ERDC/CHL

US Army Corps of Engineers®
Engineer Research and Development Center

Ship Forces on the Shoreline of the Savannah Harbor Project

Stephen T. Maynord

August 2006

Coastal and Hydraulics Laboratory

Executive Summary

Ship forces having the potential to cause shoreline erosion were evaluated at the Savannah Harbor to compare the without project (existing) and the with project (deepened) channels. Results of this study will be used by the Savannah District in a separate study to evaluate shoreline erosion.

An analysis of ship forces requires determination of comparable ship speeds in the without project (existing) and with project (deepened) channels. Field data were used to determine ship speed in the without project (existing) channel. An analytical model for ship speed, along with the assumption of equal power setting in the without project and with project channels, was used to determine ship speed in the with project channel.

Based on the Savannah District's ship traffic analysis, the total number of ships will not change in without project (existing) and with project (deepened) channels. Four traffic alternatives were evaluated that primarily differ in the number of post-Panamax ships compared to Panamax ships. Without project (existing) and with project (deepened) conditions primarily differ in draft of the post-Panamax ships and speed of all ships.

A composite value of the various ship effects was used to compare the without project (existing) and with project (deepened) channels. The composite value is based on the magnitude of ship effect for 6 different vessel classes as well as the proportion of each vessel class in the overall fleet.

At Fort Pulaski, dominant ship effects include short period bow and stern waves and long period drawdown and return velocity. The composite return velocity and drawdown per ship are 3.2 to 6.2% less in the with project (deepened) channel. The trend of slightly less drawdown and return velocity in the with project deepened channel was found in both years 2030 and 2050 and for all 4 traffic alternatives. Due to the slightly higher speed in the with project (deepened) channel, short period bow and stern waves are the shoreline attack force that increases in the with project (deepened) channel at Fort Pulaski. The composite short period bow and stern wave height per ship for years 2030 and 2050 is 1.5 to 4.4% greater in the deepened channel.

At Tybee Island, the only significant ship effect reaching the shoreline is the long period drawdown or pressure wave. It is uncertain if the south jetty blocks ship effects at high tides because ship effects generated outside the jetties reach the TI shoreline. The composite drawdown in the channel between the jetties per ship is 2.3 to 5.9% less in the with project (deepened) channel. The actual drawdown at the TI shoreline will be about 1/3 of the drawdown in the channel between the jetties.

Ship effects were tabulated and plotted for the City Front and Confined Disposal Facility sites.

ERDC/CHL
August 2006

Draft of Ship Forces on the Shoreline of the Savannah Harbor Project

Stephen T. Maynord

Coastal and Hydraulic Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39150-6199

Final report

Prepared for U.S. Army Corps of Engineers

Monitored by Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

Abstract: Ship forces having the potential to cause shoreline erosion were evaluated at Savannah Harbor to compare the without project (existing) and the with project (deepened) channels. Comparable ship speeds were determined in the without project and with project channels based on field data and an analytical model. Four traffic alternatives were evaluated that primarily differ in the number of post-Panamax ships compared to Panamax ships. At Fort Pulaski, dominant ship effects include short period bow and stern waves and long period drawdown and return velocity. The composite return velocity and drawdown per ship are 3.2 to 6.2% less in the with project channel. Due to the slightly higher speed in the with project channel, short period bow and stern waves are the shoreline attack force that increases in the with project channel at Fort Pulaski. The composite short period bow and stern wave height per ship for years 2030 and 2050 is 1.5 to 4.4% greater in the deepened channel. At Tybee Island, the only significant ship effect reaching the shoreline is the long period drawdown or pressure wave. The composite drawdown in the channel between the jetties per ship is 2.3 to 5.9% less in the with project channel.

Contents

Figures and Tables

Figures

Tables

Preface

The work reported herein was conducted for the US Army Engineer District, Savannah (SAS), by the US Army Engineer Research and Development Center (ERDC) during 2005-2006. The field work was performed during September, 2005 by personnel of ERDC and SAS. From ERDC, Messrs. Thad Pratt, John Kirklin, Chris Callegan, and Dr. Stephen Maynord participated in the field studies. From SAS, Mr. Wilbur Wiggins participated in the data collection.

The study was under the direction of Mr. Tom Richardson, Director, Coastal and Hydraulics Laboratory (CHL); Dr. William Martin, Assistant Director, CHL; Dr. Rose Kress, Chief of the Navigation Division; and Mr. Dennis Webb, Chief of the Navigation Branch, CHL. The report was written by Dr. Maynord.

At the time of publication of this report, Director of ERDC was Dr. James R. Houston, and Commander was COL Richard Jenkins.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
Degrees Fahrenheit	(F-32)/1.8	degrees Celsius
Feet	0.3048	meters
foot-pounds force	1.355818	joules
horsepower (550 foot-pounds force per second)	745.6999	watts
Knots	0.5144444	meters per second
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (force)	4.448222	newtons
pounds (force) per square foot	47.88026	pascals
Slugs	14.59390	kilograms
square feet	0.09290304	square meters

1 Introduction

Purpose

At the request of the US Army Engineer District, Savannah (SAS), the US Army Engineer Research and Development Center (ERDC) conducted an evaluation of ship forces that may cause shoreline erosion in the without project (existing) channel and in the with project (deepened) channel of the Savannah Harbor project. ERDC was asked to determine ship induced waves, drawdown, and velocity increase at the shoreline. In a follow-on study, the District will use results of this study to determine any changes in shoreline erosion in the existing and deepened channels.

Approach

The study was accomplished using (a) field measurement of ship forces and (b) analytical/empirical models to compare ship forces in the without project (existing) and with project (deepened) channels. The District asked ERDC to provide a comparison of ship forces in the existing and the deepened channels for the Fort Pulaski and Tybee Island sites (Figure 1). For the City Front and the Confined Disposal Facility sites, the District asked ERDC to provide a table showing ship forces in the existing channel. The term “channel” in this report refers to the entire width of the waterway, not just the navigable portion of the waterway.

Ship Induced Forces

The shorelines of the Savannah Harbor channel are subjected to a variety of ship induced forces. These forces result from waves generated at the bow and stern of the ship, water level lowering or drawdown from the displacement of the ship, and increased velocity from both waves and return velocity. Return velocity, like drawdown, results from the moving ship displacing water as it travels ahead. The water accelerates around the ship, moving from bow to stern. The increased water velocity alongside the ship is the return velocity. The movement of water from bow to stern also results in lowering of the water level adjacent to the ship that is the drawdown. The drawdown, that some refer to as a pressure wave, can travel large distances from the ship as will be seen in the Tybee Island data. Return velocity is parallel to and opposite to the direction of ship travel.

Savannah Harbor Characteristics

The Savannah Harbor channel is on the lower limit of what is termed a confined channel. Confined channels are those in which the ship cross sectional area takes up a significant part of the channel cross sectional area. Confined channels are often described by the blockage ratio that is the ratio of ship cross sectional area / channel cross sectional area. Blockage ratio should not be confused with "block coefficient" used subsequently that describes the hull shape of a ship. Depending on ship speed, ships having blockage ratio of more than 0.02-0.05 exhibit significant displacement effects that include drawdown and return velocity. Many confined channels have maximum blockage ratios of 0.15- 0.2. The Savannah Harbor channel has blockage ratio from about 0.02-0.095 that places it on the lower end of confined channels. Consequently, drawdown and return velocity impacts should be less than in channels with higher blockage ratio.

Confined channels can have ship passages that create a large rise in water level just after the drawdown. The water level rise is most often a single wave that inundates shoreline areas above the ambient water level. The drawdown plus the water level rise is frequently referred to as a "transverse stern wave" and has been observed numerous times by this author on the Sabine Neches Waterway (SNWW) near Port Arthur, Texas (Maynord, 2003). The SNWW is a channel more confined than the Savannah Harbor channel because it has a larger blockage ratio. The magnitude of the rise in water level above the ambient water level is a function of ship speed, shoreline geometry, channel size, and proximity of the ship to the shoreline. SAS provided a video that showed such an occurrence on the Savannah Harbor project.

During the field study, numerous ships produced a water level rise of about 1 ft. Only the "Mol Velocity" that was an inbound ship at the Confined Disposal Facility created a water level rise or transverse stern wave comparable to that seen on the video. As shown in appendix Figure B-5, the Mol Velocity created a 2.5 ft drawdown followed by a 3-4 ft rise in water level above the ambient water level. While transverse stern waves are often the dominant force on the shoreline in confined channels, the frequency of occurrence on the Savannah Harbor channel appears low based on the field data.

Another characteristic of the Savannah Harbor channel is that the traffic is predominately container ships which have relatively high ship speeds compared to other types of ships such as tankers and bulk carriers. The relatively low blockage ratio in the Savannah Harbor also results in higher ship speeds. In deep draft navigation channels dominated by tankers or bulk carriers, ship speed is relatively slow and the ships forces at the shoreline of main concern are the long period effects related to the ship induced drawdown such as the transverse stern wave. The higher speed of the container ships and the low blockage ratio at Savannah Harbor raise the possibility that short period bow and stern waves are the dominant force on the shoreline.

A third characteristic of the Savannah Harbor channel is the presence of large tides and large tidal velocities. The large tidal range tends to spread the attack of ship effects over a significant portion of the shoreline rather than occurring at the same location on the shoreline as would be the case in the absence if tides. A negative aspect of large tidal velocities is that return velocity adds to the ambient velocity for ships going against the tide, resulting in net velocities well above ambient velocities.

Savannah Harbor Ship Forces

Summarizing, the ship forces having potential to impact shoreline erosion at Savannah Harbor are as follows:

a. Short period waves formed at bow and stern of ship.

b. Long period drawdown and return velocity caused by the displacement of the moving ship. Based on the low frequency of occurrence in the field data, transverse stern waves, which are also caused by the displacement effects of the ship, will not be considered in the analysis.

One of the most critical questions in ship effects studies of existing and deepened channels is as follows: “What is the speed of comparable ships in the without project (existing) and the with project (deepened) channels?” The study outcome strongly depends on the answer to this question.

2 Field Study

Gage Locations

The field study was conducted from 15 September – 22 September 2005. Water level measurements were conducted at both sides of the channel at City Front (CF), the north side of the channel at the Confined Disposal Facility (CDF), the south side of the channel at Fort Pulaski (FP), and the shoreline at Tybee Island (TI) south of the jetties as shown in Figure 1. The District had concerns about ship effects at high tides and the field study was timed to coincide with a Spring tide. By selecting the Spring tide full moon, the maximum moonlight conditions were present to improve the performance of the cameras used for nighttime data collection.

The locations of the single pressure cell used at the each of the two CF sites and the two 13-ft long capacitance rods used at each of the CDF, FP, and TI sites are shown in Table 1. The wave stands containing the two capacitance rods, video camera, and recorder at TI and FP are shown in Figures 2 and 3. Two gages were provided for redundancy; there was no attempt to extract wave direction from the data. Because the District was concerned about ship effects at high tides reaching 9 ft MLLW, the 13 ft long capacitance rods were positioned to measure water levels up to about 11.5 to 12.0 ft MLLW. This placed the lower limit of the capacitance rods at about –1 to –1.5 ft MLLW. The lateral position of the gages was selected where the channel bottom elevation was about –2 ft MLLW. As can be seen in the measured data in the appendices, ship passages at extreme low tides often caused a water level drawdown lower than the bottom of the capacitance gages. When this happened, the data was a flat line until the water level rose back onto the gage. See for example Figures B-10, C-4, and C-31 in the appendix. Unwatering of the gage only occurred at FP and CDF. Unwatering did not happen at CF because the pressure cells were adequately submerged. Unwatering of the capacitance gages did not happen at TI because of the reduced magnitude of drawdown.

The large tidal range in the Savannah Harbor channel makes the measurement of ship induced water level changes difficult. In addition to the problems with measurement of the entire tidal range mentioned previously, the ship effects at low tides are measured with the gages close to the shoreline in shallow water versus the ship effects at high tides that are measured with gages in deeper water farther from the shoreline. Shallow water and shoreline proximity affect both the long period effects and short period bow and stern waves from the ship. Decreasing depth has several effects on waves. The most significant being shoaling which is the increase in wave height as waves move into shallow water. The increase in height occurs until the wave steepness reaches the point at which the wave breaks. These observations on shallow water effects explain some of the variability in the data but do not reduce the validity of the results.

Camera Locations

Cameras were mounted on the wave stands at CDF, FP, and TI to monitor passage of ship traffic. A camera at CF was mounted on the north side of the channel at the coordinates shown in Table 1. Cameras having low light capability were used in an attempt to observe ship characteristics during the night.

Discharge, Velocity, and Water Level Data

Discharge and velocity data from Acoustic Doppler Current Profiler (ADCP) measurements taken on September 19 at the 4 gage locations are shown in Table 2. Cross sections from the ADCP measurements at the 4 locations are shown in Figures 4-8. The observed preliminary water levels from the NOAA tide gage at FP are shown in Figure 9. Water levels and channel bathymetry are presented in MLLW. Winds during the field study were generally low which was important at the TI gage to prevent problems with separating wind waves from ship waves. Until about midday on the 19th, winds were from the south at about 4 knots. After midday on the 19th, winds were from the east-northeast at about 10 knots. The TI gage was protected somewhat from wind waves from the east-northeast by Tybee Island Point as shown in Figure 1.

Pilot Information

Along with the camera information, ship transit information was obtained from the Savannah Bar Pilots that included the ship name, the time and date the pilot boarded the ship, direction of travel, dock location, time of docking for inbound transits, and draft (assumed to be average draft because bow and stern draft was not provided). In addition to these parameters, various sources were used to obtain ship type, tonnage, overall length, and beam. This data is shown in Table 3. Each camera and wave gage had known time stamps. Team members recorded daytime ship passage events at the Coast Guard station just west of the FP gage. All of these data were used to determine when specific ships passed each wave gage as shown in Table 3.

Measured Water Level Data

The time histories of water level at the four locations along the channel are shown in Appendix A-D. The results for the two capacitance gages were similar so only one was plotted.

Summary of Field Study Results

The field study provided an understanding of the important shoreline forces in the Savannah Harbor channel as well as needed data. Results of the field study showed that short period bow and stern waves are important and provided data to select and modify a short period wave equation. The field study also provided speed data that was previously not available and insight into whether the south jetty would block ship effects from reaching TI.

3 Pilot Interview

As stated previously, ship speed is one of the most critical questions in a ship effects evaluation. Wilbur Wiggins of the Savannah District interviewed Master Captain Tommy Brown of the Savannah Bar Pilots using questions prepared by ERDC. The objective of these questions is to collect as much pertinent information as possible about ship operation in the existing and deepened channels.

a. What is the policy for running big ships (such as those with draft near design channel depths) and small ships (such as unloaded) relative to tide levels and direction of tides? Vessels have to be operated at a safe maneuvering speed but have to be run at a "competitive rate" – can't go slow (like 6 knots) – would take too much time to transit in and out of the harbor.
b. Of the 5 power levels of dead slow, slow, half, maneuver full, and full available to be used in ship transit, what power level is typically used in transiting the existing SH channel? Operates under maneuver full unless ship too powerful – have to use different speed for different ships – ship speed also varies by location in the harbor (faster in entrance channel to slow by city front) Does this power level vary with ship type and if so, what is the power level for each ship type Power level varies – may run 17 knots w/ powerful container vessels versus 12 knots for tankers and general cargo vessels
c. What power level do you anticipate in the deepened channel with deeper draft vessels? About the same – possibly slower, depending on how each ship handles
d. Where are areas along the channel where you tend to not run along the channel centerline (because of channel alignment or other factors) and where do you run in each of those reaches? Normally run the centerline of the channel unless meeting another vessel
e. What are typical and maximum speeds in the existing channel for container ships? For tankers or bulk carriers? Container – 12 to 14 knots, tanker/bulk 10-12 knots, not too powerful
f. What will be typical and maximum speeds in the deepened channel for the different ship types? Should be about the same
g. How does nighttime operation affect ship operation and ship speed? Does not affect
h. Are there other pertinent issues we have not raised that will help us understand ship operation and ship speed in existing and deepened channels? No

i. After analysis of the ship transit data, it was apparent that few of the post- Panamax ships were present during the field study to obtain both speed and ship effects data. Captain Brown was asked whether the speed of Panamax ships (for which substantial speed data was collected in the field study) differs from post Panamax ships in the existing channel. Captain Brown said he did not think that the speed would differ between Panamax and post-Panamax vessels.

From the pilot interview, the ship speeds of 12-14 knots are consistent with the speeds observed in the field study. The statement about use of maneuver full in both existing and deepened channels is consistent with other channels studied by this author.

4 Ship Traffic Frequency

Table 4 shows the characterization of the 6 ship types used in the SAS's analysis of future ship traffic including length, beam, and design draft. Table 5 shows the actual traffic distribution during the field study according to the 6 vessel types used in the traffic analysis. Each field study ship was placed in one of the 6 categories having beam closest to the actual beam. The average draft, beam, length, and actual tonnage are shown for the field study ships in each of the 6 categories in Table 5. Notice that the average draft of the field data ships in all but the Feedermax ship category is about 80% of the design draft.

Ship traffic is quantified by the number of calls with each call being equal to one inbound and one outbound transit. Based on the SAS's traffic analysis, the total number of calls will be the same for both without and with project for all traffic scenarios for any given year. For example, year 2030 has 4030 calls and year 2050 has 7801 calls for all traffic scenarios for both without and with project. Table 6 shows number of vessel calls for 4 traffic scenarios for future years 2030 and 2050. The 4 traffic scenarios are the Gulf Engineers and Consultants (GEC) forecast, GEC with 10% shift from Panamax (PA) to Post-Panamax (PP), GEC with 20% shift from PA to PP, and GEC with 30% shift from PA to PP. The only difference between the 4 scenarios is the number of PP and PA ships. The number of Sub-Panamax (SP), Handysize (HS), Feedermax (FM), and Feeder ships do not change. In 2030 the total number of PP and PA ships is 3544 for all 4 scenarios. In 2050 the total number of PP and PA ships is 7009 for all 4 scenarios. To determine the change in traffic between the GEC and the % shift scenarios, the specified percentage (such as 10%) of the total number of PP and PA ships is added to the number of PP ships and subtracted from the number of PA ships.

The vessel effect comparisons presented herein are for without project versus with project conditions for the years 2030 and 2050. Two draft conditions will be used in the analysis as follows: a) design draft and b) 80% of design draft as found during the field study. The only difference between the without project and with project traffic is the draft of the PP ships and the speed that ships will travel in the existing versus future deepened channel. All other ships, including Panamax, can draft their design draft in the without project (existing) channel. In the without project (existing) channel, PP ships are limited to 40.7 ft of draft compared to 45.3 ft in the with project (deepened) channel. The comparisons of without to with project will use a typical power setting and thus typical speed determined from the field study. Without and with project will also be compared using a higher power and thus higher ship speed. As will be shown subsequently, the typical speed in the with project deepened channel is slightly greater than the typical speed in the without project existing channel. In the same manner, the high speed in the with project deepened channel is slightly greater than the high speed in the without project existing channel.

5 Ship Speed Analysis

Ship speed in the Savannah Harbor field study was determined in several ways. First, team observers were present during daylight hours at the Coast Guard (CG) Station for several days during the study. Using a stop-watch, the time required for the bow and stern of the ship to pass a fixed point on the horizon was used with overall ship length to determine ship speed over ground. In a similar manner, the cameras were used to determine passage time for bow to stern at a fixed point on the screen and this differential time was used with overall ship length to determine ship speed over ground. Bow to stern passage time is a reliable means of determining ship speed. The low-light cameras were used in this study to try to use the bow to stern time differential for nighttime ship passage. The low light cameras resulted in limited success because identifying the precise location of the bow and stern remained difficult even with the low light cameras. This technique works best when there are various small light sources in the background that go off and on as the ship blocks the light sources. While numerous lights were present at CF and some lights were present north of the TI camera, none were present at FP and too much light was present at CDF from the Liquid Natural Gas facility on the south side of the channel.

Another speed technique that can be used at night with the cameras is to determine the field of view width of the screen and use the time of passage across the screen to determine ship speed. This worked well at TI because the camera was 4500 ft away from the channel and with the amount of camera zoom used, the angle of the field of view at TI was about 22 degrees and view width at the channel centerline was about 1730 ft. By having a small angle in the screen width, the errors that arise from the ship not being on the channel centerline are small. At FP, the view angle was 27 deg, which was also adequate. At CDF, the channel and camera were close together which required a wide camera zoom and resulted in about a 68 deg angle of the field of view. The extreme width of angle causes significant errors in speed for ships not on the channel centerline. The final method to determine ship speed is to use the time of ship passage at two points along the channel with their distance apart to determine an average speed over the reach. Time of passage at either end of the reach can be obtained from cameras, capacitance gages, or pressure cells that measure ship effects with the exception of the capacitance gages at TI because of their large distance from the channel. The reach average technique was used from TI to FP (10070 ft apart), FP to CDF (44400 ft apart), and CDF to CF (28700 ft apart). In this study, daytime passage with operating cameras always used bow to stern time from the camera. Nighttime passage with operating cameras used bow to stern at CF, CDF, and FP. Nighttime passage with operating cameras at TI used field of view width. When cameras were not operating, only average reach speeds could be determined and the capacitance gages and pressure cells provided time of passage. Table 7 shows the speeds determined for each ship in the study.

Figures 10 and 11 show inbound and outbound ship speeds relative to ground along the project reach. Speeds are summarized in Table 8. Both directions show speed decreasing toward CF and decreased speed at the Coast Guard dock that is close to the Pilot's dock. Inbound ships show the speed has decreased by up to 1.5 knots between the FP and the Coast Guard. Outbound ships show the speed has increased by up to 1.5 knots between the Coast Guard and FP. The FP camera speed is about equal to the average reach speed between CDF and FP. The average reach speed from CDF to FP is somewhat misleading because the camera speeds on each end of the CDF-FP reach are generally less than the average along the reach. Only one explanation is possible, the ship was going faster than the reach average over a significant portion of the reach. Based on the data, inbound and outbound speeds are similar.

The speeds were also analyzed for differences between night and daytime speeds as shown in Table 8. Data show a tendency for lesser nighttime speeds but it should be noted that nighttime speeds are generally the least accurate because of the greater uncertainty in the location of the bow and stern when using cameras. The data were also analyzed for effects of ship size on ship speed. A simple relation describing ship size is an estimate of the actual tonnage equal to (product of the length, beam, and draft)*block coefficient (C_b)*weight of water/2000 lbs per ton. Since block coefficient is not known for all ships, the PIANC table for typical ship dimensions and C_b was used to identify the appropriate C_b. This actual tonnage estimate is plotted against ship speed for the various locations along the channel in Figures 12 to 18. The data show a small increase in speed for decreasing ship size at CF camera and CF-CDF average which likely reflects the confined and congested area in the vicinity of CF that could have a greater influence on larger ships. At CDF and all locations downstream, variation of speed with ship size is not significant.

This paragraph answers the critical question presented in the introduction of how to determine comparable speeds in without project (existing) and with project (deepened) channels. This study is based on the premise that it is not valid to simply assume that speeds will be equal in the without project existing and the with project deepened channels because channel size affects ship speed. In the analysis of ship effects at FP and TI presented subsequently, ships in the existing channel will traverse the channel at the overall average speed given in Table 8 for both locations. This overall average speed will be used as the typical speed for ships in the without project existing channel. While the trend of all ships in the existing channel and existing fleet is no significant change in speed with ship size, the analysis herein focuses on comparing the same ship in existing and deepened channels. For example, consider the Panamax ships that are the most frequent ships in both existing and deepened channels. In both channels, the ship size at design draft conditions is 40.7 ft draft X 951 ft length X 106 ft beam. Based on this writers experience in study of other channels and the pilot interview, the Panamax ship will traverse both existing and deepened channels using maneuver full power. Since the deepened channel is 5 ft deeper and 4% greater in area, the Panamax ship will have a slightly higher speed in the deepened channel. To determine the typical ship speed in the deepened channel requires use of the assumption that the power setting will remain the same in existing and deepened channels. Note that this assumption is not that maneuver full will always be used for all ships, only that the power level will be the same in both channels. Since applied ship power is the same in both channels, the resisting force of both ships in both channels will be the same. Resisting force is determined using techniques in Maynord (2000) and depends on channel characteristics, return velocity and drawdown, ship size and type, and speed that are all known for the existing channel. The Schijf equation in the NAVEFF model (Maynord, 1996) was used to determine average return velocity and drawdown. Equating resistance force in existing and deepened channels and knowing ship size and type and channel characteristics in the deepened channel allows determining ship speed in the deepened channel. As will be shown subsequently, ship speed increased only 0.5 to 1.8% (0.05 to 0.25 knots) in the deepened channel. This small increase in ship speed reflects the fact that the channel area only increased about 4% in the deepened channel. The small increase in speed is consistent with the pilot's statement that ship speed in the deepened channel will be about the same.

6 Short Period Wave Model

The short period wave equation used herein was a modification of the equation used by Blaauw et al (1984) and Knight (1999) for maximum short period waves formed at bow and stern of the ship given as

$$H_{\max} = \beta \frac{B}{L_e} s^{-1/3} \left(\frac{V}{\sqrt{g}} \right)^{2.67}$$

Equation 1

Where

H_{max} is the maximum wave height
β is a coefficient,
B is the beam of the ship,
L_e is the entrance length of the ship,
s is the lateral distance from the ship,
V is the ship speed through the water,
g is the gravitational acceleration

Blaauw and Knight used a single coefficient to represent $\beta B/L_e$ and specified that single coefficient for particular vessels and vessel sizes. The modification used herein is to keep the coefficients separate with B/L_e representing ship hull shape effects and β representing ship size effects. The ratio B/L_e is determined using limited data from

$$\frac{B}{L_e} = 1.11 C_b - 0.33$$

Equation 2

Based on the range of C_b in Table 5, B/Le only varies from 0.42 to 0.55. The coefficient β was determined using the field study data from the FP and CDF gages. FP and CDF are 800 ft and 600 ft respectively from the center of the channel. The field data have many factors varying which makes the determination of β approximate. These factors include (1) wave shoaling at low tides described previously that would increase wave heights by 50 to 75% over deepwater wave heights, (2) unknown and variable lateral position of the ship, (3) different ship hull shapes and sizes, (4) upbound and downbound ships, (5) speed uncertainty that is particularly a problem because the wave equations use speed to about the third power, and (6) FP is a reach where the outbound ships are generally accelerating and inbound ships are generally decelerating. Only those ships having the best speed data were used in the analysis that generally came from daytime camera speeds. There were 22 inbound ships and 14 outbound ships. For all ships, β was determined to be

$$\beta = 0.0002 * beam * draft$$

Equation 3

Where

beam and draft are both in feet

Because this coefficient in the wave equation requires specific units, it should not be used as a general equation for wave height in navigation channels and is restricted to the Savannah Harbor analysis. The coefficient β is limited to a minimum of 0.2. The values derived from the product of *B/Le* and β for the Savannah Harbor data range from 0.2 to 0.64 and are similar to the range of values used by Blaauw et al (1984) and Knight (1999). The data are plotted in Figure 19 with observed wave height versus computed wave height. Several of the values on the right side of the plot having low computed wave height were ships that passed at low tide levels that would have likely resulted in shoaling of the wave heights by a factor of ranging up to 1.5.

Kamphuis (1987) found correlation of shoreline recession with wave power. Wave power per unit length of shoreline is determined as

$$P = \frac{\rho g^2 H^2 T}{16\pi}$$

Equation 4

Where

ρ is the water density
H is wave height
T is the wave period

Kamphuis used wave power in the breaking zone. Equation 4 is applicable to wave power for deep water waves and will be used herein only to compare existing and deepened channels.

7 Fort Pulaski Ship Forces Analysis

The without project (existing) and with project (deepened) cross sections at the FP gage are shown in Figure 6. The deepened 48-ft deep channel cross section assumes advance maintenance of 2 ft at FP. In ship effects studies, channel cross-section area is an important factor and the effective width and cross-section area are determined that eliminate the shallow areas on each side of the channel. The effective channel area was determined to be between bottom contours of –15 ft MLLW based on the bottom contour giving the lowest displacement effects. In the FP cross section in Figure 6, the channel width at a bottom contour of –15 ft MLLW is 1600 ft and effective channel area at a mean tide level of 3.7 ft MLLW is 63980 sq ft. With the navigation channel deepened to –50 ft MLLW, the effective channel area is 66800 sq ft and effective width remains at 1600 ft. The increase in effective area is only about 4.4%.

The typical speed of the design ships (80% of design draft and design draft) in the existing channel are set equal to the observed average speed from the field study of 11.7 knots. The design ships are also evaluated at a speed of 2 knots greater than the speed observed in the field study or 13.7 knots for the FP site in the existing channel. The higher speed was used to address a broader range of conditions and to see if conclusions were affected by the ship speed used in the analysis. The 2 knot speed increase at FP was selected because 13.7 knots is near the maximum speed observed in the field study. As will be seen subsequently, the selected ship power or speed did not affect the conclusions.

Ship speed in the deepened channel was based on techniques described in the “Ship Speed Analysis” section. Ship speeds in the deepened channel are only 0.5 to 1.8% greater except for the post-Panamax ships where draft increased from 40.7 ft to 45.3 ft in the deepened channel. For the 45.3 ft draft post-Panamax ship in the deepened channel, ship speed decreased 4-5%. The smallest category of ship, Feeder, is not used in Table 9 because the % of ships of this type is negligible. In all cases, each ship in the deepened channel had slightly less drawdown and return velocity as shown in Table 9. The conclusion of slightly less drawdown and return velocity in the with project deepened channel is true for both the typical speed comparison and for the high speed comparison. For example, at typical speeds and 80% draft, the post-Panamax ship had 1.87 ft of drawdown in the without project existing channel and 1.78 ft of drawdown in the with project deepened channel. In the same manner, at high speeds and 80% draft, the post-Panamax ship had 3.64 ft of drawdown in the without project existing channel and 3.58 ft of drawdown in the with project deepened channel. The same trends and conclusions result from typical and high speed comparisons although absolute magnitude of return velocity and drawdown differs for the two speeds. Short period bow and stern wave heights are also shown in Table 9. Because ship speed is slightly greater in the deepened channel than in the existing channel, short period bow and stern waves that depend on ship speed to an exponent of 2.67 will be greater in the deepened channel. The conclusion of slightly greater short period bow and stern wave heights in the with project deepened channel is true for both the typical speed comparison and for the high speed comparison.

Using the frequency of calls in Table 6 to incorporate the different fleet characteristics, a composite return velocity, drawdown, and short period bow and stern wave height can be developed for comparing the without project (existing) and with project (deepened) channels. For example, composite drawdown in the existing channel with the 80% draft, 2030 GEC traffic estimate, and typical ship speed is (% of PP)*(PP drawdown) + (% of PA)*(PA drawdown) + (% of SP)*(SP drawdown) + (% of HS)*(HS drawdown) + (% of FM)*(FM drawdown) = 0.052*1.87 + 0.827*1.14 + 0.063*0.96 + 0.053*0.66 + 0.004*0.40 = 1.14 ft. Tables 10-13 show all the composite parameters for FP for the 4 traffic scenarios. Conclusions and trends are the same for 2030 and 2050 and for the 4 traffic scenarios. For example, composite drawdown for typical speed, typical (80%) draft in the existing channel for 2030 GEC traffic is 1.14 ft versus composite drawdown for typical speed, typical (80%) draft in the deepened channel for 2030 traffic of 1.08 ft. Composite drawdown for high speed, typical (80%) draft in the existing channel for 2030 traffic is 2.09 ft versus composite drawdown for high speed, typical (80%) draft in the deepened channel for 2030 GEC traffic of 2.00 ft. The comparison of without project to with project composite values show the same trends and conclusions for both typical speed and higher ship speed. Considering all values in Tables 10-13, composite return velocity and drawdown at FP are about 3.2 to 6.2% less in the with project (deepened) channel.

Composite short period bow and stern wave heights at FP in Tables 10-13 show no significant difference between 2030 and 2050 but show small changes in the with project channel between traffic scenarios. All composite wave heights in Tables 10-13 range from 1.5 to 4.4% greater in the deepened channel.

Wave power, found by Kamphuis (1987) to correlate with shoreline recession, was calculated with equation 4. Bow and stern wave periods from the field study were 3-3.5 sec. The composite short period wave height increases of 1.5 to 4.4% result in wave power increases of 2.3 to 19%.

8 Tybee Island Ship Forces Analysis

One unusual characteristic of the ship effects evaluation at TI is the presence of the partially submerged jetty on the South side of the ship channel and a less partially submerged jetty on the north side of the channel. The south jetty is about 3400 ft north of the TI gages and has a variable top elevation that averages about 4 ft above MLLW. The north jetty has an average top elevation of about 7 ft MLLW. The jetties are about 2400 ft apart. The presence of these jetties makes it important to analyze differences between ships at low and high tides as well as inbound versus outbound. As stated previously, ship effects at the shoreline of navigation channels are generally short period bow and stern waves and long period drawdown or pressure wave effects. Short period bow and stern waves will likely decay in amplitude before reaching the TI shoreline that is about 4500 ft from the center of the ship channel. Bow and stern wave height generally decays with $(\text{distance})^{-1/3}$ (Sorensen, 1966). At 4500 ft from the ship, the secondary wave will be about 10% of the wave height at the ship. Any significant ship effects reaching the TI shoreline will likely be the result of the long period drawdown or pressure wave that can travel significant distances. At low tides, the jetty blocks south movement of ship effects while the ship is within the jetties. Even at high tides, the south jetty provides a significant barrier to long period ship effects. Any ship effects reaching the shoreline at the TI gages at low tides must come from outside of the east end of the jetties along a line that is about 5500 ft from TI gages to the center of the ship channel.

The ships were separated into those passing with tides of 4 ft MLLW or less and those with 7 ft MLLW or greater. Ship passages during the intermediate range of 4 to 7 ft MLLW were excluded because small depths over the jetty may or may not pass significant ship effects over the top of the jetty. The ships were also separated into inbound and outbound resulting in four different groups. Within each of the four groups, the ship effects patterns and magnitudes exhibit significant differences due to differences in draft, speed, tide direction and magnitude, ship type, and ship lateral position. Table 14 shows each ship in the 4 categories along with the drawdown at the TI wave gage. Each of the 4 categories have a ship or ships that produce drawdown of 1 ft or greater. There appears to be no strong correlation of drawdown with either stage or direction of travel. It is not possible to conclusively determine whether significant ship drawdown passes over the South jetty at high tides. The main correlation in the data is that large fast ships cause the most impact. There are several ships that defy the trend of bigger faster. Under inbound high stage ships, the MSC Eleni and Stuttgart Express are large fast ships that created little impact. The only ship in the inbound high stage category that causes any significant impact is the Jens Maersk that is somewhat compromised because it met the Talisman at TI. There is no obvious explanation for the lack of impact unless the ships were going slow before entering the jetties and fast by the time they reached the location where the TI camera monitored their speed. Several outbound high stage ships caused 6-8 sec period waves that had a height of about 1 ft. These included the Hanjin Wilmington and Mol Velocity.

Summarizing, TI experiences ship effects at both high tides over the south jetty as well as low tides below the top of the south jetty. Ship effects are caused by long period drawdown that moves from the ship channel to the TI shoreline. The drawdown causes a variety of effects when reaching the shallow shoreline area including 6-8 sec period waves having height of up to 1 ft and/or surge above the still water level. Drawdown magnitude at the TI shoreline is almost always less than that measured for the same ship at FP.

The design ship analysis for TI will be similar to the FP analysis but only drawdown will be used to quantify ship effects. In the TI cross section in Figure 5, the channel width at a bottom contour of –15 ft MLLW is 1620 ft and effective channel area at a mean tide level of 3.7 ft MLLW is 64175 sq ft. With the navigation channel deepened to –50 ft MLLW, the effective channel area is 66793 sq ft and effective width remains at 1620 ft. The increase in effective area is only about 4.3%. The effective areas and widths at FP and TI are almost identical. The typical speed of the design ships in the existing channel is set equal to the observed average speed from the field study of 12.9 knots. A faster design ship traveling at 1.5 knots greater than the typical speed will also be used in the analysis. An increase of 1.5 knots at TI was used because the Schijf equation for return velocity and drawdown does not apply using a 2 knot increase. This is not significant because a 1.5 versus a 2 knot speed increase will not affect the findings. Both the typical (80% of design draft) and design draft will be used in the analysis as shown in Table 15. In all cases, the design ship in the deepened channel had slightly less drawdown than the existing channel. Note that the computed drawdown is based on the ship located inside the jetties whereas the actual drawdown at TI shoreline may be generated while the ship is outside the jetties. The Table 15 values are for comparison purposes of without and with project. The Table 15 drawdown is generally much larger than the values that were measured at the location 4500 ft away from the center of the ship channel. In the field data, drawdown for all tests in Table 14 averaged 0.55 ft compared to PA ships in the existing channel at typical speeds having drawdown of 1.62 ft. Based on this comparison, drawdown magnitude at TI shoreline will be about 1/3 of drawdown computed for the ship between the jetties shown in Table 15.

Tables 16-19 present the composite drawdown using the drawdown from Table 15 and the traffic frequency from Table 6 to incorporate fleet composition. Conclusions and trends are the same for 2030 and 2050 and for the 4 traffic scenarios. Conclusions and trends are the same using typical speed and higher ship speed. Composite drawdown is 2.3 to 5.9% less in the with project (deepened) channel.

9 Confined Disposal Facility and City Front Ship Effects

At CDF and CF, SAS requested a table showing ship effects in the existing channel. Drawdown is used to quantify ship effects in the existing channel as shown in Table 20 for the CDF ships having significant effects. Field data for the Table 20 ships are presented in the Appendix. Due to the similarity of conditions at CDF and FP, an analysis for CDF like the FP analysis would likely result in the same conclusions as for FP.

The CF site differs from the other channel sites (CDF and FP) because ship speed, that is the most important parameter for short period waves, is too low for short period bow and stern waves to be an impact. For example, using equation 1, only one ship at CF had computed wave height exceeding 0.5 ft. The long period drawdown will be the primary ship effect to quantify at CF. The lack of significant short period bow and stern waves is the reason pressure cells were employed at the CF sites. Table 21 shows ship-induced drawdown for the CF ships. Field data for the Table 21 ships is presented in the Appendix.

10 Summary and Conclusions

Ship forces having the potential to cause shoreline erosion were evaluated at the Savannah Harbor to compare the without project (existing) and the with project (deepened) channels. Results of this study will be used by the Savannah District in a separate study to evaluate shoreline erosion.

An analysis of ship forces requires determination of comparable ship speeds in the without project (existing) and with project (deepened) channels. Field data were used to determine ship speed in the without project (existing) channel. An analytical model for ship speed, along with the assumption of equal power setting in the without project and with project channels, was used to determine ship speed in the with project channel.

Based on the Districts ship traffic analysis, the total number of ships will not change in without project (existing) and with project (deepened) channels. Four traffic alternatives were evaluated that primarily differ in the number of post-Panamax ships compared to Panamax ships. Without project (existing) and with project (deepened) conditions primarily differ in draft of the post-Panamax ships and speed of all ships.

A composite value of the various ship effects was used to compare the without project (existing) and with project (deepened) channels. The composite value is based on the magnitude of ship effect for 6 different vessel classes as well as the proportion of each vessel class in the overall fleet.

At Fort Pulaski, dominant ship effects include short period bow and stern waves and long period drawdown and return velocity. As shown in Tables 10-13, the composite return velocity and drawdown per ship are 3.2 to 6.2% less in the with project (deepened) channel. Conclusions and trends are the same for 2030 and 2050 and for the 4 traffic scenarios. Due to the slightly higher speed in the with project (deepened) channel, short period bow and stern waves are the shoreline attack force that increases in the with project (deepened) channel at Fort Pulaski. The composite short period bow and stern wave height per ship for years 2030 and 2050 is 1.5 to 4.4% greater in the deepened channel. Small changes in composite short period bow and stern waves were observed between the 4 traffic alternatives.

At Tybee Island, the only significant ship effect reaching the shoreline is the long period drawdown or pressure wave. It is uncertain if the south jetty blocks ship effects at high tides because ship effects generated outside the jetties reach the TI shoreline. As shown in Tables 16-19, the composite drawdown in the channel between the jetties per ship is 2.3 to 5.9% less in the with project (deepened) channel. The actual drawdown at the TI shoreline will be about 1/3 of the drawdown in the channel between the jetties.

Ship effects were tabulated and plotted for the City Front and Confined Disposal Facility sites.

11 References

Blauuw, H., van der Knaap, F., de Groot, M., and Pilarczyk, K. (1984). “Design of bank protection of inland navigation fairways”, Delft Hydraulics Laboratory Publication No. 320, Delft, The Netherlands.

Kamphuis, J. (1987). “Recession rate of glacial till bluffs”, ASCE Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol 113, No. 1, January, pp 60-73.

Knight, S. (1999). “Wave-height predictive techniques for commercial tows on the Upper Mississippi River-Illinois Waterway System”, ENV Report 15, US Army Engineer Research and Development Center, Vicksburg, MS.

Maynord, S. (1996). “Return velocity and drawdown in navigable waterways”, Technical Report HL-96-7, US Army Engineer Research and Development Center, Vicksburg, MS.

Maynord, S. (2000). “Power versus speed for shallow draft navigation”, ASCE Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol 126, No. 2, Mar/Apr, pp 103-106.

Maynord, S. (2003). “Ship effects before and after deepening of Sabine-Neches Waterway, Port Arthur, Texas”, ERDC/CHL TR-03-15, US Army Engineer Research and Development Center, Vicksburg, MS.

Sorensen, R. (1966). “Ship waves”, Technical report HEL-12-2, University of California, Berkeley, CA.

Table 1. Gage Locations

Location	Side of Channel	Depth, time at instrument	Starting, end date/time of Gage	Starting, end date/time of Camera	State Plane, ft Georgia East 1001
City Front	South	10-12 ft 9/17 at 1323 EST	9/17 at 1323 EST, 9/21 at 0600 EST	No camera on South	989350, 758867
City Front	North	10-12 ft 9/17 at 1313 EST	9/17 at 1313 EST, 9/21 at 0600 EST	9/17 at 1430 EST, 9/21 at 0756 EST	989966, 759588 Camera at 990049, 759744
Confined Disposal Facility	North	2.4 ft at 9/19 1450 EST	9/18 at 1200 EST, 9/21 at 0600 EST	9/15 at 1620 EST, 9/21 at 0600 EST	1015691, 766862
Fort Pulaski	South	2.3 ft at 9/19 1416 EST	9/16 at 1400 EST, 9/20 at 1400 EST	9/18 at 1445 EST, 9/20 at 1400 EST	1050315, 741509
Tybee Island	South*	3.6 ft at 9/19 1328 EST	9/16 at 1200 EST, 9/20 at 1200 EST	9/16 at 1215 EST, 9/20 at 1200 EST	1062178, 739026 center of view in camera in channel = 1060478, 743335

*South of jetty on TI

Table 2. Discharge and velocity from ADCP measurements.

Location	avg time EST	Tide Level at Ft Pulaski [ft]	Total Q [ft³/s]	Total Area [ft²]	Width [ft]	Q/Area [ft/s]	Tide Direction
Tybee, inside jetties	7:37:00	8.20	158947	74074	1852	2.1	Flood
Tybee, inside jetties	7:45:00	8.35	154275	86204	2227	1.8	Flood
Fort Pulaski	7:58:00	8.46	-179768	77943	2045	2.3	Flood
CDF	8:20:00	8.60	-115335	64451	1842	1.8	Flood
CDF	8:27:00	8.64	-113793	64344	1710	1.8	Flood
Tybee, gage to jetty	13:35:00	1.50	61689	30923	3452	2.0	Ebb
Tybee, inside jetties	13:54:00	1.00	-214458	65271	2239	3.3	Ebb
Fort Pulaski	14:07:00	0.70	210841	67189	2129	3.1	Ebb
CDF	14:40:00	0.10	138200	50467	1443	2.7	Ebb
City Front	15:10:00	-0.20	-73799	36504	944	2.0	Ebb

Table 3. Ship Log with Ship Characteristics and passage time at gages for inbound ships.

Name	type	gross tonnage	length, ft	beam, ft	draft, ft	Direct	date	Dock	CF	CDF	FP	TI	POB time
INBOUND:													
flintereems	gen cargo	4503	367	49.2	20	in	15-Sep	1615		1509			1320
khannur	lng	96235	961	136.8	37.1	in	15-Sep	1645					1330
maersk garonne	cont	50698	958	105.9	32.66	in	15-Sep	2045		1854			1720
ym south	cont	46697	906	105.6	37.9	in	15-Sep	2300		2036			1810
Jiang An Cheng		16703	571	83.97	23.75	in	15-Sep	115		2322			2130
leyla kalkavan	cont	9978	489	74.46	22.9	in	15-Sep	200		16			2245
xin fang cheng	cont	41482	861	105.9	31.8	in	16-Sep	620		417			250
new york express	cont	54437	965	105.9	29.5	in	16-Sep	725		530			400
kyriakoula	oil tanker	40680	750	105	28	in	16-Sep			1555	1520	1514	1405
sun right	cont	53359	965	105	37.9	in	16-Sep	1725		1549	1512	1502	1420
mol americas	cont	16803	604	82	27.1	in	16-Sep	1915		1800	1730	1725	1645
jens maersk	cont	30166	710	105.6	33.8	in	16-Sep	2050		1902	1836	1828	1750
cma cgm potomac	cont	31154	705	101.7	30.2	in	16-Sep	2320		2142	2104	2054	2005
zim israel	cont	37204	754	105.6	27.6	in	17-Sep	415		242	203	149	55
msc christina	cont	37579	745	105.9	32.25	in	17-Sep	450		314	230	222	130
mol elbe	cont	50352	959	105.6	34	in	17-Sep	505		329	247	238	150
msc eleni	cont	54881	932	137.8	36.25	in	17-Sep	1055		918	842	834	750
midnight sun	oil tanker	27915	590	105.6	27.6	in	17-Sep	1700	1600	1523	1447	1433	1335
darya rani	bulk	26054	610	99.71	25.9	in	17-Sep	1805	1642	1611	1535	1526	1430
alyona	cargo	32226	674	101.7	26	in	17-Sep	2355	2233	2156		2102	2015
zim iberia	cont	41507	833	105.9	33	in	18-Sep	550	432	352	310	303	145
al mariyah	cont	32534	694	105.9	28.7	in	18-Sep	1125	1023	953	918	910	825
msc elena	cont	30971	662	105.9	33.3	in	18-Sep	1235	1130	1055	1020	1010	925
emmanuel tomasos	oil tanker	23217	599	90.86	28	in	18-Sep	1535	1444	1406	1326	1311	1215
hanjin wilmington	cont	51754	950	105.6	34.4	in	18-Sep	1755	1655	1627	1547	1540	1445
condor	cont	14241	521	79.05	26.75	in	18-Sep	1950	1850	1818	1742	1736	1650
Victoria Bridge	cont	53400	965	105.6	36.1	in	18-Sep	225	37	4	2320		2200
essen express	cont	53815	965	105.9	35.5	in	19-Sep	710	538	509	430	424	330
kavo alexandros II	bulk	16608	551	85.94	30	in	19-Sep	915		824	747	741	650
angel accord	bulk	20212	581	93.15	23.1	in	19-Sep	1820	1747	1714	1630	1620	1530
mol velocity	cont	53519	965	105.9	30.5	in	19-Sep	1945	1828	1758	1722	1715	1630
borc	gen cargo	20139	531.5	88.56	35.2	in	19-Sep	2040		1930	1849	1840	1735
jervis bay	cont	50350	959	105.9	30.6	in	19-Sep	2150		1944	1908	1901	1815
ismini	oil tanker	37405	717	105.6	38	in	19-Sep	2230	2117	2044	2010	2002	1905
stuttgart express	cont	53815	965	105.9	37.6	in	19-Sep	125	2356	2320	2246	2240	2150
aurora	tanker	16454	528	91.84	22.8	in	20-Sep	840		718	642	635	555
cecile ericksen	bulk	3461	373	50.84	20.5	in	20-Sep	1125		1035	959		855
cp rome	cont	26131	642	100	33.5	in	20-Sep	2210	2123	2051			1930
ville de taurus	cont	37549	850	105		in	21-Sep	415	306	225			30
onego spirit	bulk	10490	469	72.16	22.3	in	21-Sep	925					545
stolt capability	oil tanker	24625	580	101.7	26.6	in	21-Sep	1020	506				730
msc insa	cont	51608	868	105.9	37.7	in	21-Sep	1235					915
hilli	lng	96235	961	136.8	36.4	in	21-Sep	1355					1100
besire kalkavan	cont	9978	489	74.46	25.25	in	21-Sep	45					2140
xin nan tong	cont	41482	864	105.6	30.5	in	21-Sep	250					2330

POB = time pilot boards ship

Table 3. Concluded.

OUTBOUND:(SAIL)													
Name	type	gross tonnage	length, ft	beam, ft	draft, ft	Direct	date	POB time	CF	CDF	FP	TI	
schackenborg	Ro-ro	14775	530	79.7	21.7	out	15-Sep	140					
saimaagracht	gen cargo	18231	608	82.98	22.1	out	15-Sep	1830		1958			
northern fortune	cont	30509	664	102	34.75	out	15-Sep	1900		2049			
ANL georgia	cont	40465	850	105.6	35.1	out	15-Sep	1945		2121			
general lee	gen cargo	1614	206	50.18	9.5	out	15-Sep	2035		2130			
ym shanghai	cont	40268	259	105.9	33.5	out	15-Sep	2045		2233			
cape bird	oil tanker	25108	577	101.7	28	out	15-Sep	2200		2344			
khannur	lng	96235	961	136.8	37.1	out	16-Sep	1220				1323	
talisman	bulk ?	67140	790	99.38	30.8	out	16-Sep	1655		1745	1815	1828	
xin fang cheng	cont	41482	861	105.9	31.8	out	16-Sep	1825		1934	2006	2019	
ym south	cont	46697	904	105.6	36.75	out	16-Sep	1905		2042	2122	2131	
maersk garonne	cont	50698	958	105.9	35.1	out	16-Sep	1905		2055	2135	2143	
star drivanger	gen cargo	27735	600	101.7	29.3	out	16-Sep	2035		2126	2209	2219	
leyla kalkavan	cont	9978	489	74.46	27.8	out	17-Sep	110		204	237	243	
new york express	cont	54437	965	105.9	33.8	out	17-Sep	135		304	347	357	
star florida	gen cargo	23345	615	96.76	22.7	out	17-Sep	205		322	358	407	
jens maersk	cont	30166	710	105.6	33.5	out	17-Sep	220		342	425	433	
kyriakoula	oil tanker	40680	755	105	27.7	out	17-Sep	325		514	601	612	
mol americas	cont	16803	605	82	27.5	out	17-Sep	600		738	818	828	
sun right	cont	53359	965	105	37.4	out	17-Sep	740		928	1007	1019	
cma cgm potomac	cont	31154	705	101.7	35.4	out	17-Sep	1025	1130	1200	1235	1245	
flintereems	gen cargo	4503	367	49.2	15.4	out	17-Sep	1230		1256	1331	1338	
kochnev	gen cargo	6030	371	62.98	25.6	out	17-Sep	1330		1506	1548	1556	
Jiang An Cheng		16703	571	83.97	32.8	out	17-Sep	1510	1538	1606	1650	1701	
mol elbe	cont	50352	959	105	33.25	out	17-Sep	1810	1918	1950	2038	2044	
msc christina	cont	37579	797	105.9	32.25	out	17-Sep	1905	2007	2038	2113	2125	
zim israel	cont	37204	775	105.6	27.6	out	17-Sep	2100	2137	2205	2239	2250	
msc eleni	cont	54881	932	137.8	35.75	out	17-Sep	2345	42	106	140	147	
midnight sun	oil tanker	27915	590	105.6	26.9	out	18-Sep	1230	1328	1358	1435	1443	
alyona	cargo	32226	674	101.7	26.6	out	18-Sep	1935	1944	2017	2104	2112	
zim iberia	cont	41507	833	105.9	33.6	out	18-Sep	1930	2033	2100	2140	2147	
darya rani	bulk	26054	610	99.71	27.25	out	18-Sep	2035	2043	2110	2152	2205	
sumida	cont	13400	524	82	28.7	out	18-Sep	2105	2158	2225	2304		
al mariyah	cont	32534	694	105.9	30.2	out	18-Sep	2115	2212	2239	2315	2321	
msc elena	cont	30971	662	105.9	33.4	out	19-Sep	140	216/25	318	350	359	
condor	cont	14241	521	79.05	27.75	out	19-Sep	1310	1353	1423	1452	1458	
emanuelle tomasos	oil tanker	23217	599	90.86	24.6	out	19-Sep	1350	1426	1454	1527	1533	
nelson	bulk	13677	508.5	75.11	17.7	out	19-Sep	1745		1855	1939	1948	
victoria bridge	cont	53400	965	105.6	35.75	out	19-Sep	1805	1910	1945	2041	2049	
hanjin wilmington	cont	51754	950	105.6	35.75	out	19-Sep	1905	2015	2118	2148	2156	
julia	oil tanker	12165	518	73.14	30.3	out	20-Sep	35		140	222	229	
essen express	cont	53815	965	105.9	36.4	out	20-Sep	155	234	312	348	356	
mol velocity	cont	53519	965	105.9	34.4	out	20-Sep	740	836	918	957	1004	
kavo alexandros II	bulk	16608	551	85.94	29.1	out	20-Sep	910	**938**	1004	1046	1055	
angel accord	bulk	20212	581	93.15	22.2	out	20-Sep	1830	1913	1950			
stuttgart express	cont	53815	965	105.9	40.1	out	20-Sep	2005	2055	2150			
antares	gen cargo	4793	571	83.97	14	out	20-Sep	2215	2256	2314			
aurora	tanker	16454	528	91.84	22.7	out	20-Sep	2240	**2256**	2336			
jervis bay	cont	50350	959	105.9	35.6	out	21-Sep	30	124	157			
borc	gen cargo	20139	531.5	88.56	19.25	out	21-Sep	150					
cp rome	cont	26131	642	100	33.8	out	21-Sep	715					
ismini	oil tanker	37405	717	105.6	28.6	out	21-Sep	720					
cecile ericksen	bulk	3461	373	50.84	16.5	out	21-Sep	1350					
ville de taurus	cont	37549	850	105	36.1	out	21-Sep	1725					
msc insa	cont	51608	868	105.9	37.3	out	21-Sep	2000					

Table 4. Classes of Containership Traffic for Savannah Harbor

Vessel Type	Length, ft	Beam, ft	Design Draft, ft
Post-Panamax	1044	140	45.3
Panamax	951	106	40.7
Sub-Panamax	716.3	99.8	37.7
Handysize	579.1	85.1	31.8
Feedermax	427.5	67.7	25.2
Feeder	344.7	56.1	20.0

Table 5. Field Study Ships categorized according to vessel type used in Savannah District Fleet Forecast. Category based on ship beam.

Vessel, type	# of ship transits	Field Study Summary				
		Range of draft, ft	Average draft, ft (% of design draft)	Average Beam, ft	Average Length, ft	Tonnage of average ship
Post-Panamax	5	35.8-37.1	36.5 (81)	137.2	949	114200 (0.75)*
Panamax	49	26.9-40.1	33.4(82)	105.7	852	65300 (0.68)
Sub-Panamax	16	22.2-35.4	28.5(76)	99.7	641	42200 (0.72)
Handysize	18	14.0-35.2	25.8(81)	85.2	558	28800 (0.73)
Feedermax	9	17.7-30.3	24.1(96)	71.4	469	18800 (0.73)
Feeder	5	9.5-20.5	16.4(82)	50.1	337	7000 (0.79)

*Typical C_b

Table 6. Containership Traffic for Savannah Harbor. Numbers are for both without and with project. Values in () are % of total calls.

Vessel Type	GEC		10% Increase		20% Increase		30% Increase	
	2030	2050	2030	2050	2030	2050	2030	2050
Post-Panamax	211 (5.2)	291 (3.7)	565 (14.0)	992 (12.7)	920 (22.8)	1693 (21.7)	1274 (31.6)	2394 (30.7)
Panamax	3333 (82.7)	6718 (86.1)	2979 (73.9)	6017 (77.1)	2624 (65.1)	5316 (68.1)	2270 (56.3)	4615 (59.2)
Sub-Panamax	252 (6.3)	458 (5.9)	252 (6.3)	458 (5.9)	252 (6.3)	458 (5.9)	252 (6.3)	458 (5.9)
Handysize	215 (5.3)	315 (4.0)	215 (5.3)	315 (4.0)	215 (5.3)	315 (4.0)	215 (5.3)	315 (4.0)
Feedermax	18 (0.4)	18 (0.2)	18 (0.4)	18 (0.2)	18 (0.4)	18 (0.2)	18 (0.4)	18 (0.2)
Feeder	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)
Total Calls	4030	7801	4030	7801	4030	7801	4030	7801

Table 7. Ship Log with speeds for each ship, inbound ships.

Name	Dir	Day	CF camera speed, knots	CF - CDF average speed, knots	CDF camera speed, knots	CDF - FP average speed, knots	CG observation team speed, knots	FP camera speed, knots	FP - TI average speed, knots	TI camera speed, knots
INBOUND:										
flintereems	in	15			8.7					
khannur	in	15								
maersk garonne	in	15			9.0					
ym south	in	15			6.9					
Jiang An Cheng	in	15			6.8					
leyla kalkavan	in	15			4.6					
xin fang cheng	in	16			8.4					
new york express	in	16			7.7					
kyriakoula	in	16								
sun right	in	16			11.7	11.7			12.3	15.1
mol americas	in	16			5.0	15.0	13.8	13.8	12.6	15.6
jens maersk	in	16			13.6	16.1			13.2	16.3
cma cgm potomac	in	16			12.3	11.1			11.7	13.0
zim israel	in	17			5.5	10.1			9.7	10.9
msc christina	in	17			7.4	10.1			11.6	13.0
mol elbe	in	17			8.9	10.8			8.8	12.1
msc eleni	in	17			10.4	12.0			11.0	14.2
midnight sun	in	17	5.63	7.8	10.6	10.5	9.3		10.7	10.3
darya rani	in	17	6.70	9.2	9.5	11.7	11.6		12.4	12.0
alyona	in	17	7.41	7.8	7.4	10.7			8.0	11.6
zim iberia	in	18	5.16	7.1	6.9	10.4			11.1	11.3
al mariyah	in	18	6.52	9.5	10.8	12.2	8.3		13.5	13.7
msc elena	in	18	5.75	8.2	10.9	11.9	8.0		14.4	13.5
emmanuel tomasos	in	18	5.28	7.4	8.9	9.8	4.4		7.9	9.4
hanjin wilmington	in	18	6.64	9.1	10.3	10.9	9.1	10.4	11.2	11.7
condor	in	18	8.12	8.7	12.3	12.6	10.0	14.1	16.5	18.1
Victoria Bridge	in	18	6.34	8.1	8.3	10.6		9.8		
essen express	in	19	6.52	9.4	11.4	12.1		9.5	12.1	12.1
kavo alexandros II	in	19			9.6	12.2	10.7	13.0	14.1	14.2
angel accord	in	19		8.4	9.3	10.1	9.8	10.1	10.3	11.1
mol velocity	in	19		9.1	12.5	12.5	9.5	10.4	12.8	15.5
borc	in	19			8.8	10.8		10.8	11.6	11.3
jervis bay	in	19			10.1	12.0		11.9	14.1	14.3
ismini	in	19		8.4	9.9	13.2		12.9	15.5	12.2
stuttgart express	in	19		7.5	11.0	13.5		12.7	14.3	15.2
aurora	in	20			10.8	12.2		10.4		
cecile ericksen	in	20			11.1	11.7	10.4	11.6		
cp rome	in	20	9.72	9.0	11.6					
ville de taurus	in	21	5.93	6.7	8.7					
onego spirit	in	21								
stolt capability	in	21	11.44							
msc insa	in	21								
hilli	in	21								
besire kalkavan	in	21								
xin nan tong	in	21								

CG = Coast Guard

Table 7. Concluded

OUTBOUND:(SAIL)										
schackenborg	out	15								
saimaagracht	out	15			5.3					
northern fortune	out	15			5.3					
ANL georgia	out	15			6.3					
general lee	out	15			5.8					
ym shanghai	out	15			6.6					
cape bird	out	15			5.0					
khannur	out	16								11.1
talisman	out	16			10.8	11.0			11.7	14.2
xin fang cheng	out	16			12.5	13.5			7.7	14.2
ym south	out	16			8.8	11.3			10.3	12.2
maersk garonne	out	16			9.2	11.1			11.8	13.5
star drivanger	out	16			6.3	10.0			10.7	11.9
leyla kalkavan	out	17			10.7	14.6			11.5	13.8
new york express	out	17			9.7	10.0			11.0	11.3
star florida	out	17			10.7	12.2			10.8	11.7
jens maersk	out	17			10.6	10.5			15.6	12.7
kyriakoula	out	17			7.6	9.7			9.8	10.9
mol americas	out	17			11.6	11.6			11.4	14.3
sun right	out	17			9.7	11.2	10.4	10.7W	12.6	14.3
cma cgm potomac	out	17			11.6	12.9	10.5	11.0A	13.3	14.9
flintereems	out	17			11.4	12.7	12.0	12.5A	13.0	12.1
kochnev	out	17			11.0	10.8	9.6	10.0A	10.8	10.5
Jiang An Cheng	out	17	6.6	9.8	9.7	10.1	8.7	10.0A	10.6	10.6
mol elbe	out	17	5.2	8.7	10.0	12.5			11.6	11.9
msc christina	out	17	6.0	9.0	8.0					12.7
zim israel	out	17	8.1	9.8	10.7	13.2			10.4	13.9
msc eleni	out	17	7.1	10.8	10.3	13.0			14.4	13.3
midnight sun	out	18	6.6	9.8	10.3W	11.9	10.6	10.6A	11.4	13.0
zim iberia	out	18	8.1	8.1	7.5	9.7		12.3	13.3	13.0
alyona	out	18	6.2	10.6	7.8	11.2		10.3	11.0	10.1
darya rani	out	18	8.2	10.2	7.2					11.3
sumida	out	18	6.8	10.1	7.8	12.2		12.0		
al mariyah	out	18	7.0	10.8	9.0	11.9		13.3	14.4	13.8
msc elena	out	19	7.8	11.9	10.9	12.4		12.3	13.5	11.9
condor	out	19	7.7	9.8	14.7W	14.6	13.5	12.9	14.5	16.2
emanuelle tomasos	out	19	7.2	10.0	12.3W	13.9	13.5	14.2W	15.2	16.1
nelson	out	19			9.4	9.9		10.0	10.7	10.4
victoria bridge	out	19	6.4	5.8	7.7	9.7		9.5	10.9	11.2
hanjin wilmington	out	19	2.4					14.8	14.5	12.5
julia	out	20			7.0	10.9		11.4	12.5	10.6
essen express	out	20		7.6	9.1	11.6		11.7	13.5	11.9
mol velocity	out	20		6.7	10.8W	11.2	9.9	11.7W	12.7	13.3
kavo alexandros II	out	20			9.6	9.9	9.4	9.9W	11.0	11.3
angel accord	out	20	6.9	7.9	10.1W					
stuttgart express	out	20	5.4	5.3	6.8					
antares	out	20								
aurora	out	20								
jervis bay	out	21	8.1	8.8	9.5					
borc	out	21			8.2					
cp rome	out	21								
ismini	out	21								
cecile ericksen	out	21								
ville de taurus	out	21								
msc insa	out	21								

W = ship used in wave analysis   A=ship used in wave analysis but speed adopted from Coast Guard and adjacent reach averaged speeds.

Table 8. Summary of ship speeds along channel from field study.

Location	Speed Type	Inbound, knots	Outbound, knots	Day, knots	Night, knots	Overall Average, knots
City Front	Camera	7.1	6.7	NA	NA	6.9
CF to CDF	Reach average	8.4	9.1	NA	NA	8.8
CDF	Camera	9.5	9.1	10.5	8.4	9.3
CDF to FP	Reach average	11.7	11.6	11.8	11.5	11.7
CG	Observers	9.8	10.8	10.3	NA	10.3
FP	Camera	11.5	11.8	11.6	11.7	11.7
FP to TI	Reach average	12.1	12.1	12.2	11.9	12.1
TI	Camera	13.1	12.6	13.2	12.4	12.9

Table 9. Ship effects analysis for Fort Pulaski. Return velocity and drawdown are averages over cross section based on Schijf equation in NAVEFF.

Draft / channel	Ship	Typical ship speed, knots	High ship speed, knots	Return Velocity/ Drawdown for typical speed, ft/sec	Return Velocity/ Drawdown, for high speed, ft/sec	Short period bow and stern wave height for typical/ high speed, ft
Typical (80%) draft/ existing (63980)*	PP-1044 X 140 X 36.2	11.7	13.7	2.85/1.87	4.61/3.64	1.43/2.18
“	PA-951 X 106 X 32.6	“	“	1.77/1.14	2.75/2.09	0.98/1.49
“	SP-716 X 99.8 X 30.2	“	“	1.51/0.96	2.30/1.73	0.85/1.30
“	HS-579 X 85.1 X 25.4	“	“	1.04/0.66	1.53/1.14	0.61/0.93
“	FM-428 X 67.7 X 20.2	“	“	0.64/0.40	0.92/0.67	0.39/0.59
Typical (80%) draft/ deep-ened (66800)	PP-1044 X 140 X 36.2	11.85	13.85	2.69/1.78	4.49/3.58	1.48/2.25
“	PA-951 X 106 X 32.6	11.8	13.9	1.67/1.08	2.59/1.99	1.00/1.55
“	SP-716 X 99.8 X 30.2	11.8	13.9	1.43/0.92	2.17/1.66	0.87/1.35
“	HS-579 X 85.1 X 25.4	11.75	13.85	0.98/0.62	1.45/1.08	0.62/0.96
“	FM-428 X 67.7 X 20.2	11.75	13.8	0.60/0.38	0.86/0.63	0.39/0.60
Design draft/ existing (63980)	PP-1044 X 140 X 40.7**	11.7	13.7	3.33/2.22	5.08/4.05	1.61/2.45
“	PA-951 X 106 X 40.7	“	“	2.32/1.51	3.81/2.96	1.22/1.86
“	SP-716 X 99.8 X 37.7	“	“	1.96/1.26	3.10/2.37	1.06/1.62
“	HS-579 X 85.1 X 31.8	“	“	1.34/0.85	2.01/1.51	0.76/1.16
“	FM-428 X 67.7 X 25.2			0.81/0.51	1.17/0.86	0.48/0.73
Design draft/ deepened (66800)	PP-1044 X 140 X 45.3	11.25	13.00	3.19/2.04	5.02/3.82	1.61/2.37
“	PA-951 X 106 X 40.7	11.85	13.95	2.20/1.44	3.58/2.82	1.26/1.95
“	SP-716 X	11.85	13.95	1.87/1.21	2.94/2.28	1.10/1.70

	99.8 X 37.7					
"	HS-579 X 85.1 X 31.8	11.8	13.9	1.27/0.81	1.90/1.44	0.78/1.21
"	FM-428 X 67.7 X 25.2	11.75	13.85	0.76/0.48	1.11/0.82	0.49/0.76

*(channel area, sq ft)

**limited by channel depth

Table 10. Composite return velocity (V_r), drawdown, and short period bow and stern wave height for Fort Pulaski based on Table 9 and ship frequency in Table 6 for GEC scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite for Typical Speed			Composite for High Speed		
	V_r, ft/sec	Drawdown, ft	Wave height, ft	V_r, ft/sec	Drawdown, ft	Wave height, ft
Typical Draft/ existing/2030	1.77	1.14	0.97	2.75	2.09	1.48
Typical Draft/ deepened/2030	1.67 (-5.6%)	1.08 (-5.3%)	0.99 (+2.1%)	2.59 (-5.8%)	2.00 (-4.3%)	1.54 (+4.1%)
Design Draft/ existing/2030	2.29	1.49	1.20	3.72	2.89	1.83
Design Draft/ deepened/2030	2.17 (-5.2%)	1.42 (-4.7%)	1.24 (+3.3%)	3.51 (-5.6%)	2.76 (-4.5%)	1.91 (+4.4%)
Typical Draft/ existing/2050	1.76	1.14	0.97	2.74	2.08	1.48
Typical Draft/ deepened/2050	1.66 (-5.7%)	1.08 (-5.3%)	0.99 (+2.1%)	2.59 (-5.5%)	1.99 (-4.3%)	1.54 (+4.1%)
Design Draft/ existing/2050	2.29	1.49	1.20	3.74	2.90	1.84
Design Draft/ deepened/2050	2.18 (-4.8%)	1.42 (-4.7%)	1.24 (+3.3%)	3.52 (-5.9%)	2.76 (-4.8%)	1.92 (+4.3%)

Table 11. Composite return velocity, drawdown, and short period bow and stern wave height for Fort Pulaski based on Table 9 and ship frequency in Table 6 for 10% scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite for Typical Speed			Composite for High Speed		
	Vr, ft/sec	Drawdown, ft	Wave height, ft	Vr, ft/sec	Drawdown, ft	Wave height, ft
Typical Draft/ existing/2030	1.86	1.20	1.01	2.91	2.23	1.54
Typical Draft/ deepened/2030	1.76 (-5.4%)	1.14 (-5.0%)	1.04 (+3.0%)	2.76 (-5.2%)	2.14 (-4.0%)	1.60 (+3.9%)
Design Draft/ existing/2030	2.38	1.55	1.24	3.83	2.99	1.88
Design Draft/ deepened/2030	2.26 (-5.0%)	1.47 (-5.2%)	1.27 (+2.4%)	3.64 (-5.0%)	2.84 (-5.0%)	1.95 (+3.8%)
Typical Draft/ existing/2050	1.86	1.20	1.01	2.91	2.22	1.54
Typical Draft/ deepened/2050	1.76 (-5.4%)	1.14 (-5.0%)	1.04 (+3.0%)	2.76 (-5.2%)	2.13 (-4.1%)	1.60 (+3.9%)
Design Draft/ existing/2050	2.38	1.56	1.24	3.85	3.00	1.89
Design Draft/ deepened/2050	2.27 (-4.6%)	1.47 (-5.8%)	1.27 (+2.4%)	3.65 (-5.2%)	2.85 (-5.0%)	1.96 (+3.7%)

Table 12. Composite return velocity, drawdown, and short period bow and stern wave height for Fort Pulaski based on Table 9 and ship frequency in Table 6 for 20% scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite for Typical Speed			Composite for High Speed		
	Vr, ft/sec	Drawdown, ft	Wave height, ft	Vr, ft/sec	Drawdown, ft	Wave height, ft
Typical Draft/ existing/2030	1.96	1.27	1.05	3.07	2.36	1.60
Typical Draft/ deepened/2030	1.85 (-5.6%)	1.20 (-5.5%)	1.08 (+2.9%)	2.93 (-4.6%)	2.28 (-3.4%)	1.66 (+3.8%)
Design Draft/ existing/2030	2.47	1.62	1.27	3.95	3.08	1.94
Design Draft/ deepened/2030	2.35 (-4.9%)	1.52 (-6.2%)	1.30 (+2.4%)	3.77 (-4.6%)	2.93 (-4.9%)	1.98 (+2.1%)
Typical Draft/ existing/2050	1.96	1.27	1.05	3.07	2.36	1.60
Typical Draft/ deepened/2050	1.85 (-5.6%)	1.20 (-5.5%)	1.08 (+2.9%)	2.93 (-4.6%)	2.28 (-3.4%)	1.66 (+3.8%)
Design Draft/ existing/2050	2.47	1.62	1.27	3.96	3.10	1.94
Design Draft/ deepened/2050	2.35 (-4.9%)	1.53 (-5.6%)	1.31 (+3.1%)	3.78 (-4.5%)	2.94 (-5.2%)	1.99 (+2.6%)

Table 13. Composite return velocity, drawdown, and short period bow and stern wave height for Fort Pulaski based on Table 9 and ship frequency in Table 6 for 30% scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite for Typical Speed			Composite for High Speed		
	Vr, ft/sec	Drawdown, ft	Wave height, ft	Vr, ft/sec	Drawdown, ft	Wave height, ft
Typical Draft/ existing/2030	2.05	1.33	1.09	3.24	2.50	1.66
Typical Draft/ deepened/2030	1.94 (-5.4%)	1.26 (-5.3%)	1.12 (+2.8%)	3.10 (-4.3%)	2.42 (-3.2%)	1.72 (+3.6%)
Design Draft/ existing/2030	2.56	1.68	1.31	4.06	3.18	1.99
Design Draft/ deepened/2030	2.44 (-4.7%)	1.58 (-6.0%)	1.33 (+1.5%)	3.89 (-4.2%)	3.02 (-5.0%)	2.02 (+1.5%)
Typical Draft/ existing/2050	2.05	1.33	1.09	3.24	2.50	1.67
Typical Draft/ deepened/2050	1.94 (-5.4%)	1.27 (-4.5%)	1.12 (+2.8%)	3.10 (-4.3%)	2.42 (-3.2%)	1.73 (+3.6%)
Design Draft/ existing/2050	2.57	1.68	1.31	4.08	3.20	2.00
Design Draft/ deepened/2050	2.44 (-5.1%)	1.58 (-6.0%)	1.34 (+2.3%)	3.91 (-4.2%)	3.03 (-5.3%)	2.03 (+1.5%)

Table 14. Tybee Island ship drawdown.

Category	Ship name	Gross Tonnage, speed, knots over ground	Maximum Drawdown, ft	Tide, ft MLLW and direction
Inbound/Stage < 4 ft MLLW	Sun Right	53359, 15.1	1.1	1.5, flood
“	Zim Israel	37204, 10.9	0.2	-0.1, bottom
“	MSC Christina	37579, 13.0	0.75	-0.2, bottom
“	Mol Elbe	50352, 12.1	0.85	-0.2, bottom
“	Midnight Sun	27915, 10.3	0.2	-0.4, bottom
“	Darya Rani	26054, 12.0	0.2	0.2, weak flood
“	Zim Iberia	41507, 11.3	0.9	-0.3, bottom
“	Hanjin Wilmington	51754, 11.7	0.25	-0.1, bottom
“	Condor	14241, 18.1	0.3	3.0, flood
“	Essen Express	53815, 12.1	0.9	-0.1, bottom
“	Angel Accord	20212, 11.1	0.2	-0.2, bottom
“	Mol Velocity	53519, 15.5	0.8	0.7, flood
“	Jervis Bay	50350, 14.3	0.2	4.4, flood
“	Borc	20139, 11.3	0.1	3.6, flood
Inbound/Stage > 7 ft MLLW	MSC Elini	54841, 14.2	0.2	8.2, weak ebb
	MSC Elena	30971, 13.5	0.1	6.3, ebb
	Kavo Alexandros II	16608, 14.2	0.1	7.8,ebb
	Jens Maersk	30166, 14.2	1.4	8.4, flood
	Stuttgart Express	53815, 15.2	0.25	8.4, weak ebb
Outbound/Stage < 4 ft MLLW	Khannur	96235, 11.1	0.5	-0.4, bottom
	New York Express	54437, 11.3	1.3	2.0, flood
	Star Florida	23345, 11.7	0.8	2.5, flood
	Jens Maersk	30166, 12.7	1.65	3.4, flood
	CMA CGM Potomac	31154, 14.9	0.45	1.6, ebb
	Kochnev	6030, 10.5	0.2	0.9, flood
	MSC Eleni	54881, 13.3	0.5	0.8, ebb
	Midnight Sun	27915, 13.0	0.2	0.1 ebb
	MSC Elena	30971, 11.9	0.5	-0.4, bottom
	Condor	14241, 16.2	0.25	0.9, ebb
	Emmanuelle Tomassos	23217, 16.1	0.35	0.2, weak ebb
	Essen Express	53815, 11.9	0.5	0.3, weak ebb

Outbound/Stage > 7 ft MLLW	YM South	46697, 12.2	0.5	7.3, ebb
	Maersk Garonne	50698, 13.5	0.7	7.0, ebb
	Kyriakoula	40680, 10.9	0.45	7.1, flood
	Mol America	16803, 14.3	0.35	8.3, top
	Mol Elbe	50352, 11.9	0.35	9.1, top
	MSC Christina	37579, 12.7	0.75	8.7, weak ebb
	Zim Iberia	41507, 13.0	0.95	8.8, top
	Darya Rani	26054, 11.3	0.2	8.6, weak ebb
	Victoria Bridge	53400, 11.2	0.65	7.9, flood
	Hanjin Wilmington	51754, 12.5	1.1	8.6, top
	Mol Velocity	53519, 13.3	1.35	8.7, top
	Kavo Alexandros II	16608, 11.3	0.25	8.7, top

Table 15. Design ship analysis for Tybee Island. Return velocity and drawdown are averages over cross section based on Schijf equation.

Design Ship / channel	Ship	Typical ship speed, knots	High ship speed, knots	Drawdown for typical speed, ft	Drawdown for high speed, ft
Typical (80%) draft/ existing (64175)*	PP-1044 X 140 X 36.2	12.9	14.4	2.85	4.01
"	PA-951 X 106 X 32.6	"	"	1.62	2.78
"	SP-716 X 99.8 X 30.2	"	"	1.36	2.24
"	HS-579 X 85.1 X 25.4	"	"	0.91	1.42
"	FM-428 X 67.7 X 20.2	"	"	0.54	0.82
Typical (80%) draft/ deepened (66793)	PP-1044 X 140 X 36.2	13.15	14.55	2.76	3.95
"	PA-951 X 106 X 32.6	13.05	14.65	1.55	2.66
"	SP-716 X 99.8 X 30.2	13.05	14.6	1.3	2.13
"	HS-579 X 85.1 X 25.4	13.0	14.55	0.87	1.35
"	FM-428 X 67.7 X 20.2	13.0	14.5	0.52	0.78
Design draft/ existing (64175)	PP-1044 X 140 X 40.7**	12.9	14.4	3.53	4.46
"	PA-951 X 106 X 40.7	"	"	2.21	3.47
"	SP-716 X 99.8 X 37.7	"	"	1.82	3.08
"	HS-579 X 85.1 X 31.8	"	"	1.19	1.92
"	FM-428 X 67.7 X 25.2			0.7	1.07
Design draft/ deepened (66793)	PP-1044 X 140 X 45.3	12.55	13.6	3.22	4.24
"	PA-951 X 106 X 40.7	13.1	14.5	2.13	3.4
"	SP-716 X 99.8 X 37.7	13.05	14.6	1.73	3.01
"	HS-579 X 85.1 X 31.8	13.05	14.6	1.14	1.83
"	FM-428 X 67.7 X 25.2	13.0	14.55	0.66	1.02

*(channel area, sq ft)

**limited by channel depth

Table 16. Composite drawdown for Tybee Island based on Table 15 and ship frequency in Table 6 for GEC traffic scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite drawdown for typical speed, ft	Composite drawdown for high speed, ft
Typical Draft/ existing/2030	1.63	2.73
Typical Draft/ deepened/2030	1.56 (-4.3%)	2.62 (-4.0%)
Design Draft/ existing/2030	2.19	3.4
Design Draft/ deepened/2030	2.10 (-4.1%)	3.32 (-2.4%)
Typical Draft/ existing/2050	1.62	2.73
Typical Draft/ deepened/2050	1.55 (-4.3%)	2.62 (-4.0%)
Design Draft/ existing/2050	2.19	3.42
Design Draft/ deepened/2050	2.10 (-4.1%)	3.34 (-2.3%)

Table 17. Composite drawdown for Tybee Island based on Table 15 and ship frequency in Table 6 for 10% traffic scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite drawdown for typical speed, ft	Composite drawdown for high speed, ft
Typical Draft/ existing/2030	1.73	2.84
Typical Draft/ deepened/2030	1.66 (-4.0%)	2.73 (-3.9%)
Design Draft/ existing/2030	2.31	3.49
Design Draft/ deepened/2030	2.20 (-4.8%)	3.40 (-2.6%)
Typical Draft/ existing/2050	1.73	2.84
Typical Draft/ deepened/2050	1.66 (-4.0%)	2.74 (-3.5%)
Design Draft/ existing/2050	2.31	3.50
Design Draft/ deepened/2050	2.20 (-4.8%)	3.41 (-2.6%)

Table 18. Composite drawdown for Tybee Island based on Table 15 and ship frequency in Table 6 for 20% traffic scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite drawdown for typical speed, ft	Composite drawdown for high speed, ft
Typical Draft/ existing/2030	1.84	2.95
Typical Draft/ deepened/2030	1.77 (-3.8%)	2.84 (-3.7%)
Design Draft/ existing/2030	2.43	3.58
Design Draft/ deepened/2030	2.29 (-5.8%)	3.47 (-3.1%)
Typical Draft/ existing/2050	1.84	2.96
Typical Draft/ deepened/2050	1.77 (-3.8%)	2.85 (-3.7%)
Design Draft/ existing/2050	2.43	3.59
Design Draft/ deepened/2050	2.30 (-5.3%)	3.49 (-2.8%)

Table 19. Composite drawdown for Tybee Island based on Table 15 and ship frequency in Table 6 for 30% traffic scenario. Values in () shows percent change from without project to with project.

Draft/channel/ traffic year	Composite drawdown for typical speed, ft	Composite drawdown for high speed, ft
Typical Draft/ existing/2030	1.95	3.05
Typical Draft/ deepened/2030	1.88 (-3.6%)	2.96 (-3.0%)
Design Draft/ existing/2030	2.54	3.66
Design Draft/ deepened/2030	2.39 (-5.9%)	3.55 (-3.0%)
Typical Draft/ existing/2050	1.95	3.07
Typical Draft/ deepened/2050	1.88 (-3.6%)	2.97 (-3.3%)
Design Draft/ existing/2050	2.55	3.68
Design Draft/ deepened/2050	2.40 (-5.9%)	3.57 (-3.0%)

Table 20. Drawdown in existing channel for CDF ships.

CDF - Inbound		
Name	**Date**	**Drawdown (ft)**
Emmanuel Tomassos	18	1.1
Hanjin Wilmington	18	1.4*
Essen Express	19	1.5*
Angel Accord	19	0.4
Mol Velocity	19	2.7*
Stuttgart Express	19	0.9
Ville de Taurus	21	1.3
CDF - Outbound		
Name	**Date**	**Drawdown (ft)**
Midnight Sun	18	0.6
MSC Elena	19	1.9*
Emmanuel Tomassos	19	1.0
Condor	19	2.0
Essen Express	20	1.4
Mol Velocity	20	2.4
Angel Accord	20	1.5
Jervis Bay	21	1.5

* Drawdown below bottom of gage

Table 21. Drawdown in existing channel for CF ships.

CF - Inbound		
Name	**Date**	**Drawdown (ft)**
Darya Rani	17	0.2
Aloyna	17	0.2
Zim Iberia	18	0.2
Al Mariyah	18	0.1
MSC Eleni	18	0.2
Emmanuel Tomassos	18	0.4
Hanjin Wilmington	18	0.4
Condor	18	0.2
Victoria Bridge	19	0.6
Essen Express	19	0.5
Angel Accord	19	0.2
Mol Velocity	19	0.4
Ismini	19	0.6
Stuttgart Express	19	0.5
CP Rome	20	0.4

CF - Outbound		
Name	**Date**	**Drawdown (ft)**
Jian an Cheng	17	0.55
Mole Elbe	17	0.25
MSC Christina	17	0.3
Zim Israel	17	0.5
MSC Eleni	18	0.2
Midnight Sun	18	0.2
Alyona	18	0.3
Zim Iberia	18	0.8
Darya Rani	18	0.55
Sumida	18	0.2
Al Mariyah	18	0.2
MSC Elena	19	0.3
Condor	19	0.2
Emanuel Tomassos	19	0.1
Victoria Bridge	19	0.7
Hanjin Wilmington	19	0.35
Essen Express	20	0.3
Mol Velocity	20	0.55
Kavo Alexandros II	20	0.2
Angel Accord	20	0.4
Stuttgart Express	20	0.5
Jervis Bay	21	0.4

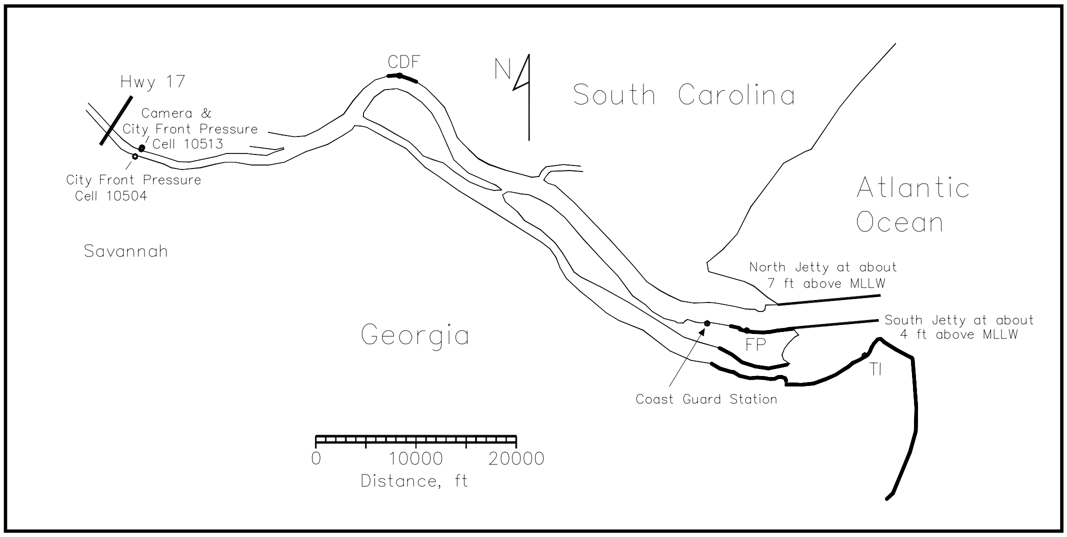

Figure 1. Locations of gages and cameras.

Figure 2. Picture of capacitance gage at Tybee Island

Figure 3. Picture of capacitance gage at Fort Pulaski

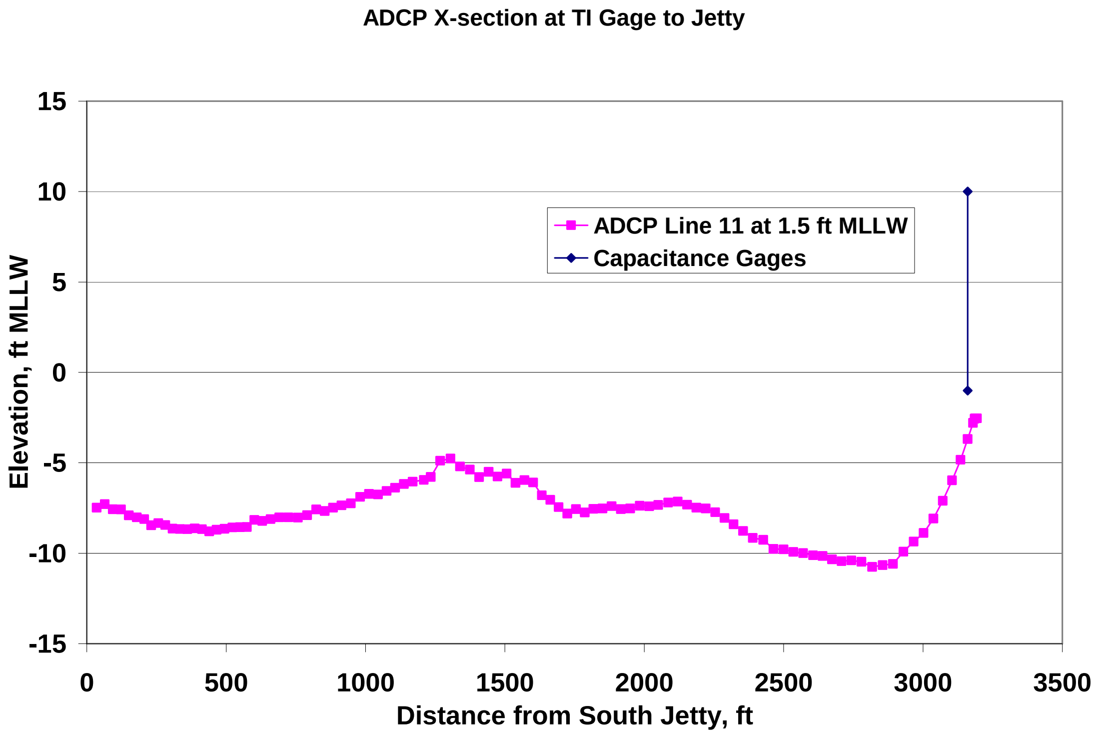

Figure 4. Cross section at Tybee Island- south Jetty to wave gage.

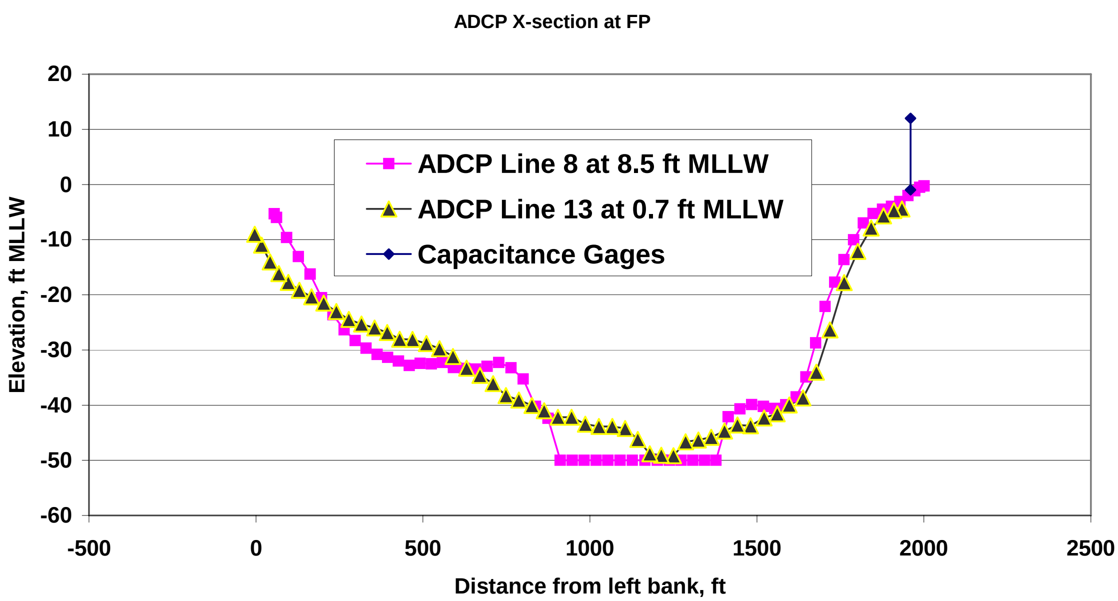

Figure 5. Cross section at Tybee Island- between jetties

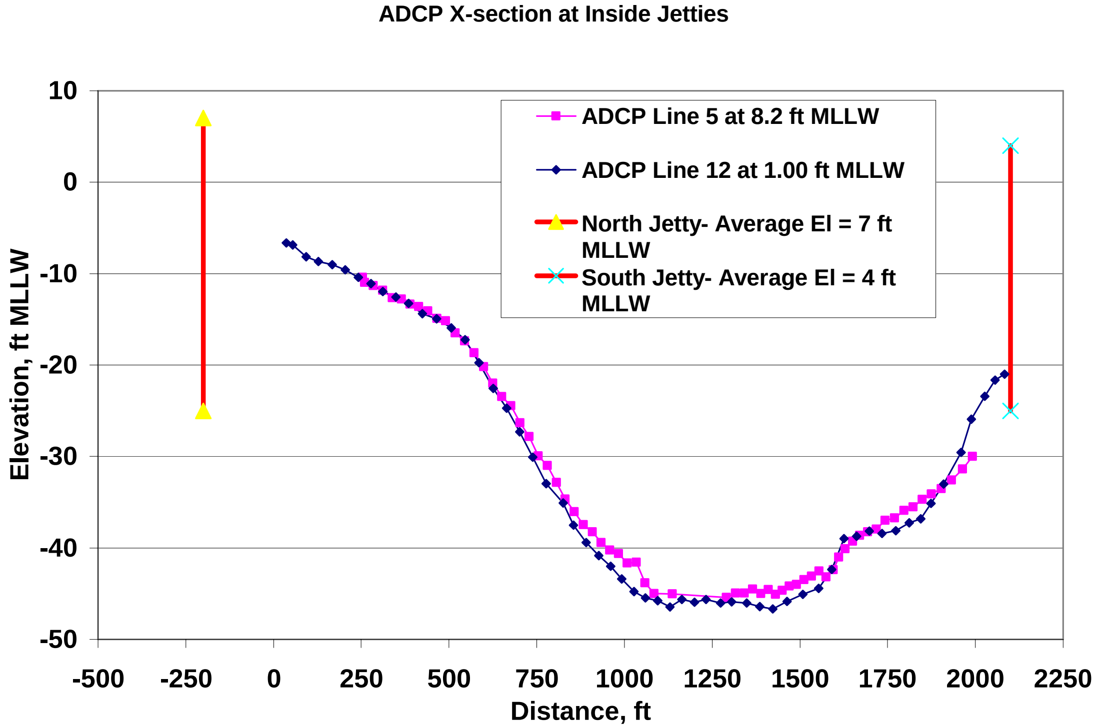

Figure 6. Cross section at Fort Pulaski

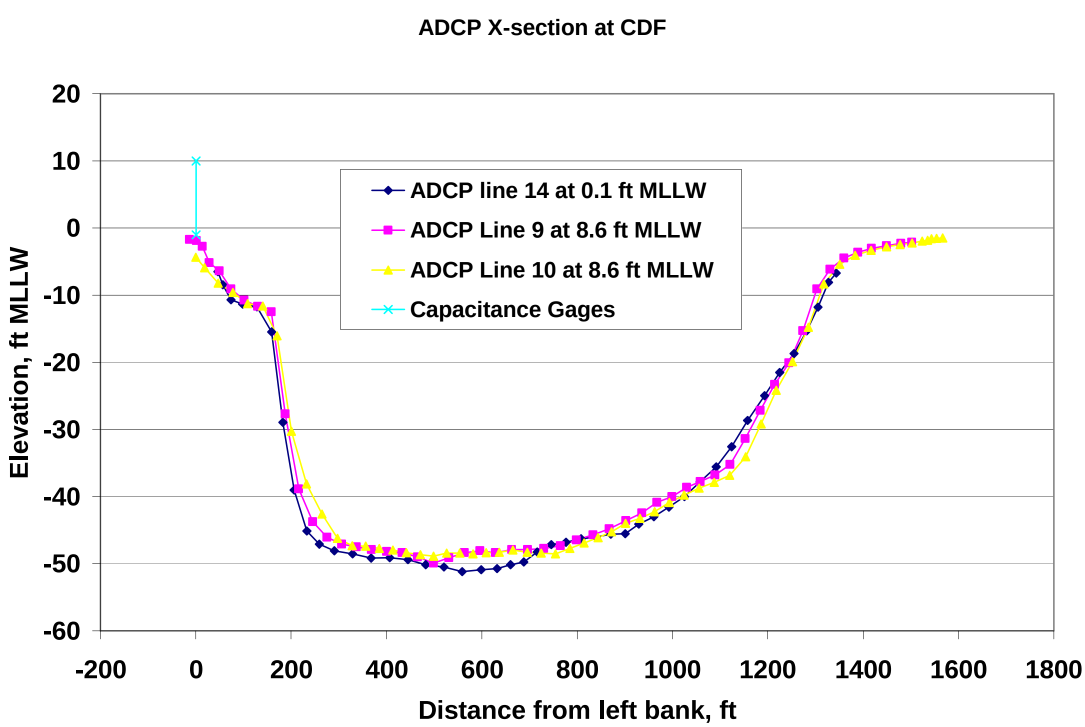

Figure 7. Cross section at CDF

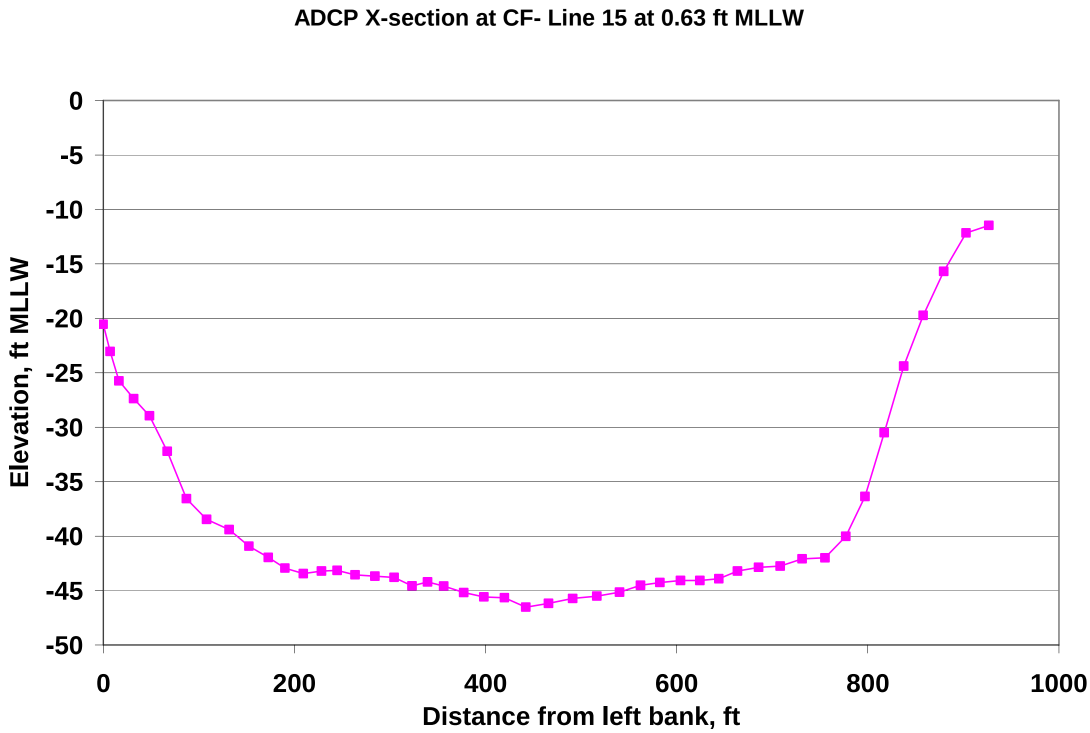

Figure 8. Cross section at City Front

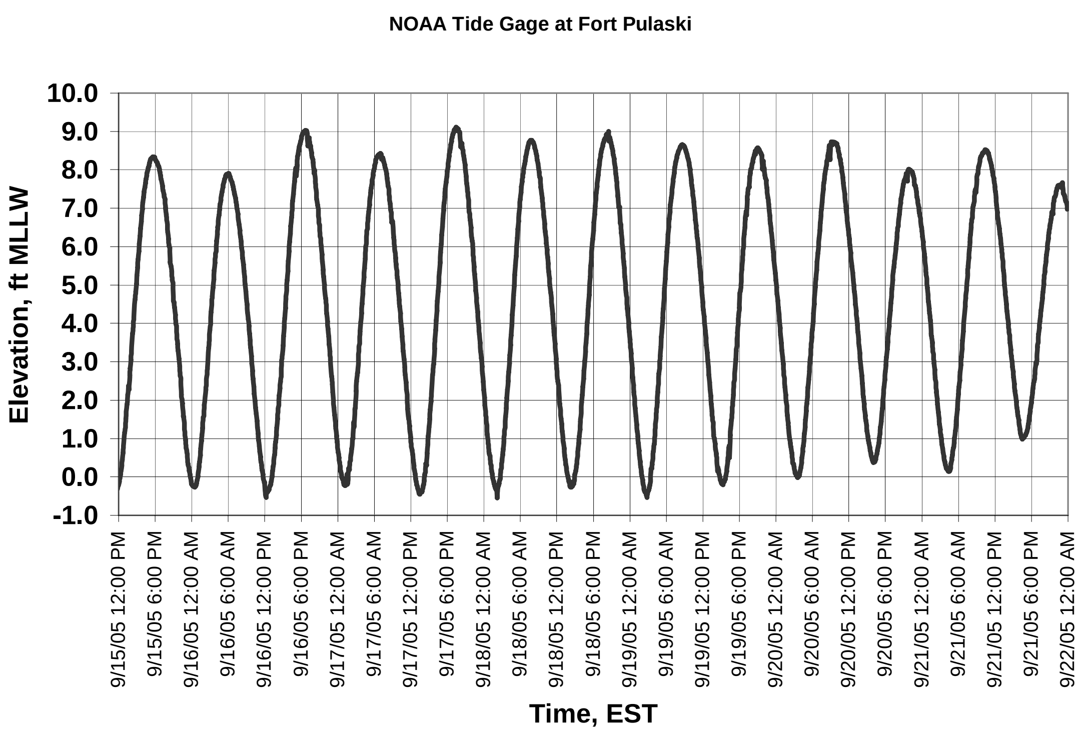

Figure 9. Tides at Fort Pulaski during field study.

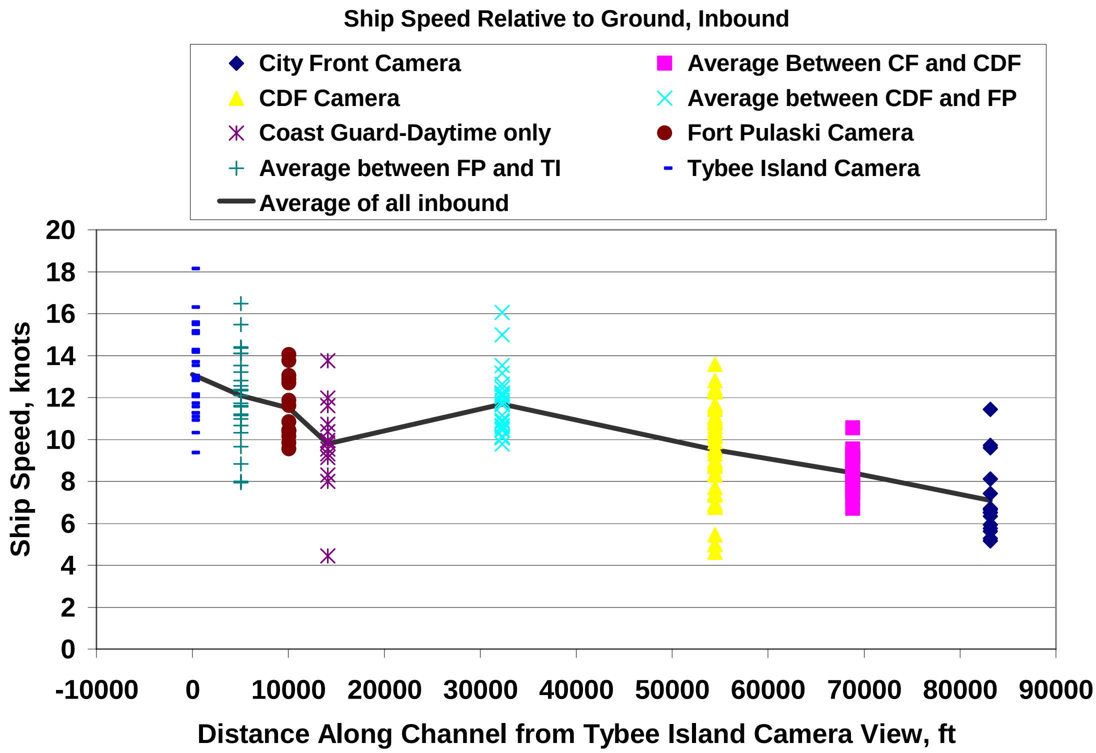

Figure 10. Ship speed along reach for inbound ships.

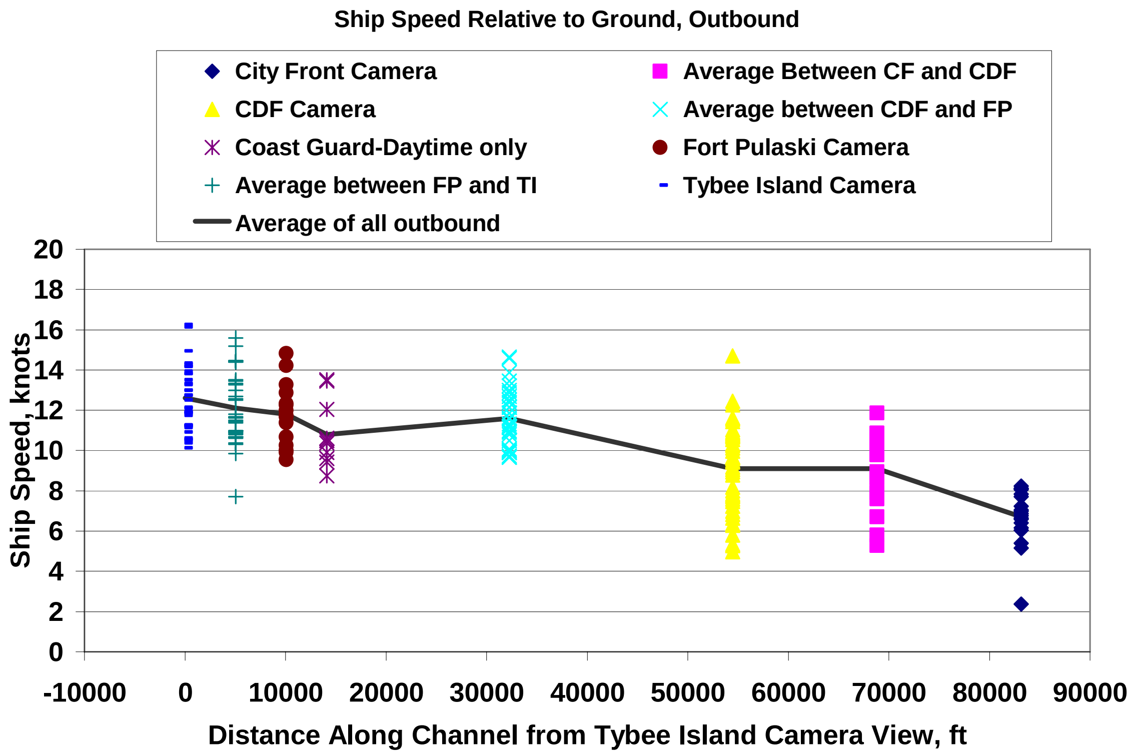

Figure 11. Ship speed along reach for outbound ships.

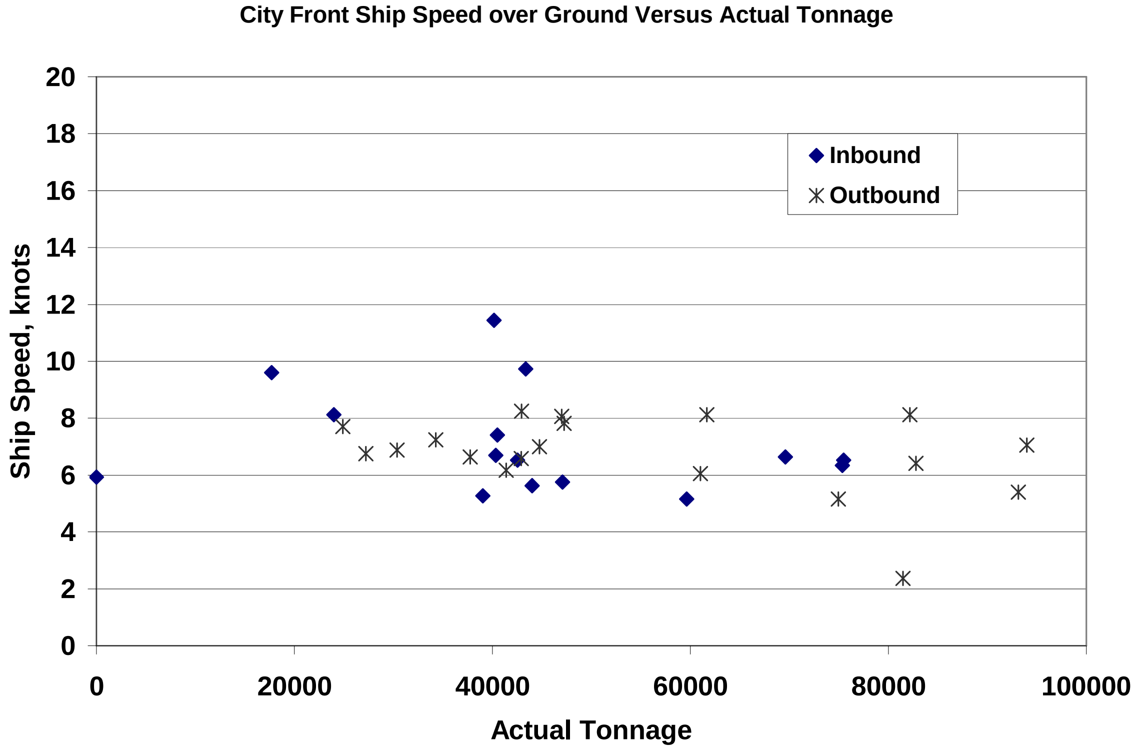

Figure 12. Ship speed versus ship size at City Front.

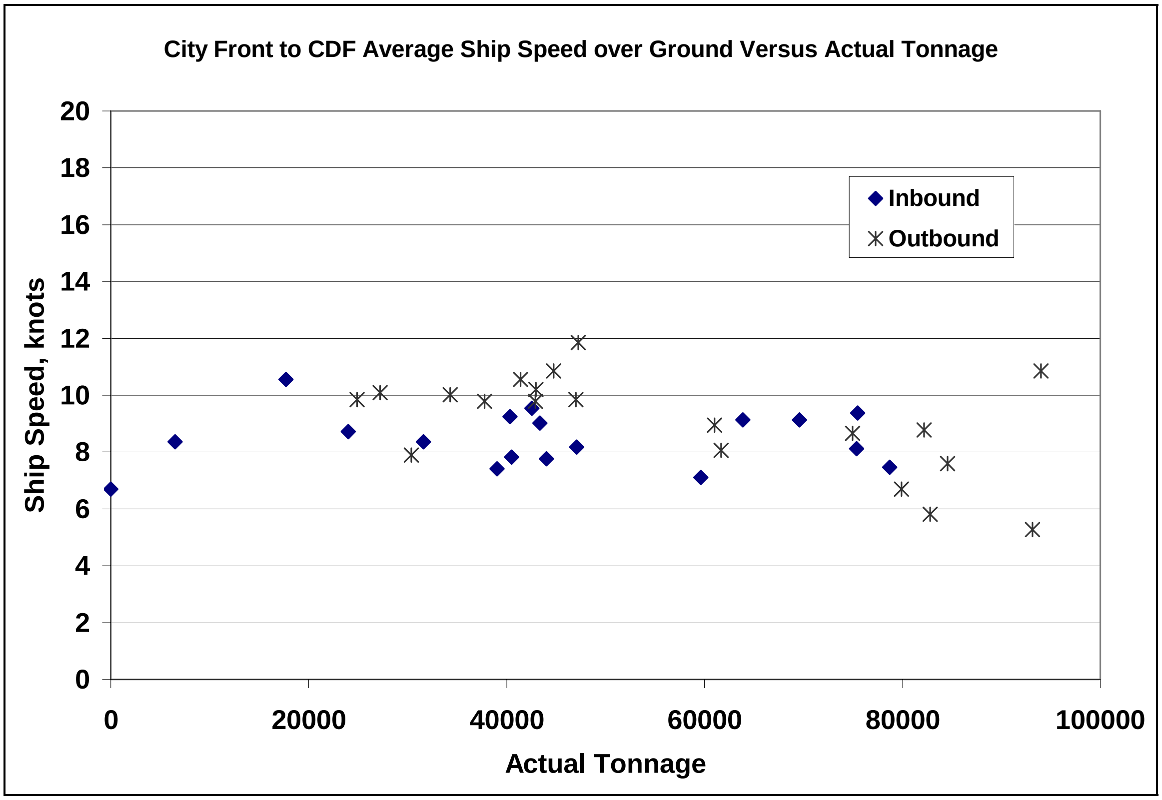

Figure 13. Ship speed versus ship size averaged over CF to CDF reach.

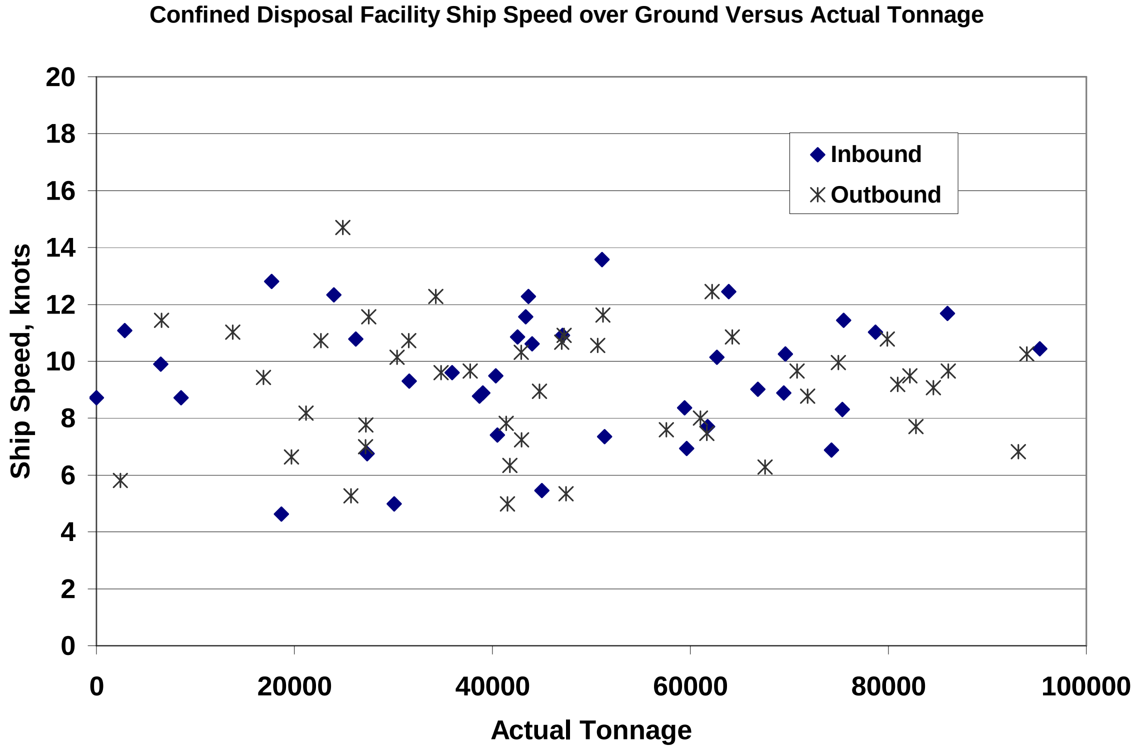

Figure 14. Ship Speed versus ship size at CDF camera.

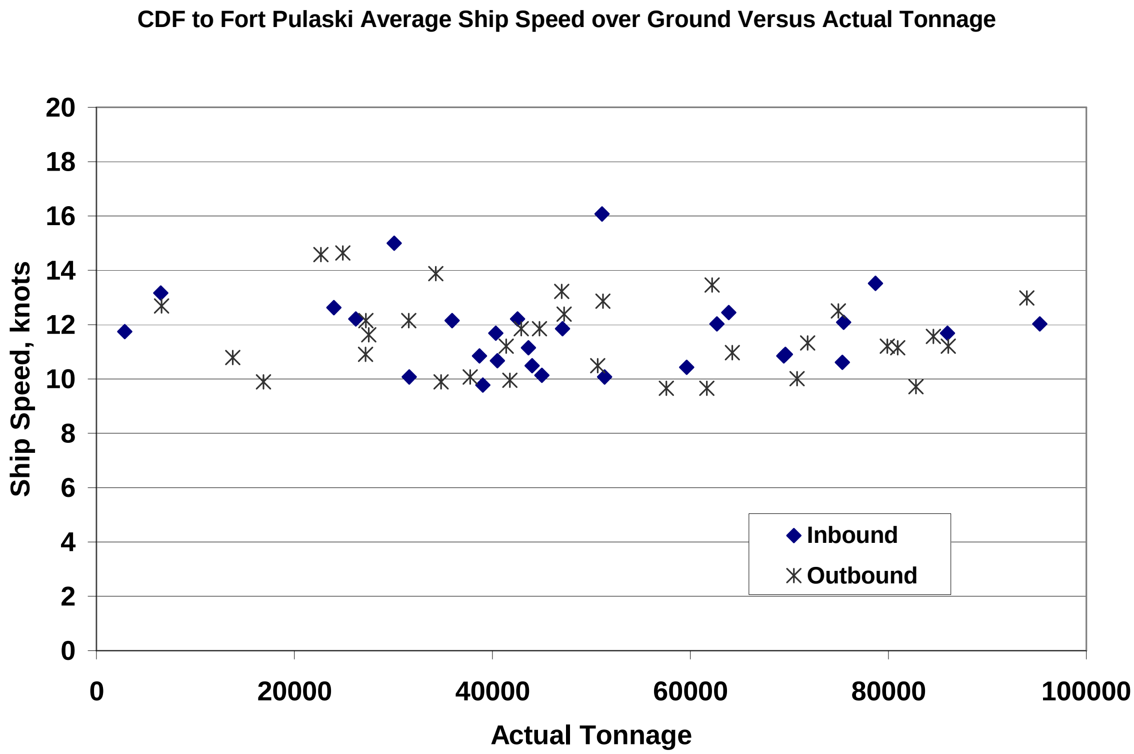

Figure 15. Ship speed versus ship size averaged over CDF to Fort Pulaski reach.

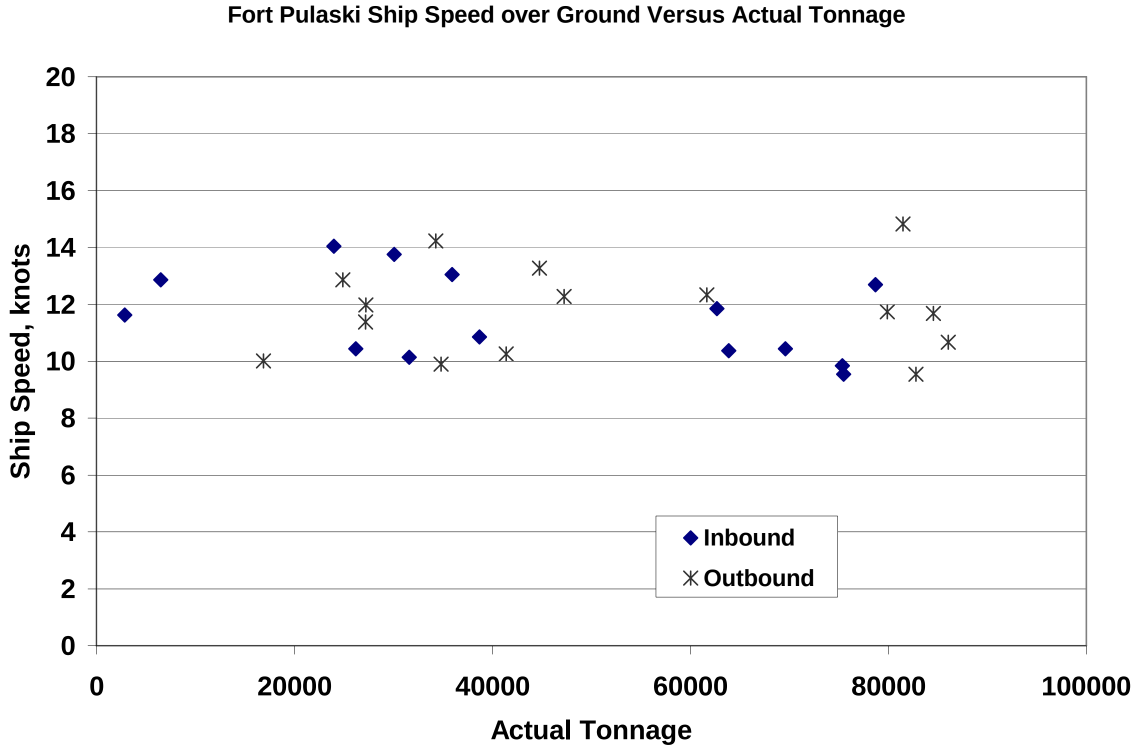

Figure 16. Ship Speed versus ship size at Fort Pulaski camera.

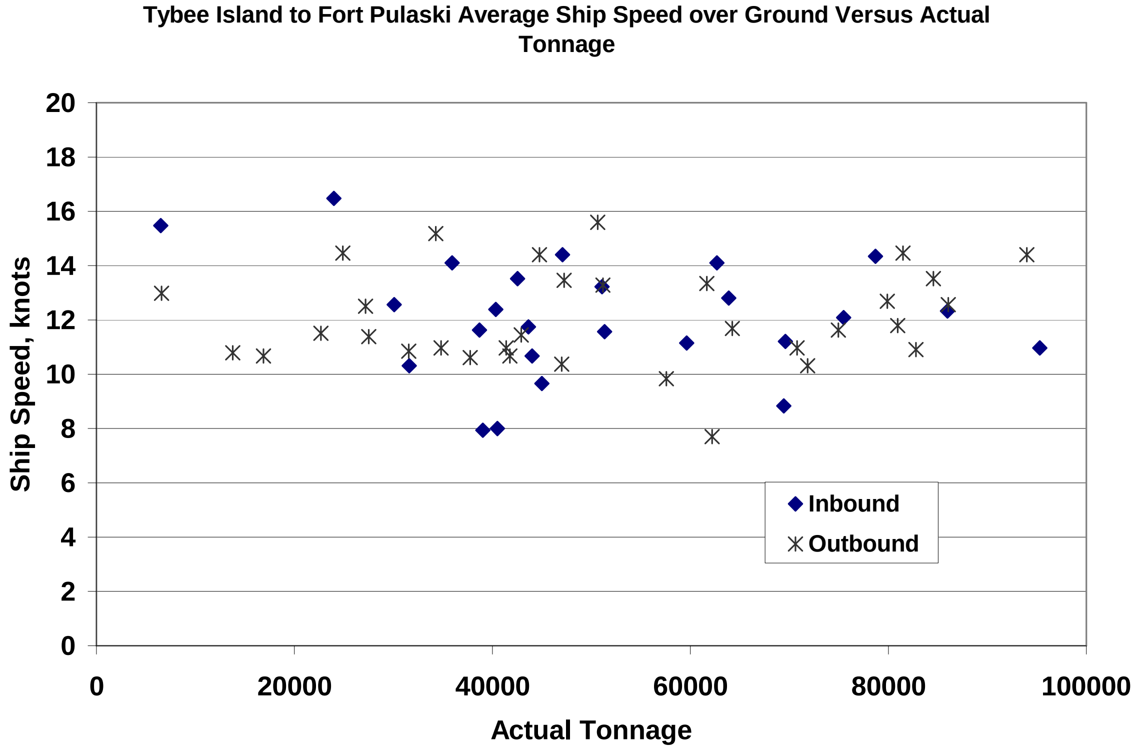

Figure 17. Ship speed versus ship size averaged over reach between Fort Pulaski and TI.

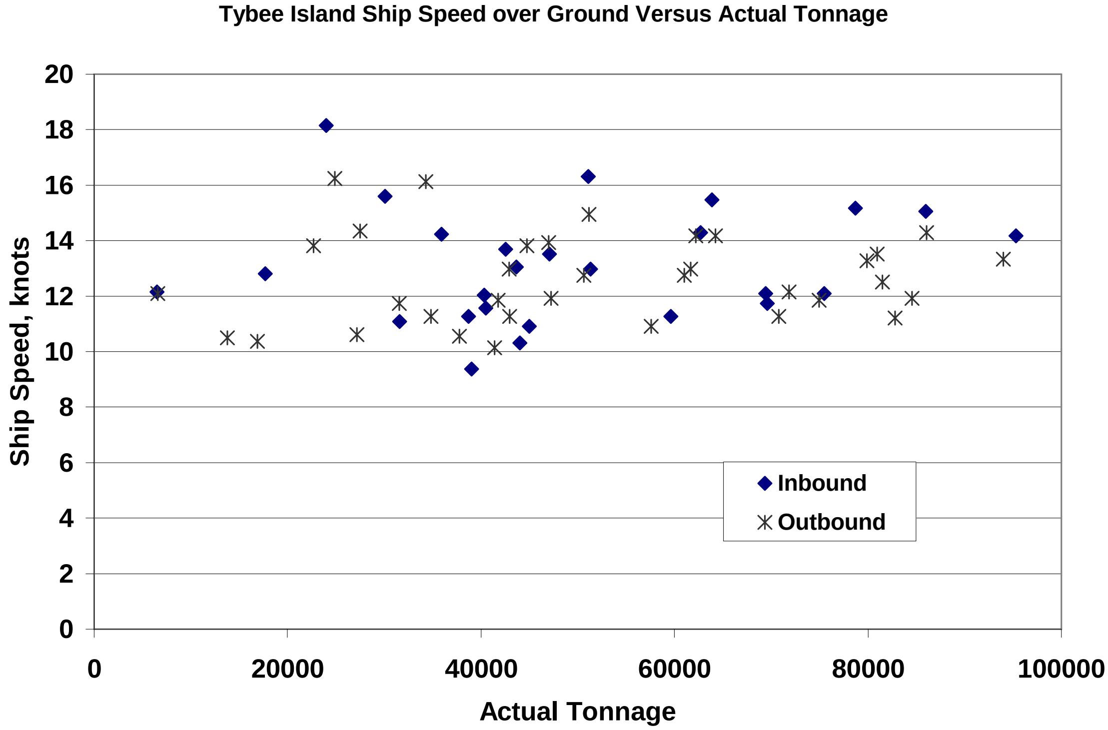

Figure 18. Ship speed versus ship size at Tybee Island.

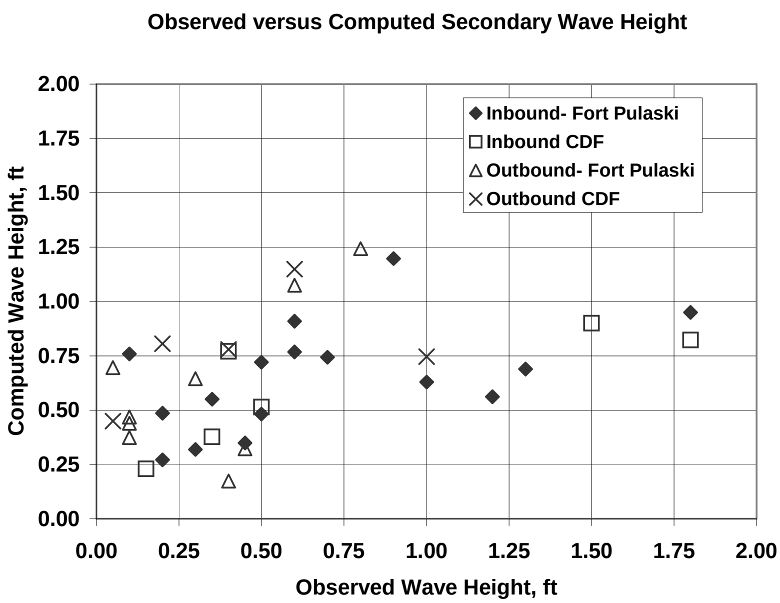

Figure 19. Observed versus computed short period bow and stern wave height using modified Gates and Herbich equation.