.17	6.56E+008
3.29	1.32E+009

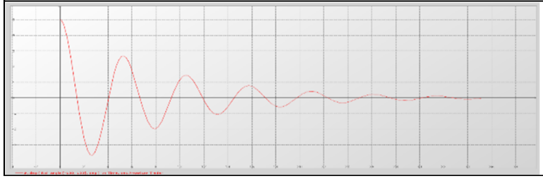


Fp	Fn	Roll angle	*Tm	Trim	Roll damping
-0.14	0	0	1.48	0	0.51
-0.11	0.17		2.17		0.18
-0.08			3.29		0.1
-0.06					
-0.03					
0					
0.03					
0.06					
0.08					
0.11					
0.14					

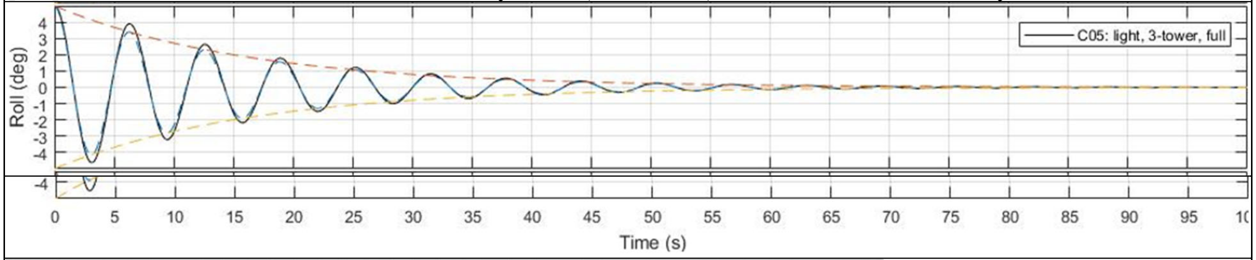
Roll damping coefficient vs. Froude roll rate number Fp and Froude number Fn;
Fp = (p - p_wp) * sqrt (B / g), Fn = u / sqrt (L * g), where
p is roll rate through the water, p_wp is roll rate of water particles, B is ship breadth, g is acceleration of gravity, u is longitudinal ship speed and L is characteristic length.

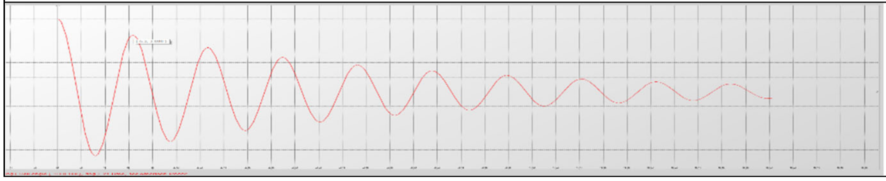
[C2] MITAGS' Case 1: Roll Decay Test (OrcaFlex) – Reconstructed Decay





[C5] MITAGS' Main Load: Roll Decay Test (OrcaFlex) – Reconstructed Decay





[C3] MITAGS' Case 2: Roll Decay Test (OrcaFlex) – Reconstructed Decay

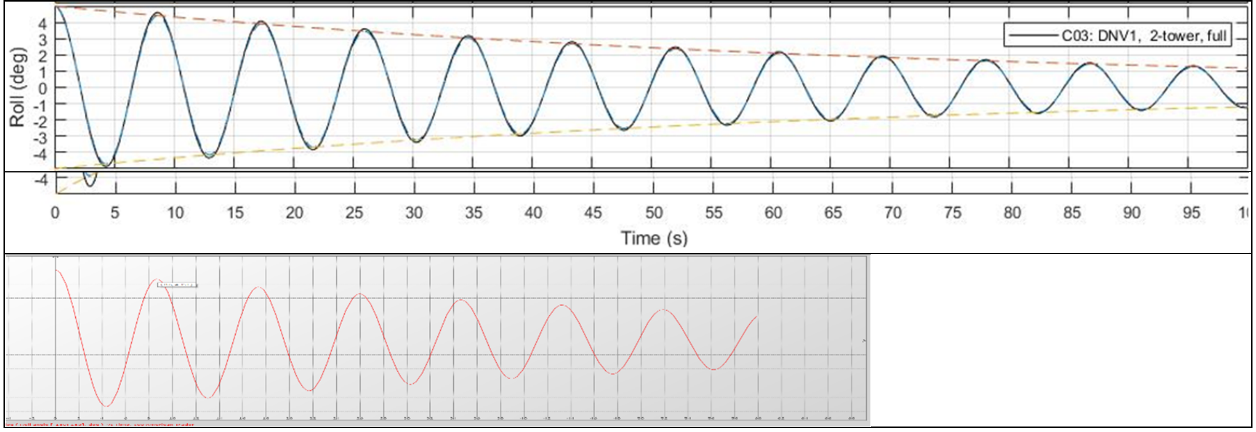


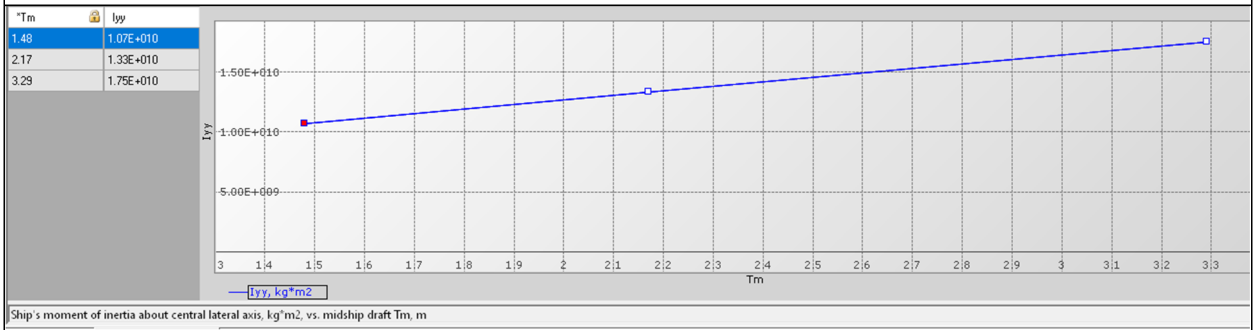
Figure 32 - Roll Damping and Decay Verification

A.2.4.2.2 Pitch Damping

The upper graphs in each table show information developed in OrcaFlex. The lower graphs show restitution from an initial pitch of 5° measured by MITAGS.

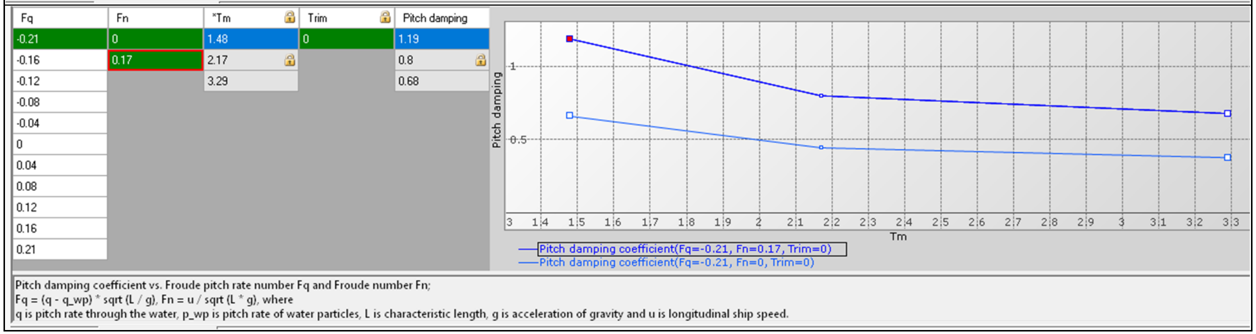
Damping Variable Settings for MITAGS Model

Pitch Coefficients



*Tm	Iyy
1.48	1.07E+010
2.17	1.33E+010
3.29	1.75E+010

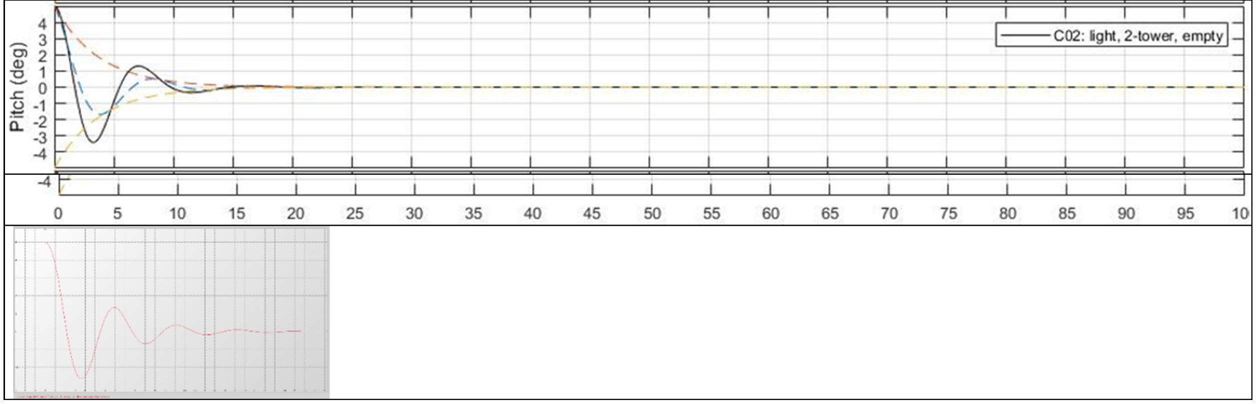
Ship's moment of inertia about central lateral axis, kg*m2, vs. midship draft Tm, m



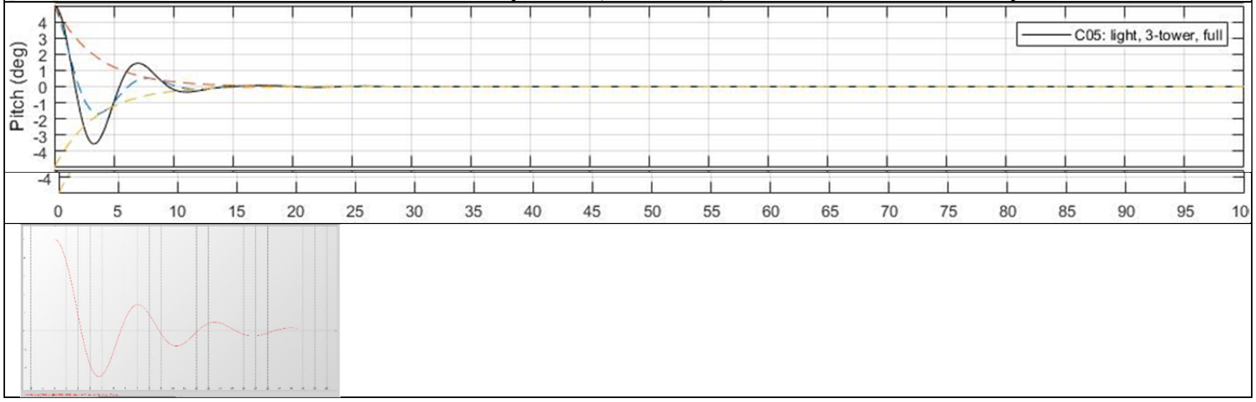
Fq	Fn	*Tm	Trim	Pitch damping
-0.21	0	1.48	0	1.19
-0.16	0.17	2.17		0.8
-0.12		3.29		0.68
-0.08				
-0.04				
0				
0.04				
0.08				
0.12				
0.16				
0.21				

Pitch damping coefficient vs. Froude pitch rate number Fq and Froude number Fn;
Fq = (q - q_wp) * sqrt (L / g), Fn = u / sqrt (L * g), where
q is pitch rate through the water, p_wp is pitch rate of water particles, L is characteristic length, g is acceleration of gravity and u is longitudinal ship speed.

[C2] MITAGS' Case 1: Pitch Decay Test (OrcaFlex) – Reconstructed Decay



[C5] MITAGS' Main Load: Pitch Decay Test (OrcaFlex) – Reconstructed Decay



[C3] MITAGS' Case 2: Pitch Decay Test (OrcaFlex) – Reconstructed Decay

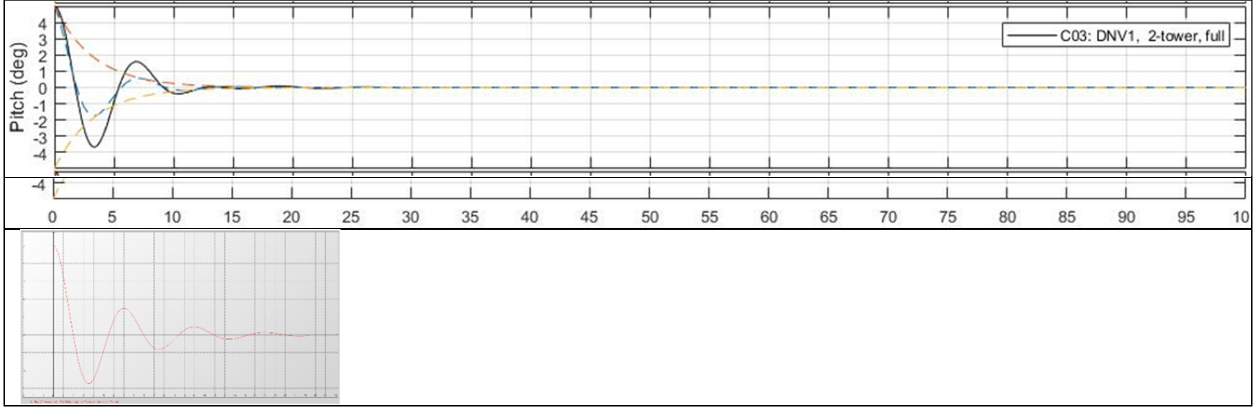


Figure 33 - Pitch Damping and Decay Verification

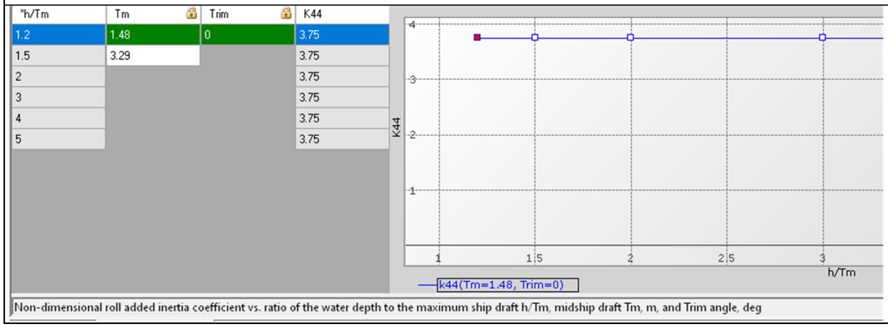
A.2.4.2.3 Heave Damping

The upper graphs in each table show information developed in OrcaFlex. The lower graphs show restitution from an initial heaver of 1 m measured by MITAGS.

Damping Variable Settings for MITAGS Model

Heave Coefficients

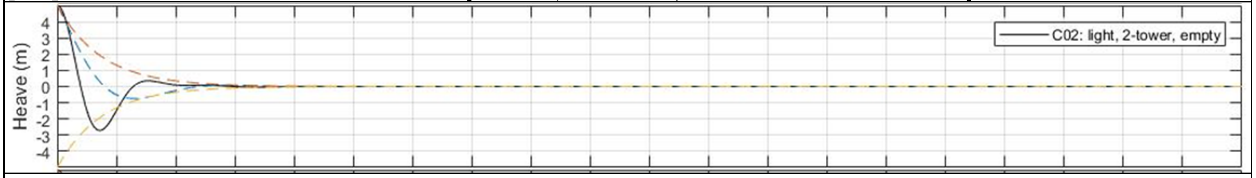
The NTPro heave response is a function of displacement and hull form; no coefficients are included, therefor it cannot be tuned separately. The NTPro heave period is approximately twice the value determined in Orcaflex.



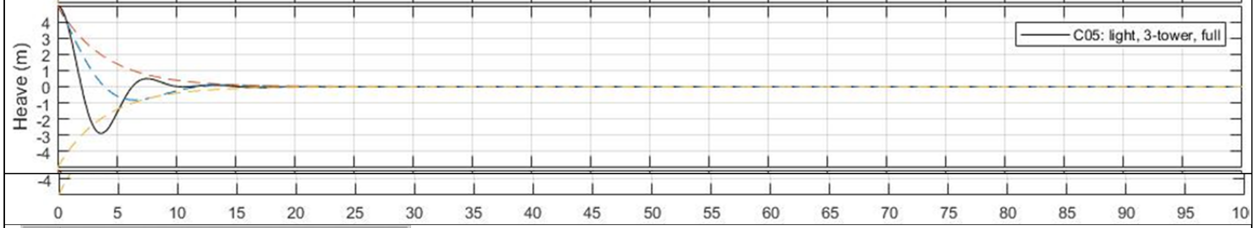
*h/Tm	Tm	Trim	K44
1.2	1.48	0	3.75
1.5	3.29		3.75
2			3.75
3			3.75
4			3.75
5			3.75

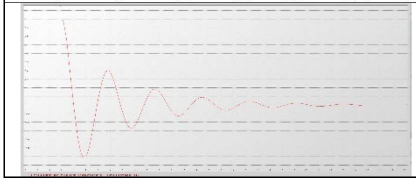
Non-dimensional roll added inertia coefficient vs. ratio of the water depth to the maximum ship draft h/Tm, midship draft Tm, m, and Trim angle, deg

[C2] MITAGS' Case 1: Heave Decay Test (OrcaFlex) – Reconstructed Decay



[C5] MITAGS' Main Load: Heave Decay Test (OrcaFlex) – Reconstructed Decay





[C3] MITAGS' Case 2: Heave Decay Test (OrcaFlex) – Reconstructed Decay

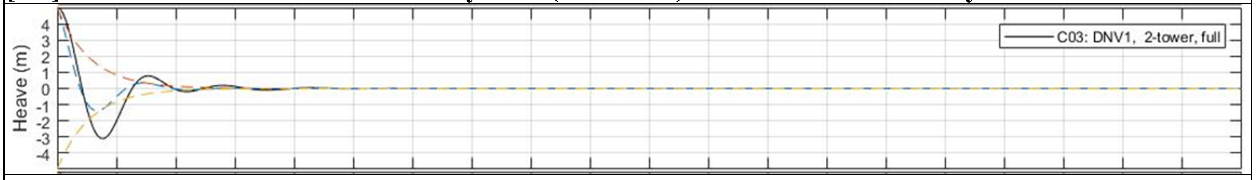


Figure 34 - Heave Damping and Decay

A.2.4.3 Dynamic Coefficients: Maneuvering Motions

Vessel maneuvering coefficients for the 455 barge were scaled from a similar vessel. Coefficients for aero and hydrodynamic drag and hydrodynamic added mass were further refined based on calculations performed using Computational Fluid Dynamics (CFD). Unsteady Reynolds Average Navier Stokes based CFD was performed using the software Star-CCM+. The effect of wind shadowing from the WTIV on the 455 was also modeled in CFD to understand upstream wind velocities on the WTIV and changing wind loads on the barge as it moved into the vicinity of the WTIV.

A.2.4.3.1 Aerodynamic Drag

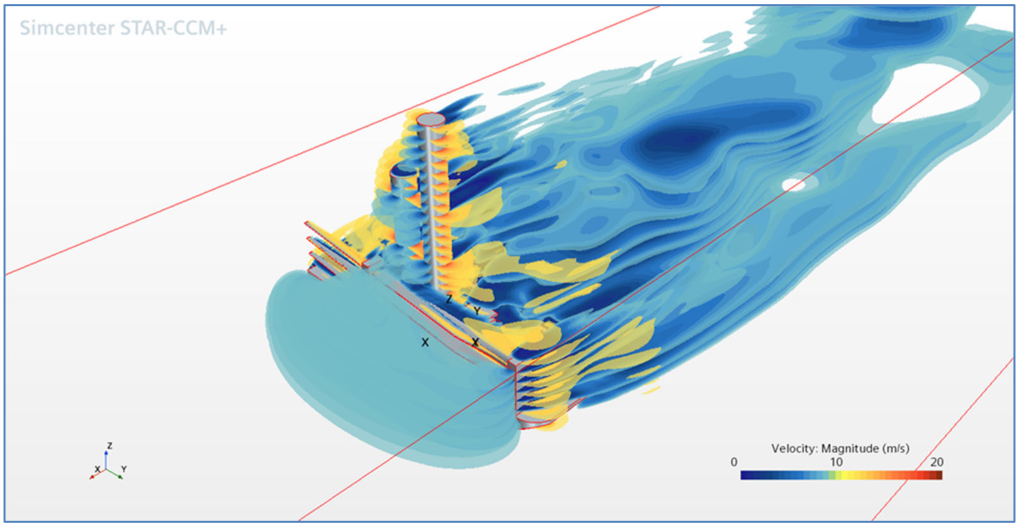


Figure 35 - Wind Drag Calculation, 10m/s Steady Wind, 90-degrees to Barge Heading

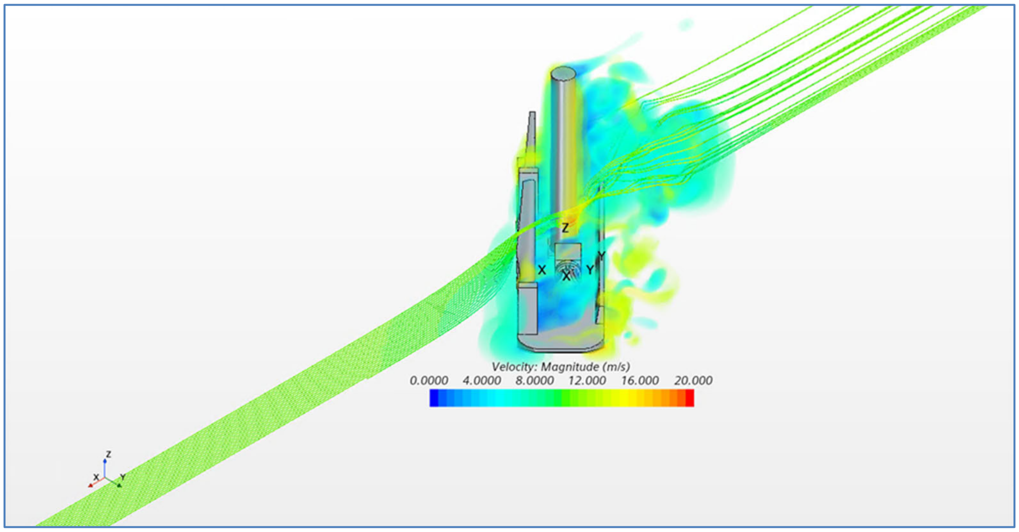


Figure 36 - Wind Drag Calculation, 10m/s Steady Wind, 45-degrees to Barge Heading

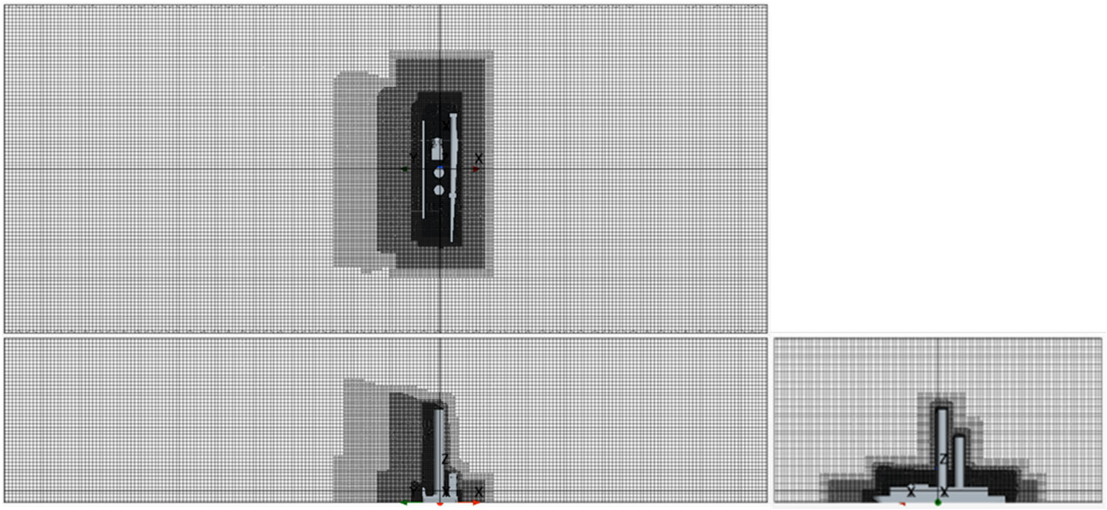


Figure 37 - Aerodynamic Drag Mesh for URANS Calculations

A.2.4.3.2 Hydrodynamic Drag

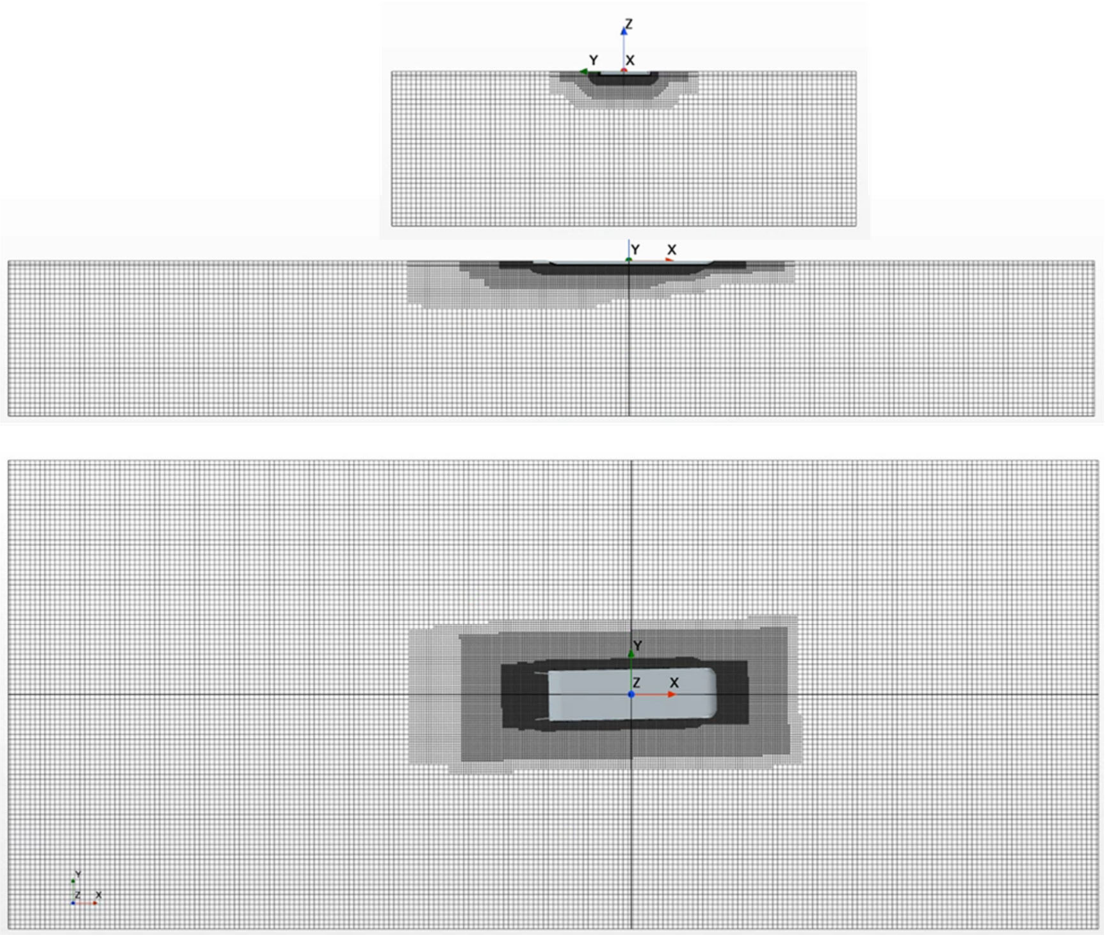


Figure 38 - Hydrodynamic Drag CFD Mesh

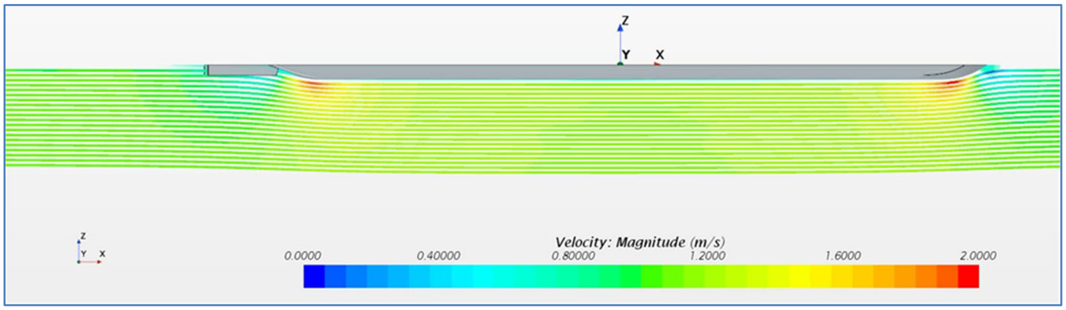


Figure 39 - Hydrodynamic Drag Calculation, 2 knots 0-degree Drift Angle

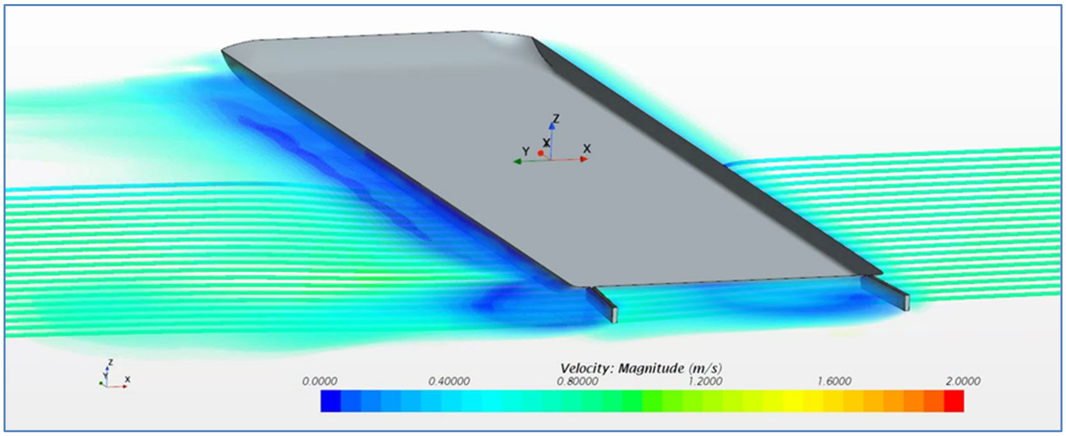


Figure 40 - Hydrodynamic Drag, 90-degree Drift Angle

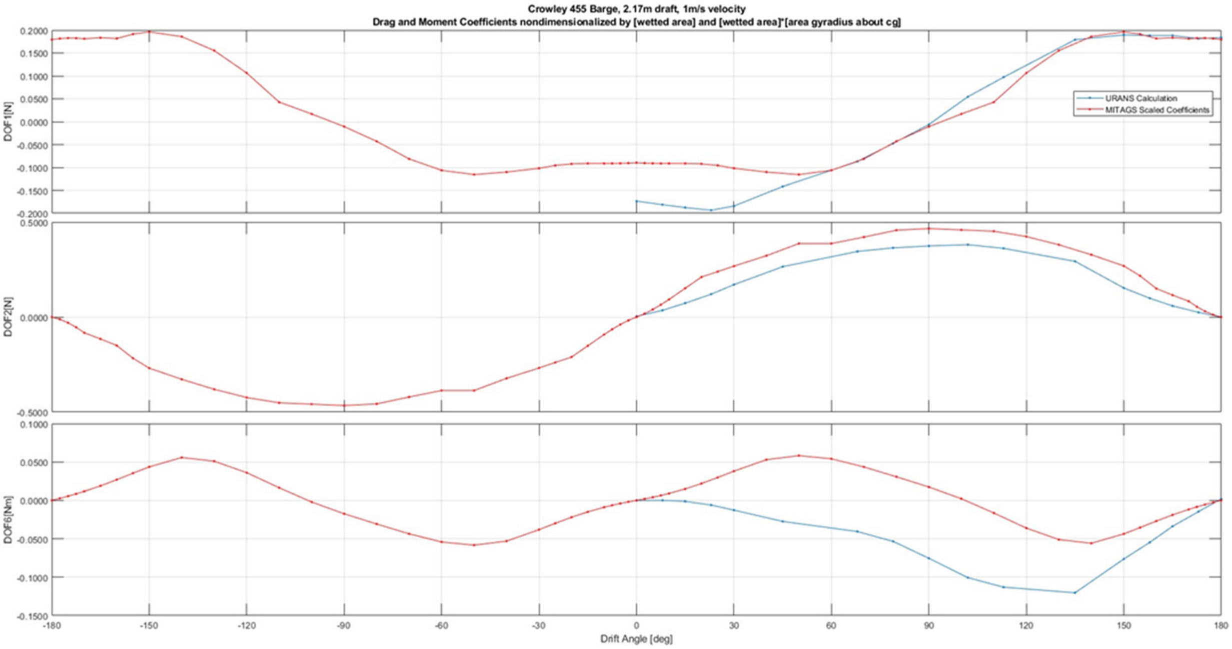


Figure 41 - Hydrodynamic Drag Base Scaled Coefficients & URANS Updated Coefficients

A.2.4.3.3 Hydrodynamic Yaw Added Mass

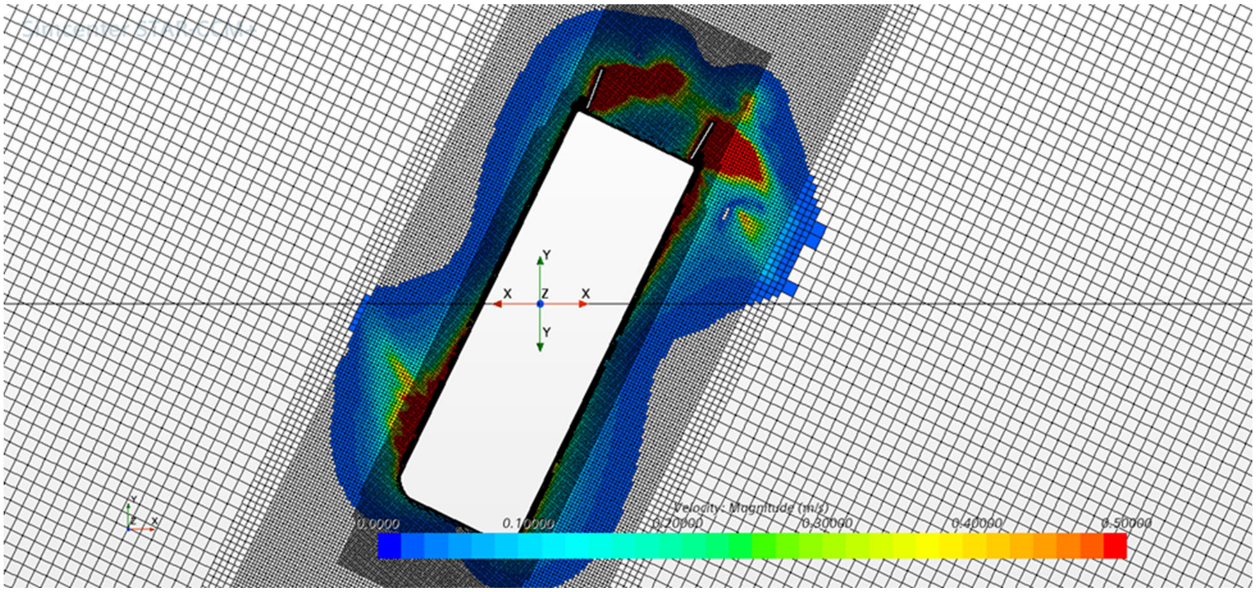


Figure 42 - Hydrodynamic Yaw Added Mass Calculation in CFD

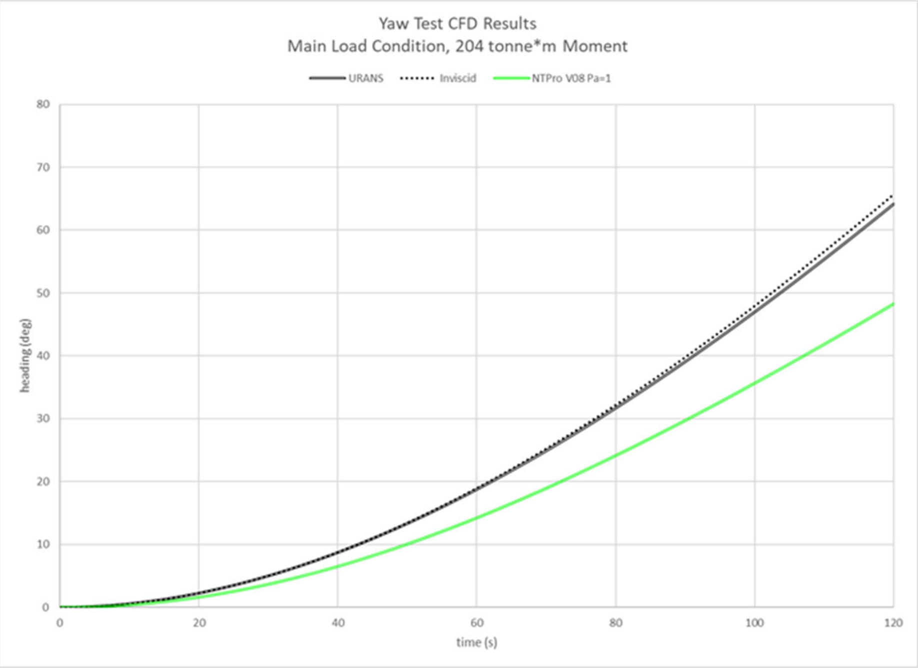


Figure 43 - Comparison of Main Case Mass Moments of Inertia & URANS Calculated Added Mass

A.2.4.3.4 Aerodynamic Wind Shadowing WTIV on Feeder Barge

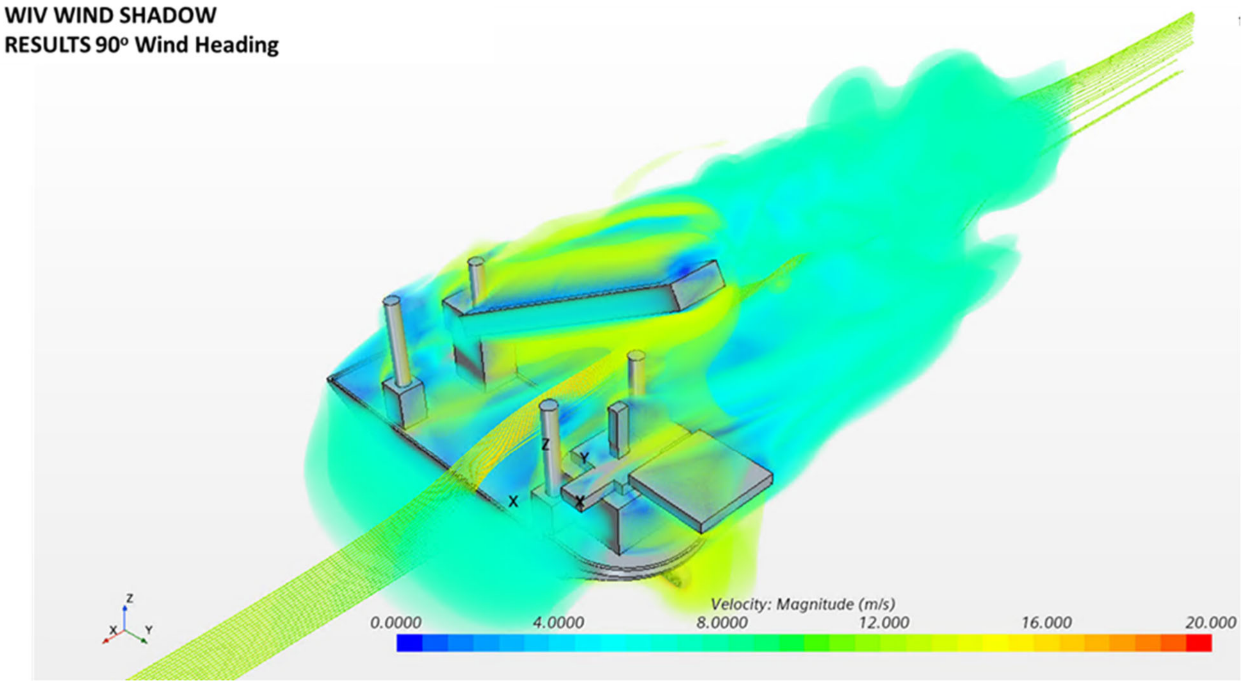


Figure 44 - Wind Shadow, 90-degrees to WTIV Heading

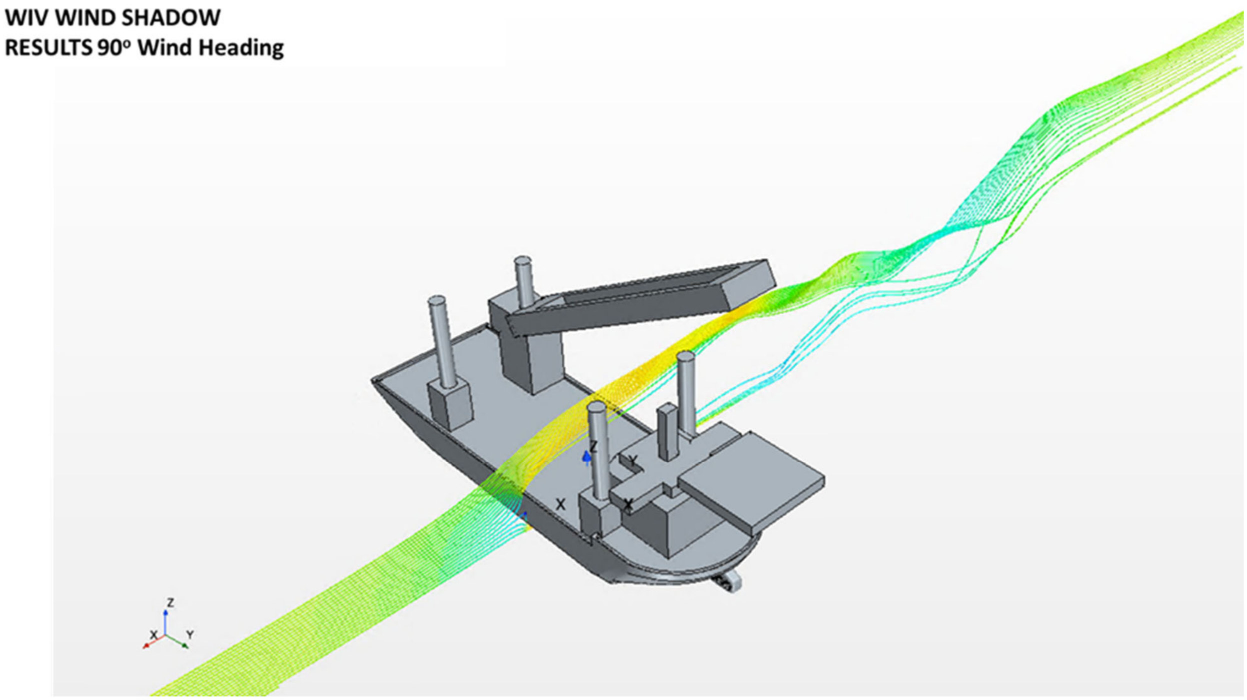


Figure 45 - Wind Shadow, 90-degrees to WTIV Heading

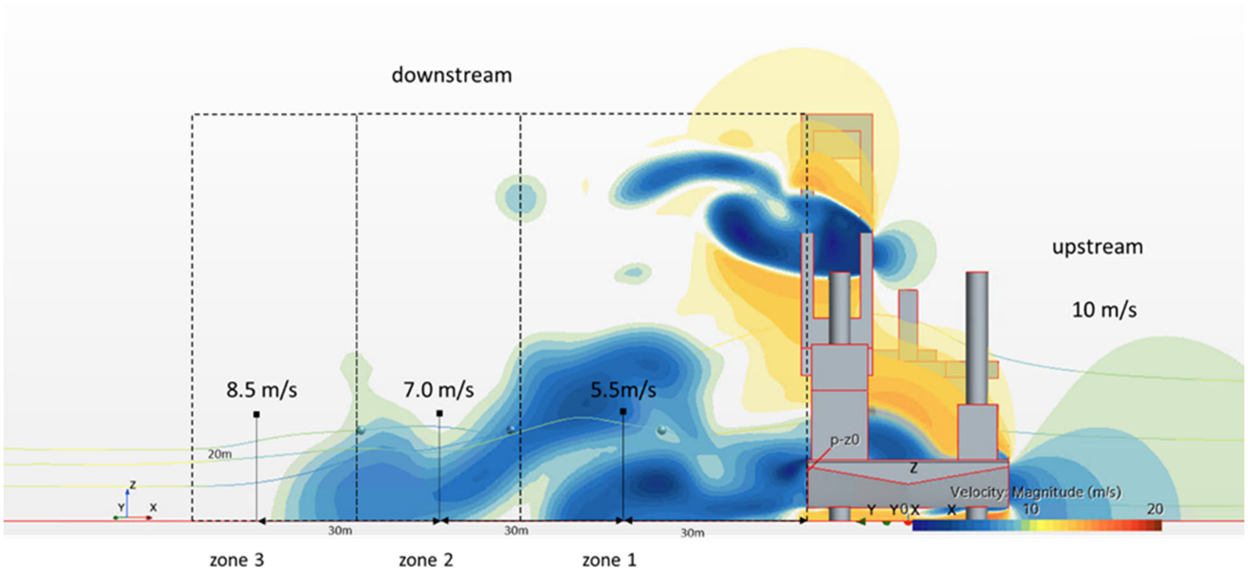


Figure 46 - Wind Shadow Profile for Barge

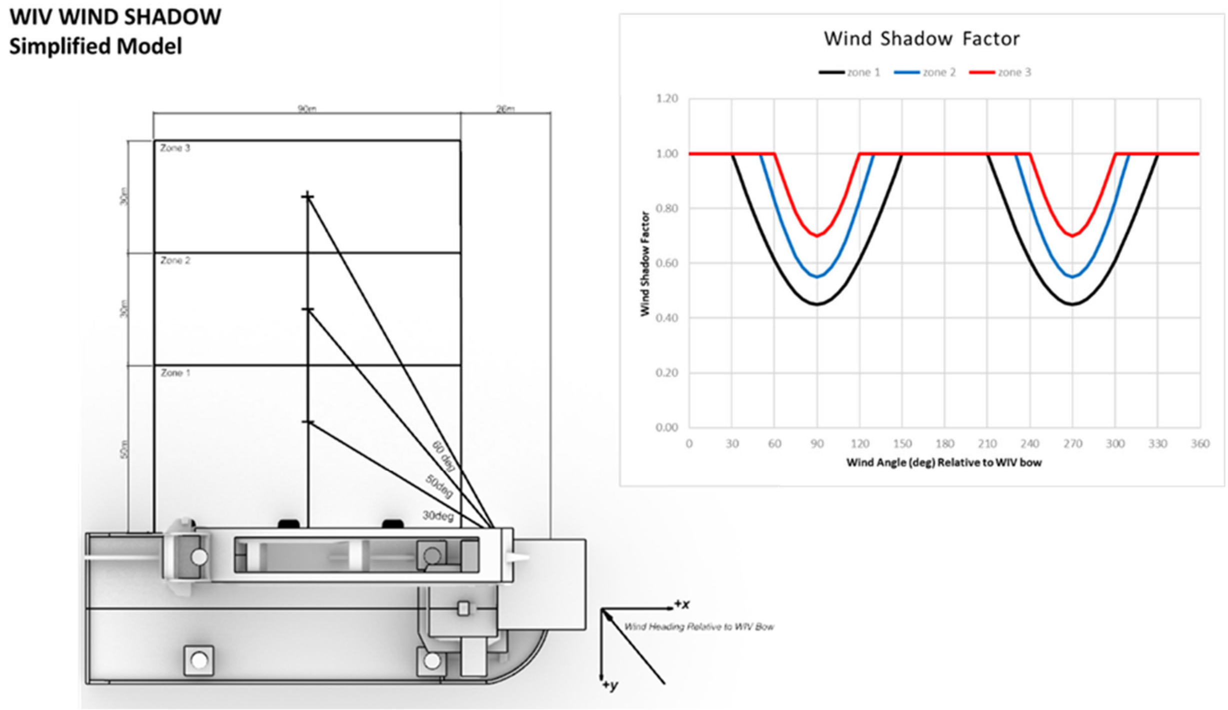


Figure 47 - Simplified Wave Shadow Model of Barge

A.3 Cargo Feeder System: Tugs

For this study, the barge will be handled by two tugs. The lead tug will tow the barge to the site from the load port. The assist tug will meet the barge on site and pick up a line off the stern.

A.3.1 Lead Tug: Ocean Class

The **Ocean Class** tug will tow the barge from the barge's bow with a bridle off the tug's stern winch.

Ocean Class

Length Overall	146.00	ft, or	44.50	m	
Length on Design WL	140.00	ft, or	42.67	m	
Breadth	46.00	ft, or	14.02	m	
Depth	25.00	ft, or	7.62	m	
Design Draft	20.00	ft, or	6.10	m	
Forward Helm*	- 49.33	ft, or	- 15.04	m aft of bow (34% length overall)	
Aft Helm*	- 71.58	ft, or	- 21.82	m aft of bow (49% length overall)	
Height of Eye (BL)	50.71	ft, or	15.46	m	
Height of Eye (WL)	30.71	ft, or	9.36	m	
Winch Location*	- 84.25	ft, or	- 25.68	m aft of bow (58% length overall)	
Guide Pin Location*	-136.38	ft, or	- 41.57	m aft of bow (93% length overall)	
^ tow line end point					
* From fwd extent of hull (end of LOA)					

Bow Winch/Windlass	Markey WYWD-20 (single drum)				
Winch Ctr Height (BL)	30.25	ft, or	9.22	m	
Roller Height (BL)	25.50	ft, or	7.77	m	
Tow Pt (abv WL)	7.88	ft, or	2.40	m	
Bollard Pull	320,700	lbs or	145.47	MT	
Main Engines	2 x Cat (C-280-12), 5,440 BHP @ ? RPM				
	10,880	HP, or	8,113	kW	
Propulsors	12.79	ft, or	3.90	m	Ducted Nozzle
Bow Thruster	5.50	ft, or	1.68	m	
	850	HP, or	634	kW	

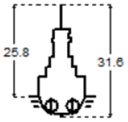
MITAGS Model: Conventional Twin Screw Tug 6 / Tug Twin Screw Crowley_(100t)

PILOT CARD

Ship name	Conventional twin screw tug 6 (bp 100t) 3.0.35.1 *			Date	17.02.2016
IMO Number	N/A	Call Sign	N/A	Year built	N/A
Load Condition	Load Condition				
Displacement	1730.81 tons		Draft forward	5.79 m / 19 ft 0 in	
Deadweight	N/A tons		Draft forward extreme	5.79 m / 19 ft 0 in	
Capacity			Draft after	5.79 m / 19 ft 0 in	
Air draft	25.81 m / 84 ft 10 in		Draft after extreme	5.79 m / 19 ft 0 in	

Ship's Particulars

Length overall	41.33 m	Type of bow	Sloping
Breadth	12.8 m	Type of stern	U-shaped
Anchor(s) (No./types)	1 (StbdBow)		
No. of shackles	10		(1 shackle =25 m / 13.7 fathoms)
Max. rate of heaving, m/min	30		

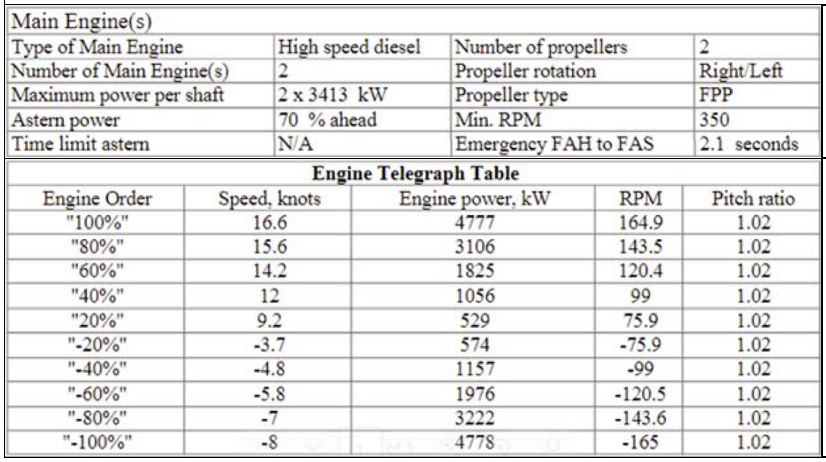


Steering characteristics

Steering device(s) (type/No.)	Normal balance rudder / 2	Number of bow thrusters	N/A
Maximum angle	35	Power	N/A
Rudder angle for neutral effect	0 degrees	Number of stern thrusters	N/A
Hard over to over(2 pumps)	10 seconds	Power	N/A
Flanking Rudder(s)	0	Auxiliary Steering Device(s)	N/A

Stopping			Turning circle	
Description	Full Time	Head reach	Ordered Engine: 100%, Ordered rudder: 35 degrees	
FAH to FAS	37.2 s	0.9 cbls	Advance	0.46 cbls
HAH to HAS	40.2 s	0.84 cbls	Transfer	0.12 cbls
SAH to SAS	44.2 s	0.71 cbls	Tactical diameter	0.35 cbls

MITAGS Model: Conventional Twin Screw Tug 6 / Tug Twin Screw Crowley_(100t)



Main Engine(s)			
Type of Main Engine	High speed diesel	Number of propellers	2
Number of Main Engine(s)	2	Propeller rotation	Right/Left
Maximum power per shaft	2 x 3413 kW	Propeller type	FPP
Astern power	70 % ahead	Min. RPM	350
Time limit astern	N/A	Emergency FAH to FAS	2.1 seconds

Engine Telegraph Table

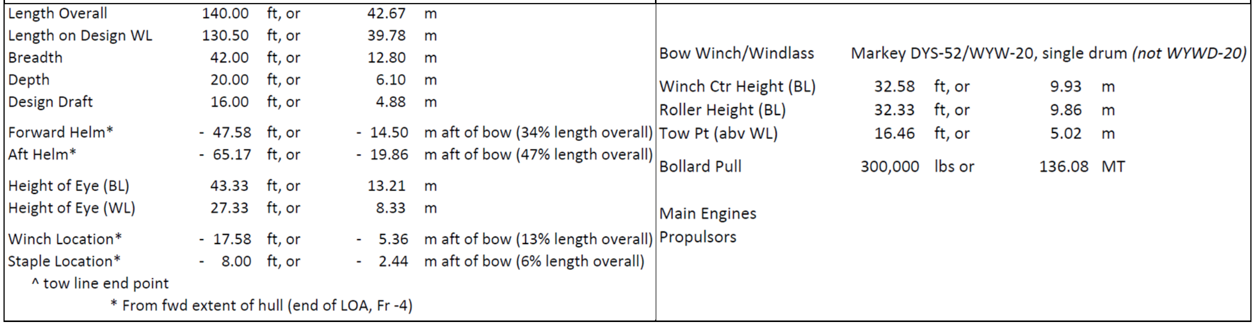
Engine Order	Speed, knots	Engine power, kW	RPM	Pitch ratio
"100%"	16.6	4777	164.9	1.02
"80%"	15.6	3106	143.5	1.02
"60%"	14.2	1825	120.4	1.02
"40%"	12	1056	99	1.02
"20%"	9.2	529	75.9	1.02
"-20%"	-3.7	574	-75.9	1.02
"-40%"	-4.8	1157	-99	1.02
"-60%"	-5.8	1976	-120.5	1.02
"-80%"	-7	3222	-143.6	1.02
"-100%"	-8	4778	-165	1.02

For this study, a bow thruster was added to the model. The bow thruster was assumed to be 850 hp (634 kW).

A.3.2 Assist Tug: Alert Class

The **Alert Class** tug will be attached to a single tow line from the barge's stern with a winch on the tug's bow.

Alert Class



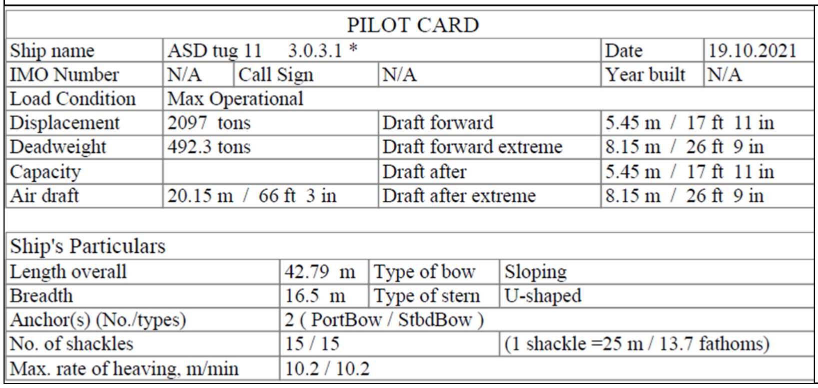
Length Overall	140.00	ft, or	42.67	m	
Length on Design WL	130.50	ft, or	39.78	m	
Breadth	42.00	ft, or	12.80	m	
Depth	20.00	ft, or	6.10	m	
Design Draft	16.00	ft, or	4.88	m	
Forward Helm*	- 47.58	ft, or	- 14.50	m aft of bow (34% length overall)	
Aft Helm*	- 65.17	ft, or	- 19.86	m aft of bow (47% length overall)	
Height of Eye (BL)	43.33	ft, or	13.21	m	
Height of Eye (WL)	27.33	ft, or	8.33	m	
Winch Location*	- 17.58	ft, or	- 5.36	m aft of bow (13% length overall)	
Staple Location*	- 8.00	ft, or	- 2.44	m aft of bow (6% length overall)	

^ tow line end point

* From fwd extent of hull (end of LOA, Fr -4)

Bow Winch/Windlass	Markey DYS-52/WYW-20, single drum *(not WYWD-20)*			
Winch Ctr Height (BL)	32.58	ft, or	9.93	m
Roller Height (BL)	32.33	ft, or	9.86	m
Tow Pt (abv WL)	16.46	ft, or	5.02	m
Bollard Pull	300,000	lbs or	136.08	MT
Main Engines				
Propulsors				

MITAGS Model: ASD Tug 11



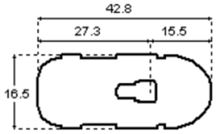
PILOT CARD

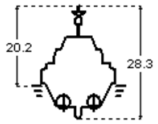
Ship name	ASD tug 11 3.0.3.1 *			Date	19.10.2021
IMO Number	N/A	Call Sign	N/A	Year built	N/A
Load Condition	Max Operational				
Displacement	2097 tons		Draft forward	5.45 m / 17 ft 11 in	
Deadweight	492.3 tons		Draft forward extreme	8.15 m / 26 ft 9 in	
Capacity			Draft after	5.45 m / 17 ft 11 in	
Air draft	20.15 m / 66 ft 3 in		Draft after extreme	8.15 m / 26 ft 9 in	

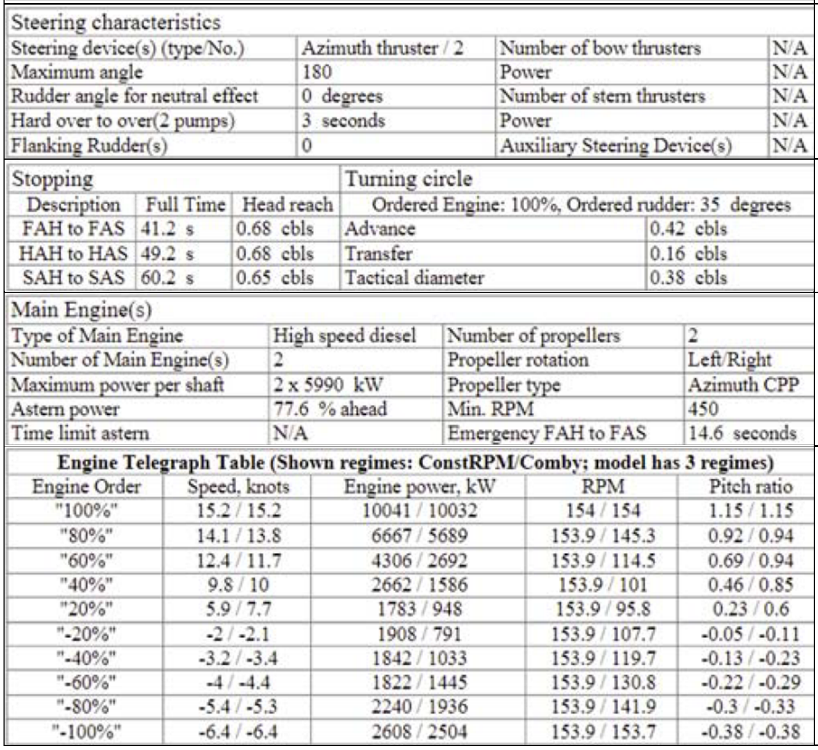
Ship's Particulars

Length overall	42.79 m	Type of bow	Sloping
Breadth	16.5 m	Type of stern	U-shaped
Anchor(s) (No./types)	2 (PortBow / StbdBow)		
No. of shackles	15 / 15		(1 shackle =25 m / 13.7 fathoms)
Max. rate of heaving, m/min	10.2 / 10.2		

MITAGS Model: ASD Tug 11







Steering characteristics			
Steering device(s) (type/No.)	Azimuth thruster / 2	Number of bow thrusters	N/A
Maximum angle	180	Power	N/A
Rudder angle for neutral effect	0 degrees	Number of stern thrusters	N/A
Hard over to over(2 pumps)	3 seconds	Power	N/A
Flanking Rudder(s)	0	Auxiliary Steering Device(s)	N/A

Stopping			Turning circle	
Description	Full Time	Head reach	Ordered Engine: 100%, Ordered rudder: 35 degrees	
FAH to FAS	41.2 s	0.68 cbls	Advance	0.42 cbls
HAH to HAS	49.2 s	0.68 cbls	Transfer	0.16 cbls
SAH to SAS	60.2 s	0.65 cbls	Tactical diameter	0.38 cbls

Main Engine(s)			
Type of Main Engine	High speed diesel	Number of propellers	2
Number of Main Engine(s)	2	Propeller rotation	Left/Right
Maximum power per shaft	2 x 5990 kW	Propeller type	Azimuth CPP
Astern power	77.6 % ahead	Min. RPM	450
Time limit astern	N/A	Emergency FAH to FAS	14.6 seconds

Engine Telegraph Table (Shown regimes: ConstRPM/Comby; model has 3 regimes)

Engine Order	Speed, knots	Engine power, kW	RPM	Pitch ratio
"100%"	15.2 / 15.2	10041 / 10032	154 / 154	1.15 / 1.15
"80%"	14.1 / 13.8	6667 / 5689	153.9 / 145.3	0.92 / 0.94
"60%"	12.4 / 11.7	4306 / 2692	153.9 / 114.5	0.69 / 0.94
"40%"	9.8 / 10	2662 / 1586	153.9 / 101	0.46 / 0.85
"20%"	5.9 / 7.7	1783 / 948	153.9 / 95.8	0.23 / 0.6
"-20%"	-2 / -2.1	1908 / 791	153.9 / 107.7	-0.05 / -0.11
"-40%"	-3.2 / -3.4	1842 / 1033	153.9 / 119.7	-0.13 / -0.23
"-60%"	-4 / -4.4	1822 / 1445	153.9 / 130.8	-0.22 / -0.29
"-80%"	-5.4 / -5.3	2240 / 1936	153.9 / 141.9	-0.3 / -0.33
"-100%"	-6.4 / -6.4	2608 / 2504	153.9 / 153.7	-0.38 / -0.38

A.3.3 Assist Tug: Alternates

A tractor tug with a Voith Schneider Propeller (VSP) will replace the assist tug as a sensitivity case.

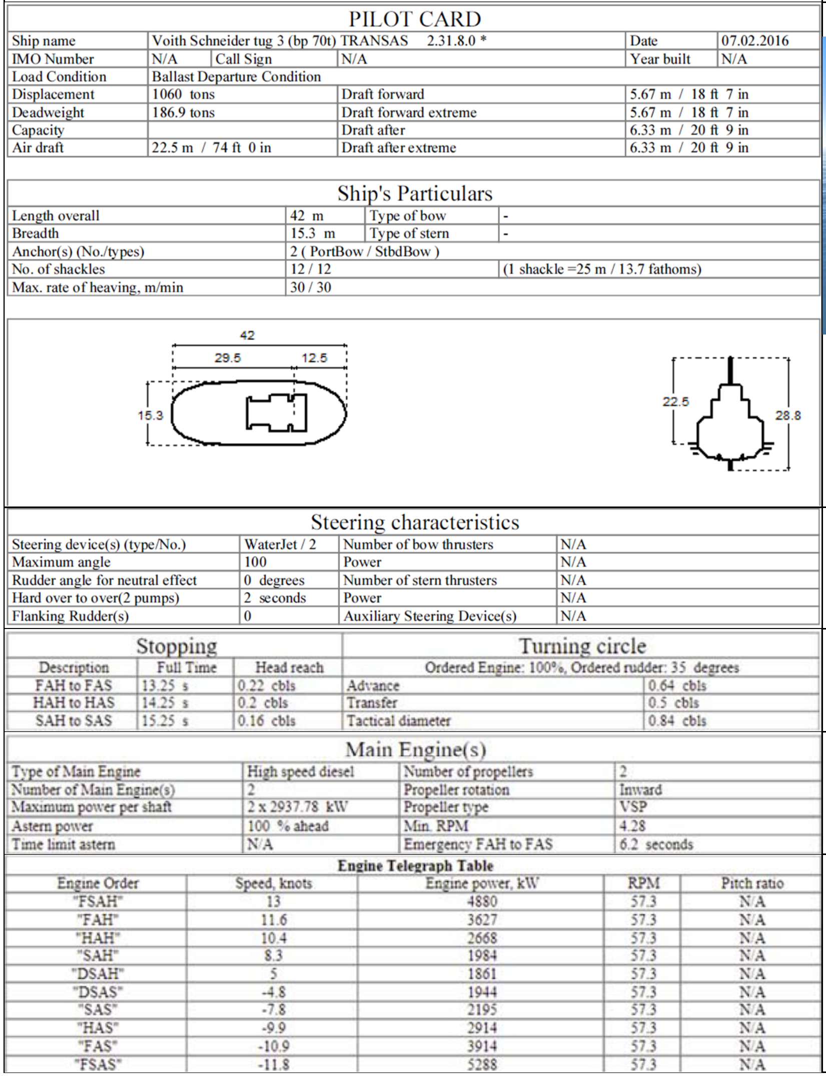
Protector Class

Protector Class:	PROTECTOR, GUARD			
Length Overall	120.00	ft, or	36.58	m
Breadth	41.50	ft, or	12.65	m
Depth	23.83	ft, or	7.26	m
Design Draft	16.92	ft, or	5.16	m
Bollard Pull	120,000	lbs or	54.43	MT
Main Engines	2 x Cat (3606), 2,750 BHP @ 1000 RPM			
Propulsors	2 x Voith Schneider (32GII/200), 2030 kW @ 1000 RPM			

Harbor Class

Harbor Class:	MASTER, ADMIRAL, GUIDE, LEADER, SCOUT, CHIEF			
Length Overall	105.00	ft, or	32.00	m
Breadth	36.00	ft, or	10.97	m
Depth		ft, or	0.00	m
Design Draft	16.50	ft, or	5.03	m
Bollard Pull	111,500	lbs or	50.58	MT
Main Engines	2 x Cat (3516-b), 2,400 BHP @ ? RPM			
	4,800	HP, or	3,579	kW
Propulsors	2 x Voith Schneider			

MITAGS Model: Voith Tug 3 (70t)



PILOT CARD

Ship name	Voith Schneider tug 3 (bp 70t) TRANSAS 2.31.8.0 *			Date	07.02.2016
IMO Number	N/A	Call Sign	N/A	Year built	N/A
Load Condition	Ballast Departure Condition				
Displacement	1060 tons		Draft forward	5.67 m / 18 ft 7 in	
Deadweight	186.9 tons		Draft forward extreme	5.67 m / 18 ft 7 in	
Capacity			Draft after	6.33 m / 20 ft 9 in	
Air draft	22.5 m / 74 ft 0 in		Draft after extreme	6.33 m / 20 ft 9 in	

Ship's Particulars

Length overall	42 m	Type of bow	-
Breadth	15.3 m	Type of stern	-
Anchor(s) (No./types)	2 (PortBow / StbdBow)		
No. of shackles	12 / 12		(1 shackle =25 m / 13.7 fathoms)
Max. rate of heaving, m/min	30 / 30		

Steering characteristics

Steering device(s) (type/No.)	WaterJet / 2	Number of bow thrusters	N/A
Maximum angle	100	Power	N/A
Rudder angle for neutral effect	0 degrees	Number of stern thrusters	N/A
Hard over to over(2 pumps)	2 seconds	Power	N/A
Flanking Rudder(s)	0	Auxiliary Steering Device(s)	N/A

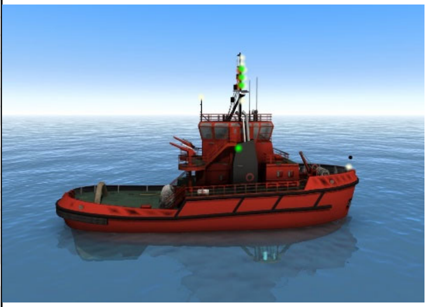
Stopping			Turning circle	
Description	Full Time	Head reach	Ordered Engine: 100%, Ordered rudder: 35 degrees	
FAH to FAS	13.25 s	0.22 cbls	Advance	0.64 cbls
HAH to HAS	14.25 s	0.2 cbls	Transfer	0.5 cbls
SAH to SAS	15.25 s	0.16 cbls	Tactical diameter	0.84 cbls

Main Engine(s)

Type of Main Engine	High speed diesel	Number of propellers	2
Number of Main Engine(s)	2	Propeller rotation	Inward
Maximum power per shaft	2 x 2937.78 kW	Propeller type	VSP
Astern power	100 % ahead	Min. RPM	4.28
Time limit astern	N/A	Emergency FAH to FAS	6.2 seconds

Engine Telegraph Table

Engine Order	Speed, knots	Engine power, kW	RPM	Pitch ratio
"FSAH"	13	4880	57.3	N/A
"FAH"	11.6	3627	57.3	N/A
"HAH"	10.4	2668	57.3	N/A
"SAH"	8.3	1984	57.3	N/A
"DSAH"	5	1861	57.3	N/A
"DSAS"	-4.8	1944	57.3	N/A
"SAS"	-7.8	2195	57.3	N/A
"HAS"	-9.9	2914	57.3	N/A
"FAS"	-10.9	3914	57.3	N/A
"FSAS"	-11.8	5288	57.3	N/A



A.3.4 Tug Tow Line Characteristics

For the base case, the tow line was assumed to be Samson Saturn 12 (HMPE) 3.25" diameter with a minimum breaking strength of 411 MT (453 ST) for both tugs. In the simulator, the "Aramid" material was selected for its "extensibility" (elastic elongation) of 3%. Sensitivity cases were run with 64 mm (2.5 inch) tow wire.

For the simulation, the lead tug initially had line out with the distance set to 90 m (295 ft) from the transom of the tug to the bow of the barge. The distance includes a 76 mm (3 in) chain bridle with legs that are each 27 m (90 ft) long. The length of the bridle along a straight line from the barge to the tow shackle is 23.5 m (77 ft).

For the simulation, the support tug initially had line out with the distance set to 80 m (262 ft) from the bow of the tug to the stern of the barge.

A.3.5 WTIV Mooring Line Characteristics

The mooring lines were assumed to pass through sheaves on the side of the WTIV. The sheaves were located so that the line contact point was 3 m (10 ft) above the barge deck when loaded to the post-cargo discharge draft. The sheave location was selected as a compromise between being low enough to minimize the vertical force on the barge but high enough so that the line will not chafe on the barge deck edge.

The mooring lines were assumed to pass through openings in the wing wall to quick release mooring hooks. The hooks are located 3 m (10 ft) in from the side shell – see barge model.

The mooring lines were assumed to have a minimum breaking strength of 384 MT (425 ST). In the simulator, the "Nylon" material was selected for its extensibility of 22%.

For the base case, the barge was moored only with breast lines, but it was quickly determined that spring lines were necessary to help minimize the watch circle.

A.3.6 WTIV Fenders

In the simulator, the WTIV appears to have three fenders, however, fender contact, and response was not simulated. The fenders were shown on the side of the WTIV as a visual queue for the operators only. The barge speed, acceleration, location of the center of gravity and relative position when the barge crossed the fender contact plane was recorded.

Appendix B. Metocean Data

B.1 Overview

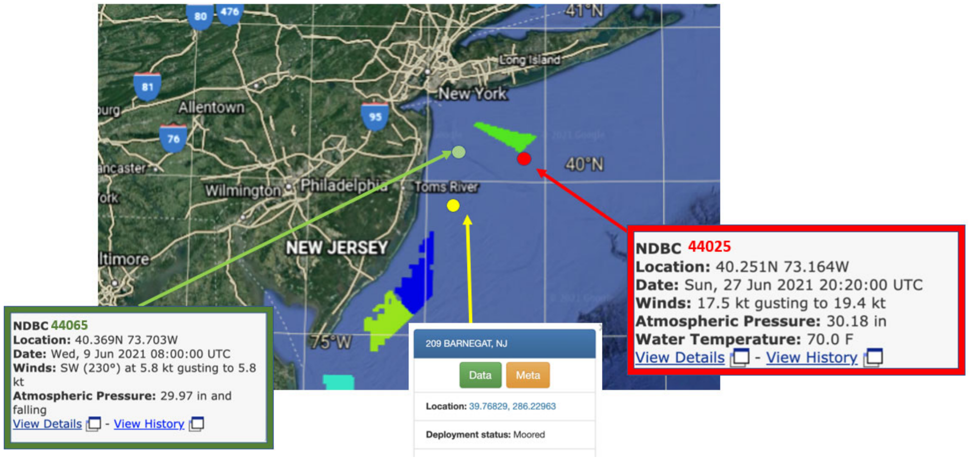
The Maritime Navigation Mission Simulation was planned and performed to help understanding and evaluating different stages of operation during WTIV operation, as it is outlined in other sections of this document. This appendix covers the following topics:

- Environmental conditions
- Simulation data collection
- Simulation data verification, processing and findings

B.2 Environmental Conditions

One of the most important aspects of any type of *maritime navigation mission simulation* is accurate environmental data. The environmental data, here after called Metocean data, consists of water wave and wind information at a specific location (site). Metocean data are usually measured and recorded by private/federally funded buoys. For this project, buoy data were obtained from the National Oceanographic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC). Since there are a limited number of buoys out in the ocean and different buoy types measure and report information differently, the first step is to choose the buoy as close to the site of interest with the best information.

Figure 48 provides information on the available measurement site locations close to this wind project.



NDBC 44025
Location: 40.251N 73.164W
Date: Sun, 27 Jun 2021 20:20:00 UTC
Winds: 17.5 kt gusting to 19.4 kt
Atmospheric Pressure: 30.18 in
Water Temperature: 70.0 F

NDBC 44065
Location: 40.369N 73.703W
Date: Wed, 9 Jun 2021 08:00:00 UTC
Winds: SW (230°) at 5.8 kt gusting to 5.8 kt
Atmospheric Pressure: 29.97 in and falling

209 BARNEGAT, NJ
Location: 39.76829, 286.22963
Deployment status: Moored

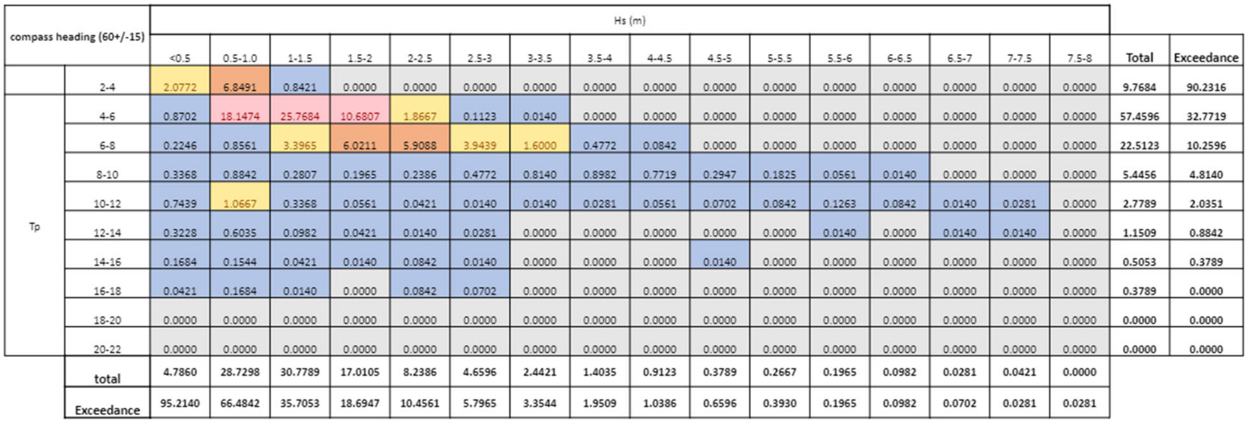
Figure 48 - Buoy Stations in Vicinity of the Target Wind Farm

Buoy 44025 off Long Island was selected for this study, due to the availability of directional spectrum and proximity to the project site. Data sets were retrieved from the NDBC database[1]. The data measurement period was 1992 to 2020. Data from the buoy also included standard meteorological data including wind-speed, wind-direction, wave-heights, wave-period, wave-direction and directional spectra data. The data has been quality checked and outliers have been removed.

There are several layers of information that can be harvested from the buoy measurements as described below.

B.2.1 Statistical and Probabilistic Characteristics of the Wave Field

This includes the significant wave height, peak period, mean direction, joint probabilities, etc. The outcomes of such information are useful in setting up the general characteristics of the environmental conditions and are widely used in practice as the only source of defining the environmental conditions. Table 3 and Figure 49 present two examples of joint probabilities computed from the buoy measurements for different wave characteristics.



compass heading (60+/-15)		Hs (m)																	
		<0.5	0.5-1.0	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5	5-5.5	5.5-6	6-6.5	6.5-7	7-7.5	7.5-8	**Total**	**Exceedance**
	2-4	2.0772	6.8491	0.8421	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**9.7684**	**90.2316**
Tp	4-6	0.8702	18.1474	25.7684	10.6807	1.8667	0.1123	0.0140	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**57.4596**	**32.7719**
	6-8	0.2246	0.8561	3.3965	6.0211	5.9088	3.9439	1.6000	0.4772	0.0842	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**22.5123**	**10.2596**
	8-10	0.3368	0.8842	0.2807	0.1965	0.2386	0.4772	0.8140	0.8982	0.7719	0.2947	0.1825	0.0561	0.0140	0.0000	0.0000	0.0000	**5.4456**	**4.8140**
	10-12	0.7439	1.0667	0.3368	0.0561	0.0421	0.0140	0.0140	0.0281	0.0561	0.0702	0.0842	0.1263	0.0842	0.0140	0.0281	0.0000	**2.7789**	**2.0351**
	12-14	0.3228	0.6035	0.0982	0.0421	0.0140	0.0281	0.0000	0.0000	0.0000	0.0000	0.0000	0.0140	0.0000	0.0140	0.0140	0.0000	**1.1509**	**0.8842**
	14-16	0.1684	0.1544	0.0421	0.0140	0.0842	0.0140	0.0000	0.0000	0.0000	0.0140	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.5053**	**0.3789**
	16-18	0.0421	0.1684	0.0140	0.0000	0.0842	0.0702	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.3789**	**0.0000**
	18-20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**	**0.0000**
	20-22	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**	**0.0000**
	total	**4.7860**	**28.7298**	**30.7789**	**17.0105**	**8.2386**	**4.6596**	**2.4421**	**1.4035**	**0.9123**	**0.3789**	**0.2667**	**0.1965**	**0.0982**	**0.0281**	**0.0421**	**0.0000**		
	Exceedance	**95.2140**	**66.4842**	**35.7053**	**18.6947**	**10.4561**	**5.7965**	**3.3544**	**1.9509**	**1.0386**	**0.6596**	**0.3930**	**0.1965**	**0.0982**	**0.0702**	**0.0281**	**0.0281**		

Table 3 - Example Joint Probability Table (Hs and Tp of Wave Field)

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[1] https://www.ndbc.noaa.gov/station_page.php?station=44025

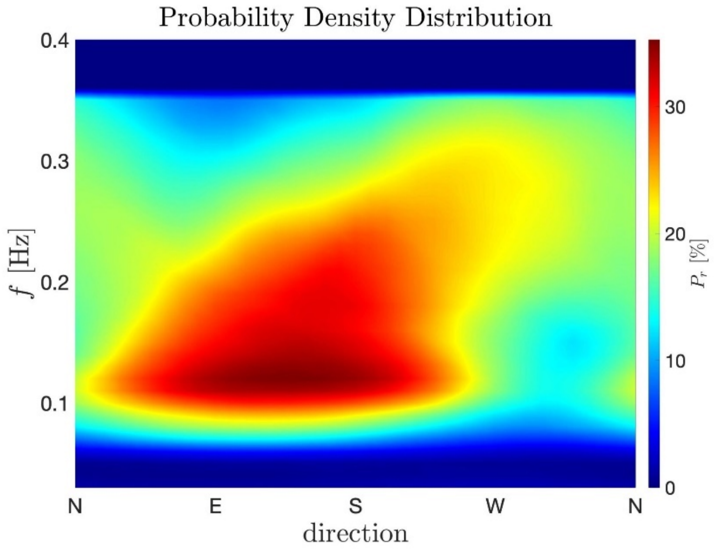


Figure 49 - Example of Joint Probability Density Distribution (Frequency and Direction)

B.2.2 Full 2D Spectral Information

Some buoys collect full 2D spectral information. These provide more details on the wave field, specifically, the direction of approach of waves. The figure below represents an example of a full 2D directional spectrum.

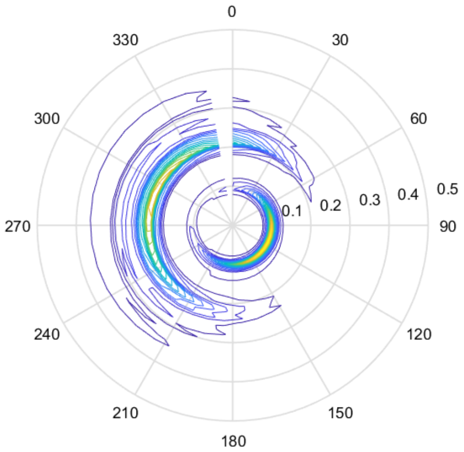


Figure 50 - Example of Directional Spectrum

For this *maritime navigation mission simulation* study, both types of information were used to identify and model the environmental conditions as accurately and possible. Some of the most important aspects are described below.

B.2.3 Metocean Data Used for Study

For this *maritime navigation mission simulation* study, both types of information collected from the buoys were used to identify and model the environmental conditions as accurately and possible. Some of the most important aspects are described below.

B.2.3.1 Statistical and Probabilistic Properties

To optimize cargo transloading performance, an important first step is to determine the most probable wind and wave direction. The roses were developed from the measured data for the past 22 years (since 2000). Historically, the most probable wave and wind conditions are:

- Dominant Wind Direction: 210º; wind speed less than 18 knots (9.4 m/s) 80% of the time
- Dominant Wave Direction: 120º; significant wave height (Hs) less than 1.75 m 80% of the time

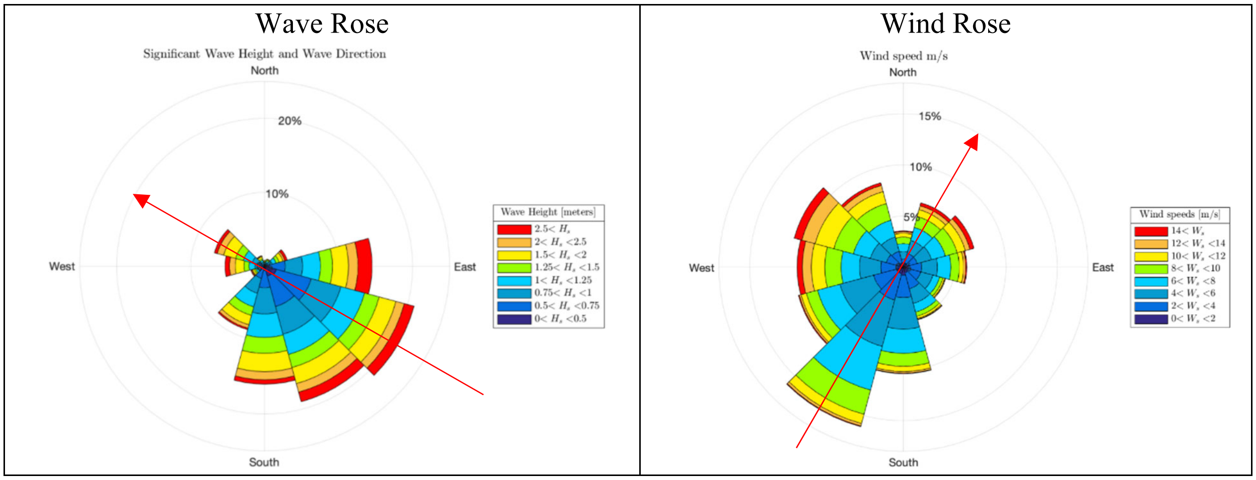


Figure 51 - Wind Rose and Wave Rose at Station 44025

The dominant wind and wave directions were used to position the WTIV and the approaching feeder barge, as described in Appendix A.1.3.

B.2.3.2 Non-Exceedance Persistence

Another useful way to look at the weather data is to use statistical analysis tool to generate non-exceedance probabilities, which are presented in Table 4 for different persistence durations. Such information can be complimentary to the mission simulation results to get a sense of operational availability.

	6 – 12 hr	12 – 18 hr	18 – 24 hr	24 – 36 hr	36 - 48 hr	48 - 72 hr	> 72 hr
Hs < 1.00 m							
probability	7.23	5.09	3.55	4.15	2.33	1.82	1.66
non-exceedance	25.84	18.61	13.52	9.97	5.81	3.48	0.00
Hs < 1.25 m							
probability	8.84	6.01	5.03	6.06	3.81	4.26	4.47

	6 – 12 hr	12 – 18 hr	18 – 24 hr	24 – 36 hr	36 - 48 hr	48 - 72 hr	> 72 hr
non-exceedance	38.48	29.64	23.63	18.60	12.54	8.73	0.00
Hs < 1.50 m							
probability	9.32	6.49	5.38	8.02	5.35	5.67	8.07
non-exceedance	48.31	38.98	32.50	27.12	19.09	13.74	0.00
Hs < 2.00 m							
probability	10.27	6.87	5.80	7.68	6.87	7.45	14.86
non-exceedance	59.79	49.53	42.66	36.86	29.18	22.31	0.00

Table 4 - NDBC 44025 - Non-Exceedance Persistence (%) Years: 1992-2020

B.2.3.3 Full 2D Spectral Information

This NDBC buoy station measures full wave 2D spectrum and reports the parameters needed to regenerate the data. These 2D spectra were re-generated using 36-bins in direction (with 10-degree steps) and 47-bins in frequency, for a total of 1692-bins. An example of such 2D spectrum is presented in below.

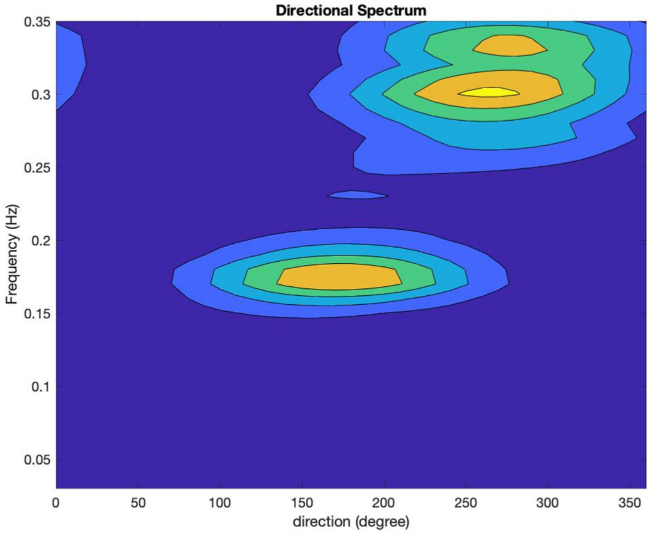


Figure 52 - Example of 2D Spectrum with Contours Representing Significant Wave Height

One of the downsides of working with a full 2D spectrum is the amount of information. Most simulation software cannot handle so much input data at all, or, if they can accept it, take so long to run to be impractical. To address such issues, there are several ways to simplify the full 2D spectrum into something manageable. The target is to decompose the full 2D spectrum into a limited number of components to reduce the amount of input information, without losing critical information.

B.2.3.3.1 Data Simplification: Wave Steepness Method

An example of such approach could be the wave steepness method to divide wind seas from swells, used by NOAA since 1997. This method determines a separation frequency by assuming that wind-seas are steeper than swell and that maximum steepness, or ratio of wave height to length, occurs in the wave spectrum near the peak of wind-seas energy. The steepness method performs well under conditions of building or sustained wind-seas, but the method often overestimates wind-seas under conditions of abating winds and seas, or under light winds when significant swell is present. The respective parts of the processed spectrum are used to compute significant wave height, peak frequency (or period), and mean direction of the swell and wind-seas portions of the spectrum.

B.2.3.3.2 Data Simplification: Partitioning Method

Another more recent method uses image processing to determine wave field systems. This method can be used in dividing the full 2D spectrum into sub-systems, an example of this method is presented below. This partitioning method and its subsequent weather systems were found to be interesting but were not pursued when the 2D Spectral Bin Energy Selection Method (described below) was found to work with the NTPro software.

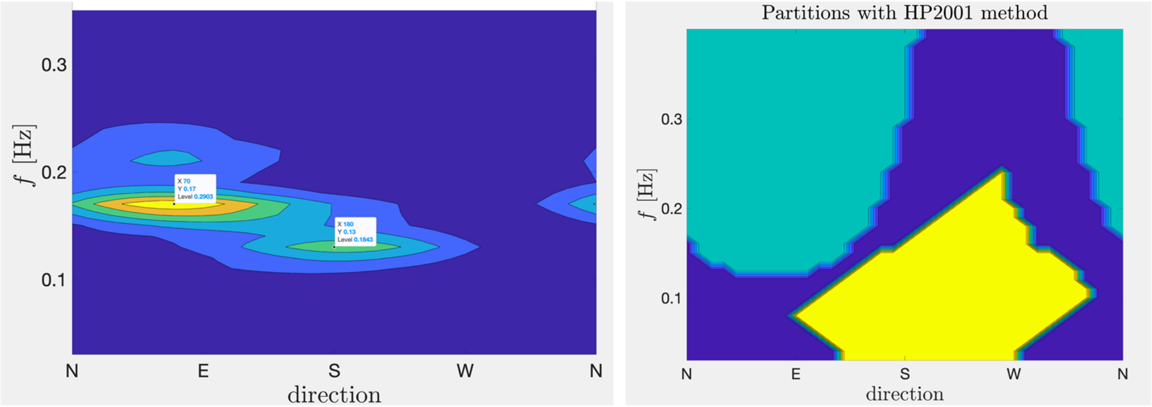


Figure 53 - Original 2D Spectrum (left) and Sub-System Partitions (right)

B.2.3.3.3 2D Spectral Bin Energy Selection Method – Data Truncation

For this study, a novel energy selection method was developed to truncate the metocean data into a usable form for the NTPro software. To record the full 2D spectrum, the wave height, period, and direction parameters measured at this NDBC buoy location were used to generate 2D spectrum described by 36-bins in direction (measured in 10-degree slices) and 47-bins in frequency, for a total of 1692-bins. NTPro permits twenty (20) 2D spectra be entered to simulate the environment. Therefore, out of the 1,692 bins, the twenty (20) bins with the largest energy content were selected to be provided to NTPro to represent the target environmental conditions. For example, if the waves are almost unidirectional, as it is presented in Figure 54, there is good agreement between the measured and estimated wave fields. If the wave field is multi-directional, the energy method is a little less accurate in preserving the measured characteristics, as the example in Figure 55 depicts.

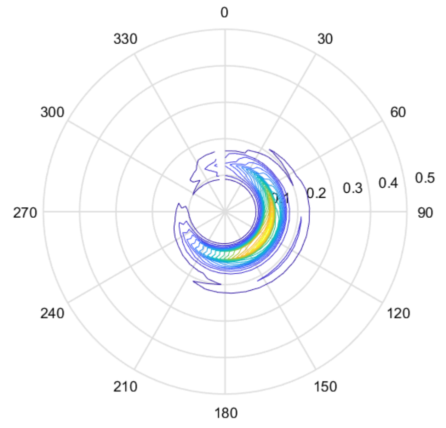
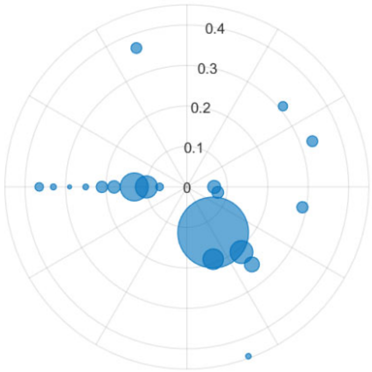
Spectrum Measured by NDBC	Spectrum Submitted to NTPro
	
$Hs = 1.5\ m, Tp = 7.7\ s, Dir = 120°$	$Input$: $Hs = \mathbf{1.5\ m}, Tp = \mathbf{7.7\ s}, Dir = 120°$

Figure 54 - Uni-directional Wave Spectra

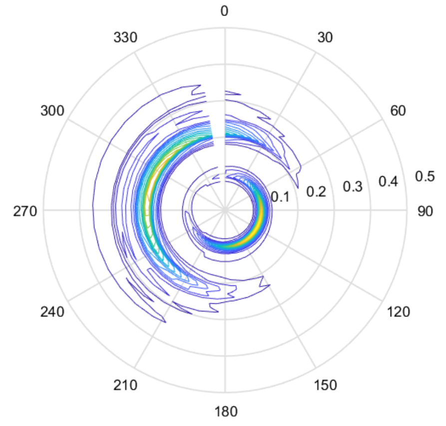
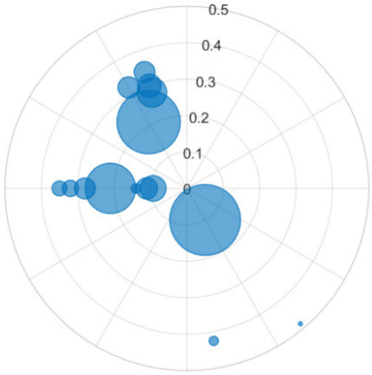
Spectrum Measured by NDBC	Spectrum Submitted to NTPro
	
$Hs = 1.5\ m, Tp = 10\ s, Dir = 120°$	$Input$: $Hs = \mathbf{1.45\ m}, Tp = \mathbf{11.6\ s}, Dir = 120°$

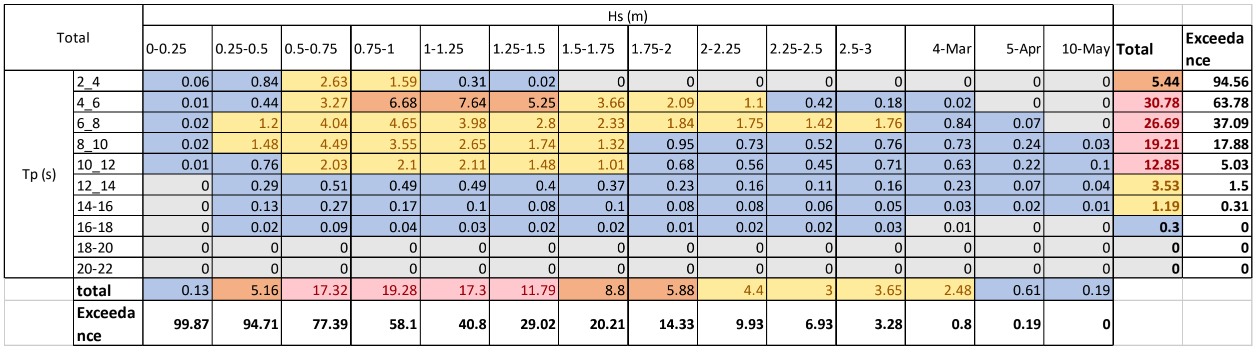
Figure 55 - Multi-directional Wave Spectra

The data was analyzed to develop exceedance / non-exceedance tables so real-world time steps that represented the most probable combinations of significant wave height (Hs), peak period (Tp) and direction could be selected for use in the simulation. As shown above, this method truncates the spectrum data but still produces waves with Hs of at least 95% and 99.8% of the wave energy. The wave direction for each bin is exactly as input.

B.2.3.3.4 2D Spectral Bin Energy Selection Method – Data Selection

Time in the *maritime navigation mission simulator* is limited. Therefore, the environmental parameters for testing must be selected so that the wave and wind conditions tested proceed from most probable to less probable. The joint probability of wave parameters was used to define the ranges of significant wave height and periods. See Table 5. Such ranges were defined as:

- Significant wave height: $0.5 \leq Hs \leq 2.1$ m
- Peak period: $4 \leq Tp \leq 11$ s



Total		Hs (m)															
		0-0.25	0.25-0.5	0.5-0.75	0.75-1	1-1.25	1.25-1.5	1.5-1.75	1.75-2	2-2.25	2.25-2.5	2.5-3	4-Mar	5-Apr	10-May	**Total**	**Exceedance**
Tp (s)	2_4	0.06	0.84	2.63	1.59	0.31	0.02	0	0	0	0	0	0	0	0	**5.44**	**94.56**
	4_6	0.01	0.44	3.27	6.68	7.64	5.25	3.66	2.09	1.1	0.42	0.18	0.02	0	0	**30.78**	**63.78**
	6_8	0.02	1.2	4.04	4.65	3.98	2.8	2.33	1.84	1.75	1.42	1.76	0.84	0.07	0	**26.69**	**37.09**
	8_10	0.02	1.48	4.49	3.55	2.65	1.74	1.32	0.95	0.73	0.52	0.76	0.73	0.24	0.03	**19.21**	**17.88**
	10_12	0.01	0.76	2.03	2.1	2.11	1.48	1.01	0.68	0.56	0.45	0.71	0.63	0.22	0.1	**12.85**	**5.03**
	12_14	0	0.29	0.51	0.49	0.49	0.4	0.37	0.23	0.16	0.11	0.16	0.23	0.07	0.04	**3.53**	**1.5**
	14-16	0	0.13	0.27	0.17	0.1	0.08	0.1	0.08	0.08	0.06	0.05	0.03	0.02	0.01	**1.19**	**0.31**
	16-18	0	0.02	0.09	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.03	0.01	0	0	**0.3**	**0**
	18-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**
	20-22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**
	total	0.13	5.16	17.32	19.28	17.3	11.79	8.8	5.88	4.4	3	3.65	2.48	0.61	0.19		
	Exceedance	**99.87**	**94.71**	**77.39**	**58.1**	**40.8**	**29.02**	**20.21**	**14.33**	**9.93**	**6.93**	**3.28**	**0.8**	**0.19**	**0**		

Table 5 - Joint Probability of Wave Parameters (Sig. Wave Height and Peak Period), Station 44025

The local water depth at the buoy station is about 50 meters, which results in the waves conditions mostly in intermediate to deep water waves. The input wave conditions selected is shown in Figure 56. The peak directions of the waves were chosen in a range to identify the directionality effects on the maneuverability of the vessels. Wind speed and directions were also chosen in a range to examine their effects on the operations.

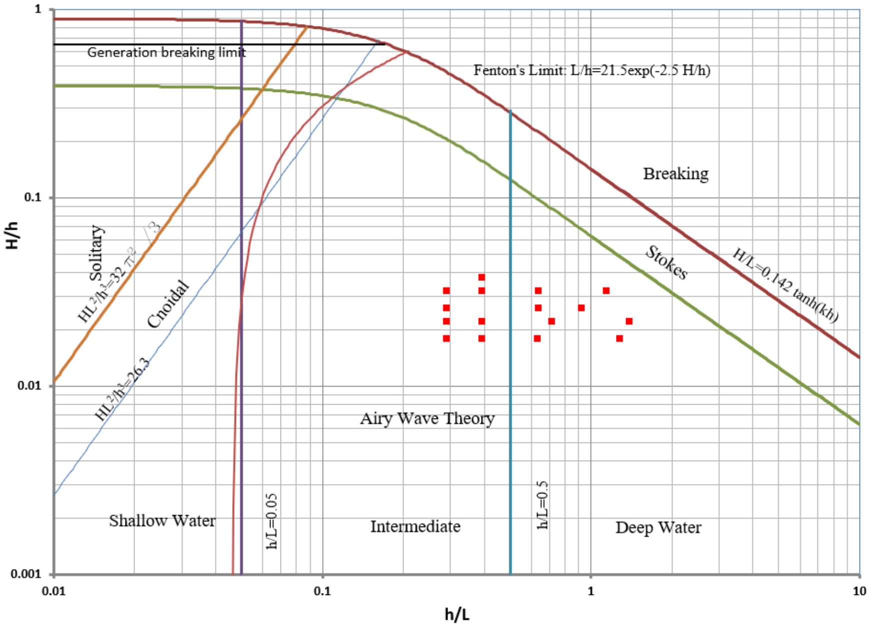


Figure 56 - Parameters of Wave Inputs to NTPro

After identifying the wave parameters with the highest probability, specific times in history that match the target input parameters were found in the NDBC data set. Then, the real measured data from that time step was used to generate 2D spectrum described by 36-bins in direction (measured in 10-degree slices) and 47-bins in frequency, for a total of 1692-bins and that measured data was reduced to a 20-bin representation, as described above and input into the simulation software.

B.2.3.3.5 2D Spectral Bin Energy Selection Method – Simulation Output Verification

To verify that the simulated waves were a good match to the input data, the significant wave height (Hs) and peak wave period (Tp) were measured. See Figure 57. Both the input and the simulated environmental data were measured at the center of the feeder barge. A comparison of the input and simulated significant wave heights reveals that the NTPro software produced significant wave heights slightly larger than the target. The mean bias was found to be 1.05 with standard deviation in bias of 13%.

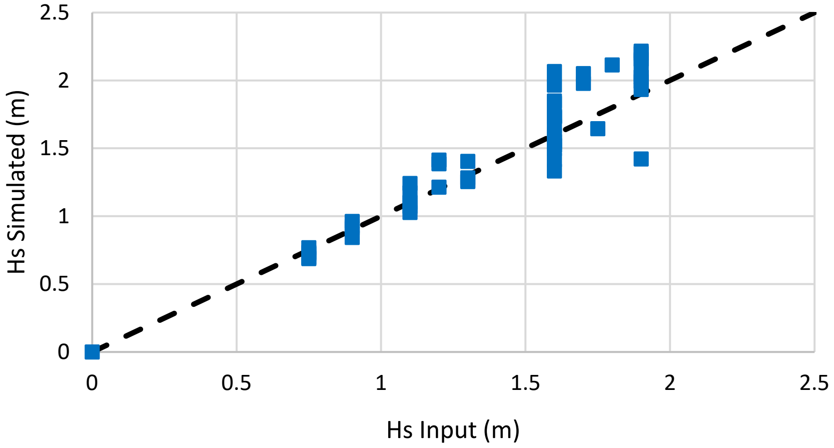


Figure 57 - Input vs. Simulated Significant Wave Height (Hs)

The same comparison was made for the peak periods. See Figure 58. This comparison showed that the NTPro software overestimates the periods with mean bias of 1.08 and standard deviation in bias of 28%. After in-depth investigation, no logical explanation was found for the relatively large values of bias and standard deviation in peak periods.

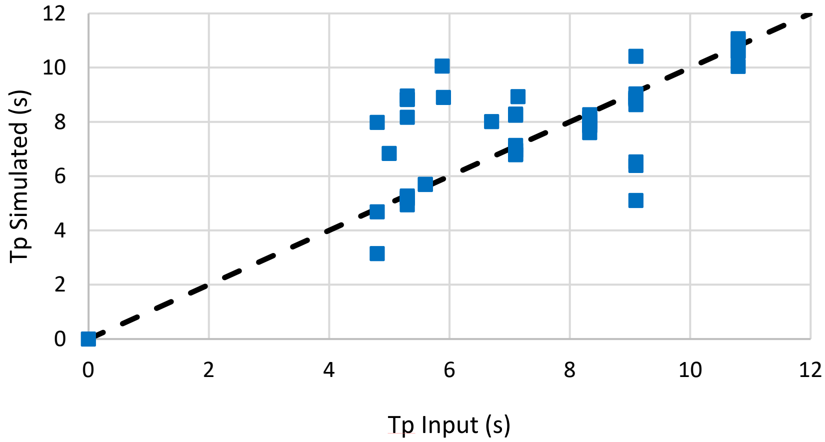


Figure 58 - Input vs. Simulated Peak Wave Period (Tp)

The difference between the selected wave conditions input to the NTPro program and the measured condition output is shown in Figure 59.

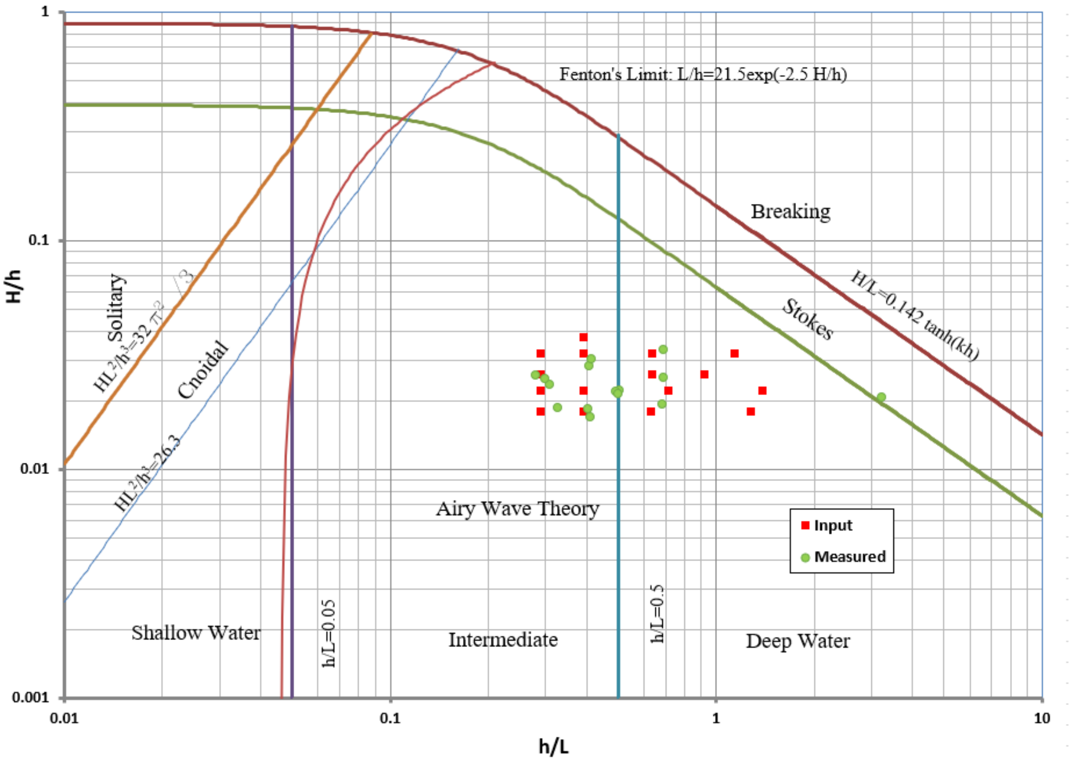


Figure 59 - Comparison of Wave Parameters Input to Output (Measured)

The direction of the wave field was exactly matching the input condition.

Wind characteristics, both velocity and direction, were exact matches to the input values.