Subject: 2011 Reanalysis of Ship Forces at the Shoreline using Updated Draft Information, Savannah Harbor, Savannah, Georgia July 2011

General

Based on updated ship draft information, the ship forces at the shoreline of Savannah Harbor (SH) were reanalyzed using the updated draft information. This reanalysis report is a supplement to the Maynord (2007) report. Since the Maynord (2007) study, sailing draft distribution data had become available that allowed better estimates of comparable ship drafts in the existing and deepened channels. In the 2007 study, a typical/average draft and a large/design draft ship were used to evaluate ship forces. In this reanalysis, the typical ship compared in the existing and deepened channels was the 50% or median ship draft from the sailing draft distributions. In this reanalysis, the large draft ship compared in the existing and deepened channels was the 95% ship draft from the sailing draft distributions.

The drafts used for each ship class are shown in Table 1. Because distributions were not available for Sub-Panamax and their draft was not affected by deepening, the typical draft Sub-Panamax ship was equal to the average draft determined in the 2005 field study. The large draft Sub-Panamax ship had draft equal to the design draft used in the 2007 study. In the 2007 study, a Post-Panamax ship having a beam of 140 ft was the design ship. In this reanalysis, the design ship has not changed but Post-Panamax beams were refined to Generation 1 having average beams of 131.7 ft and Generation 2 having average beams of 142.9 ft.

Table 1. Ship drafts used in 2011 reanalysis of ship forces.

Class	BeamX Length, ft	Draft description	Draft in Existing 42-ft channel, ft	Draft in Deepened 48-ft channel, ft
Sub-Panamax-Typical Draft	99.8X716	Average from 2005 field study	30.2	30.2
Sub-Panamax-Large Draft	99.8X716	Design draft from 2005 study	37.7	37.7
Panamax- Typical Draft	106X951	50%	34.3	34.4
Panamax- Large Draft	106X951	95%	40.0	40.6
PPX Gen 1-Typical Draft	131.7X954	50%	36.2	41.1
PPX Gen 1- Large Draft	131.7X954	95%	41.2	45.6
PPX Gen 2-Typical Draft	142.9X1106	50%	36.3	41.7
PPX Gen 2- Large Draft	142.9X1106	95%	41.8	46.6

Because of the changes in draft, ship speed had to be recomputed along with drawdown, return velocity, and wave height. In addition, the ship speed model and the ship wave equations were updated. Due to the updated draft information and improved ship speed and wave height models, all conclusions herein supercede conclusions in the 2007 report.

A large number of tables and plots are presented herein to provide background information and a complete description of ship forces along the shoreline. More concise Discussion of Results and Summary and Conclusions sections are presented in the final sections of this report.

Ship Operation and Speed Trends Along SH

In the 2007 study, predicting ship speed in the deepened channel was based on existing speeds, change in ship draft, engine power setting, and increase in channel area. While those parameters are still important in certain portions of the channel, there are three areas of the channel where ships must slow down to control their wake. Along the SH channel, ships must slow down at the Coast Guard (CG) Station, the LNG facility if a ship was docked, and beginning at Old Fort Jackson to the docks in Savannah (Figure 1). These three wake reduction areas affect a large portion of the channel because it takes significant channel distance for a ship to slow down and speed up. In these wake reduction areas, large ships must slow down more than small ships for the same level of acceptable wake effects. In these wake reduction areas, the requirement for safe wake had a far greater effect on ship speed than deepening of the channel.

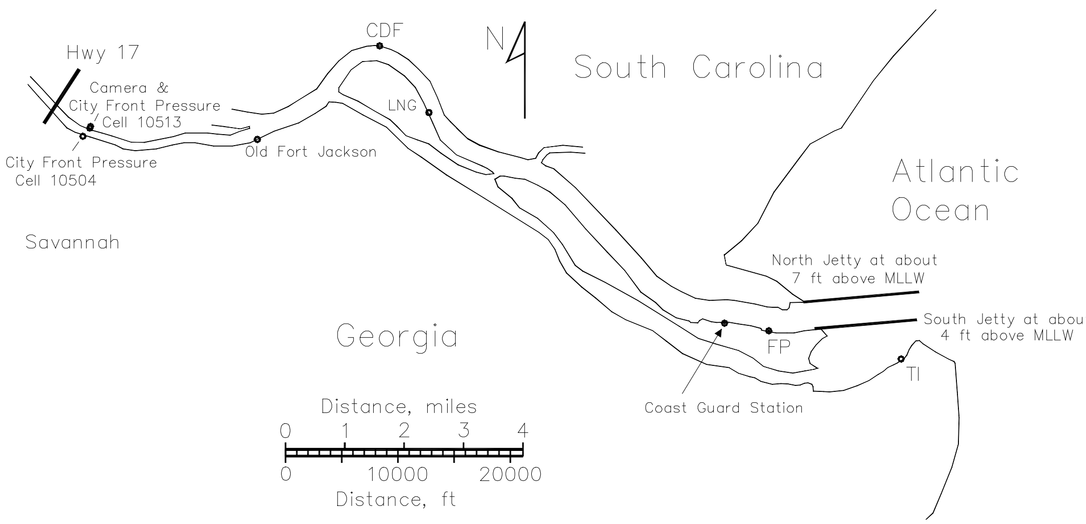

Figure 1. Layout of Savannah Harbor Channel.

Based on recent discussions with Capt Browne of the SH Pilots, the trend of speed along the SH is shown in Figure 2. While many differences exist between ships, these trends were for typical ships transiting the SH. Speeds will be assigned to this trend plot later in this report. Power or bell settings on typical ships used in SH were stop engines, dead slow, slow, half, and full bell. While many ships can adjust their propeller speed by setting a specified rate of rotation, these fine adjustments are only used in special circumstances. At Savannah Harbor, one of the special circumstances is achieving the 10 knot restriction during the Right Whale restricted period. Based on discussions with pilots at several ship channels, pilots typically use full bell unless operational constraints such as wake reduction areas are present. The only higher bell is sea speed that requires heated fuel and is almost never used at SH or any other inland channels this author is aware of. Trends for typical ships are described as follows:

Inbound Ship: Approaching ship is typically traveling at full bell at speeds of about 11-13 knots unless the Right Whale restrictions limit ship speed to 10 knots. At some point inside the jetties, the ship starts to slow down to control its wake at the Coast Guard.

Once past the Coast Guard, the ship typically powers up to full bell and will typically reach the maximum speed for full bell depending on the tide condition and type, size, and power of the ship. Well before the LNG dock, the ship starts slowing down to control its wake at the LNG dock. Once past the LNG dock, the ship increases speed and for a short channel distance the typical ship is operating at full bell. The ship typically does not reach maximum speed for full bell in this short reach. Well before Old Fort Jackson, the ship starts to slow down to control its wake at Old Fort Jackson. From Old Fort Jackson to the City Front, the ship is operating at restricted speeds.

Outbound Ship: The ship leaves a dock in Savannah and travels at restricted speed all the way to Old Fort Jackson. Once past Old Fort Jackson, the ship powers up to full bell for a short distance. The ship typically does not reach maximum speed for full bell in this short reach. Well before the LNG dock, the ship starts slowing down to control its wake at the LNG dock. Once past the LNG dock, the typical ship powers up to full bell and will typically reach the maximum speed for full bell depending on the tide condition and type, size, and power of the ship. Well before reaching the Coast Guard, the ship starts slowing down to control its wake at the Coast Guard. Once past the Coast Guard, the ship powers up to full bell and will reach the maximum speed for full bell at a distance that depends on the tide condition and type, power, and size of the ship unless the Right Whale restrictions limit ship speed to 10 knots.

One variation of these descriptions of speed trends along the SH was when a ship was not present at the LNG dock and ships do not have to slow down at that location. A speed plot will be presented showing that variation.

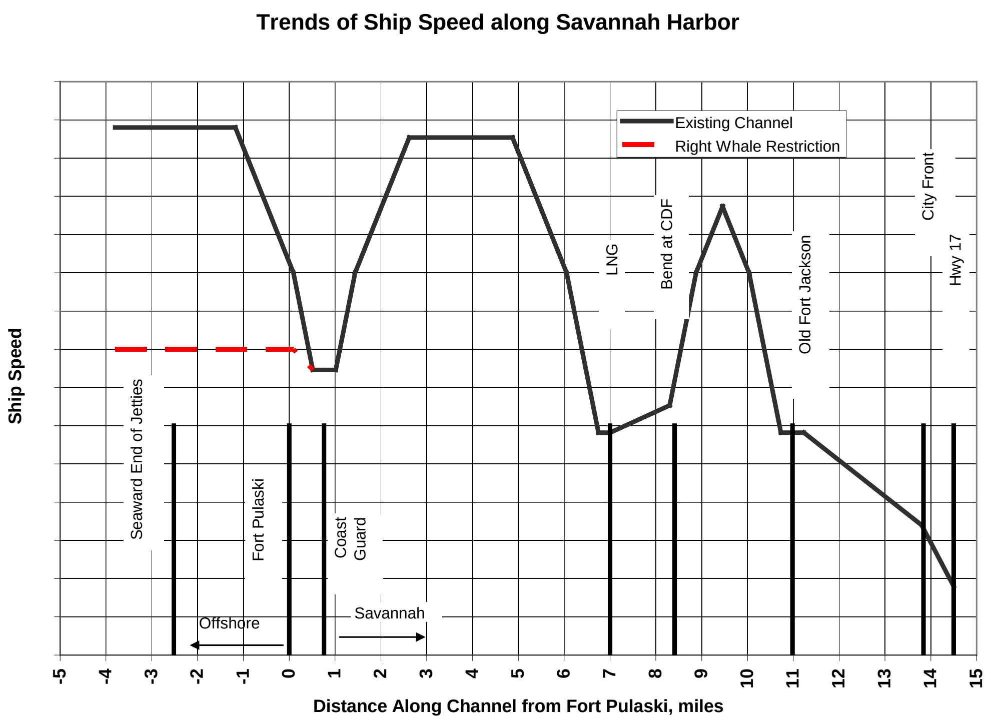

Figure 2. Trends of ship speed along the Savannah Harbor channel.

Allowable Speeds in Wake Reduction Areas

To assign ship speed magnitudes to the trend plots, an analysis was conducted to determine the allowable ship speeds in wake reduction areas where Savannah Harbor (SH) ships must slow down between Tybee Island and the docks in Savannah. Ships must slow down to prevent their wake from adversely affecting moored ships and other marine vessels or structures. As a general rule, large ships must travel slower than small ships to prevent wake effects, all other factors being equal.

One of the most important measures of a ship's effect on moored vessels is the magnitude of the long period water level drawdown that occurs when a ship moves along a channel. Drawdown can be measured with various types of gages or calculated from ship speed, ship size, and channel size. During the SH field study in Sept 2005, drawdown was measured at the City Front using a submerged pressure cell located as shown in Figure 1. Table 2 shows the measured drawdown during passage of ships during the 2005 field study. Also shown in the Table is ship size, ship speed, channel area at the tide level during ship passage, and calculated drawdown using the Schijf (1949) equations. The Schijf equations compare best to observed data when shallow areas on each side of the channel were omitted and channel cross sections between the -20 contours were used in the application of the Schijf equations.

At the Coast Guard Station, only ship speed was measured by an observer during the 2005 field study. Ship beam, draft, ship speed relative to water, and channel size were used in the Schijf equation to compute water level drawdown as shown in Table 3.

Table 2. Drawdown for Largest Ships at City Front during 2005 field study. Channel width at -20 contour equals 858 ft.

Ship-direction	Time/date	Beam, ft	Draft, ft	Vg, knots	Vw, knots	Channel area, sq ft	Drawdown, ft	
							Measured	Calculated
Midnight Sun- in	1600/ 17th	106	27.6	5.6	4.1	39850	-	0.13
Zim Iberia- in	0432/ 18th	106	33	5.2	4.2	39850	0.2	0.16
Al Mariya-in	1023/ 18th	106	28.7	6.5	7.5	40700	0.1	0.48
MSC Elena-in	1130/ 18th	106	33.3	5.75	6.75	39000	0.2	0.48
Hanjin Wilming-ton-in	1655/ 18th	106	34.4	6.6	5.6	39000	0.4	0.33
Victoria Bridge- in	0037/ 19th	106	36.1	6.3	7.3	37300	0.6	0.67
Essen Express- in	0538/ 19th	106	35.5	6.5	5.0	40275	0.5	0.26
Mol Elbe- out	1918/ 17th	105	33.25	5.2	5.2	43250	0.25	0.23
MSC Christina- out	2007/ 17th	106	32.25	6	5.5	42400	0.3	0.26
Zim Israel- out	2137/ 17th	106	27.6	8.1	7.1	40700	0.5	0.41
Midnight Sun- out	1328/ 18th	106	26.9	6.6	5.6	36450	0.2	0.27
Zim Iberia-out	2033/ 18th	106	33.6	8.1	8.1	43250	0.8	0.64
Al Mariya- out	2212/ 18th	106	30.2	7.0	6.0	40700	0.2	0.31
MSC Elena- out	1200/ 19th	106	33.4	7.8	6.3	35600	0.3	0.46
Victoria Bridge- out	1910/ 19th	106	35.75	6.4	7.9	41550	0.7	0.69
Stuttgart Express- out	2055/ 20th	106	40.1	5.4	6.4	40700	0.5	0.50
Jervis Bay- out	0124/ 21st	106	35.6	8.1	7.1	39000	0.4	0.58

Table 3. Computed drawdown for Ships at Coast Guard Station causing largest drawdown. Channel width at -20 contour equals 1600 ft.

Ship-direction	Time/ date	Beam, ft	Draft, ft	Vg, knots	Vw, knots	Channel area, sq ft	Drawdown, ft	
							Measured	Calculated
Mol Americas-in	1737/ 16th	82	27.1	13.8	12.4	72000	NM	0.67
MSC Eleni- in	0850/ 17th	137.8	36.25	8.0	8.5	67980	"	0.65
Hanjin Wilming-ton- in	1552/ 18th	105.6	34.4	9.1	8.6	60780	"	0.54
Mol Velocity-in	1730/ 19th	106.0	30.5	9.5	9.0	60780	"	0.54
Sun Right- out	0957/ 17th	105	37.4	10.4	9.4	63980	"	0.70
Condor-out	1445/ 19th	79.1	27.8	13.5	11.9	58060	"	0.84
Emanuelle Tomasos	1535/ 19th	90.9	24.6	13.5	12.1	58060	"	0.91
Mol Velocity-out	0950/ 20th	106.0	34.4	9.9	9.9	71180	"	0.63

NM=no drawdown measurements were made at the Coast Guard Station

Other than 2 small ships, the highest calculated drawdown at the Coast Guard was 0.7 ft. The measured drawdown at City Front in Table 2 were up to 0.8 ft with only one ship having that maximum value. A maximum allowable drawdown to prevent passing ship problems of 0.7 ft was used in this study. Based on the 0.7 ft maximum drawdown, maximum allowable ship speed can be computed for various ship sizes at the three wake reduction points in the channel. Tables 4-7 show maximum allowable speed producing 0.70 ft of drawdown at Coast Guard Station, LNG dock, City Front, and Hwy 17 Bridge, respectively. Note that the 95% draft Gen 2 ship at Hwy 17 in the deepened channel had a blockage ratio of 0.20. This value is larger than the maximum quoted in the 2007 report because Gen 2 ships at Hwy 17 were not addressed. Calculations were based on average tide level and calculated ship speed was relative to the water (V_w). Note that at City Front, based on Tables 2 and 6, ships were often traveling at less than maximum allowable wake reduction speeds and drawdown was less than the maximum of 0.7 ft. This was likely due to caution in this congested area.

The difference in channel areas between existing and deepened channels was inconsistent in the 2007 study. All existing channel cross sections in the 2007 report had channel bottom elevations that were below -42 ft MLLW and generally average -43 ft MLLW over the 500-ft wide navigation channel. All existing channel cross section areas were increased by (48-43)*500 = 2500 sq ft to provide a consistent effect of deepening.

Table 4. Maximum ship speed at Coast Guard Station that does not exceed a drawdown of 0.7 ft to insure safe transit. Used measured channel cross section at FP for Coast Guard Station. Channel width used in the Schijf equation at -20 contour = 1600 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for 0.70 ft drawdown, kn	Return velocity, drawdown
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	63980	10.52	1.23,0.7
“	“	37.7(design draft)	“	9.59	1.34,0.7
“ (D)	“	30.2 (avg 2005 draft)	66480	10.75	1.20,0.7
“	“	37.7(design draft)	“	9.80	1.31,0.7
Panamax (E)	106 X 951	34.3 (50% draft)	63980	9.73	1.32,0.7
“	“	40.0 (95% draft)	“	9.10	1.40,0.7
“ (D)	“	34.4 (50% draft)	66480	9.93	1.29,0.7
“	“	40.6 (95% draft)	“	9.24	1.38,0.7
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	63980	8.62	1.47,0.7
“	“	41.2 (95% draft)	“	8.10	1.56,0.7
“ (D)	“	41.1 (50% draft)	66480	8.30	1.53,0.7
“	“	45.6 (95% draft)	“	7.89	1.60,0.7
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	63980	8.28	1.53,0.7
“	“	41.8 (95% draft)	“	7.73	1.63,0.7
“ (D)	“	41.7 (50% draft)	66480	7.92	1.59,0.7
“	“	46.6 (95% draft)	“	7.48	1.67,0.7

E=existing channel, D=deepened channel

Table 5. Maximum ship speed at LNG and at Old Fort Jackson that does not exceed a drawdown of 0.7 ft to insure safe transit. Used measured channel cross section at CDF. Channel width used in Schijf equation at -20 contour equals 1075 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for 0.70 ft drawdown, kn	Return velocity, drawdown
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	50500	9.72	1.32, 0.7
“	“	37.7(design draft)	“	8.77	1.45, 0.7
“ (D)	“	30.2 (avg 2005 draft)	53000	9.98	1.29, 0.7
“	“	37.7(design draft)	“	9.01	1.42,0.7
Panamax (E)	106 X 951	34.3 (50% draft)	50500	8.91	1.43,0.7
“	“	40.0 (95% draft)	“	8.27	1.53,0.7
“ (D)	“	34.4 (50% draft)	53000	9.15	1.40,0.7
“	“	40.6 (95% draft)	“	8.44	1.50,0.7
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	50500	7.79	1.61,0.7
“	“	41.2 (95% draft)	“	7.28	1.71,0.7
“ (D)	“	41.1 (50% draft)	53000	7.51	1.67,0.7
“	“	45.6 (95% draft)	“	7.10	1.75,0.7
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	50500	7.46	1.68,0.7
“	“	41.8 (95% draft)	“	6.92	1.79,0.7
“ (D)	“	41.7 (50% draft)	53000	7.13	1.74,0.7
“	“	46.6 (95% draft)	“	6.71	1.84,0.7

Table 6. Maximum ship speed at City Front that does not exceed a drawdown of 0.7 ft to insure safe transit. Channel width used in Schijf equation at -20 contour equals 858 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for 0.70 ft drawdown, kn	Return velocity, drawdown
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	38300	8.5	1.49,0.7
"	"	37.7(design draft)	"	7.6	1.65,0.7
" (D)	"	30.2 (avg 2005 draft)	40800	8.8	1.44,0.7
"	"	37.7(design draft)	"	7.9	1.60,0.7
Panamax (E)	106 X 951	34.3 (50% draft)	38300	7.7	1.62,0.7
"	"	40.0 (95% draft)	"	7.1	1.73,0.7
" (D)	"	34.4 (50% draft)	40800	7.8	1.57,0.7
"	"	40.6 (95% draft)	"	7.4	1.71,0.7
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	38300	6.70	1.84,0.7
"	"	41.2 (95% draft)	"	6.23	1.96,0.7
" (D)	"	41.1 (50% draft)	40800	6.5	1.90,0.7
"	"	45.6 (95% draft)	"	6.1	1.99,0.7
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	38300	6.4	1.92,0.7
"	"	41.8 (95% draft)	"	5.9	2.05,0.7
" (D)	"	41.7 (50% draft)	40800	6.1	1.97,0.7
"	"	46.6 (95% draft)	"	5.7	2.08,0.7

Table 7. Maximum ship speed at Hwy 17 that does not exceed a drawdown of 0.7 ft to insure safe transit. Channel width used in Schijf equation at -20 contour equals 662 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for 0.70 ft drawdown, kn	Return velocity, drawdown
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	30630*	7.6	1.64,0.7
"	"	37.7(design draft)	"	6.8	1.84,0.7
" (D)	"	30.2 (avg 2005 draft)	33130	8.0	1.58,0.7
"	"	37.7(design draft)	"	7.1	1.75,0.7
Panamax (E)	106 X 951	34.3 (50% draft)	30630	6.9	1.80,0.7
"	"	40.0 (95% draft)	"	6.3	1.93,0.7
" (D)	"	34.4 (50% draft)	33130	7.2	1.72,0.7
"	"	40.6 (95% draft)	"	6.6	1.87,0.7
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	30630	5.9	2.05,0.7
"	"	41.2 (95% draft)	"	5.45	2.19,0.7
" (D)	"	41.1 (50% draft)	33130	5.8	2.11,0.7
"	"	45.6 (95% draft)	"	5.4	2.21,0.7
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	30630	5.6	2.14,0.7
"	"	41.8 (95% draft)	"	5.12	2.30,0.7
" (D)	"	41.7 (50% draft)	33130	5.4	2.19,0.7
"	"	46.6 (95% draft)	"	5.0	2.31,0.7

*Three cross sections near the highway the HWY 17 crossing were plotted and the average area at mean tide level was 30630 sq ft and the width at the -20 contour was 662 ft. If the 500 ft navigation channel is deepened to 48-ft, the area at mean tide will be 33130 sq ft.

Ship Speed Model to Determine Speed in Full Bell Reaches with Updated Drafts

As stated in the 2007 report on ship forces, one of the most important parameters in determining the effects of deepening on forces at the shoreline was ship speed. More specifically, the speed of a ship in the existing channel versus the speed of the same ship with a larger draft in the deepened channel was the key comparison of effects. It is not a valid comparison to assume a speed for the existing channel and assume another speed for the deepened channel or to assume the two channels will have equal speed. The reason for needing accurate ship speed is that shoreline forces related to drawdown, return velocity, and wave height are related to ship speed V^2 up to ship speed V^5 depending on which ship effect and which equation is selected. Using wave height as an example and using wave height varying at about ship speed V^3, an error in ship speed of 10% will result in an error in wave height of 33%. Because of the importance of this issue, the speed model used for SH was refined in this reevaluation of ship forces at the shoreline. Speeds in this reanalysis are expressed in hundredths of a knot. While this has no practical significance, it was done because of the sensitivity of shoreline forces to small changes in speed.

In deep water in the absence of wind waves, ship resistance that must be overcome by the propeller is primarily friction along the hull plus wave making resistance. In a relatively shallow channel or canal, additional resistance arises from shallow water effects, drawdown of the water level, and return velocity. In the SH report on Ship Forces at the Shoreline (Maynord, 2007), the van de Kaa (1978) equation was used as the ship speed model and total resistance R_t is given by

$$R_t = \frac{1}{2} C_f \rho (V_w + V_r)^2 S + \frac{1}{2} C'_p \rho V_w{}^2 BT - \frac{1}{2} C''_p \rho (V_w + V_r)^2 BT + \rho g BT z_s \qquad (1)$$

where C_f = friction coefficient, ρ = water density, V_w = ship speed relative to water, V_r = return velocity in channel due to displacement of ship, S = wetted area of hull, C'_p = pressure or wave-making coefficient at bow, C''p = pressure or wave making coefficient at stern, B = ship beam, T = average ship draft, g = gravitational acceleration, and z_s = squat at the stern of the ship. The first term in Eq. 1 is friction resistance with ship velocity relative to water increased by return velocity to account for restricted channel effects, the second and third terms are pressure or wave-making resistance, and the fourth term is the confined channel resistance related to squat at the stern of the ship. Van de Kaa states that the values of C'_p and C''_p for confined channels will differ from the corresponding values for deep water. For barges, C'_p and C''_p were replaced by a single coefficient C_p and resistance tests in restricted channels have shown that C_p can be negative up to a value of -0.5 for high speeds when Eq. 1 was used with z_s = z from the Schijf equation. For deep draft ships of interest to this study, only deep water coefficients were known and C'_p and C''_p have been replaced by a single coefficient.

While the van de Kaa equation was still valid, ship speed models exist that consider more of the ship details important to both the friction resistance and the wave-making resistance. In this reanalysis, the Holtrop and Mennen (1982) and Harvald (1983) equations that are only applicable to deep water were evaluated for the friction and wave-making resistance in Eq. 1. The Holtrop and Mennen method for deep water was programmed by M.G. Parsons of the University of Michigan Department of Naval Architecture and Marine Engineering and was used to compare to the Harvald equations. For the ship sizes and speeds at SH, the two equations give similar deep water speeds and resistances and the Harvald (1983) approach was used to determine friction (first term) and deepwater wave-making/pressure (second and third terms) in Eq 1. Neither Holtrop and Mennen (1982) nor Harvald (1983) accounts for shallow and restricted channel effects as dealt with in Eq 1. The only change to the Harvald (1983) equations was the correction for the ratio of beam/draft. The standard curves for Harvalds wave-making coefficients were based on beam/draft = 2.5. Harvald provides a correction that was added to the wave-making coefficient for beam/draft either less than or greater than 2.5 defined as

$$C_{B/T} = 0.00016(B/T - 2.5) \qquad (2)$$

Note that the correction can be either positive or negative based on the value of beam/draft. Above a B/T of about 3, the correction began to dominate the total wave-making resistance and the correction was limited to the value determined for B/T = 3. Since the ship resistance equations of Harvald (1983) were generally applicable to design draft conditions and most ships have B/T at design draft of 3 or less, this limit on the correction was realistic.

To account for shallow/restricted channel effects on friction, ship velocity used in the Harvald method to compute the friction resistance was increased by the return velocity as done in the first term in Eq 1. To address effects of drawdown in restricted channels, the restricted channel squat term $\rho gBTz_s$ was replaced by $K_z\rho gBTz$ where z is the drawdown determined using the Schijf equation. The coefficient K_z will be determined herein using SH data and accounted for several restricted channel effects including using deepwater wave-making resistance coefficients for shallow water and the relationship of stern squat to water level drawdown from the Schijf equation. The equation becomes

$$R_t = \frac{1}{2} C_f \rho (V_w + V_r)^2 S(from\,Harvald) + \frac{1}{2} C_p \rho V_w{}^2 S(from\,Harvald) + K_z \rho\, g\, BTz \qquad (3)$$

Note that Harvald uses S rather than BT in the wave resistance term.

In addition to restricted channel effects that reduce ship speed, shallow water can also reduce ship speed in channels where the width restriction is not present. Schlicting in Harvald (1983) provides a plot of speed correction for shallow water effects. Norrbin (1986) provides a plot of shallow water and restricted channel effects on ship speed. EM 1110-2-1613 presents a replot of the plot from Norrbin (1986). Figure 3 shows the speed reduction for shallow water effects from Schlicting and Norrbin for propeller and ship speeds typical of ships at SH. Both methods will be used subsequently to check for shallow water effects on speed.

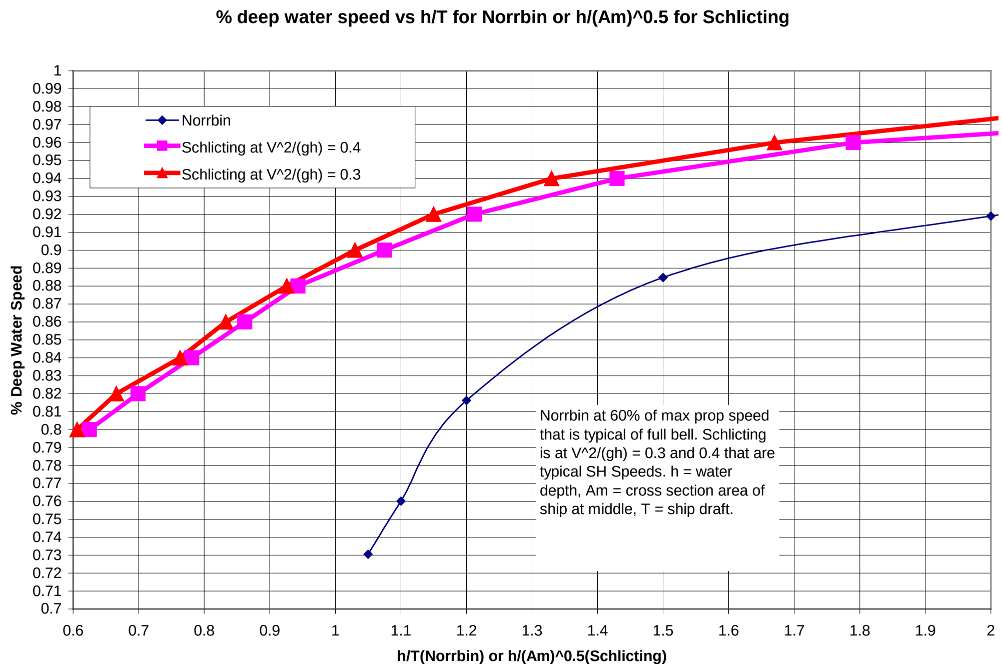

Figure 3. Effects of shallow water on ship speed.

Data from the Pilot Cards of four container ships obtained for calibration purposes were used to obtain the deep water ship speeds and propeller RPM for sea speed and the four maneuvering bells that are full bell, half ahead, slow ahead, and dead slow ahead. The Harvald approach was used to determine the resistance R for ship speed at full bell for deep water when no shallow water or confined channel effects were present. Using the wake fraction and the thrust deduction fraction, the hull efficiency η_H was determined using

$$\eta_H = \frac{1-t}{1-w} \quad (4)$$

where t is the thrust deduction fraction and w is the wake fraction. The required thrust from the propeller T was calculated from

$$T = \frac{RV}{\eta_H V_A} = \frac{R}{1-t} \quad (5)$$

where R is the deep water resistance from Harvald, V is ship speed, and V_A is the approach velocity to the propeller = V(1-w). The effective power is

$$P_E = RV \quad (6)$$

Since the shaft power at full bell will be about the same in deep and restricted water conditions, the shaft power at full bell was the parameter that was used to determine comparable ship speed in both deep water and shallow/restricted channel conditions. The shaft power P_s is

$$P_s = \frac{P_E}{\eta_H \eta_O \eta_R \eta_S} \quad (7)$$

where η_O = propeller efficiency, η_R = relative rotative efficiency about equal to 1, η_S = shaft efficiency equal to about 0.99. The propeller efficiency was a key parameter in determining P_s that depends on details of the propeller. The following method was used to eliminate the need to design propellers for each ship used in this analysis. The advance coefficient is a key parameter describing propeller efficiency as well as other propeller coefficients and is defined as

$$J = \frac{V_A}{nD} \tag{8}$$

where n is propeller speed in rev/sec and D is propeller diameter. For the four calibration ships discussed subsequently using typical propeller diameters for the Panamax and Post-Panamax ships, deep water advance coefficient for both sea speed and full bell varied from 0.6 to 0.7. For a Wageningen B 4-55 propeller having Pitch/diameter = 1.0, the propeller efficiency is equal to

$$\eta_O = -0.56J^2 + 1.39J - 0.036 \tag{9}$$

Using an advance coefficient J = 0.7 in deep water for all ships, J equals 0.7 x (V_A restricted/V_A deep) for the restricted channel condition. For deep water having J = 0.7, η_O = 0.66.

The shaft power for four calibration ships will be determined using equations 2 through 9 for deep water conditions. In all calculations herein, wake fraction = 0.32 and thrust deduction = 0.16 based on Harvald (1983).

The characteristics of the 4 calibration ships are shown in Table 8. Computed shaft power is shown for full bell because this is the power setting typically used at SH and other deep draft channels.

Table 8. Characteristics of 4 calibration ships.

Ship Class	Length, ft (m)	Beam, ft (m)	Draft, ft (m)	Sea Speed, knots (propeller RPM)	Full Bell Speed, knots (propeller RPM)	Computed shaft power at Full Bell, hp
Panamax	964.6 (294.1)	105.6 (32.2)	41.3 (12.6)	25 (102)	13.4 (53)	6224
Post-Panamax	1043 (318.2)	137 (41.8)	Aft: 40.0 (12.2) Forward: 37.5 (11.5)	25 (94)	17 (65)	15575
Panamax	930 (283.5)	105 (32)	44.5 (13.6)	20.5 (90)	15.1 (65)	8806
Post-Panamax	984 (300)	140.9 (43)	47.6 (14.5)	25.2 (102)	16 (65)	14279

The remaining issue in the speed model was to determine K_z to account for the restricted channel effects. This determination was done with speed and draft data for the average Panamax and Post-Panamax ships observed during the Sept 2005 field study. The average Panamax ship at Tybee cross section had length of 855 ft (260.7m), beam of 105.7 (32.2 m), draft of 33.3 ft (10.15m), and average speed of all 33 ships of 12.9 knots.

The average Post-Panamax ship observed in the 2005 field study results in a length of 949.4 ft = 289.4 m, beam of 137 ft = 41.8 m, and draft of 36.5 ft = 11.1 m. Average ship speed was measured for three of the 5 Post-Panamax ships that passed during the 2005 field study. The average speed was 12.9 knots and ranged from 11.1 to 14.2 knots.

The third resistance term in Eq. 3 representing restricted channel effects was found equal to 0.1ρgBTz. The coefficient K_z = 0.1 resulted in a shaft power from the Panamax ship of 8434 hp compared to the two calibration ships having 6224 hp and 8806 hp. The 0.1 coefficient resulted in a shaft power from the Post-Panamax ship of 15558 hp compared to the two calibration ships having 15575 hp and 14279 hp. The coefficient was selected on the high side of the calibration ship power ranges to insure that restricted channel effects were not underestimated. It is important to note that using Eq. 3 with K_z = 0.1 results in a significant portion of the total resistance at Tybee being from the drawdown term and the added friction by including return velocity. For the 855 ft long Panamax ship, the resistance in the existing channel at Tybee was composed of 49% friction in deep water, 15% wave-making in deep water, and 36% from the drawdown term and the additional friction from including the return velocity. For the 949.4 ft long Post-Panamax ship, the resistance in the existing channel at Tybee was composed of 38% friction in deep water, 13% wave-making in deep water, and 49% from the drawdown term and the additional friction from including the return velocity.

Summarizing, the steps in the speed method are as follows:

1. Assume a deep water ship speed.
2. Use Harvald to compute wave resistance at assumed deep water ship speed.
3. Use Harvald to compute friction resistance at assumed deep water ship speed.
4. Determine total resistance by summing steps 2 and 3. Determine effective power using total resistance R and assumed deep water ship speed.
5. Determine shaft power. If shaft power equals target shaft power, go to step 6. If not go to step 1 and assume a new deep water ship speed.
6. Assume a restricted channel ship speed.
7. Use Schijf equation to compute drawdown (z) and return velocity (Vr) using restricted channel ship speed.
8. Use Harvald to compute wave resistance at assumed restricted channel ship speed.
9. Use Harvald to compute friction resistance at assumed restricted channel ship speed plus computed return velocity.
10. Determine added resistance due to drawdown and other restricted channel effects equal to 0.1ρgBTz.
11. Determine total resistance equal to sum of steps 8, 9, and 10.
12. Determine effective power using total resistance and assumed restricted channel ship speed.
13. Compute shaft power P_s using effective power and shafting, propeller, and hull efficiencies. Propeller efficiency based on assumed restricted channel speed and deep water ship speed determined above.
14. If computed shaft power was equal to the target shaft power defined for each class, the solution was complete. If not, assume new restricted channel speed and repeat, starting at step 6.

15. Check ship speed in existing and deepened channels to make certain correct shallow water effects in Figure 3 are shown in the computed speeds.

Harvald (1983) discusses the Schlicting method of dealing with shallow water effects and states “It should be noted that the method can only be considered a good engineering solution of a complicated problem, not as a theoretically correct method.” The speed approach developed herein using Harvald (1983) plus the empirically derived resistance for shallow water/restricted channel effects was an engineering solution that includes the most important restricted channel physical effects of drawdown and return velocity. The approximate nature of this approach results from various factors, one of the most important being that most ship design coefficients, such as C_b, wake factor, and thrust deduction, are for maximum draft in deep water at large speed. Refinements could be made to this approach but the approach contains the dominant restricted channel effects and empirical coefficients have been derived to match conditions at SH.

A check was made on this ship speed method using the Norrbin plot (Figure 4) taken from EM 1110-2-1613 showing restricted channel speeds. No portion of the Norrbin plot was used in developing the speed method developed herein. Norrbin’s plot was for channels having a blockage ratio (area of ship)/(area of channel) of 0.2 through 0.275. Since the blockage ratio of 0.2 was the largest channel of Norrbin and the one closest to the generally larger channel present at SH, the 0.2 blockage ratio was used in the comparison. For a typical range of speeds, the Norrbin plot shows that in a blockage ratio channel of 0.2, the speed will be 66% of the deep water speed for slow ship speeds and 60-63% of the deep water speed for fast ship speeds. Note that in a channel having a blockage ratio of 0.2, speeds for typical size Panamax ships at SH were limited to about 9 knots because of the size of the channel and power of the ship. For the average Panamax ship in the field study at SH in 2005, length was 855 ft, beam was 105.7 ft, and draft was 33.3 ft. The ship cross section area was 33.3*105.7 = 3520 sq ft resulting in a channel area of 3520/0.2 = 17600 sq ft. The channel used to test the Norrbin plot with the SH ship had 1V:1H side slopes, typical SH depth of 45 ft, area of 17600 sq ft, bottom width of 346 ft, and water surface width of 436 ft. Using the Harvald approach modified herein for restricted channel effects results in the speeds in Table 9. The Harvald resistance equations along with the restricted channel modifications developed herein show reasonable agreement with the 60-66% determined from the Figure 4 Norrbin plot.

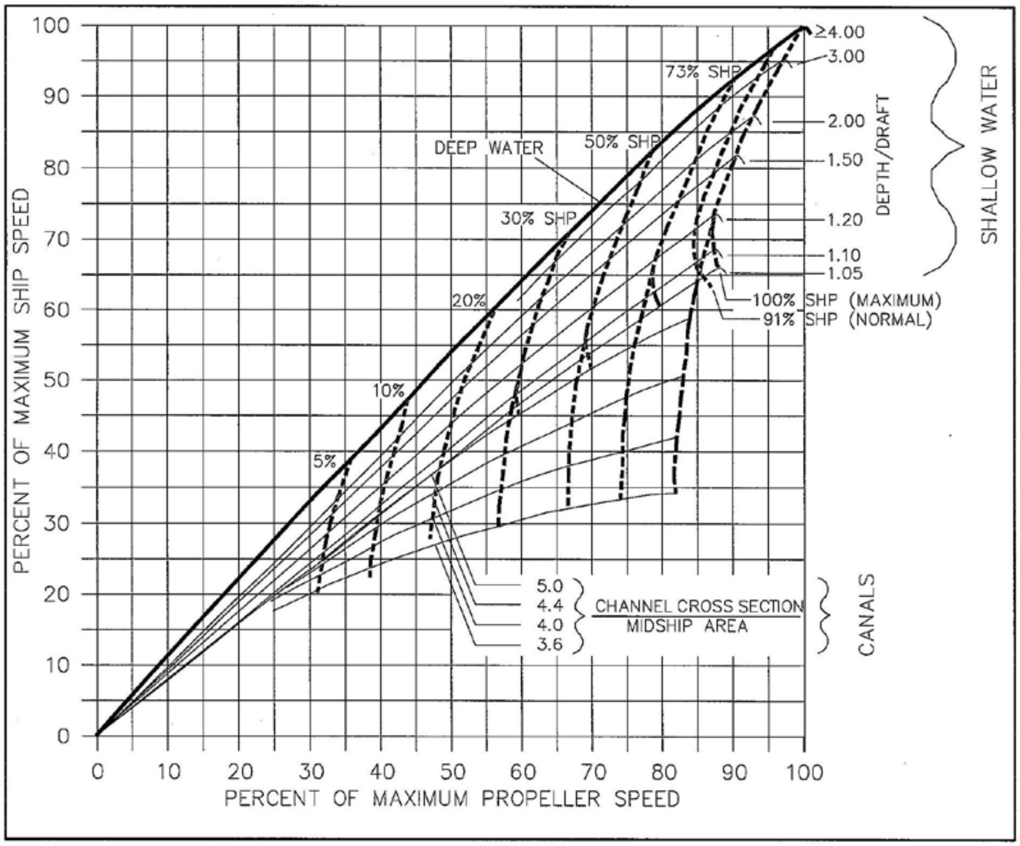

Figure 4. Shallow water and restricted channel effects on ship speed from Norrbin (1986).

Table 9. Ship speeds in deep water and restricted channel from modified Harvald approach for comparison to Norrbin.

Speed in restricted channel, knots	Shaft power, hp	Speed in deep water, knots	Restricted speed/deep water speed
6	1827	9.32	0.64
7	3085	11.16	0.63
8	5060	13.23	0.60
9	8388	15.74	0.57

In addition to the Norrbin comparison, the ship speed equations were compared to three Panamax container ships in the Houston Ship Channel whose speed was measured in a 2003 field study reported in Maynord, Hite, and Sanchez (2006). While other ship types were present, these were the only container ships where their speed was not affected by meeting other ships in the channel. The cross section in the reach where the speed was measured had a width of 738 ft at the -20 contour and area of 32287 ft^2. The target shaft power used in the calculations was 8434 hp that was the value used for typical Panamax ships at full bell in this analysis. Comparison of observed and computed speeds are shown in Table 10. Reasonable agreement is seen in observed versus computed using the speed model developed herein.

Table 10. Ship speed measured in Houston Ship Channel and ship speed from speed model developed herein.

Ship Name	Length x Beam x Draft, ft	Measured Speed, kn	Calculated Speed, kn
TMM Hermosillo	885 x 106 x 32	11.9	11.5
Lykes Ambassador	889 x 106 x 32	11.2	11.5
Lykes Ambassador	889 x 106 x 36	10.5	10.8

Ship Speed at Full Bell

There are three reaches where ships typically travel at full bell at SH. Depending on the length of the reach, ship characteristics, and tide conditions, the ship may or may not reach the maximum speed for full bell. The three locations were at Tybee Island, a portion of the reach between the Coast Guard Station and the LNG facility, and a portion of the reach between LNG and old Fort Jackson. These were the only locations where the ship was generally not constrained by operational issues, the primary of which were wake reduction or the Right Whale restriction on speed. Even in the full bell areas, ships must slow down if other boats are near the shoreline or near the jetties. The previously described ship speed method was used to determine these speeds as shown in Tables 11 to 13. The speed of the 50% draft ship in the existing channel at Tybee Island for all classes was equal to a speed of 12.9 knots based on the observations during the 2005 field study. The 12.9 knot speed at Tybee for all ship classes was chosen to provide a consistent comparison in this analysis. The 12.9 knot speed, the average/typical draft, and the existing Tybee Island cross section were used to determine the full bell target shaft power for that ship class. In the calibration phase of developing this speed model for typical ships, a Panamax ship had a shaft power at full bell of 8434 hp. To insure the analysis was conducted with ships at the upper end of shaft power, the Panamax ship shaft power based on the 12.9 knot speed was 9285 hp as shown in Tables 11-13. The speed for all other conditions of draft, channel location, and channel deepening was determined using the ship speed model and the target full bell shaft power for each class. The tables for full bell speed also show the full bell speed in deep water from Harvald.

Speeds at full bell shown in the tables reflect both shallow water and restricted channel effects on ship speed. Since both effects were present to some degree at SH, speeds in the tables should always be less than the reduction in speed from shallow water effects alone. Speeds in the tables were checked to insure that speed from both effects was smaller than the shallow water effects given in Figure 3. For example, the Gen 2 ship at 95% draft in the deepened channel at Tybee would be operating at a depth of 51.7 ft at mean tide level used in the calculations. The depth/draft (h/T) = 51.7/46.6 = 1.11 and $h/(Am)^{0.5}$ = $51.7/(142.9*46.6)^{0.5}$ = 0.63. Based on Norrbin and h/T = 1.11, % deep water speed = 76%. Based on Schlicting and $h/(Am)^{0.5}$ = 0.63, % deep water speed = 80%. The two shallow water methods were in reasonable agreement. The computed speed in Table 11 for the Gen 2 ship at Tybee was 11.73 knots for restricted channel and 16.57 knots for deep water yielding a percentage of 71%. In this example and all cases in the full bell tables, computed speed in the restricted channel was always less than speed based on only shallow water effects and the shallow water correction was exceeded as required. As would be expected in the relatively large channel at SH, most of the speed reduction can be attributed to shallow water effects.

Table 11. Maximum ship speed at Tybee Island at Full Bell. Channel width at -20 contour = 1620 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for full bell, kn	Target shaft power, hp	Deep water ship speed, kn	Return vel, Drawdown, ft/sec, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	64175	12.90	6306	15.37	1.92,1.36
"	"	37.7(design draft)	"	11.87	"	14.71	2.03,1.33
" (D)	"	30.2 (avg 2005 draft)	66675	13.02	"	15.37	1.83,1.30
"	"	37.7(design draft)	"	11.99	"	14.71	1.94,1.28
Panamax (E)	106 X 951	34.3 (50% draft)	64175	12.90	9285	15.78	2.43,1.74
"	"	40.0 (95% draft)	"	12.20	"	15.39	2.53,1.71
" (D)	"	34.4 (50% draft)	66675	13.03	"	15.77	2.31,1.66
"	"	40.6 (95% draft)	"	12.27	"	15.35	2.41,1.64
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	64175	12.90	14260	17.22	3.52,2.58
"	"	41.2 (95% draft)	"	12.20	"	16.7	3.53,2.46
" (D)	"	41.1 (50% draft)	66675	12.40	"	16.71	3.37,2.37
"	"	45.6 (95% draft)	"	11.83	"	16.33	3.41,2.30
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	64175	12.90	17793	17.57	4.01,2.97
"	"	41.8 (95% draft)	"	12.14	"	17.02	4.02,2.81
" (D)	"	41.7 (50% draft)	66675	12.36	"	17.02	3.83,2.71
"	"	46.6 (95% draft)	"	11.73	"	16.57	3.86,2.61

Table 12. Maximum ship speed at Reach between CG and LNG at Full Bell. Average cross section from FP and CDF used in analysis. Channel width at -20 contour = 1338 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for full bell, kn	Target shaft power, hp	Deep water ship speed , kn	Return vel, drawdown, ft/sec, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	57240	12.78	6306	15.37	2.02,1.42
"	"	37.7(design draft)	"	11.71	"	14.71	2.15,1.40
" (D)	"	30.2 (avg 2005 draft)	59740	12.91	"	15.37	1.91,1.35
"	"	37.7(design draft)	"	11.85	"	14.71	2.05,1.34
Panamax (E)	106 X 951	34.3 (50% draft)	57240	12.77	9285	15.78	2.55,1.81
"	"	40.0 (95% draft)	"	12.04	"	15.39	2.66,1.79
" (D)	"	34.4 (50% draft)	59740	12.91	"	15.77	2.41,1.72
"	"	40.6 (95% draft)	"	12.12	"	15.35	2.54,1.71
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	57240	12.75	14260	17.22	3.66,2.65
"	"	41.2 (95% draft)	"	12.02	"	16.7	3.70,2.54
" (D)	"	41.1 (50% draft)	59740	12.24	"	16.71	3.52,2.45
"	"	45.6 (95% draft)	"	11.64	"	16.33	3.57,2.38
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	57240	12.75	17793	17.57	4.15,3.05
"	"	41.8 (95% draft)	"	11.95	"	17.02	4.19,2.90
" (D)	"	41.7 (50% draft)	59740	12.19	"	17.02	3.98,2.79
"	"	46.6 (95% draft)	"	11.53	"	16.57	4.03,2.69

Table 13. Maximum ship speed at Reach between CDF and Old Fort Jackson at Full Bell and actual speed based on limited length of reach. Cross section from CDF used in analysis. Channel width at -20 contour = 1075 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for full bell, kn	Target shaft power, hp	Deep water ship speed , kn	Return vel, drawdown, ft/sec, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	50500	12.63* (12.28)**	6306	15.37	2.01, 1.36
"	"	37.7(design draft)	"	11.53 (11.53)	"	14.71	2.30,1.48
" (D)	"	30.2 (avg 2005 draft)	53000	12.78 (12.41)	"	15.37	1.89,1.29
"	"	37.7(design draft)	"	11.68 (11.68)	"	14.71	2.18,1.41
Panamax (E)	106 X 951	34.3 (50% draft)	50500	12.62 (11.87)	9285	15.78	2.35,1.55
"	"	40.0 (95% draft)	"	11.85 (11.54)	"	15.39	2.68,1.73
" (D)	"	34.4 (50% draft)	53000	12.77 (11.99)	"	15.77	2.21,1.47
"	"	40.6 (95% draft)	"	11.95 (11.63)	"	15.35	2.54,1.65
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	50500	12.56 (10.80)	14260	17.22	2.71,1.65
"	"	41.2 (95% draft)	"	11.79 (10.53)	"	16.7	3.08,1.84
" (D)	"	41.1 (50% draft)	53000	12.04 (10.65)	"	16.71	2.85,1.72
"	"	45.6 (95% draft)	"	11.42 (10.44)	"	16.33	3.14,1.87
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	50500	12.56 (10.63)	17793	17.57	2.93,1.76
"	"	41.8 (95% draft)	"	11.72 (10.35)	"	17.02	3.34,1.99
" (D)	"	41.7 (50% draft)	53000	11.99 (10.46)	"	17.02	3.12,1.86
"	"	46.6 (95% draft)	"	11.29 (10.25)	"	16.57	3.47,2.06

*Speed that would have been reached in a long enough reach. **Actual speed that was reached in the short reach between CDF and Old Fort Jackson. The actual speed was used to determine return velocity and drawdown.

Regarding the speeds in Tables 11-13, ships in restricted channels have what is called a "limiting speed" that can not be exceeded by a self-propelled displacement ship. Further description of the limiting speed concept is given in USACE (2006). In addition to providing calculation of return velocity and drawdown, the Schijf (1949) equation will provide an estimate of the limit speed based on ship cross section area, channel cross section area, and average depth of the channel. At other deep draft ship channels studied by this author, ships generally travel at 75 to 90 percent of the limit velocity calculated using Schifj. Using the SH reach between the Coast Guard and LNG as an example, ships in Table 12 were traveling at 76 to 91 percent of their limit speed with the lowest percent for the Sub-Panamax and the highest percent for the Gen 2 ships. The speeds used in this analysis were consistent with other ship channels and at the high end of speeds for the Gen 1 and Gen 2 ships.

Speed Plots Along Channel

Speeds have been quantified at the wake reduction areas (CG, LNG, Old Fort Jackson to Hwy 17) and at the three full bell reaches (Tybee, between CG and LNG, and between CDF and Old Fort Jackson). It was uncertain if ships will reach full bell speed in the reach between CDF and Old Fort Jackson. Ship speed acceleration and deceleration is highly variable and depends on the ship characteristics and the operational procedures of the pilot. Information was collected from container ship data observed on the Houston Ship Channel in Maynord, Hite, and Sanchez (2006), discussions with a SH pilot, and observed speeds between the Coast Guard Station and Fort Pulaski during the 2005 field study. Based on the field study, the ships accelerate and decelerate at about 3 knots per mile between Coast Guard Station and Fort Pulaski between speeds of about 9 knots and 11 knots. Like almost any vehicle, acceleration at higher speeds will show lower acceleration rates. Between Fort Pulaski and the camera at Tybee, the acceleration/deceleration was 0.7 knots per mile but it was uncertain where along the reach the ship reached its constant speed. For the speed plots, ship speeds above 11 knots will use an acceleration of 1/2 of the 3 knots/mile value or 1.5 knots per mile. The 3.0 and 1.5 knot/mile values were used for acceleration and deceleration of ships that were either (1) accelerating from safe wake speeds to full bell speeds or (2) decelerating from full bell speeds to safe wake speeds. The acceleration/deceleration values adopted here were not a critical issue because they only affect the length of channel in which full bell constant speeds were reached.

The ships were also assumed to travel at the safe wake speed for 0.25 mile (about 1.5 ship lengths) on each side of the safe wake location. These rules and the calculated speeds in the tables were used to develop the speed plots in Figures 5 to 12. Speeds were adjusted at the bend at CDF to reflect the trends observed during the field study by setting the CDF speed equal to 4% greater than the LNG speed. All plots show the 10 knot speed restriction during the Right Whale season. Somewhat similar to the Right Whale restriction, a ship will not always be moored at the LNG dock and ship speeds will not be reduced. Figure 13 shows the speed plot for the 50% Gen 1 Post-Panamax ship for this case. All other ship classes and drafts will have this same trend when LNG ships are not present.

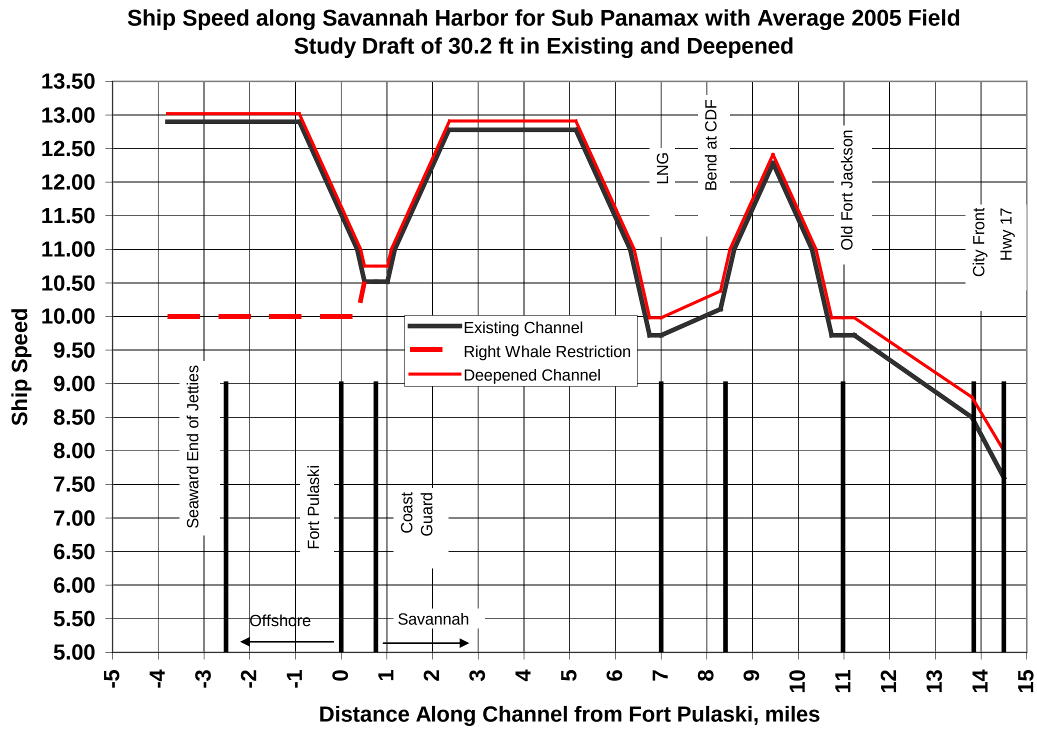

Figure 5. Ship speed for Sub-Panamax with average 2005 field study draft of 30.2 ft in Existing and Deepened channels.

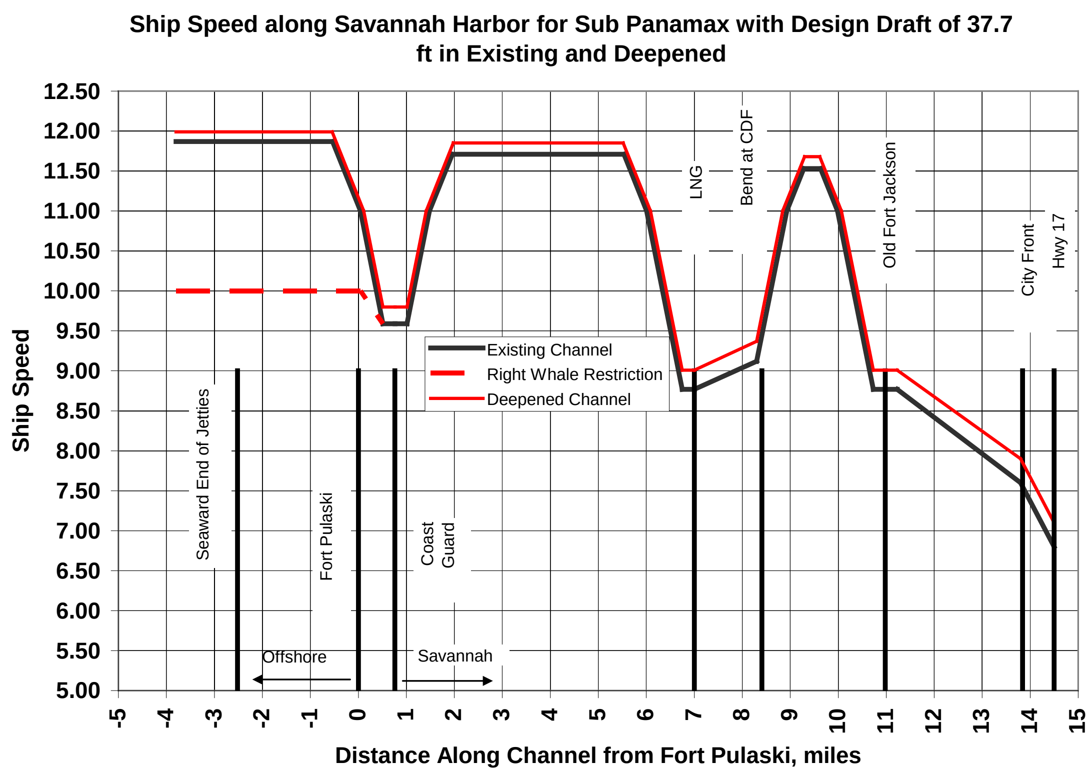

Figure 6. Ship speed for Sub-Panamax with design draft of 37.7 ft in Existing and Deepened channels.

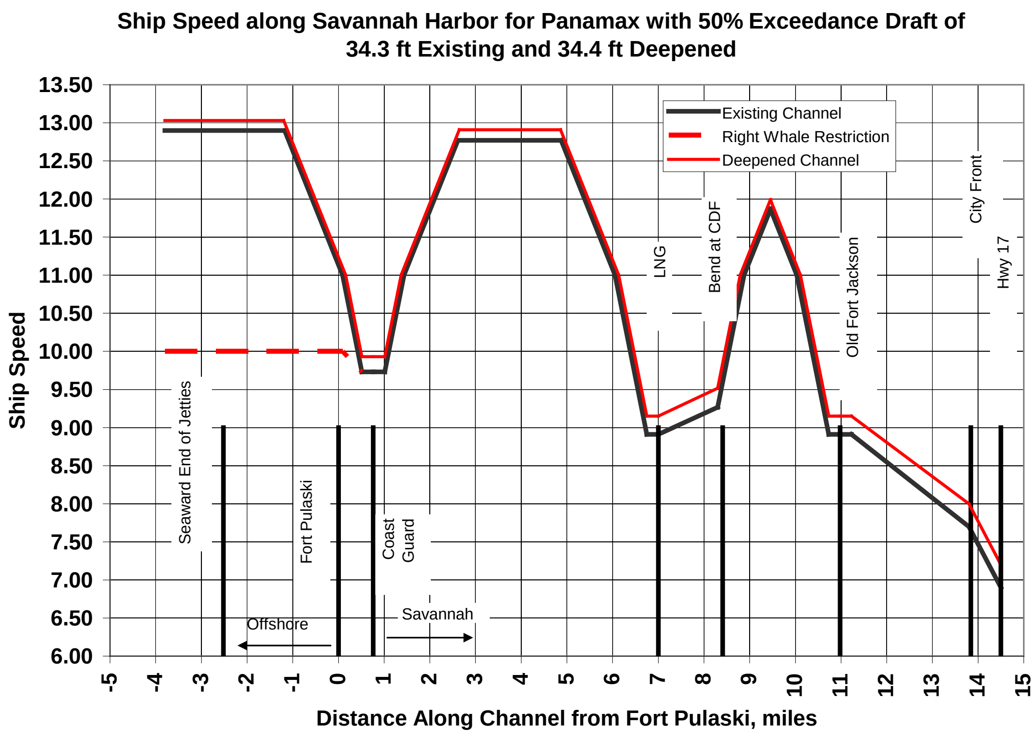

Figure 7. Ship speed for Panamax with 50% draft of 34.3 ft in Existing and 34.4 ft in Deepened channels.

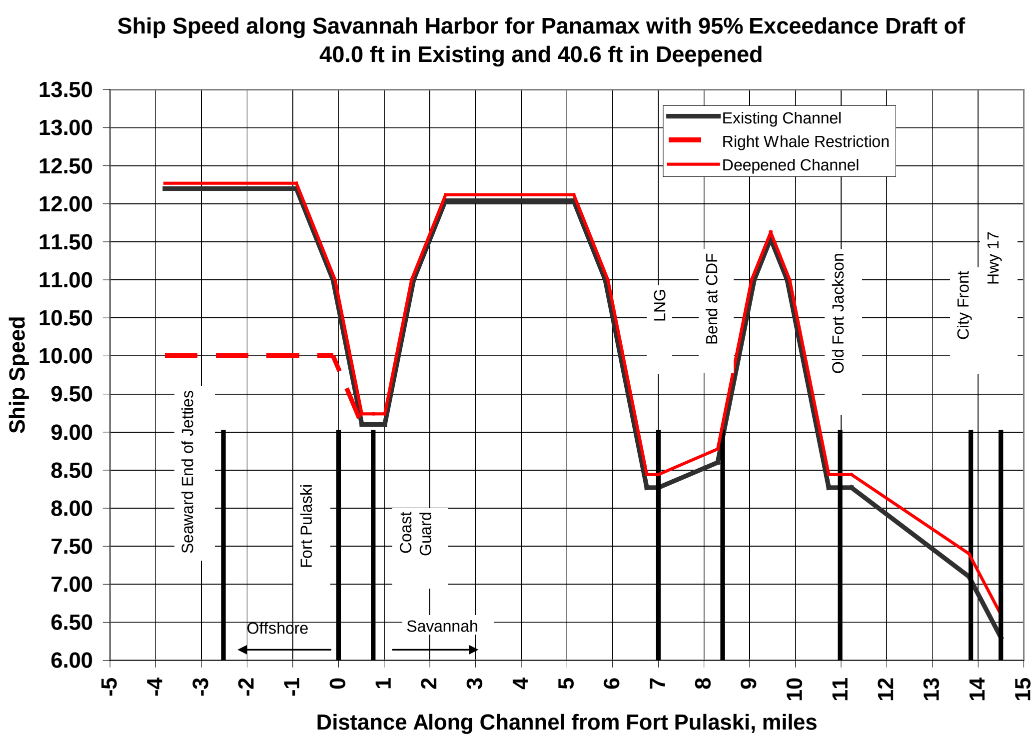

Figure 8. Ship speed for Panamax with 95% draft of 40.0 ft in Existing and 40.6 ft in Deepened channels.

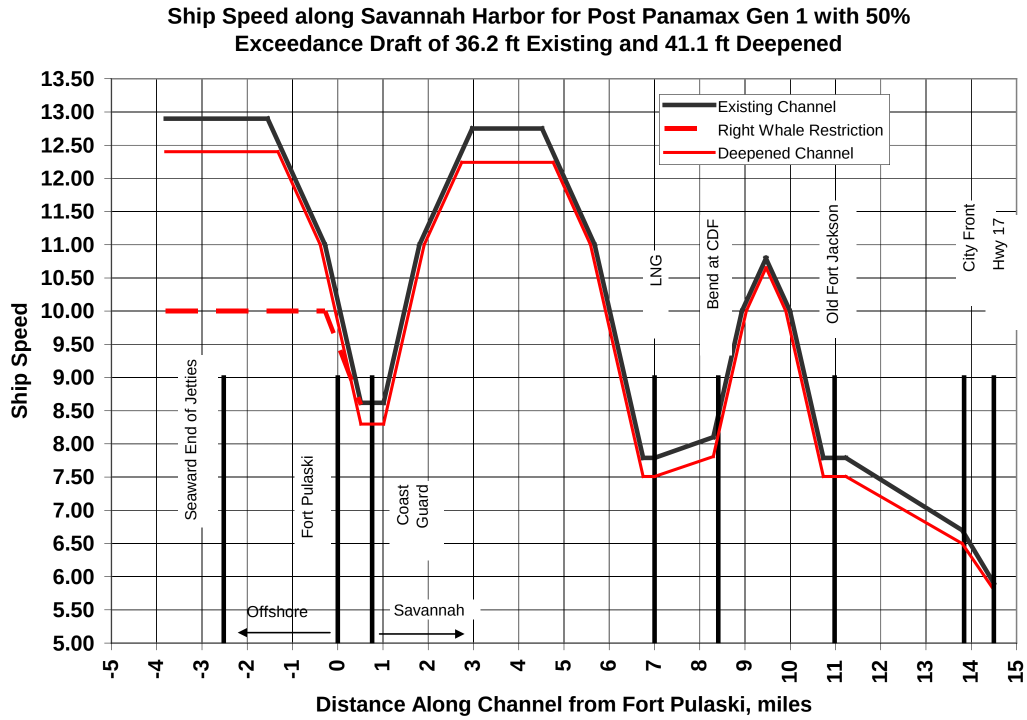

Figure 9. Ship speed for Post-Panamax Gen 1 with 50% draft of 36.2 ft in Existing and 41.1 ft in Deepened channels.

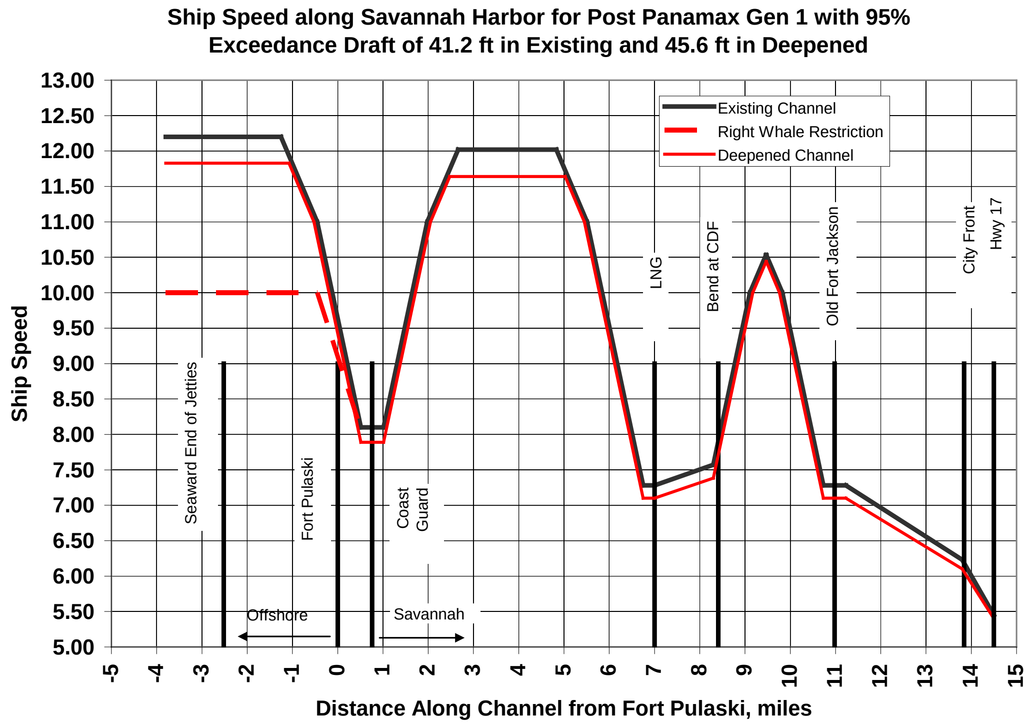

Figure 10. Ship speed for Post-Panamax Gen 1 with 95% draft of 41.2 ft in Existing and 45.6 ft in Deepened channels.

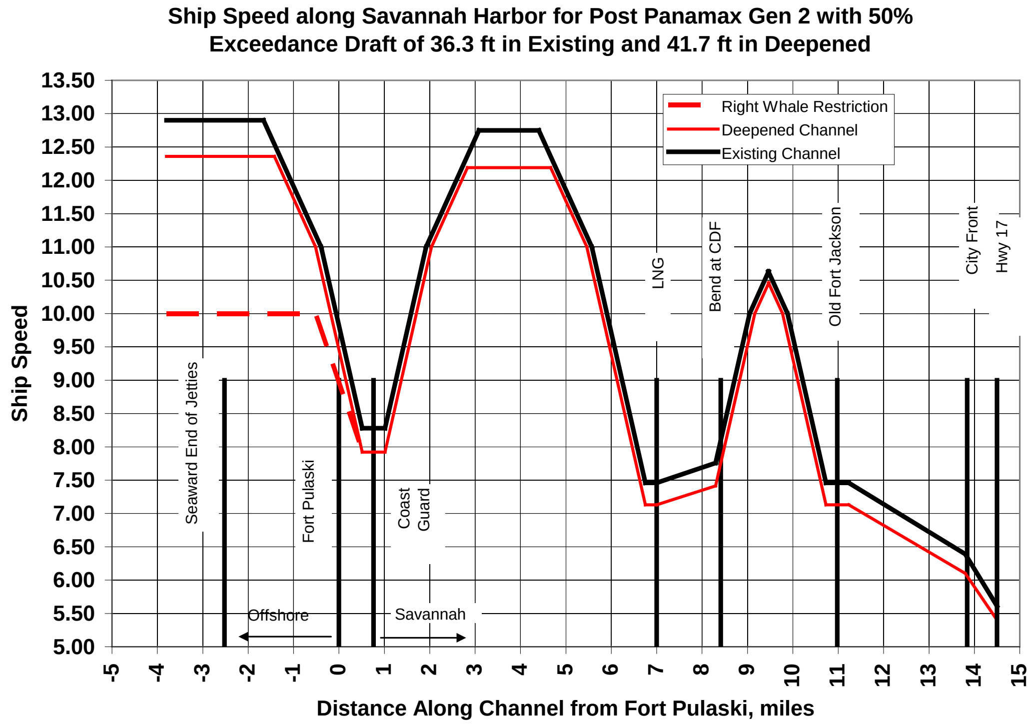

Figure 11. Ship speed for Post-Panamax Gen 2 with 50% draft of 36.3 ft in existing and 41.7 ft in Deepened channel.

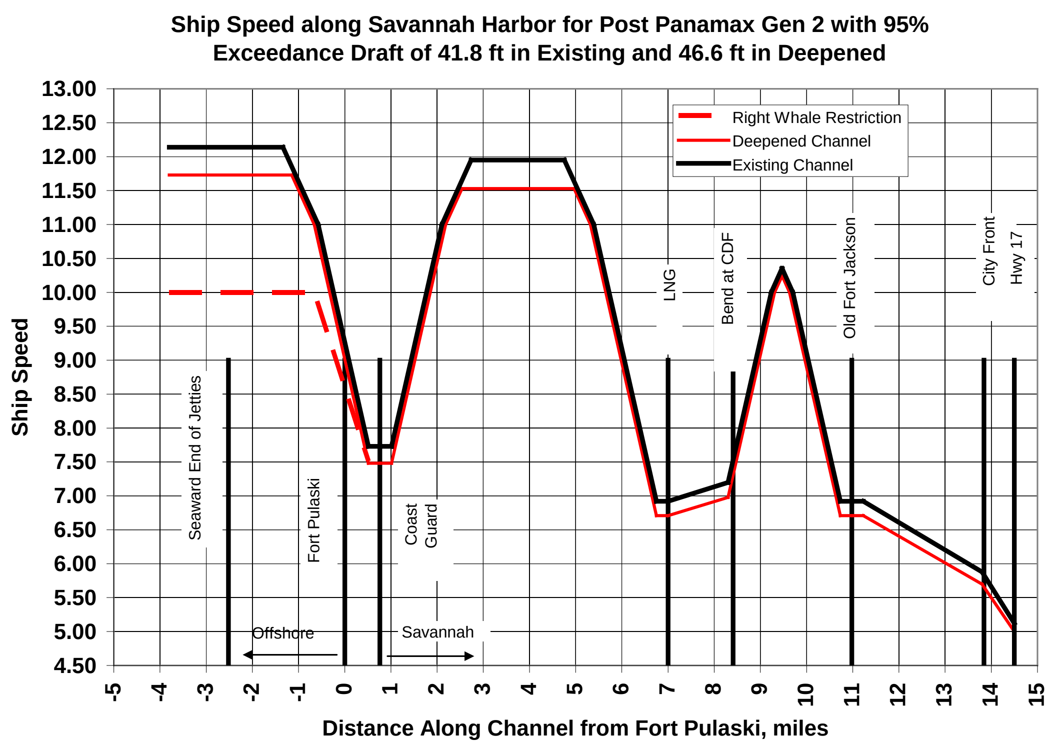

Figure 12. Ship speed for Post-Panamax Gen 2 with 95% draft of 41.8 ft in existing channel and 46.6 ft in deepened channel.

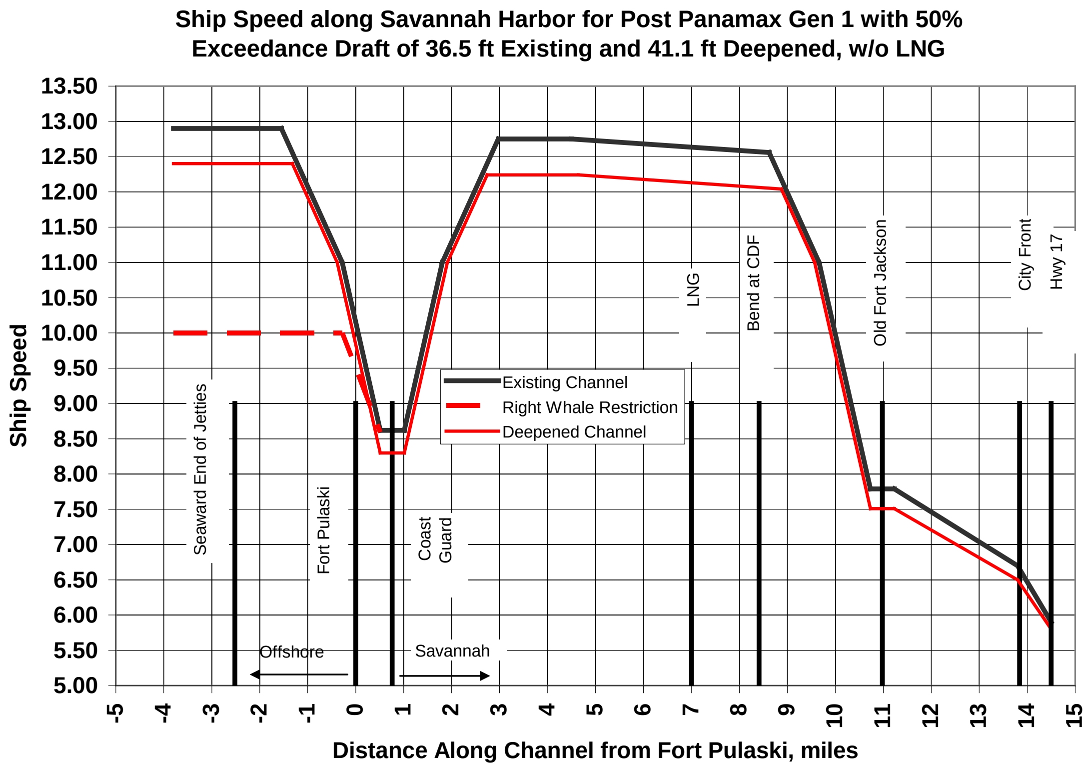

Figure 13. Ship speed for Post-Panamax Gen 1 with 50% draft of 36.5 ft in Existing and 41.1 ft in Deepened channels, without ship at LNG dock.

Revisions to Ship Wave Equation

In this reanalysis based on updated ship draft information, the ship wave equation was also examined to see if any changes were needed. In the 2007 study, the ship wave equation used was from Blaauw et al (1984) given as

$$H_{\max} = \beta \frac{B}{L_e} s^{-1/3} \left(\frac{V}{\sqrt{g}} \right)^{2.67} \qquad (10)$$

where,

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

Knight (1999) also used this equation but the equation will be referred herein as the "Blaauw equation" to give credit to the original developer. In the 2007 study, B/L_e was related to block coefficient C_b based on limited data where C_b was the block coefficient given by the equation

$$\frac{B}{L_e} = 1.11 C_b - 0.33 \qquad (11)$$

Based on a report by Seelig and Kriebel (2001), ship hull shape drawings at the water line along with the corresponding C_b were obtained and plotted in Figure 14 along with the 2007 equation for B/L_e. The two equations do not differ greatly but the revised equation was recommended as follows

$$\frac{B}{L_e} = 1.33 C_b - 0.42 \qquad (12)$$

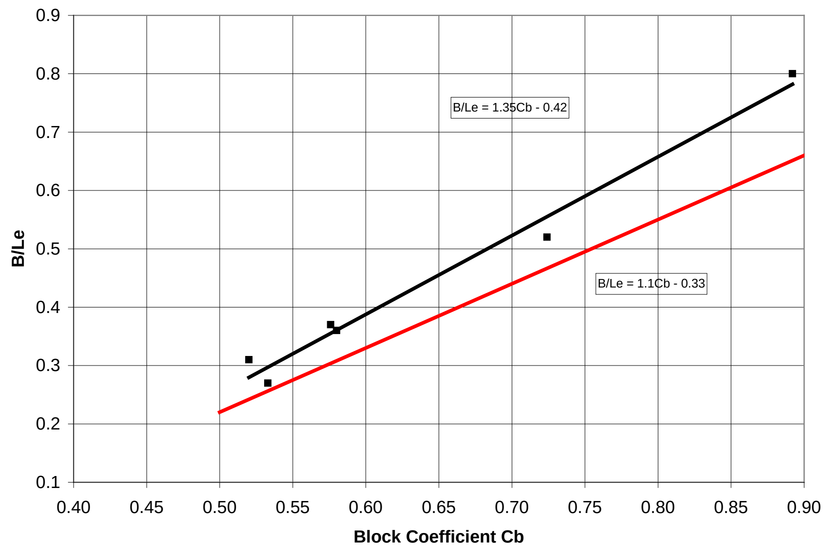

Figure 14. B/Le versus Cb. The black line is the revised equation.

In the 2007 study, the β coefficient used in Eq. 10 to account for the size of the ship was given by the equation

$$\beta = 0.0002 * B * T \qquad (13)$$

Where both B and T were in ft and the wave equation must use the same units with this definition of β. A more general form of the equation for β is

$$\beta = C * B^{P1} T^{P2} \qquad (14)$$

In the 2007 study, it was assumed that P1 = P2 = 1 and C was found equal to 0.0002. The assumption of P1=P2=1 means that draft and beam have equal importance and that wave height varies linearly with their product. This assumption is very important at SH because the ship forces evaluation is attempting to distinguish differences in wave height for changes in draft and/or beam. This important assumption was evaluated in this reanalysis.

Are there any wave height predictive equations that define the effects of variable beam and draft on wave height? The Weggel and Sorensen (1986) equations use the displacement volume of the hull along with numerous exponents and coefficients, most of which were functions of the depth Froude number. At channel depths, ship speeds, and ship sizes typical of the SH, wave height from the Weggel and Sorensen equations at a constant speed of 12 knots decreased by 27% as ship draft and ship beam both increased by 50% and the Weggel and Sorensen equations were not used.

Seilig and Kreibel (2001) and Kriebel and Seelig (2005) developed an empirical model for ship-generated waves. They assembled an impressive set of data from 16 different sources. One concern of this method was that the response of the equations did not trend as expected when changes were only made to the block coefficient. It is understood that another Kriebel and Seelig parameter "β_{ks}" also addresses hull shape and offsets the trend of block coefficient. In addition, at the ship speeds, ship sizes, and channel depths at SH, the wave height varies with ship speed with an exponent of a little greater than the fifth power. This was the result of the 0.1 being subtracted from the F* parameter in the

Kriebel and Seelig equation. This exponent was larger than most other wave height equations. As discussed with one of the developers of the equation, David Kriebel, the equations do not have ship beam as a parameter. Draft is used in the equations. The absence of beam is because of the high degree of correlation of beam and draft in the database. Beam and draft and ship length in the data base all have correlations of 0.96 or higher. This means that draft can generally substitute for beam and about equal goodness of fit of the observed data can be achieved with the regression equation. When a correlation of this type exists, one must cautiously use the equations when trying to determine the effect of beam and draft on wave height. In the Kriebel and Seelig (K&S) data set, the beam averaged 3.06 times the draft.

For example, consider the Gen 2 ship that drafts 46.6 ft, had a beam of 142.9 ft, and length of 1106 ft with speed of 11.53 knots in the deepened channel between the Coast Guard Station and the LNG. This example had a B/T ratio of 142.9/46.6 = 3.07 or about equal to the average of the database and the Kriebel and Seelig equations can be used with this ship. The computed wave height using the Kreibel and Seelig method was 0.73 ft. Suppose the draft was reduced to 41.7 ft for the same ship and this allows the ship to speed up to 12.19 knots as shown in Table 12 for the reach between CG and LNG. If the draft and speed were changed to 41.7 ft and 12.19 knots, the wave height from the K&S equations was 0.75 ft. However, when the draft was changed to 41.7 ft and since beam is not an input, the K&S regression equations were providing a solution that reflects a ship having about a 41.7 X 3.06 =127.6 ft beam rather than 142.9 ft as used in this example. The best way around this problem was to solve for a ship that was close to the 41.7 ft X 142.9 ft ship but use a ship that had a B/T = 3.06 to best match the characteristics of the K&S data base. The midship area of the actual ship was 41.7 X 142.9 = 5959 sq ft. A comparable ship having the same midship area and B/T = 3.06 was 44.1 ft X 135.1 ft. Using Kriebel and Seelig with this comparable ship results in a wave height of 0.87 ft. If the correlations within the data set are not considered, the wave height can be either overestimated or underestimated as was the case in this example. If these correlations are ignored, one could incorrectly conclude that beam does not matter and calculations would show that a ship beam of 1-ft will have the same wave height as a ship beam of 140 ft. Note that for the container ships at SH, the β_{ks} coefficient in the Kriebel and Seelig method was set equal to 4.0 and C_b = 0.65.

We now go back to the question of whether Kriebel and Seelig can help determine the effect of various combinations of ship beam and draft. Because beam was not included, the equations can not address effects of various combinations of beam and draft on wave height. However, the Kriebel and Seelig equations should provide insight on how midship area = beam*draft relates to wave height. Using depth = 50 ft, draft from 30 to 45 ft, beam = 3.06*draft, length = 17.6*draft (average from Kriebel data base), C_b = 0.65, Kriebel β_{ks} = 4.0, and ship speed of 12.5 knots that was typical of SH harbor ships, wave height from Kriebel and Seelig varies as $(\text{beam*draft})^{0.34}$. The exponent was found to be almost invariant for SH speeds ranging from 10-15 knots.

For the range of ships at SH from Sub-Panamax to gen 2 Post-Panamax ships, beam and draft effects on wave height using $(\text{beam*draft})^{0.34}$ varied by only 32%. This finding was consistent with Knight (1999) where the coefficient in the wave equation varied from 0.5 to 0.7 for drafts changing from 2 to 9- ft or widths changing from 35 to 105 ft. Using the Knight coefficients with corresponding midship area results in wave height varying as $(beam*draft)^{0.23}$ that was similar to the relationship derived using the Kriebel and Seelig wave equation. The finding of this analysis of Kriebel and Seelig (2005) and Knight (1999) was that the wave equation coefficient β varies much less than linearly with midship area as used in the 2007 study.

Since the Kriebel and Seelig equation was based on ships and not barges as used in the Knight study, the β used in the Blaauw wave height equation is

$$\beta = C(beam * draft)^{0.34} \tag{15}$$

Note that this equation and Eq 10 must be used in feet units. Based on the SH field data, C = 0.03 provides a conservative estimate of wave height except for 5 or 6 points that were likely affected by shoaling or were the result of ship drawdown and not secondary waves from the ship. Comparison of Blaauw equation using equations 10, 12, and 15 with the SH field study data are shown in Figure 15. Equations 10, 12, and 15 should be restricted to SH until a more general form is developed.

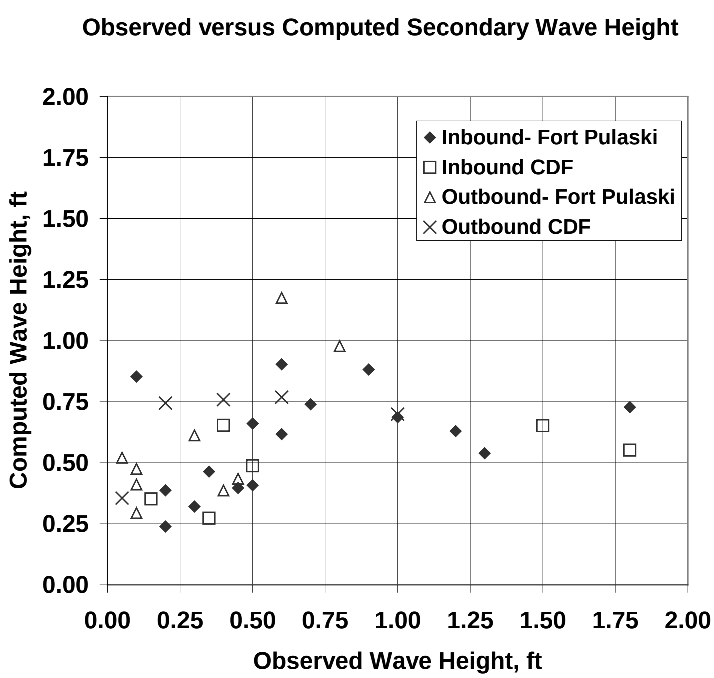

Figure 15. Observed versus computed secondary wave height from Blaauw equation for 2005 SH field study data.

Wave height prediction is extremely complicated at best because so many parameters are important. To insure the most complete information for SH, secondary wave height from both the Blaauw equation as revised herein and the Kriebel and Seelig equations were presented for each location. The Kriebel and Seelig approach uses $\beta_{ks} = 4.0$ and both methods use $C_b = 0.65$ for all ships. Note that the Kriebel and Seelig equations take into account the water depth and show a reduction in wave height because of increased depth in the deepened channel. At mean tide, depth used in the K&S wave equation was 44 + 3.7 = 47.7 ft in the existing channel based on typical depths in the measured cross sections. In the deepened channel depth used in the analysis was 48 + 3.7 = 51.7 ft at mean tide.

Secondary Ship Wave Heights Along the Channel

Tables 14-16 show the secondary wave heights at the 3 full bell areas and Tables 17-20 show the secondary wave height at the wake reduction areas. Note that secondary wave heights in the wake reduction areas were low to non-existent. Also note that the Kriebel and Seelig predicted wave heights vary over a larger range than the Blaauw equation predicted wave heights. This was primarily the result of (1) the Kriebel and Seelig wave height equation varying with ship speed to about the fifth power whereas the Blaauw equation varies with ship speed to the 2.67 power and (2) the Kriebel and Seelig wave height equation varies with depth.

Table 14. Secondary wave height at Tybee Island at Full Bell. Distance from center of navigation channel to Tybee shoreline = 3500 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed for full bell, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	12.90	0.74	0.50
"	"	37.7(design draft)	"	11.87	0.59	0.43
" (D)	"	30.2 (avg 2005 draft)	51.7	13.02	0.68	0.51
"	"	37.7(design draft)	"	11.99	0.53	0.44
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	12.90	0.60	0.53
"	"	40.0 (95% draft)	"	12.20	0.52	0.48
" (D)	"	34.4 (50% draft)	51.7	13.03	0.54	0.55
"	"	40.6 (95% draft)	"	12.27	0.46	0.49
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	12.90	0.81	0.58
"	"	41.2 (95% draft)	"	12.20	0.70	0.53
" (D)	"	41.1 (50% draft)	51.7	12.40	0.63	0.55
"	"	45.6 (95% draft)	"	11.83	0.55	0.50
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	12.90	0.73	0.60
"	"	41.8 (95% draft)	"	12.14	0.63	0.54
" (D)	"	41.7 (50% draft)	51.7	12.36	0.56	0.56
"	"	46.6 (95% draft)	"	11.73	0.48	0.51

Table 15. Secondary wave height at Reach between CG and LNG at Full Bell. Distance to shoreline = 725 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed for full bell, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12, & 15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	12.78	1.20	0.82
"	"	37.7(design draft)	"	11.71	0.93	0.70
" (D)	"	30.2 (avg 2005 draft)	51.7	12.91	1.09	0.85
"	"	37.7(design draft)	"	11.85	0.84	0.73
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	12.77	0.96	0.88
"	"	40.0 (95% draft)	"	12.04	0.82	0.79
" (D)	"	34.4 (50% draft)	51.7	12.91	0.86	0.90
"	"	40.6 (95% draft)	"	12.12	0.72	0.81
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	12.75	1.28	0.96
"	"	41.2 (95% draft)	"	12.02	1.09	0.85
" (D)	"	41.1 (50% draft)	51.7	12.24	0.99	0.90
"	"	45.6 (95% draft)	"	11.64	0.84	0.81
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	12.75	1.15	0.98
"	"	41.8 (95% draft)	"	11.95	0.97	0.87
" (D)	"	41.7 (50% draft)	51.7	12.19	0.87	0.92
"	"	46.6 (95% draft)	"	11.53	0.73	0.82

Table 16. Secondary wave height at Reach between CDF and Old Fort Jackson at Full Bell. Distance from center of navigation channel to closest shoreline = 600 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed for full bell, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	12.63* (12.28)**	1.02	0.79
“	“	37.7(design draft)	“	11.53 (11.53)	0.91	0.72
“ (D)	“	30.2 (avg 2005 draft)	51.7	12.78 (12.41)	0.94	0.81
“	“	37.7(design draft)	“	11.68 (11.68)	0.82	0.74
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	12.62 (11.87)	0.67	0.77
“	“	40.0 (95% draft)	“	11.85 (11.54)	0.68	0.75
“ (D)	“	34.4 (50% draft)	51.7	12.77 (11.99)	0.60	0.79
“	“	40.6 (95% draft)	“	11.95 (11.63)	0.60	0.77
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	12.56 (10.80)	0.54	0.65
“	“	41.2 (95% draft)	“	11.79 (10.53)	0.55	0.64
“ (D)	“	41.1 (50% draft)	51.7	12.04 (10.65)	0.47	0.65
“	“	45.6 (95% draft)	“	11.42 (10.44)	0.48	0.65
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	12.56 (10.63)	0.43	0.65
“	“	41.8 (95% draft)	“	11.72 (10.35)	0.45	0.63
“ (D)	“	41.7 (50% draft)	51.7	11.99 (10.46)	0.37	0.65
“	“	46.6 (95% draft)	“	11.29 (10.25)	0.39	0.64

*Speed that would have been reached in a long enough reach. **Actual speed that was reached in the short reach between CDF and Old Fort Jackson. The actual speed was used to determine wave height.

Table 17. Secondary waves at Coast Guard Station for ship speed that does not exceed a drawdown of 0.7 ft. Distance to shoreline = 850 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	10.52	0.38	0.46
"	"	37.7(design draft)	"	9.59	0.28	0.39
" (D)	"	30.2 (avg 2005 draft)	51.7	10.75	0.36	0.49
"	"	37.7(design draft)	"	9.80	0.26	0.41
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	9.73	0.17	0.40
"	"	40.0 (95% draft)	"	9.10	0.14	0.35
" (D)	"	34.4 (50% draft)	51.7	9.93	0.16	0.42
"	"	40.6 (95% draft)	"	9.24	0.12	0.37
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	8.62	0.11	0.32
"	"	41.2 (95% draft)	"	8.10	0.09	0.28
" (D)	"	41.1 (50% draft)	51.7	8.30	0.08	0.30
"	"	45.6 (95% draft)	"	7.89	0.07	0.27
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	8.28	0.07	0.29
"	"	41.8 (95% draft)	"	7.73	0.05	0.26
" (D)	"	41.7 (50% draft)	51.7	7.92	0.04	0.27
"	"	46.6 (95% draft)	"	7.48	0.04	0.24

Table 18. Secondary waves at LNG and Old Fort Jackson for ship speed that does not exceed a drawdown of 0.7 ft. Distance from center of navigation channel to closest shoreline = 600 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	9.72	0.26	0.42
"	"	37.7(design draft)	"	8.77	0.18	0.35
" (D)	"	30.2 (avg 2005 draft)	51.7	9.98	0.26	0.45
"	"	37.7(design draft)	"	9.01	0.17	0.37
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	8.91	0.10	0.36
"	"	40.0 (95% draft)	"	8.27	0.07	0.31
" (D)	"	34.4 (50% draft)	51.7	9.15	0.10	0.38
"	"	40.6 (95% draft)	"	8.44	0.07	0.33
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	7.79	0.06	0.27
"	"	41.2 (95% draft)	"	7.28	0.04	0.24
" (D)	"	41.1 (50% draft)	51.7	7.51	0.04	0.26
"	"	45.6 (95% draft)	"	7.10	0.03	0.23
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	7.46	0.03	0.25
"	"	41.8 (95% draft)	"	6.92	0.02	0.22
" (D)	"	41.7 (50% draft)	51.7	7.13	0.02	0.23
"	"	46.6 (95% draft)	"	6.71	0.01	0.21

Table 19. Secondary waves at City Front for ship speed that does not exceed a drawdown of 0.7 ft. Distance from center of navigation channel to closest shoreline = 500 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	8.5	0.11	0.31
"	"	37.7(design draft)	"	7.6	0.07	0.25
" (D)	"	30.2 (avg 2005 draft)	51.7	8.8	0.12	0.34
"	"	37.7(design draft)	"	7.9	0.07	0.28
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	7.7	0.03	0.26
"	"	40.0 (95% draft)	"	7.1	0.02	0.22
" (D)	"	34.4 (50% draft)	51.7	8.0	0.03	0.28
"	"	40.6 (95% draft)	"	7.4	0.02	0.24
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	6.7	0.01	0.19
"	"	41.2 (95% draft)	"	6.23	0.01	0.17
" (D)	"	41.1 (50% draft)	51.7	6.5	0.01	0.19
"	"	45.6 (95% draft)	"	6.1	0.01	0.16
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	6.39	0.00	0.18
"	"	41.8 (95% draft)	"	5.88	0.00	0.15
" (D)	"	41.7 (50% draft)	51.7	6.1	0.00	0.16
"	"	46.6 (95% draft)	"	5.7	0.00	0.14

Table 20. Secondary waves at Hwy 17 for ship speed that does not exceed a drawdown of 0.7 ft. Distance from center of navigation to closest shoreline = 400 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	7.6	0.05	0.25
"	"	37.7(design draft)	"	6.8	0.03	0.20
" (D)	"	30.2 (avg 2005 draft)	51.7	8.0	0.06	0.29
"	"	37.7(design draft)	"	7.1	0.03	0.23
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	6.9	0.01	0.21
"	"	40.0 (95% draft)	"	6.3	0.00	0.17
" (D)	"	34.4 (50% draft)	51.7	7.2	0.01	0.23
"	"	40.6 (95% draft)	"	6.6	0.00	0.19
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	5.9	0.00	0.15
"	"	41.2 (95% draft)	"	5.45	0.00	0.13
" (D)	"	41.1 (50% draft)	51.7	5.8	0.00	0.15
"	"	45.6 (95% draft)	"	5.4	0.00	0.13
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	5.6	0.00	0.13
"	"	41.8 (95% draft)	"	5.1	0.00	0.11
" (D)	"	41.7 (50% draft)	51.7	5.4	0.00	0.13
"	"	46.6 (95% draft)	"	5.0	0.00	0.11

Evaluation of Higher Ship Speed

In the 2007 study, a typical and a high speed were used in the analysis. The high speed was somewhat arbitrarily set at 2 knots greater at Fort Pulaski and 1.5 knots greater at Tybee. In this reanalysis, all speeds in this reanalysis so far were based on 12.9 knots from the 2005 field study for the typical draft ship at Tybee. Ship speeds for all other drafts and other channel locations were determined using the ship speed model developed herein. Capt Browne of SH has stated that what is being called the typical speed of 12.9 knot at Tybee is on the high side of what is typically used. The previous analysis showing the speeds were up to 91% of the limiting speed confirms the statement of Capt Browne. Even if 12.9 knots was higher than typical, it is likely that some ships will travel at faster than 12.9 knots at Tybee Island. To make certain that the full range of conditions was addressed, a higher speed was evaluated at Tybee. The pilots frequently say that all ships are different and one way they are different is that some are more powerful than others. To determine the appropriate higher speed, the ship shaft power based on the 12.9 knots was increased by 15% and the speed model developed herein was used to determine the higher ship speed. The resulting speeds at Tybee along with return velocity and drawdown are shown in Table 21. The resulting speeds along with wave height are shown in Table 22. Table 21 showing the deep water speeds demonstrates that the use of a 15% power increase was likely an extreme condition because pilot cards seen by this author show that ships will not have deep water speeds as high as shown in this table. Another comparison showing the large power represented by this higher speed was the shaft power for 15% increase compared to the shaft power determined for the calibration ships. The Panamax calibration ships had full bell shaft power of 6224 hp and 8806 hp compared to the 15% increased power of 10678 hp. The Post-Panamax calibration ships had shaft power of 15575 hp and 14279 hp compared to 15% increased power of 16397 hp for Generation 1 Post-Panamax ships and 20462 hp for Generation 2 Post-Panamax ships. Deep water ship speeds for the 15% increase in power result in an increase of about 1 knot above the speeds determined for typical power conditions. Restricted channel ship speeds for the 15% increase in power result in an increase of about 0.5 knot above the speeds determined for typical power conditions. The arbitrary 1.5 and 2 knot speed increase used in the 2007 study was not realistic. The composite values in Table 24 (discussed subsequently) show that the 15% increased power speeds result in the same response as the typical speed for the three effects of drawdown, return velocity, and wave height. For that reason, conclusions based on typical speeds (that are high according to the pilots), were accepted as representative of SH.

Table 21. Maximum ship speed at Tybee Island with 15% increase in target shaft power. Channel width at -20 contour = 1620 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel area, sq ft	Ship speed for 15% power increase, kn	Target shaft power, hp	Deep water ship speed, kn	Return vel, drawdown, ft/sec, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	64175	13.38	7252	16.13	2.14,1.57
"	"	37.7(design draft)	"	12.31	"	15.43	2.23,1.52
" (D)	"	30.2 (avg 2005 draft)	66675	13.52	"	16.13	2.03,1.50
"	"	37.7(design draft)	"	12.46	"	15.43	2.13,1.46
Panamax (E)	106 X 951	34.3 (50% draft)	64175	13.35	10678	16.55	2.71,2.01
"	"	40.0 (95% draft)	"	12.63	"	16.14	2.79,1.97
" (D)	"	34.4 (50% draft)	66675	13.50	"	16.55	2.57,1.92
"	"	40.6 (95% draft)	"	12.72	"	16.11	2.66,1.88
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	64175	13.27	16399	18.07	3.93,2.98
"	"	41.2 (95% draft)	"	12.57	"	17.51	3.90,2.81
" (D)	"	41.1 (50% draft)	66675	12.79	"	17.53	3.72,2.71
"	"	45.6 (95% draft)	"	12.22	"	17.14	3.74,2.61
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	64175	13.23	20462	18.43	4.48,3.42
"	"	41.8 (95% draft)	"	12.48	"	17.85	4.44,3.21
" (D)	"	41.7 (50% draft)	66675	12.72	"	17.86	4.23,3.10
"	"	46.6 (95% draft)	"	12.10	"	17.38	4.24,2.97

Table 22. Secondary wave height at Tybee Island with 15% increase in target shaft power. Distance from center of navigation channel to Tybee shoreline = 3500 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed at 15% increase, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	13.38	0.90	0.55
"	"	37.7(design draft)	"	12.31	0.72	0.48
" (D)	"	30.2 (avg 2005 draft)	51.7	13.52	0.83	0.57
"	"	37.7(design draft)	"	12.46	0.65	0.49
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	13.35	0.73	0.58
"	"	40.0 (95% draft)	"	12.63	0.63	0.53
" (D)	"	34.4 (50% draft)	51.7	13.50	0.66	0.60
"	"	40.6 (95% draft)	"	12.72	0.56	0.54
PPX Gen 1 (E)	131.7 X 953.8	36.2 (50% draft)	47.7	13.27	0.94	0.63
"	"	41.2 (95% draft)	"	12.57	0.82	0.57
" (D)	"	41.1 (50% draft)	51.7	12.79	0.74	0.60
"	"	45.6 (95% draft)	"	12.22	0.65	0.55
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	13.23	0.84	0.64
"	"	41.8 (95% draft)	"	12.48	0.73	0.58
" (D)	"	41.7 (50% draft)	51.7	12.72	0.65	0.61
"	"	46.6 (95% draft)	"	12.10	0.57	0.55

Composite Values of Drawdown, Return Velocity, and Secondary Wave Height

In the 2007 ship forces study, composite values of drawdown, return velocity, and secondary wave height were presented to simplify the comparison of existing and deepened channels. The composite value in this reanalysis combines Sub-Panamax, Panamax, Gen 1 Post-Panamax, and Gen 2 Post-Panamax effects into a single number based on the percent of each class in the total traffic numbers. Note that the composite values do not reflect differences in total number of ships and only reflect the composition of the fleet. In the 2007 study, Handy size and Feedermax were included in the composite values but were omitted in this reanalysis because one reviewer believed they may tend to reduce the composite value in a way that would reduce their validity. Sub-Panamax was retained because it often had the highest secondary wave heights. The LNG and General Cargo ships were also omitted because their numbers did not change with and without deepening. Only the year 2030 was compared in the analysis of existing (42-ft channel) and deepened (48-ft channel). The traffic numbers by ship class are shown in Table 23.

Table 23. Vessel calls for 2030 by vessel size class based on April 2011 forecast.

Class	Channel Depth, ft	Number calls	% Total
Sub-Panamax (SPM)	42 (existing)	947	23.15
Panamax (PMX)	"	1196	29.23
Gen 1 Post-Panamax (PPXGn I)	"	1421	34.73
Gen 2 Post-Panamax (PPXGn II)	"	527	12.88
Total	"	4091	100
Sub-Panamax	48 (deepened)	947	26.30
Panamax	"	975	27.08
Gen 1 Post-Panamax	"	661	18.36
Gen 2 Post-Panamax	"	1018	28.27
Total	"	3601	100

The composite value (CV) using drawdown as an example was calculated by

CV = (%SPM)*(SPM drawdown) + (%PMX)*(PMX drawdown) + (%PPXGn I)*(PPXGn I drawdown) + (%PPXGn II)*(PPXGn II drawdown) (16)

Composite values of drawdown, return velocity, and the two secondary wave methods are shown in Table 24 for the three areas where ships navigate at full bell.

Table 24. Composite drawdown, return velocity, and wave height at full bell reaches for 2030, June 2010 forecast.

Location	Draft	Drawdown, ft		Return Velocity, fps		Wave Height, Kriebel, ft		Wave Height, Maynord, ft	
		42-ft	48-ft	42-ft	48-ft	42-ft	48-ft	42-ft	48-ft
Tybee*	Typical	2.10	1.99	2.90	2.81	0.72	0.60	0.55	0.54
"	Large	2.02	1.94	2.95	2.88	0.61	0.50	0.49	0.48
CG to LNG	Typical	2.17	2.06	3.02	2.93	1.15	0.95	0.91	0.89
"	Large	2.10	2.01	3.10	3.02	0.96	0.78	0.80	0.79
CDF to OFJ	Typical	1.57	1.58	2.47	2.50	0.67	0.60	0.72	0.73
"	Large	1.74	1.74	2.82	2.82	0.66	0.58	0.69	0.70
Tybee+15%	Typical	2.43	2.29	3.23	3.11	0.86	0.72	0.60	0.59
"	Large	2.32	2.21	3.26	3.16	0.73	0.60	0.54	0.53

*Tybee drawdown and return velocity are in the channel and not at the shoreline.

Evaluation of Fort Pulaski

In the 2007 study, Fort Pulaski was an analysis location where it was shown that wave power increased by up to 19%. In this reevaluation, a greater understanding of the ship speeds along the channel was developed, the ship speed model was improved and validated against independent data, and the wave equation was updated and a second wave equation added to the analysis. Fort Pulaski is in a location where speeds are dictated, not primarily by the power and size of the ship, but by the requirement to control its wake at the Coast Guard Station. Based on the speed plots presented herein, Table 25 shows speeds at Fort Pulaski along with computed wave heights from the two wave equations. The composite wave heights in Table 25 show wave heights were less than or equal in the deepened channel than in the existing channel for both wave equations. Fort Pulaski ship speeds and thus forces were also limited by the Right Whale speed restriction for 6 months of the year.

Table 25. Secondary wave height at Fort Pulaski. Distance from center of navigation channel to shoreline = 850 ft.

Ship Class (channel, E or D)	Beam X Length, ft	Draft, ft (basis for value)	Channel depth, ft	Ship speed*, kn	Wave height, K&S, ft	Wave height, Blaauw eqs 10,12,15, ft
Sub-Panamax (E)	99.8 X 716	30.2 (avg 2005 draft)	47.7	11.53	0.64	0.59
"	"	37.7(design draft)	"	11.07	0.64	0.57
" (D)	"	30.2 (avg 2005 draft)	51.7	11.64	0.58	0.61
"	"	37.7(design draft)	"	11.17	0.57	0.59
Panamax (E)	106 X 951	34.3 (50% draft)	47.7	11.13	0.41	0.58
"	"	40.0 (95% draft)	"	10.63	0.37	0.54
" (D)	"	34.4 (50% draft)	51.7	11.23	0.35	0.59
"	"	40.6 (95% draft)	"	10.78	0.34	0.56
PPX Gen 1 (E)	131.7 X 953.8	36.5 (50% draft)	47.7	10.16	0.33	0.49
"	"	41.6 (95% draft)	"	9.64	0.29	0.45
" (D)	"	41.1 (50% draft)	51.7	9.84	0.26	0.47
"	"	45.6 (95% draft)	"	9.43	0.23	0.44
PPX Gen 2 (E)	142.9 X 1106	36.3 (50% draft)	47.7	9.82	0.23	0.46
"	"	41.8 (95% draft)	"	9.27	0.20	0.42
" (D)	"	41.7 (50% draft)	51.7	9.46	0.17	0.44
"	"	46.6 (95% draft)	"	9.02	0.15	0.40
Composite existing- Typical draft					0.41	0.54
Composite deepened- Typical draft					0.34	0.53
Composite existing- Large draft					0.38	0.50
Composite deepened- Large draft					0.33	0.50

*Ship speed from plots of ship speed along the channel given previously.

Alternate Comparison Parameter using Wave Height Converted to Wave Power, Drawdown, and Return Velocity

General The composite values of drawdown, return velocity, and wave height all show values in the deepened channel that were less than or equal to values in the existing channel. The composite values reflect the composition of the fleet but not the total number of ships. Wave heights along the channel were generally low from both wave height equations but some ship classes show increased wave height in the deepened channel and need further analysis. Drawdown was up to about 3-ft and needs to be examined in this reanalysis. An alternate method to the composite values was developed where the number of ships in each class as well as the distribution was reflected in a single number representing the ship forces on the shoreline.

Short Period Waves As stated in the 2007 report, wave power is a parameter that had been used to evaluate shoreline recession. Deepwater wave power per unit length of wave given in the 2007 report required correction of the number in the denominator and was given as

$$P = \frac{\rho g^2 H^2 T_w}{32\pi} \qquad (17)$$

where H is the secondary wave height from the Kriebel and Seelig equation or the Blaauw wave height equation, ρ is water density, and T_w is wave period. In this comparison of power, the variation in power was based on Eq. 17 with wave period =3.4 sec based on the 2005 field data. The Seelig and Kriebel (2001) equations for wave period for a typical SH speed of 12.9 knots was 3.5 sec. T varied only +-10% over the range of speeds at SH and a constant T_w=3.4 sec was used for all ships. Eq. 17 becomes $P = 0.123H^2$ where H was in feet and P is in hp/ft of wave front.

Tables 26 to 29 show secondary wave power for each ship class for typical and deep draft ships at Fort Pulaski and the three full bell locations along the channel. While the tables contain details on individual ship classes, the main focus are the sums of wave power from all ship classes combined, shown highlighted in yellow. For example, the total power at Tybee in Table 26 for the existing channel and typical draft was 266 hp/ft of wave front based on the K&S wave equation. This number is compared to the total power for the deepened channel and typical draft of 160 hp/ft of wave front based on the K&S wave equation. The Blaauw wave equation shows this same trend of lesser wave power in the deepened channel. The large draft ships also show the same trend of lesser wave power in the deepened channel.

Table 26. Secondary wave power for existing and deepened channels at Tybee.

	Tybee		K&S Equation		Blaauw Equation	
Channel/	Ship Class	Number	Wave Height	N*Wave	Wave Height	N*Wave
Draft		of Ships	ft	Power	ft	Power
		(N)		hp/ft		hp/ft
Existing/	SubPanamax	947	0.74	64	0.50	29
Typical	Panamax	1196	0.60	53	0.53	41
	Gen 1	1421	0.81	115	0.58	59
	Gen 2	527	0.73	35	0.60	23
	Sum	4091		266		153
Deep/	SubPanamax	947	0.68	54	0.51	30
Typical	Panamax	975	0.54	35	0.55	36
	Gen 1	661	0.63	32	0.55	25
	Gen 2	1018	0.56	39	0.56	39
	Sum	3601		160		130
Existing/	SubPanamax	947	0.59	41	0.43	22
Large	Panamax	1196	0.52	40	0.48	34
	Gen 1	1421	0.70	86	0.53	49
	Gen 2	527	0.63	26	0.54	19
	Sum	4091		192		123
Deep/	SubPanamax	947	0.53	33	0.44	23
Large	Panamax	975	0.46	25	0.49	29
	Gen 1	661	0.55	25	0.50	20
	Gen 2	1018	0.48	29	0.51	33
	Sum	3601		112		104

Table 27. Secondary wave power for existing and deepened channels at Fort Pulaski.

	Fort Pulaski		K&S Equation		Blaauw Equation	
Channel/	Ship Class	Number	Wave Height	N*Wave	Wave Height	N*Wave
Draft		of Ships	ft	Power	ft	Power
		(N)		hp/ft		hp/ft
Existing/	SubPanamax	947	0.64	48	0.59	41
Typical	Panamax	1196	0.41	25	0.58	49
	Gen 1	1421	0.33	19	0.49	42
	Gen 2	527	0.23	3	0.46	14
	Sum	4091		95		146
Deep/	SubPanamax	947	0.58	39	0.61	43
Typical	Panamax	975	0.35	15	0.59	42
	Gen 1	661	0.26	5	0.47	18
	Gen 2	1018	0.17	4	0.44	24
	Sum	3601		63		127
Existing/	SubPanamax	947	0.64	48	0.57	38
Large	Panamax	1196	0.37	20	0.54	43
	Gen 1	1421	0.29	15	0.45	35
	Gen 2	527	0.20	3	0.42	11
	Sum	4091		85		128
Deep/	SubPanamax	947	0.57	38	0.59	41
Large	Panamax	975	0.34	14	0.56	38
	Gen 1	661	0.23	4	0.44	16
	Gen 2	1018	0.15	3	0.40	20
	Sum	3601		59		114

Table 28. Secondary wave power for existing and deepened channels at reach between CG and LNG.

	CG to LNG:		K&S Equation		Blaauw Equation	
Channel/	Ship Class	Number	Wave Height	N*Wave	Wave Height	N*Wave
Draft		of Ships	ft	Power	ft	Power
		(N)		hp/ft		hp/ft
Existing/	SubPanamax	947	1.20	168	0.82	78
Typical	Panamax	1196	0.96	136	0.88	114
	Gen 1	1421	1.28	286	0.96	161
	Gen 2	527	1.15	86	0.98	62
	Sum	4091		675		416
Deep/	SubPanamax	947	1.09	138	0.85	84
Typical	Panamax	975	0.86	89	0.90	97
	Gen 1	661	0.99	80	0.90	66
	Gen 2	1018	0.87	95	0.92	106
	Sum	3601		402		353
Existing/	SubPanamax	947	0.93	101	0.70	57
Large	Panamax	1196	0.82	99	0.79	92
	Gen 1	1421	1.09	208	0.85	126
	Gen 2	527	0.97	61	0.87	49
	Sum	4091		468		324
Deep/	SubPanamax	947	0.84	82	0.73	62
Large	Panamax	975	0.72	62	0.81	79
	Gen 1	661	0.84	57	0.81	53
	Gen 2	1018	0.73	67	0.82	84
	Sum	3601		268		278

Table 29. Secondary wave power for existing and deepened channels at reach between CDF and OFJ.

	CDF to OFJ		K&S Equation		Blaauw Equation	
Channel/	Ship Class	Number	Wave Height	N*Wave	Wave Height	N*Wave
Draft		of Ships	ft	Power	ft	Power
		(N)		hp/ft		hp/ft
Existing/	SubPanamax	947	1.02	121	0.79	73
Typical	Panamax	1196	0.67	66	0.77	87
	Gen 1	1421	0.54	51	0.65	74
	Gen 2	527	0.43	12	0.65	27
	Sum	4091		250		261
Deep/	SubPanamax	947	0.94	103	0.81	76
Typical	Panamax	975	0.60	43	0.79	75
	Gen 1	661	0.47	18	0.65	34
	Gen 2	1018	0.37	17	0.65	53
	Sum	3601		181		239
Existing/	SubPanamax	947	0.91	96	0.72	60
Large	Panamax	1196	0.68	68	0.75	83
	Gen 1	1421	0.55	53	0.64	72
	Gen 2	527	0.45	13	0.63	26
	Sum	4091		230		240
Deep/	SubPanamax	947	0.82	78	0.74	64
Large	Panamax	975	0.60	43	0.77	71
	Gen 1	661	0.48	19	0.65	34
	Gen 2	1018	0.39	19	0.64	51
	Sum	3601		159		221

Drawdown As stated in Maynord (2004), confined channels can experience transverse stern waves that can be a significant ship generated force at the shoreline. In highly confined waterways like the Sabine Neches Waterway (SNWW) reported in Maynord (2003), a transverse stern wave forms following the ship drawdown and appears as a moving bore along the bankline traveling at the speed of the ship. The transverse stern wave moves perpendicular to the bank rather than at an angle to the bank with the secondary ship waves. At the SNNW, the front of the transverse stern wave was steep and the time from the trough of the transverse stern wave to the crest was about 5 sec or less. The field data collected at SH in 2005 shows a milder slope of the wave front with time from trough to crest of about 10-20 sec. The milder wave front slope at SH was because of the relatively larger channel at SH compared to the SNWW and the presence of a berm at SNWW. The wave power Eq. 17 was not applicable to transverse stern waves but the effects of the transverse stern wave on ship forces at the shoreline are likely quantified by the wave height squared. Transverse stern wave height is generally 10-20% greater than the drawdown. In this analysis of ship forces at the shoreline, the transverse stern wave height will be set equal to the 1.2 times the drawdown and the transverse stern wave will be squared to compare the effects of transverse stern waves in existing and deepened channels. Note that squaring the transverse stern wave height was a relative measure of wave power to compare different channel depths, different ships, and different locations. It was not a value that can be compared to the secondary wave height power presented previously. This was the best way to quantify the shoreline forces of the up to 3-ft of drawdown calculated for some of the ships.

When examining the various locations along the channel, Tybee shoreline was a long distance from the navigation channel and has Right Whale restrictions 6 months out of the year. Fort Pulaski was in an area where the ships are slowing down to prevent wake at the Coast Guard Station, speeding up after passing the Coast Guard Station, and has Right Whale restrictions. The reach between CDF and Old Fort Jackson was generally too short for ships to reach full bell speed and drawdown was about 80% of drawdown at the reach between the Coast Guard Station and LNG. Only the reach between the Coast Guard Station and the LNG dock was relatively unrestricted and was the reach where drawdown was the highest. The square of the transverse stern wave height was summed for all ships and existing and deepened channels as shown in Table 30 for typical and large draft ships. This analysis shows the same result whether all typical draft ships were used or all large draft ships were used. The sum of the transverse stern wave height squared, which was used herein as a relative indicator of wave power, was less in the deepened channel. This finding was true even if only Gen 1 and Gen 2 ships were summed and compared.

Table 30. Drawdown and relative wave power for existing and deepened channels at reach between the Coast Guard Station and LNG. Transverse stern wave height set equal to 1.2 times the drawdown.

	CG to LNG			
Channel/	Ship Class	Number	Drawdown (z),	Relative Wave Power
Draft		of Ships	ft	N*(1.2*z)^2
		(N)		
Existing/	SubPanamax	947	1.42	2750
Typical	Panamax	1196	1.81	5642
	Gen 1	1421	2.65	14370
	Gen 2	527	3.05	7059
	Sum	4091		29821
Deep/	SubPanamax	947	1.35	2485
Typical	Panamax	975	1.72	4154
	Gen 1	661	2.45	5713
	Gen 2	1018	2.79	11411
	Sum	3601		23763
Existing/	SubPanamax	947	1.40	2673
Large	Panamax	1196	1.79	5518
	Gen 1	1421	2.54	13202
	Gen 2	527	2.90	6382
	Sum	4091		27775
Deep/	SubPanamax	947	1.34	2449
Large	Panamax	975	1.71	4105
	Gen 1	661	2.38	5392
	Gen 2	1018	2.69	10608
	Sum	3601		22553

Although the reach from CDF to Old Fort Jackson (OFJ) had less drawdown than the reach from CG to LNG, the CDF to OFJ reach does show some individual ship classes where drawdown increases in the deepened channel. Table 31 shows the sum of transverse stern wave height squared for all ship classes and both typical and large draft. The indicator of transverse stern wave power was less in the deepened channel for both typical and large drafts. Also note that the power as indicated by transverse stern wave height squared at CDF to OFJ was about 49 to 71% of the power from CG to LNG, showing the CG to LNG reach to have the greatest ship forces from drawdown and transverse stern waves.

Table 31. Drawdown and relative wave power for existing and deepened channels at reach between CDF and Old Fort Jackson. Transverse stern wave height set equal to 1.2 times the drawdown.

Channel/ Draft	CDF to OFJ Ship Class	Number of Ships (N)	Drawdown (z), ft	Relative Wave Power N*(1.2*z)^2
Existing/	SubPanamax	947	1.36	2522
Typical	Panamax	1196	1.55	4138
	Gen 1	1421	1.65	5571
	Gen 2	527	1.76	2351
	Sum	4091		14582
Deep/	SubPanamax	947	1.29	2269
Typical	Panamax	975	1.47	3034
	Gen 1	661	1.72	2816
	Gen 2	1018	1.86	5071
	Sum	3601		13191
Existing/	SubPanamax	947	1.48	2987
Large	Panamax	1196	1.73	5154
	Gen 1	1421	1.84	6928
	Gen 2	527	1.99	3005
	Sum	4091		18074
Deep/	SubPanamax	947	1.41	2711
Large	Panamax	975	1.65	3822
	Gen 1	661	1.87	3328
	Gen 2	1018	2.06	6221
	Sum	3601		16083

Return Velocity

Return velocity at SH was a maximum at the reach from CG to LNG where computed return velocity was up to 4.19 ft/sec for the 95% draft Gen 2 ship in the existing channel. Composite return velocity at CG to LNG was less in the deepened channel. Scour is a function of shear stress and shear stress is equal to a coefficient times velocity squared. The square of return velocity will be used to quantify the ship forces at the shoreline using the total number of ships in each ship class and summing. Table 32 shows results from the CG to LNG reach. Scour potential as indicated by return velocity squared will be less in the deepened channel based on Table 32. In addition, this author has not seen a navigation channel where return velocity was the dominant or obvious cause of shoreline erosion whereas transverse stern waves have been recognized as a significant cause at SNWW.

Table 32. Return Velocity and relative scour potential for existing and deepened channels at reach from CG to LNG.

	CG to LNG			
Channel/	Ship Class	Number	Return	Relative Scour Potential
Draft		of Ships	Velocity,	N*Vret^2
		(N)	ft/sec	
Existing/	SubPanamax	947	2.02	3864
Typical	Panamax	1196	2.55	7777
	Gen 1	1421	3.66	19035
	Gen 2	527	4.15	9076
	Sum	4091		39753
Deep/	SubPanamax	947	1.91	3455
Typical	Panamax	975	2.41	5663
	Gen 1	661	3.52	8190
	Gen 2	1018	3.98	16126
	Sum	3601		33433
Existing/	SubPanamax	947	2.15	4378
Large	Panamax	1196	2.66	8462
	Gen 1	1421	3.7	19453
	Gen 2	527	4.19	9252
	Sum	4091		41545
Deep/	SubPanamax	947	2.05	3980
Large	Panamax	975	2.54	6290
	Gen 1	661	3.57	8424
	Gen 2	1018	4.03	16533
	Sum	3601		35228

Discussion of Results

The sailing draft distributions provide consistent drafts to use in comparing ship forces in existing and deepened channels. The 50% exceedance draft was used to reflect a typical ship that frequently occurred at SH. The 95% draft was used to reflect a large draft ship that was not as frequent yet not so rare that it could not have an effect on shoreline erosion.

Evaluation of ship forces from drawdown, return velocity, and waves must be based on accurate ship speed because these effects vary with speed raised to anywhere from the 2^{nd} to the 5^{th} power depending on which ship force and prediction equation are used. Just as important as accurate speed prediction was consideration of operational constraints on ship speed. Ship pilots are responsible for the wake of their ship and there are three areas along the SH channel where ship wake must be controlled. Because of the distance required to slow down and accelerate a ship, the wake reduction areas affect a significant length of the channel.

Long period drawdown is the best descriptor of the effect of passing ships on moored vessels. Existing ships along the SH at wake reduction areas slow down such that their drawdown was about 0.7 ft or less. Maximum ship speed in each wake reduction area was determined for each ship class and draft using the 0.7 ft drawdown limit.

The ship speed model used in the 2007 study was updated and a full description provided in this study. In addition, the ship speed model was validated with independent restricted channel results from Norrbin, observed ships on the Houston Ship Channel, and shallow water effects of Schlicting and Norrbin.

Ship pilots at SH and other channels studied will typically travel at full bell if not confronted by operational constraints such as wake reduction areas or Right Whale restrictions. The ship speed model was used to determine ship speeds at the three areas in SH where ships can travel at full bell.

Using speeds in the full bell reaches and the wake reduction areas, speed plots were presented for each ship class, both 50% and 95% drafts, and existing and deepened channels. The deepened channel had cross sectional area that is about 5% greater than the existing channel. The speed plots show that Sub-Panamax ships, whose draft was not affected by channel deepening, will go faster in the deepened channel. Panamax ships, whose drafts increase by up to 1.5% in the deepened channel, will go slightly faster in the deepened channel. Generation 1 Post-Panamax ships, whose drafts increase by about 11% in the deepened channel, will go slower in the deepened channel. Generation 2 Post-Panamax ships, whose drafts increase by about 12-15% in the deepened channel, will go slower in the deepened channel.

The ship wave model developed in the 2007 study was updated and a second ship wave equation by Kriebel and Seelig (2005) was also used to predict ship wave heights.

Based on updated ship drafts, recomputed speeds along the channel, drawdown, return velocity, and wave height are described at various locations along the channel. From the viewpoint of changes in ship forces leading to changes in bank erosion, the three reaches where the ships were operating at full bell, and thus highest speeds, were the areas of primary concern. The best summary information is shown in Tables 26-31.

At the full bell reach at Tybee Island, the presence of the south jetty and the 3500 ft distance from shoreline to navigation channel were significant factors in the magnitude and prediction of ship forces at the shoreline. Composite drawdown in the channel, return velocity in the channel, and secondary wave height at the shoreline were less in the deepened channel when compared to the existing channel (Table 24). Wave heights at Tybee Island shoreline from the Kriebel and Seelig equation were less in the deepened channel for all vessel classes and drafts (Table 14). Wave heights in the deepened channel from the Blaauw wave equation revised herein were up to 2.3% larger for Sub-Panamax, up to 3.8% larger for Panamax, up to 5.7% less for the Gen 1 ship, and up to 6.7% less for the Gen 2 ship (Table 14). Wave height magnitudes were low at up to 0.81 ft in the Kriebel and Seelig equation and wave power from these waves will likely be dominated by wind waves in this exposed coastal location. During the Right Whale restriction, 10 knot speeds in existing and deepened channels will result in negligible secondary wave heights and lesser drawdown and return velocity in the deepened channel. Summing secondary wave power for all ships shows decreased wave power in the deepened channel from both wave equations (Table 26).

Fort Pulaski was treated as a full bell location in the 2007 study. Based on this reanalysis and improved understanding of speeds along the SH channel, speeds at Fort Pulaski were strongly affected by the wake reduction area at the Coast Guard Station. Fort Pulaski was in a location where speeds were dictated, not primarily by the power and size of the ship, but by the requirement of the pilot to control the ship's wake at the Coast Guard Station. In addition, during 6 months of the year, speeds were restricted by the Right Whale 10-knot limit that was not present in 2007. In the 2007 study, Fort Pulaski was an analysis location where it was shown that wave power increased by up to 19% in the deepened channel. Wave height determined in this reanalysis using the Kriebel and Seelig wave height equation decreases for all ship classes and drafts in the deepened channel (Table 25). Wave height determined using the Blaauw wave equation updated herein decreases for Gen 1 and Gen 2 Post-Panamax and increases for Sub-Panamax and Panamax in the deepened channel (Table 25). Secondary wave heights were low with the largest wave height from either equation equaling 0.64 ft. Summing secondary wave power for all ships shows decreased wave power in the deepened channel from both wave equations (Table 27).

At the full bell reach between CDF and Old Fort Jackson (OFJ), ships typically do not reach their maximum speed for full bell but do achieve speeds that were close to the full bell speed. Composite drawdown, return velocity, and wave height were up to 1.4% greater in the deepened channel (Table 24). Note that the composite wave height only addresses the fleet composition and not the total number of ships in each class. The 1.4% increase in composite wave height corresponds to a 3% increase in wave power. When considering total numbers of ships by summing wave power for all ship classes, wave power decreases in the deepened channel from both wave equations (Table 29). When considering a relative measure of power using drawdown to represent transverse stern waves (Table 31), the sum of relative power from all ship classes was less in the deepened channel.

The full bell reach between the Coast Guard Station and the LNG dock was the only reach not restricted by operational constraints like the Coast Guard Station or Right Whale or limited channel length like CDF to OFJ. The CG to LNG reach had the highest magnitude of composite drawdown, return velocity, and wave height of all reaches (Table 24). Composite values combining all ship classes of drawdown, return velocity, and wave height were less in the deepened channel when compared to the existing channel (Table 24). When considering total numbers of ships by summing wave power for all ship classes, wave power decreases in the deepened channel from both wave equations (Table 28). When considering a relative measure of power using drawdown to represent transverse stern waves (Table 30), the sum of relative power from all ship classes was less in the deepened channel.

Summary and Conclusions

This reanalysis of ship forces addressed the following items:

- Updated draft information in the form of sailing draft distributions was used to define ship drafts to compare in the existing and deepened channels for each vessel class.
- The trends of speeds along the channel were identified and showed three wake reduction areas and 3 reaches where ships typically use full bell
- Ship speeds were determined in the wake reduction areas based on maximum allowable drawdown to prevent moored ship effects.
- A revised ship speed model was developed and described. The model was validated against restricted channel data by Norrbin and shallow water effects on speed by Schlicting and Norrbin. Empirical coefficients were determined using SH ship event data collected in a 2005 field study.
- The ship speed model was used to determine ship speed in the three reaches where ships navigate at full bell. Drawdown and return velocity were determined in the reaches where full bell was used.
- Plots of speed along the entire SH channel were developed for each vessel class using the wake reduction speeds and the speeds in reaches using full bell.
- The Blaauw ship wave equation was revised and a ship wave equation by Kriebel and Seelig (2005) was obtained.
- Wave height was determined at the wake reduction areas and the three full bell reaches for both existing and deepened channels using both the Kriebel and Seelig equations and the Blaauw equation that was revised herein.
- Using forecasts of ship calls for existing and deepened channels, composite values of drawdown, return velocity, and wave height were determined that combine all ship classes into a single number for comparison.
- Drawdown and wave height were evaluated using total number of ships in each ship class and drawdown and wave height squared to reflect wave power.

Secondary wave power was not increased in the deepened channel. This was based on (1) the Kriebel and Seelig equation showing a decrease in composite wave height in the deepened channel and a decrease in wave height for all ship classes and drafts, (2) the Blaauw ship wave equation showing equal or less composite wave height in existing and deepened channel, and (3) summing wave power to account for actual numbers of ships in each ship class results in decreased wave power in the deepened channel from both wave equations and all locations.

Although field data show transverse stern waves at SH to have mild wave front slopes, transverses stern waves can be the dominant shoreline force from deep draft ships. At all reaches including the reach having the largest ship forces at the shoreline, CG to LNG, wave force as indicated by summing TSW height squared from all ships was less in the deepened channel.

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.

Harvald, S.A. 1983. “Resistance and Propulsion of Ships”, John Wiley and Sons, New York.

Holtrop, J. and Mennen, G. 1982. “An approximate power prediction method”, International Shipbuilding Progress, Vol 29, No 335, July.

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.

Kriebel, D.L. and Seelig, W.N. 2005. “An Empirical Model for Ship-Generated Waves”, 7th International Conference on Mathematical and Numerical Aspects of Waves (Waves 05), Madrid.

Maynord, S. (2003). “Ship Effects Before and After Deepening of Sabine-Neches Waterway, Port Arthur, Texas”, Technical Report ERDC/CHL TR-03-15, US Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Maynord, S. (2004). “Ship forces at the bankline of navigation channels”, Maritime Engineering 157, Issue MA2, June.

Maynord, Stephen T. 2007. “Ship Forces on the Shoreline of the Savannah Harbor Project”, Technical Report ERDC/CHL TR-07-7, US Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Maynord, S, Hite, J., and Sanchez, M. 2006. “Atkinson Island Mooring Basin Alternatives, Houston Ship Channel”, ERDC/CHL TR-06-19, US Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Norrbin, N. 1986. “Fairway design with respect to ship dynamics and operational requirements”, SSPA Maritime Consulting, Gothenburg.

Schijf, J. 1949. “Proceedings of the 17th International Navigation Congress”, PIANC, Subject 2, Lisbon.

Seelig, W.N. and Kriebel, D.L. 2001. “Ship-Generated Waves,” Naval Facilities Engineering Service Center, Technical Report TR-6022-OCN.

US Army Corps of Engineers 2006. “Hydraulic Design of Deep Draft Navigation Projects”, EM 1110-2-1613.

Van de Kaa, E. 1978. “Power and Speed of Push Tows in Canals”, Proc of Symposium on Aspects of Navigability in Constraint Waterways”, Delft.

Weggel J. and Sorensen, R. 1986. “Ship Wave Prediction for Port and Channel Design”, ASCE Ports ’86, pp. 797-814.