Evaluation of Ship Effects on Bank Recession in Existing and Proposed Channels of the Sabine Neches Waterway, Texas

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1. **Summary**. Bank recession was evaluated on the Sabine Neches Waterway without and with deepening and widening of the navigation channel. The Galveston District determined ship sizes and frequency of passage for both historical ship traffic in the existing channel and future ship traffic in the existing and proposed channels. Based on observed ship speed on the SNWW and other ship channels, ship speed was determined for each ship in the existing fleet and each ship in the future fleet for both existing and proposed channels. Knowing size and speed for each ship, the numerical model HIVEL2D was used to determine the ship induced velocity at the bank for each ship in the fleet for both existing and proposed channels. The bank velocity was converted to a force at the bank and the bank force was used to determine the magnitude of bank recession for each ship. Frequency of ship passage was used with bank recession from each ship to determine total bank recession. Two sites were selected as representative of the SNWW. The North site is located upstream of the Martin Luther King Bridge and has no bank protection. Between 1974 and 1993, the North site experienced 300 ft of bank recession. With the proposed project, the North site navigation channel will remain at 400 ft bottom width and will be deepened to 48 ft. The South site is located downstream of the Martin Luther King Bridge and has rubble bank protection. Between 1974 and 1993, the South site experienced 180 ft of bank recession. With the proposed project, the South site navigation channel will be widened from 500 to 700 ft bottom width and will be deepened to 48 ft. Using historical ship passage frequency, the bank recession techniques were calibrated to match the observed historical bank recession at the two sites. The bank recession techniques and frequency of future ship passage were used to estimate bank recession without and with widening and/or deepening of the ship channel. At the North site, where channel area with project does not change significantly because of deepening only, bank recession is greater in 2030 and 2060 than presently for both without and with project conditions. Bank recession increase at the North site is the result of increased traffic in future years. At the South site, where channel area with project changes significantly because of deepening and widening, without and with project results are different. Without project, bank recession at the South site increases above present levels because of increased traffic in future years. For with project conditions in 2030 and 2060 at the South site, bank recession decreases slightly below present levels because of the large increase in channel size. For both North and South sites in 2030 and 2060, with project bank recession is less than without project recession, because of the larger channel and the lesser traffic in with project conditions. Reduced ship speed, particularly for the large unloaded ships that cause the most recession per ship, will reduce bank recession in both existing and proposed channels.

2. The objective of this study is to estimate bank recession without and with project deepening and widening on the Sabine Neches Waterway (SNWW).

3. The assumptions used in this analysis are as follows:

a. All of the observed erosion is assumed to be the result of ship effects. Currents along the shoreline and wind wave magnitudes are low along the SNWW. Observed tug and tow/barges effects were small at the shoreline during the SNWW field study of ship effects (Maynord (2003)). At the 12 knot and less ship speeds used herein, the transverse stern wave dominates secondary ship waves formed at bow and stern. The assumption of the observed erosion being only caused by ships provides some overestimation of erosion rates from ships because other erosion mechanisms caused some of the observed erosion, even if that erosion contribution was small in magnitude.

b. The ship effects are only computed for the present bank position but are used to represent ship effects for both past and future bank positions. This incorporates some conservatism (overestimation) in future bank recession estimates.

c. The approach used herein does not attempt to define the bank and berm profile during the erosion process, only the magnitude of recession of the bank.

d. All material eroded from the bank is assumed to be removed from the shoreline area and not allowed to deposit.

4. The steps in the bank recession evaluation are described in the following paragraphs.

5. **Site Selection**. The Galveston District evaluated historical bank recession along the SNWW as shown in Table 1 and Figure 1. Locations 3 and 6 are the same locations of the measurements made in the 2003 ship effects study reported in Maynord (2003) and are selected for this analysis. The site selection is based on evaluating the two different proposed channels (400 ft wide by 50 ft deep (location 6) and 700 ft wide by 50 ft deep (location 3)) and selecting typical distances of the sailing line from the shoreline. The selected sites have berm bathymetry data collected during the Maynord (2003) SNWW ship effects study. The two sites are shown in Figure 1 and further described as follows:

a. North site - The North site is located on the East bank and is north of the MLK Bridge in the unprotected portion that is actively receding. The north site corresponds to Location 6 in Table 1 where 300 ft of recession occurred during the 19 years from 1974-1993. The present shoreline is about 1100 ft from the channel centerline. This site is the same location as the North site capacitance gages used in the 2003 field study. The existing channel was calibrated to the observed bank recession using historical traffic. Bank recession was determined for without project and with the 400 ft wide project deepened to 50 ft for 2030 and 2060 ship traffic.

b. South site - The South site is located on the East bank and is south of the MLK Bridge in the rubble-protected portion that is experiencing a reduced rate of bank recession. The South site corresponds to Location 3 in Table 1 where 180 ft of recession occurred during the 19 years from 1974-1993. The shoreline is about 725 ft from the channel centerline. This site is the same location as the South site capacitance gages used in the SNWW field study. The existing channel was calibrated to observed bank recession using historical traffic. Bank recession was determined for without project and with the 700 ft wide project deepened to 50 ft for 2030 and 2060 ship traffic.

6. **Representative Ship Classes and Historical and Future Traffic.** Coordination with the District resulted in selection of the following ship classes for the existing channel:

550 X 80 X 29 and 39 ft draft: ship area = 2320 & 3120
700 X 106 X 29 and 39 ft draft : ship area = 3074 & 4134
800 X 140 X 29 and 39 ft draft : ship area = 4060 & 5460
900 X 164 X 29 and 39 ft draft : ship area = 4756 & 6396

For the proposed channels, the following ships were used to represent the fleet:

550 X 80 X 29 and 39 ft draft: ship area = 2320 & 3120
700 X 106 X 29, 39, and 46 ft draft : ship area = 3074, 4134, & 4876
800 X 140 X 29, 39, and 46 ft draft : ship area = 4060, 5460, & 6440
900 X 164 X 29, 39, and 46 ft draft : ship area = 4756, 6396, & 7544

Two vessel traffic growth scenarios were estimated. The initial **base forecast** reflects continuation of the historical trend that tonnage has increased at a much higher rate than trips. The base scenario assumes a continuation of this scenario. An **alternative growth forecast** or **high growth traffic scenario** was also prepared. The alternative growth scenario was based on the relative relationship between 2000-02 trips and tonnage. The effect of this alternative scenario is higher trip volumes for 2030 and 2060 than the base scenario, which assumed a continuation of the historical trend towards larger vessels.   The alternative scenario assumes a much lower increase in the volume of tonnage moving to larger vessels.

Tables 2-4 show past and future levels of ship traffic provided by the District for the above ship classes and traffic growth scenarios. Less traffic for with project conditions results from the larger ships in the proposed channel. In calibration of the erosion model to historical traffic, 1972 traffic represented 1974-1976 (2 years), 1980 represented 1976 -1985 (9 years), 1990 represented 1985-1991 (6 years), and 1993 represented 1991-1993 (2 years).

7. Tidal Datums. While this bank recession study uses water levels and channel bathymetry relative to Mean Low Tide (MLT), various datums exist on the SNWW. Equal elevations relative to MLT, Mean Lower Low Water (MLLW), and NAVD 88 are shown in Table 5. For completion of the SNWW feasibility study, all references to tidal datums will be in MLT. Since most of the modeling and the ERDC reports for this study have already been completed, and additional time and cost would be involved for field surveys to relate various datums to existing Bench Marks and TCOON gages, it has been decided that ERDC reports will not be revised to use consistent datum. Instead a 'Datums Table' showing elevations for various datums based on Sabine Pass data, will be included in each ERDC Report. If an issue arises with respect to compliance with HQUSACE guidance, then MLT datums will be converted to Mean Lower Low Water (MLLW) during the Preconstruction Engineering and Design (PED) Phase of the project.

8. **Ship Speed**. Speeds of existing ships in the existing channels, existing ships in the proposed channels, and expected future ships in the proposed channels are the most critical issue in this evaluation. The following are important in selecting ship speeds:

a. Ship speed varies with many factors including:

(1) Ship characteristics- type, length, beam, draft, cargo type, some ships handle better than others.

(2) Channel size- depth, bottom width, shape

(3) Channel alignment, presence of bridges, other structures

(4) Channel perimeter- Moored vessels, bank material

(5) Pilot

(6) Environmental conditions, weather, other vessels, tides

(7) Percent of limit speed - channel and ship size determine a limit speed that requires a large amount of power to reach and is rarely approached by large displacement ships. Some pilots refer to this phenomenon as "hydraulics". Most ships travel at about 70-90% of the computed limit speed. Computing the limit speed is relatively simple in rectangular or trapezoidal channels having steep side slopes. Computing limit speeds in channels like SNWW is complicated by the presence of the shallow berm and the mild side slopes and can only be considered approximate. In the SNWW vessel effects study (Maynord (2003)), limit speed was computed by excluding the shallow berm adjacent to the channel from the channel area and width used in the limit speed computations.

b. As part of this study, SNWW pilot Ellen Warner was contacted about ship operation on the existing and proposed SNWW. Captain Warner stated the following:

(1) Loaded and unloaded ships travel about 6 and 8 knots, respectively.

(2) Ships will travel 0.5 to 1.0 knot faster when the channel is widened from 500 to 700 ft and deepened to 50 ft.

(3) Both unloaded and loaded ships typically use an engine RPM of maneuver full and that will remain the same in the proposed channels. Ships generally use one of five engine RPM settings of dead slow, slow, half, maneuver full, and full ahead.

c. The Maynord (2003) ship effects study on the SNWW has important differences compared to this study. The 2003 study placed almost complete emphasis on use of limit speed to select ship speeds to evaluate vessel effects in the SNWW. That approach is valid for ships that have large blockage ratio (*BR* = ship cross section area/channel cross section area excluding berms) greater than about 0.2 but does not take into account the other factors listed above that are likely important for all *BR* but particularly those where *BR* is less than about 0.2. The 2003 study evaluated different ship speeds but intentionally did not state that the speeds were expected speeds. The 2003 study was limited to primarily evaluating the transverse stern wave height for different ships and did not consider the frequency of traffic in existing and proposed channels or estimate the anticipated bank recession. This study considers all aspects of estimating bank recession, including size and frequency of ship traffic as well as the amount of bank recession from each ship.

d. This bank recession study takes a comprehensive look at the factors that affect ship speed and determines expected speeds for the entire fleet in the existing and proposed channels. The approach used herein for the existing channel is to use the observed ship speed data to select ship speed based on a plot of *BR* versus observed ship speed. Channel areas and *BR* are shown in Table 6. All areas are at a water level of 2.5 ft MLT and are based on the navigation channel including side slopes but do not include the shallow berms adjacent to the channel. For a 140 ft beam ship drafting 29 ft in the North site existing channel, the *BR* = 140*29/25000 = 0.162. In cases where the observed data have to be extrapolated to *BR* larger than the range of observed data, ship speed was limited to no greater than 90% of the computed limit speed. The observed SNWW data is separated into loaded ships of draft greater than or equal to 35 ft and unloaded ships of draft less than or equal to 31 ft. All of the SNWW ships used in this analysis are tankers/bulk carriers having large block coefficients. Block coefficient is a measure of ship fineness or streamlining and is equal to underwater ship volume/ (ship length*beam* draft). The observed SNWW data are plotted in Figure 2 and the best-fit equation for unloaded ships is

$$Speed\ Unloaded = 7.21\,BR^{-0.16} \qquad \text{Equation 1}$$

Where speed is in knots. The equation for the loaded ships is

$$Speed\ Loaded = 4.97\,BR^{-0.27} \qquad \text{Equation 2}$$

As stated previously, speed from equations 1 and 2 was limited to no greater than 90% of the computed limit speed. Figure 2 also shows data from tankers on the Houston Ship Channel and container ships on the Mississippi River Gulf Outlet (MRGO). These data were not used in development of the SNWW speed equations but are shown for comparison. North and South site expected ship speeds in the existing channel from the equations are shown in Table 6.

e. For the North site proposed channel, the channel area is similar to the existing South site and equations 1 and 2 and 90% limit rule are used for the North site proposed channel. Equations 1 and 2 do not address intermediate drafts in the proposed channel between 29 ft (unloaded) and 46 ft (loaded) ships. In the proposed channel, a draft of 39 ft is neither unloaded nor fully loaded and is referred to herein as an “intermediate” draft in the proposed channel. For intermediate drafts of 39 ft in the proposed North site channel for ship beams of 106, 140, and 164 ft, the average speed of loaded and unloaded ships from the equations was used as the expected speed. For example, the speed of 8.59 knots for the 140 X 39 ft ship was the average of 9.40 knots from the unloaded equation and 7.78 knots from the loaded equation. North site proposed channel ship speeds to be used in the evaluation are also shown in Table 6.

f. For the South site proposed channel only, the channel area is significantly greater than the existing channels at North and South sites and the above equations may not be valid for estimating ship speed. Three techniques were used to estimate the ship speed at the South site proposed channel as follows:

(1) SNWW pilots estimate a 0.5 to 1.0 knot speed increase for ships where the channel goes from 500 ft to 700 ft wide. For existing ships in the proposed channel, a 1.0 knot increase in ship speed above the value from the existing South site channel was used as shown in Table 6 under the heading “SNWW pilot estimate”. For example, the 106 ft beam X 39 ft draft ship travel at 8.42 knots in the existing channel at the South site. Based on the SNWW pilot estimate, this same ship will travel at 8.42 + 1.0 = 9.42 knots in the proposed 700 X 50 ft channel. For the proposed 106 ft X 46 ft draft loaded ship in the proposed channel, the SNWW pilot estimate of 0.5 knot increase is applied to the loaded ship speed in the existing channel resulting in 8.42 + 0.5 = 8.92 knots.

(2) The study at Atkinson Island in the Houston Ship Channel collected ship speed data in a channel that had area similar to the South site proposed channel. The data were limited to high block coefficient ships (tankers, bulk carriers) and the data were only adequate to define a relationship for unloaded ships as shown in Figure 3. Speeds from the Atkinson Island equation are also shown on Table 6.

(3) Based on the information provided by the SNWW pilot, the proposed ships will continue to use engine RPM of maneuver full for unloaded and loaded ships in the proposed channel. This means that the resistance in the existing channel and the proposed channel will be about equal because the ship will be using about the same amount of propulsion. Knowing speed in the existing channel and the conclusion of equal resistance allows determining speed in the proposed channel using equations for ship resistance. Ship resistance is determined using modification of the techniques in Maynord (2000). The ship resistance R is

$$R = 1/2\, C_{fric}\, S\,(V + V_r)^2 + C_{draw}\,\rho g B T Z + 1/2\, C_p\, \rho V^2\,(0.98BT)$$

Where $C_{fric} = 0.075\,(Log10(VL/\nu)\text{-}2)^{-2} + 0.00025$, L = ship length, V = ship speed, ν = kinematic viscosity of water, S = hull area = $0.8(2TL+LB)$, T = ship draft, B = ship beam, V_r = return velocity using Schijf equation, ρ = water density, g = gravity, Z = average drawdown using Schijf equation, and C_p = pressure loss coefficient. Data from the Houston Ship Channel were used to determine the drawdown coefficient C_{draw} = 0.15. A pressure loss coefficient of 0.0235 for ships having block coefficient of 0.8 was taken from the book by Lap (no date). Speed results from this technique are also shown in Table 6.

(4) Since the above 3 techniques give about the same result and all 3 appear valid, all three were averaged except for loaded ships where only two methods provided data (no Atkinson Island data for loaded ships). Results are also shown in Table 6.

g. The speeds in the Table 6 represent average expected speeds. Some ships of the same size will travel slower (and cause less erosion) and some will travel faster (and cause more erosion) such as those that are behind schedule. Based on the observed data, there are groupings of data where there are multiple data points for the same blockage ratio. The standard deviation of ship speed for the different data sets is about 0.75 knots. This analysis uses the average expected speed in the numerical simulations but recognizes the reality that there is a distribution of speeds about the expected value for each ship.

9. **HIVEL2D model -** The HIVEL2D model was used in the 2003 ship effects and this evaluation of bank recession. HIVEL2D provides the time history of velocity that quantifies the ship effects attacking the shoreline. For consistency, all ships were run in the outbound direction at both the North and South sites. At the North site, the node at 583663.8, 908873.0 was used for defining vessel effects. In the existing and deepened North site grids, the node number is 27315. At the South site, the node at 571040.2, 869268.0 was used for defining vessel effects. In the existing and deepened South site grids, the node numbers are 20889 and 21226, respectively. The grid along the path of the vessel used elements 50 ft long by 20 ft wide that was shown in the 2003 study to address element size effects. Time step was 1 sec at the North and South sites that is below the time step shown in previous studies to eliminate time step effects. Time steps were output every 2 TS at the North and South sites. HIVEL2D time histories of velocity for the both sites and both channels are shown in Figures 4 to 19. These figures show important differences between various ship sizes. Consider Figure 10 that shows the computed velocity time history from a 800X140 ship in the existing channel at the South site. The first "hump" in the velocity time history for both ship drafts is the return velocity that acts in a direction opposite to the ship travel. The peak return velocity for the unloaded and loaded ships are about equal. The second hump in velocity is the transverse stern wave or bore that is moving in the same direction as the ship travels. The unloaded ship almost always has a larger 2^{nd} hump in velocity compared to the loaded ship. The higher speed of the unloaded ship often has a greater impact than the larger draft of the loaded ship. This is consistent with observations of ship effects by this author and statements by the Port Arthur Field office during this author's first visit to the site in 2002. Also consistent with field observation is the short-lived nature of the transverse stern wave effect. Figures 8-11 show how the unloaded ships transverse stern wave velocity spike increases with increasing ship size up to 140 ft beam and is about equal for the 140 and 164 ft beam. Comparison of South site existing and proposed channels shows a decrease in ship effects in the larger proposed channel. The North site, where existing and proposed channels are not greatly different in cross sectional area, shows lesser change in velocity between existing and proposed channels.

10. As discussed in Maynord (2003), HIVEL2D will not run when the ship draft approaches the channel depth. Past experience with HIVEL2D has shown that a deep draft ship can be modeled with a wider, lesser draft ship as long as the cross sectional area of the ship (equal to beam*draft) is correct. The wider and lesser draft ships and sailing lines in the HIVEL2D simulations of the existing and proposed channels are shown in Tables 7 and 8, respectively. Coordinates for sailing lines at South and North sites are shown in Tables 9 and 10. CN stands for the sailing line

centered between two adjacent nodes and ON stands for the sailing line on the nodes. The two sailing lines were 10 ft apart and were required by HIVEL2D to model different ship widths. The 10 ft of difference in lateral position was evaluated in HIVEL2D and found to have an insignificant impact.

11. **Conversion of Velocity to Shear Stress**. The HIVEL2D velocity time history must be converted to a time history of shear stress to use in the bank recession model. The relation of velocity to shear stress must consider (1) the velocity magnitude, (2) the velocity profile which generally depends on the extent of boundary layer development, and (3) the level of turbulence that often correlates well with whether the flow is expanding that causes an increase in turbulence or contracting that causes a decrease in turbulence. Bank recession is also affected by the pore pressure change in the channel boundary material due to water level changes. Where channel boundary materials are relatively impervious, pore pressures in the embankment material remain elevated as the water level falls. These excess pore pressures result in a decrease in shear strength and less stable boundary materials. A rising water level does the opposite. Consider the time history of velocity from HIVEL2D at the South site existing channel that is shown in Figure 10. Refer to the time history for the 140 ft beam X 29 ft draft ship traveling at 9.8 knots. Important time periods along the time history and the above 4 factors are discussed for each time period in Table 11. The above time history description describes the difficulty of quantifying the ship attack on the bank and berm. Furthermore, the bank response is influenced by the makeup of the boundary material and the degree to which excess pore pressures develop.

12. The time history of velocity from HIVEL2D is converted to a time history of shear stress using the equation

$$\tau = 1/2\, C_f\, \rho V_H^{\,2} \qquad \text{Equation 3}$$

where τ is the bed shear stress, C_f is the friction coefficient discussed subsequently, and V_H is the depth averaged velocity from the HIVEL2D model. Whether the boundary is hydraulically smooth or rough affects the selection of C_f. The use of bottom velocity or depth averaged velocity in equation 3 also affects the selection of C_f. Bottom velocity results in larger values of C_f. In uniform flow in an open channel, C_f for depth-averaged is approximately 0.0015- 0.004 depending on boundary roughness. Previous work was evaluated to address C_f during vessel passage as follows:

a. Stive (1984)- Stive studied bores having Froude numbers lower than ship induced bores and concluded that they have some characteristics similar to hydraulic jumps. Stive used the work of Rouse (1958) on hydraulic jumps.

b. Rouse (1958)- Rouse presented turbulence data for hydraulic jumps that included Froude numbers that are comparable to ship induced bores that are often about 4. Based on Rouse data converted to depth-averaged velocity in the hydraulic jump, C_f varies from 0.01 to 0.05. Based on this author's observation of turbulence in ship bores and hydraulic jumps, the ship bore is closer to the lower end of the hydraulic jump range.

c. Schiereck (2001)- Schiereck present C_f in waves based on bottom velocity that varies from a low of about 0.01 to a high of 0.3 depending on wave amplitude at the bottom and the bed roughness. Schiereck documents that waves have significantly higher C_f than currents.

d. Puleo (1998)- Puleo reports on studies in the swash zone that document very high sediment concentration in the bore front. A significant drop in energy flux occurs across the bore and has a strong correlation to sediment transport across the bore. Puleo suggested that sediment load may not scale with flow velocity.

For ship passage, C_f values used in this investigation are selected based on values in the literature and how the turbulence and boundary layer affect the shear stress. Adopted values are as follows:

a. Bow wave - C_f = 0.005 is adopted because it is somewhat greater than C_f for uniform flow in channels to account for the developing boundary layer.

b. Drawdown/return velocity- C_f = 0.01 is adopted to account for the developing boundary layer and because this is a zone of significant acceleration that hinders boundary layer development.

c. Surge/bore front- Because of high turbulence and an undeveloped boundary layer, C_f = 0.015 is adopted.

d. Bore decay- Varies linearly from C_f = 0.015 to C_f = 0.005.

e. Return to ambient- C_f = 0.005 is adopted for conditions close to uniform flow.

The appropriate values of C_f for navigation induced bores is an extremely complex subject that has not been addressed previously. In addition, the turbulent fluctuations in a bore are critical to scour of erodible materials. Although these C_f values have significant uncertainty, the same values were used in the calibration as well as in the without and with project projections. This should reduce the impact of these uncertainties.

13. **Bank Recession Model**. The steps in the bank recession model are as follows:

a. The model uses the shoreline velocity from HIVEL2D to quantify the effects from passage of the ship. Velocities from HIVEL2D represent conditions before, during, and after passage of the transverse stern wave. HIVEL2D velocity is converted to shear stress using the techniques discussed above.

b. Erosion of the channel bed adjacent to the shoreline is determined from

$$E = C_e \left(\frac{\tau - \tau_{cr}}{\tau_{cr}}\right)^P \qquad \text{Equation 4}$$

Where E is the erosion rate in ft/sec, C_e is a coefficient having units of ft/sec, τ is the bed shear stress at the shoreline in Pascals from the HIVEL2D velocity-shear stress calculations, and P is an exponent that generally varies between 1.5 and 2.5 for cohesive soils but values from 1.0-3.0 have been determined based on soil mineralogy, bulk density, and many other factors. Davies et al (2003) used P =1 to assess shoreline erosion from vessel effects. Lower values of P cause more of the ships in the fleet to contribute to the bank recession. Higher values of P result in only the ships producing the highest τ contributing to the bank recession. A P value of 1.5 is adopted herein based on the Davies study and the typical range of P. Equation 4 is applicable for all τ greater than the critical shear stress, τ_{cr}. Based on results from Nana Parchure shown in Table 12, critical shear stress of the surface layer material is about 0.5 Pa. Critical shear stress will likely be greater for deeper materials exposed during bank recession. After exposure, these deeper materials generally experience a gradual decrease in critical shear stress due to a variety of processes. As noted by Davies et al (2003), some means is needed to limit large spikes in shear stress from causing unrealistic erosion from a single ship. Davies used an upper limit of about 25 Pa and this same limit is used herein. Deposition on the bed adjacent to the shoreline of the eroded material is assumed to be negligible. Recession of the bank depends on erosion of the channel bed adjacent to the shoreline determined from equation 4. This study does not attempt to define the relationship of bed erosion to bank recession. Instead, both the bed erosion and the relationship of bed erosion to bank recession are combined into the coefficient C_e. In this application of equation 4, E is the bank recession rather than the bed erosion. Calibration of the bank recession model involved adjusting the coefficient C_e to match the observed bank recession.

14. **Calibration of the North Site** The North site was calibrated to the observed erosion of 300 feet over the 19-year period from 1974-1993. Using the 1972 traffic for 1974-1976, 1980 traffic for 1976-1985, 1990 traffic for 1985-1991, and 1993 traffic for 1991-1993, C_e in the erosion equation was determined to be 0.00000104 ft/sec that was based on the observed recession over the 19 year period of 300 ft. The 8 ships used to describe the fleet had the following amounts of erosion per ship and number of ships over the 19 years: (1) 550X80X29- 0.0023 ft/ship for 21293 ships; (2) 550X80X39- 0.0014 ft/ship for 5725 ships; (3) 700X106X29- 0.0082 ft/ship for 18353 ships; (4) 700X106X39- 0.0032 ft/ship for 6369 ships; (5) 800X140X29- 0.0121 ft/ship for 4002 ships; (6) 800X140X39- 0.0068 ft/ship for 3444 ships; (7) 900X164X29- 0.0131 ft/ship for 110 ships; and (8) 900X164X39- 0.0078 ft/ship for 70 ships. Total number of ships over the 19- year period was 59366. Bank recession per ship is compared in Table 13.

15. **Calibration of the South Site** The South site was calibrated to the observed erosion of 180 feet over the 19-year period from 1974-1993. The erosion at this site is reduced by the presence of rubble and application of the erosion equation to the rubble impacted bank has much greater uncertainty than application to an unprotected bank because of the local variation in strength of the rubble and the unknown time of placement of the rubble during the 19 year period. Using the 1972 traffic for 1974-1976, 1980 traffic for 1976-1985, 1990 traffic for 1985-1991, and 1993 traffic for 1991-1993, C_e in the erosion equation was determined to be 0.000000833 ft/sec that was based on the observed recession over the 19 year period of 180 ft. The 8 ships used to describe the fleet had the following amounts of erosion per ship and number of ships over the 19 years: (1) 550X80X29- 0.0021 ft/ship for 21293 ships; (2) 500X80X39- 0.0004 ft/ship for 5725 ships; (3) 700X106X29- 0.0048 ft/ship for 18353 ships; (4) 700X106X39- 0.0006 ft/ship for 6369 ships; (5) 800X140X29- 0.0090 ft/ship for 4002 ships; (6) 800X140X39- 0.0013 ft/ship for

3444 ships; (7) 900X164X29- 0.0128 ft/ship for 110 ships; and (8) 900X164X39- 0.0021 ft/ship for 70 ships. Total number of ships over the 19-year period was 59366. Bank recession per ship is compared in Table 13.

16. **Bank Recession estimates for 2000-2002**. The calibrated models were used to estimate recession for the observed traffic of 2000-2002 that is used herein to represent "present" conditions. Results are shown in Table 14 and show about 23 ft/year at the North site and 14 ft/year at the South site. If aerial photographs are available for sometime near the present, the bank recession model could be tested against bank recession from data not used in development of the model.

17. **Bank Recession Estimates for Future Years**. In the North and South Site proposed channels, the 11 ships used to describe the fleet had bank recession per ship shown in Table 13.

Table 15 shows the predicted bank recession for the years 2030 and 2060 for the alternative fleet and base scenarios. Results show the following:

a. At the North site, where channel area with project does not change significantly because of deepening only, bank recession is greater in 2030 and 2060 than presently (2000-2002) for both without and with project conditions. Bank recession increase at the North site is the result of increased traffic in future years.

b. At the South site, where channel area with project changes significantly because of deepening and widening, without and with project results are different. Without project, bank recession increases above present levels (2000-2002) because of increased traffic in future years. For with project conditions at the South site, bank recession decreases slightly (for 3 of the 4 traffic scenarios) below present levels because of the large increase in channel size, even though traffic increases.

c. For both sites, with project bank recession is less than without project recession, because of the larger channel and the lesser traffic in with project conditions.

18. **Reducing Bank Recession**. From the amounts of erosion per ship (Table 13) for both the existing and proposed channels, the larger beam unloaded ships are causing most of the erosion. Modest speed control of all ships, but particularly the larger beam unloaded ships, would lead to a significant decrease in bank recession.

References

Davies, M.H. et al. 2003. “Water level impacts on erosion and flooding along the St Lawrence River”, Canadian Coastal Conference.

Maynord, S.T. 2000. “Power versus speed for shallow draft navigation”, ASCE J of Waterway, Port, Coastal, and Ocean Engineering, Vol. 126, No. 2.

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

Puleo, J. 1998. “Importance of bore-generated turbulence to swash zone sediment transport”, AGU Fall meeting, San Francisco.

Rouse, H., Siao, T.T., and Nagaratnam, S. 1958. “Turbulence characteristics of the hydraulic jump, J of the Hydraulics Division, Vol 84, No HY1.

Schiereck, G.J. 2001. Introduction to bed, bank, and shore protection, Spon Press, London and New York.

Stive, M.J.F. 1984. “Energy dissipation in waves breaking on gentle slopes, Delft Hydraulics Laboratory, Publication 321.

Table 1. SUMMARY OF SABINE NECHES WATERWAY SHORELINE EROSION ANALYSES

Location #	Channel Locaton	Shoreline Change		Estimated Annual Erosion Ft/Yr	Comments
		1970-1974	1974-1993		
1	Sabine Pass	60'	0	2.6	
2	Pt Arthur		240'	12.6	No measurable shoreline erosion from 1970 to 1974.
3	Pt Arthur		180'	9.5	No measurable shoreline erosion from 1970 to 1974.
4	Pt Arthur		80'	4.2	No measurable shoreline erosion from 1970 to 1974.
5	Sabine Neches	120'	260'	16.5	
6	Sabine Neches		300'	15.8	Photo revisions were done in 1970-75.
7	Sabine Neches		170'	8.9	No Quad sheets prior to 1970-74 photo revisions could be found.

Note: Location 7 is upstream of the upstream end of Pleasure Island.

Table 2. Past Ship Traffic, Total Deep-Draft Piloted Vessels, Movements by Vessel Size and Loaded Draft.

	Beam	& LOA *	%	Vessels	29 ft draft	39 ft draft
Yr: 1972				Inbound and Outbound Totals		
10000	80	500	48%	1910	1615	295
50000	106	700	50%	1988	1681	307
90000	140	800	1%	38	19	19
120000	164	900	0%	2	1	1
			100%	3939	3317	622
Yr: 1980				Inbound and Outbound Totals		
10000	80	500	44%	1820	1281	539
50000	106	700	46%	1894	1333	561
90000	140	800	10%	409	204	204
120000	164	900	0%	4	2	2
			100%	4127	2820	1307
Yr: 1990				Inbound and Outbound Totals		
10000	80	500	49%	817	782	35
50000	106	700	28%	462	360	102
90000	140	800	23%	386	212	174
135000	164	900	1%	16	10	6
			100%	1681	1364	316
Yr: 1993				Inbound and Outbound Totals		
10000	80	500	45%	958	921	37
50000	106	700	22%	464	417	47
90000	140	800	32%	691	428	263
135000	164	900	1%	22	15	7
			100%	2136	1781	355
Yr: 2000				Inbound and Outbound Totals		
10000	80	500	27%	866	809	57
50000	106	700	26%	823	637	186
105000	140	800	45%	1438	791	647
150000	164	900	2%	49	31	19
			100%	3177	2268	909
Yr: 2001				Inbound and Outbound Totals		
10000	80	500	27%	942	901	42
50000	106	700	25%	857	596	261
105000	140	800	47%	1633	863	770
150000	164	900	1%	38	22	16
			100%	3471	2382	1089
Yr: 2002				Inbound and Outbound Totals		
10000	80	500	29%	998	956	42
50000	106	700	27%	932	643	289
105000	140	800	42%	1444	775	669
150000	164	900	2%	82	44	38
			100%	3456	2418	1038

* Median beam for 80 to 106-foot range. Maximum 10% beam for 140 to 164-foot range.

Table 3. Future traffic, Self-Propelled Piloted Vessels Inbound and Outbound, Combined Total, Alternative Fleet Forecast

Yr: 2030			Vessels by Sailing Draft (ft)				Vessels by Sailing Draft (ft)				
DWT	Beam &	LOA	% of Trips	Total Trips	29 ft	39 ft	% of Trips	Total Trips	29 ft	39 ft	46 ft
			Without Project Condition (ALT)				With 50-foot Channel (ALT)				
10000	80	500	27%	1758	1672	85	32%	1758	1672	85	0
50000	106	700	30%	1924	1323	601	32%	1743	1225	89	429
105000	140	800	41%	2655	1431	1224	34%	1896	1048	14	834
163000	164	900	3%	164	92	72	2%	117	67	5	45
			100%	6501	4519	1982	100%	5513	4012	193	1308
Yr: 2060											
			Without Project Condition (ALT				With 50-foot Channel (ALT				
10000	80	500	27%	2775	2639	137	32%	2775	2639	137	0
50000	106	700	31%	3110	2136	974	32%	2734	1894	143	697
105000	140	800	40%	4031	2172	1859	34%	2874	1587	21	1266
163000	164	900	2%	250	140	110	2%	173	100	7	66
			100%	10166	7087	3079	100%	8556	6220	308	2028

Table 4. Future traffic, Self-Propelled Piloted Vessels Inbound and Outbound, Combined Total, Base Scenario

Yr: 2030			Vessels by Sailing Draft (ft)				Vessels by Sailing Draft (ft)				
DWT	Beam	&LOA	% of Trips	Total Trips	29 ft	39 ft	% of Trips	Total Trips	29 ft	39 ft	46 ft
			Without Project Condition (BASE)				With 50-foot Channel (BASE)				
10000	80	500	25%	1392	1327	65	30%	1392	1327	65	0
50000	106	700	26%	1452	1001	450	27%	1264	901	69	294
105000	140	800	47%	2618	1412	1206	40%	1853	1026	13	814
163000	164	900	3%	166	93	73	3%	118	67	5	45
			100%	5628	3834	1794	100%	4626	3321	151	1154
Yr: 2060											
			Without Project Condition (BASE)				With 50-foot Channel (BASE)				
10000	80	500	21%	1534	1462	72	26%	1534	1462	72	0
50000	106	700	22%	1599	1103	496	24%	1392	992	76	324
105000	140	800	53%	3834	2072	1762	47%	2711	1504	16	1192
163000	164	900	3%	237	134	103	3%	164	95	7	63
			100%	7204	4771	2433	100%	5801	4052	170	1578

Table 5. Referencing Table for Different Datums for Sabine Pass, Texas*

Mean Low Tide (MLT), ft		Mean Lower Low Water (MLLW), ft		NAVD 88, ft
0.0	=	-0.36	=	-0.78
0.36	=	0.0	=	-0.42
0.78	=	0.42	=	0.0
1.0	=	0.64	=	0.22
2.0	=	1.64	=	1.22
3.0	=	2.64	=	2.22
4.0	=	3.64	=	3.22

* This table provides the best estimate of equal elevations at the three datums but the relationships between the datums have not been fully field-verified.

Table 6. Expected Ship Speeds

Site/ channel	Ship size, beamX draft, ft	Ship Area, sq ft	*BR*	Ship Speed, knots					
				BR eq Speed	SNWW pilot estimate	Atkinson Island Equation	Equal Power estimate	90% of Vlimit	Speed used
South/ exist	80X29	2320	0.0795	10.8	NU***	NU	NU	12.48	10.8
A=29170*	80X39	3120	0.107	9.09	NU	NU	NU	11.49	9.09
W=740**	106X29	3074	0.105	10.34	NU	NU	NU	11.51	10.34
	106X39	4134	0.142	8.42	NU	NU	NU	10.40	8.42
	140X29	4060	0.139	9.88	NU	NU	NU	10.43	9.88
	140X39	5460	0.187	7.82	NU	NU	NU	9.17	7.82
	164X29	4756	0.163	9.64	NU	NU	NU	9.75	9.64
	164X39	6396	0.219	7.49	NU	NU	NU	8.41	7.49
North/ exist	80X29	2320	0.0928	10.55	NU	NU	NU	11.65	10.55
A=25000	80X39	3120	0.125	8.72	NU	NU	NU	10.62	8.72
W=670	106X29	3074	0.123	10.08	NU	NU	NU	10.61	10.08
	106X39	4134	0.165	8.08	NU	NU	NU	9.46	8.08
	140X29	4060	0.162	9.65	NU	NU	NU	9.51	9.51
	140X39	5460	0.218	7.50	NU	NU	NU	8.21	7.5
	164X29	4756	0.190	9.40	NU	NU	NU	8.80	8.80
	164X39	6396	0.256	7.18	NU	NU	NU	7.41	7.18
South/ Future	80X29	2320	0.0549	11.47	11.8	12.1	11.85	14.7	11.92
A=42262	80X39	3120	0.0738	10.05	10.09	NU	10.10	13.8	10.10
W=910	106X29	3074	0.0727	10.96	11.34	11.42	11.38	13.8	11.38
	106X39	4134	0.098	9.88	9.42	NU	9.7	12.34	9.56
	106X46	4876	0.115	8.91	8.92	NU	9.3	12.17	9.11
	140X29	4060	0.096	10.49	10.88	10.79	11.1	12.82	10.93
	140X39	5460	0.129	9.32	8.82	NU	9.4	11.69	9.11
	140X46	6440	0.152	8.27	8.32	NU	8.4	10.77	8.36
	164X29	4756	0.1125	10.22	10.64	10.44	11.0	12.2	10.69
	164X39	6396	0.151	9.02	8.49	NU	9.2	10.98	8.85
	164X46	7544	0.178	7.92	7.99	NU	8.2	10.00	8.1
North/future	80X29	2320	0.0807	10.79	NU	NU	NU	12.98	10.79
A=28760	80X39	3120	0.108	9.05	NU	NU	NU	11.94	9.05
W=670	106X29	3074	0.107	10.31	NU	NU	NU	11.92	10.31
	106X39	4134	0.144	9.11	NU	NU	NU	10.23	9.11
	106X46	4876	0.170	8.03	NU	NU	NU	10.06	8.03
	140X29	4060	0.141	9.86	NU	NU	NU	10.80	9.86
	140X39	5460	0.190	8.59	NU	NU	NU	9.51	8.59
	140X46	6440	0.224	7.44	NU	NU	NU	8.46	7.44
	164X29	4756	0.165	9.62	NU	NU	NU	10.11	9.62
	164X39	6396	0.222	8.32	NU	NU	NU	8.7	8.32
	164X46	7544	0.262	7.14	NU	NU	NU	7.60	7.14

*A=channel area in square ft,**W= channel top width in feet,***NU=not used

Table 7. Actual and HIVEL2D ship drafts and sailing lines in existing channel.

Length, ft	Actual Ship		HIVEL2D ship		Sailing line
	Beam, ft	Draft, ft	Beam, ft	Draft, ft	
550	80	29	100	23.2	ON
“	“	39	100	31.2	“
700	106	29	120	25.6	CN
“	“	39	120	34.45	“
800	140	29	140	29	ON
“	“	39	180	30.3	“
900	164	29	200	23.8	CN
“	“	39	200	32.0	“

Table 8. Actual and HIVEL2D ship drafts and sailing lines in proposed channel.

Length, ft	Actual Ship		HIVEL2D ship		Sailing line
	Beam, ft	Draft, ft	Beam, ft	Draft, ft	
550	80	29	100	23.2	ON
“	“	39	“	31.2	“
700	106	29	120	25.6	CN
“	“	39	“	34.45	“
“	“	46	“	40.63	“
800	140	29	140	29	ON
“	“	39	“	39	“
“	“	46	180	35.78	
900	164	29	200	23.8	CN
“	“	39	“	32.0	“
“	“	46	“	37.7	“

Table 9. Sailing line coordinates for South Site, CN and ON

X, CN	Y, CN	X, ON (ON-60)	Y, ON (ON-60)
566599	879079	566613(566665)	879078(879103)
571074	867065	571087(571151)	867065(867077)
572207	865327	572214	865334
574094	863573	574101	863579
575469	862710	575468	862722
584873	859493	584873	859505

Table 10. Sailing line coordinates for North Site, CN and ON

X, CN	Y, CN	X, ON	Y, ON
593918	924794	593909.0	924799.0
592764	923128	592756.0	923134.0
587604	915802	587598.0	915812.0
586284	914244	586273.0	914245.0
585150	912596	585142.0	912603.0
584018	910947	584006.0	910949.0
582707	909438	582701.0	909446.0
581353	907965	581343.0	907969.0
580087	906417	580077.0	906420.0
578912	904799	578904.0	904805.0
575393	899939	575382.0	899937.0
574433	898184	574422.0	898186.0
573667	896550	573658.0	896556.0
570450	892464	570505.0	892549.0

Table 11. Variation of velocity, boundary layer, turbulence, and pore pressure during ship passage.

	Bow wave	Drawdown/ return velocity	Surge/bore front	Bore decay	Return to ambient
Time	500-600	600-700	700-704	704-740	>740
Velocity magnitude	Low	Moderate	High	High to low	Low
Boundary Layer	Developing	Developing	Undeveloped	Developing	Developed
Turbulence	Low	Low	High	High to Low	Low
Pore pressure effect	No significant effect	Decreases material strength	Increases material strength	Small decrease in material strength	No significant effect

Table 12.Critical shear stress values for Sabine Sediment samples for each of the seven eroding areas

Bed Sample #	Eroding Area #	% Sand	% Silt/Clay	% Moisture Content	% Organic Content	τ_{cr} (Pa)
P1	1	52.95	47.05	36.00	2.41	0.50
P6	2 & 3	14.57	85.43	51.00	4.53	0.45
P7	4	15.08	84.92	50.00	4.68	0.45
P9	5	26.14	73.86	31.00	4.81	0.48
P15	6	21.39	78.61	38.00	4.00	0.48
P19	7	4.48	95.52	39.00	3.93	0.40

Table 13. Comparison of Bank Recession per Ship

Ship	North-existing	South-existing	North-proposed	South-proposed
	Bank Recession, ft per ship			
550X80X29	0.0023	0.0021	0.0016	0.0008
550X80X39	0.0014	0.0004	0.0011	0.0003
700X106X29	0.0082	0.0048	0.0051	0.0020
700X106X39	0.0032	0.0006	0.0080	0.0005
700X106X46	Not present	Not present	0.0042	0.0005
800X140X29	0.0121	0.0090	0.0126	0.0045
800X140X39	0.0068	0.0013	0.0120	0.0011
800X140X46	Not present	Not present	0.0055	0.0009
900X164X29	0.0131	0.0128	0.0127	0.0069
900X164X39	0.0078	0.0021	0.0130	0.0019
900X164X46	Not present	Not present	0.0081	0.0014

Table 14. Calculated Bank Recession per year for Traffic in Years 2000-2002.

Year	Total ships	North Site Recession, ft	South Site Recession, ft
2000	3177	22	13
2001	3471	24	14
2002	3456	23	14

Table 15. Bank Recession per year for Future Traffic, Without and With Project

Year/ scenario	Total ships WOP/WP	North Site Recession, ft		South Site Recession, ft	
		WOP	WP- 50 ft	WOP	WP-50 ft
2030 Alt	6501/5513	44	31	26	10
2060 Alt	10166/8556	68	47	40	16
2030 Base	5628/4626	40	28	23	9
2060 Base	7204/5801	54	37	32	12

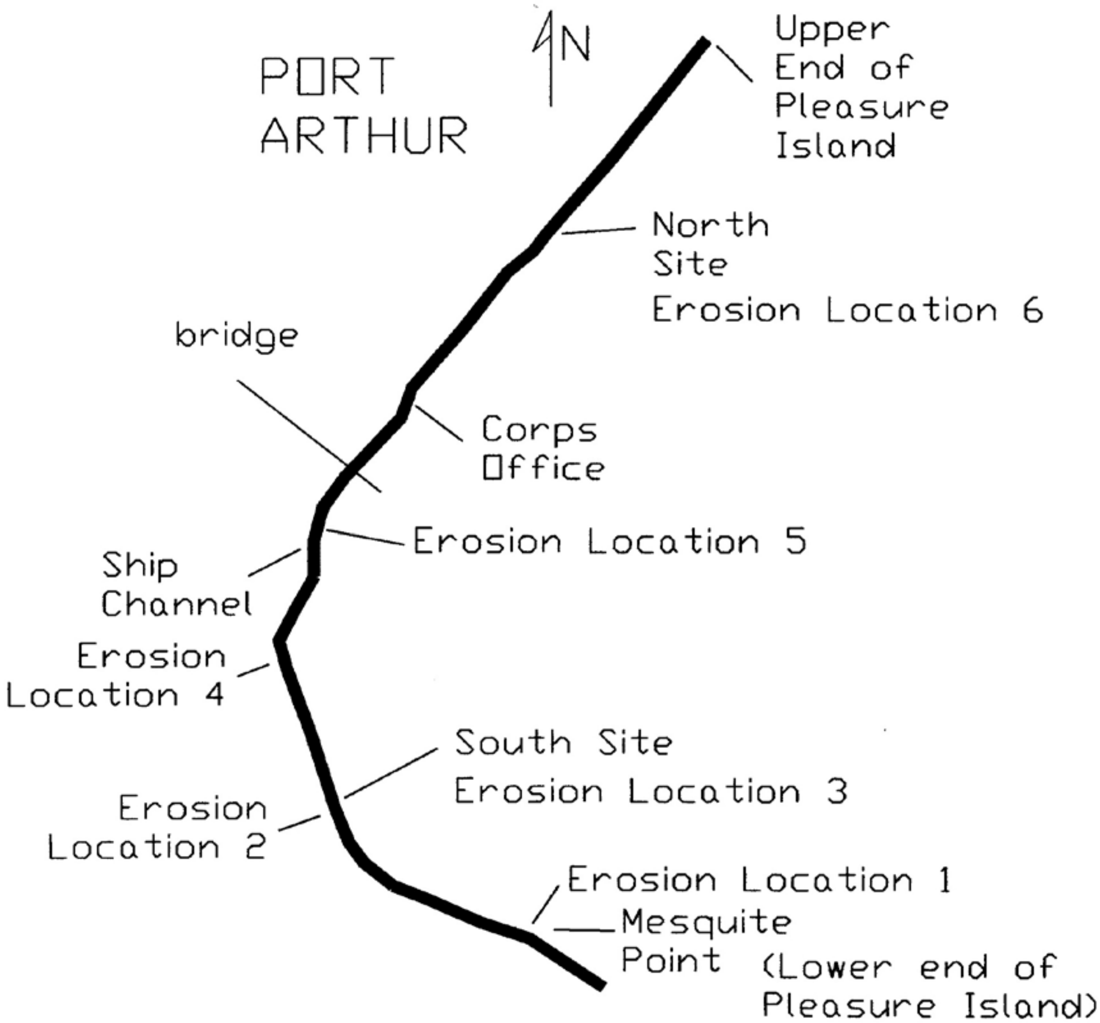

Figure 1. North and South site locations.

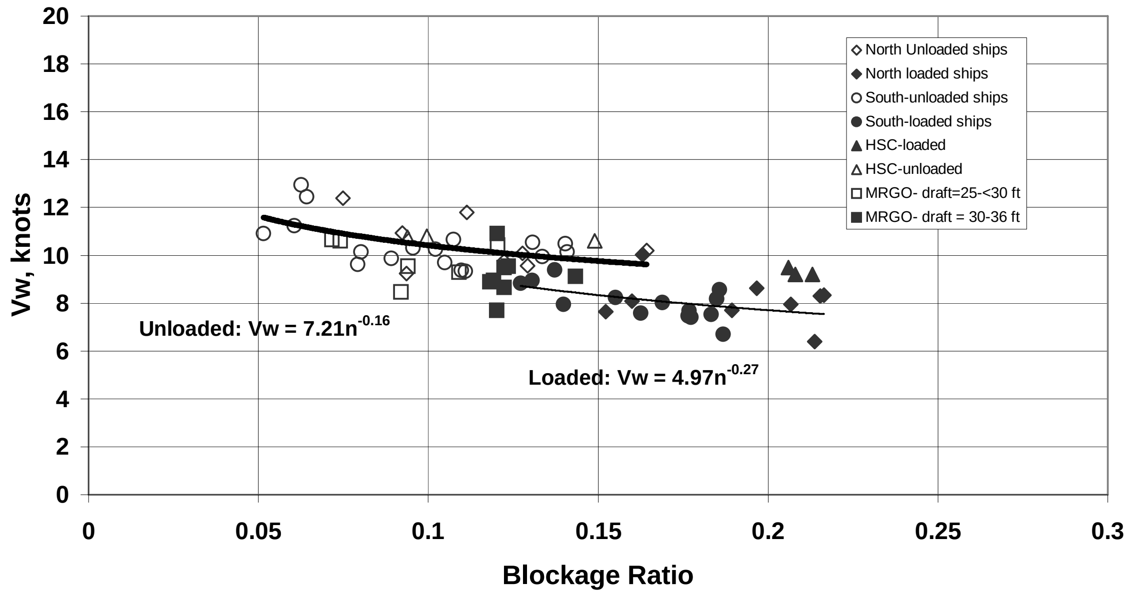

Figure 2. Speed versus Blockage Ratio using SNWW Data

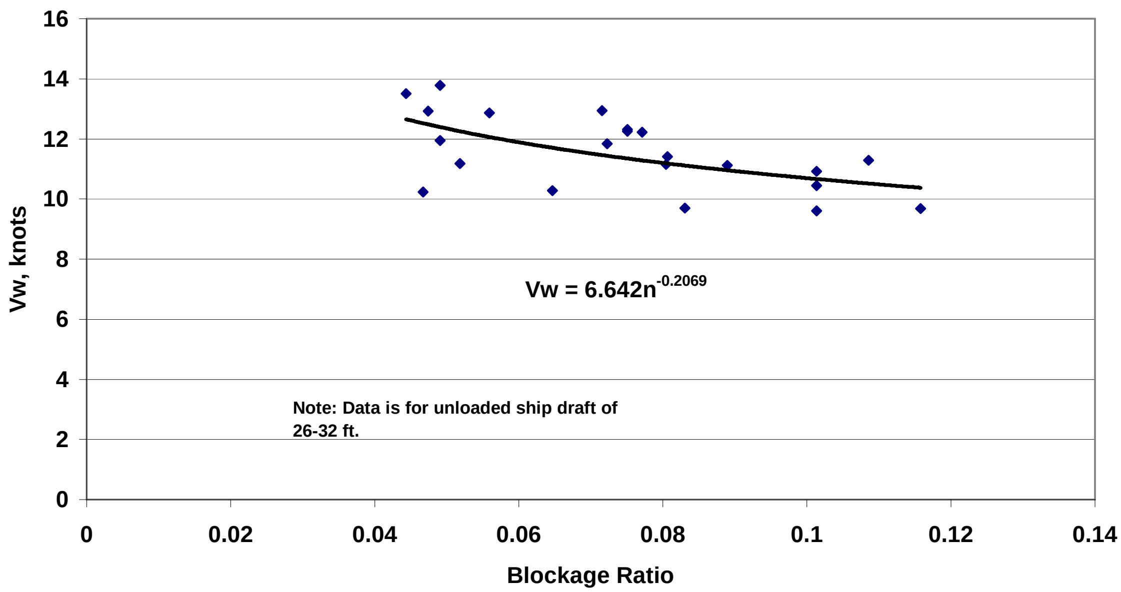

Figure 3. Speed versus blockage ratio using Atkinson Island data from Houston Ship Channel.

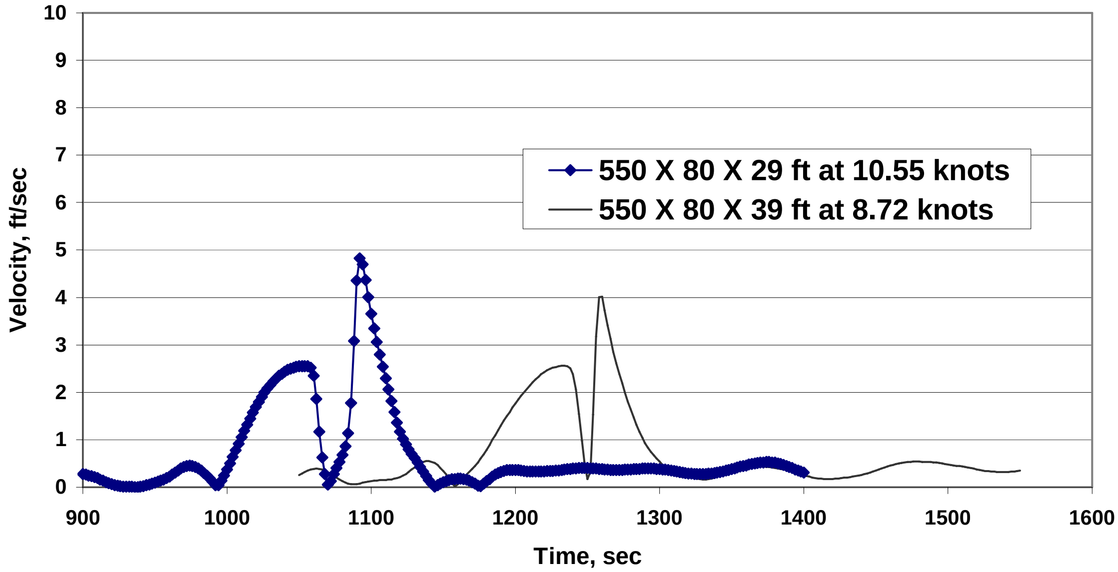

Figure 4. North site, existing channel, 80 ft beam ships.

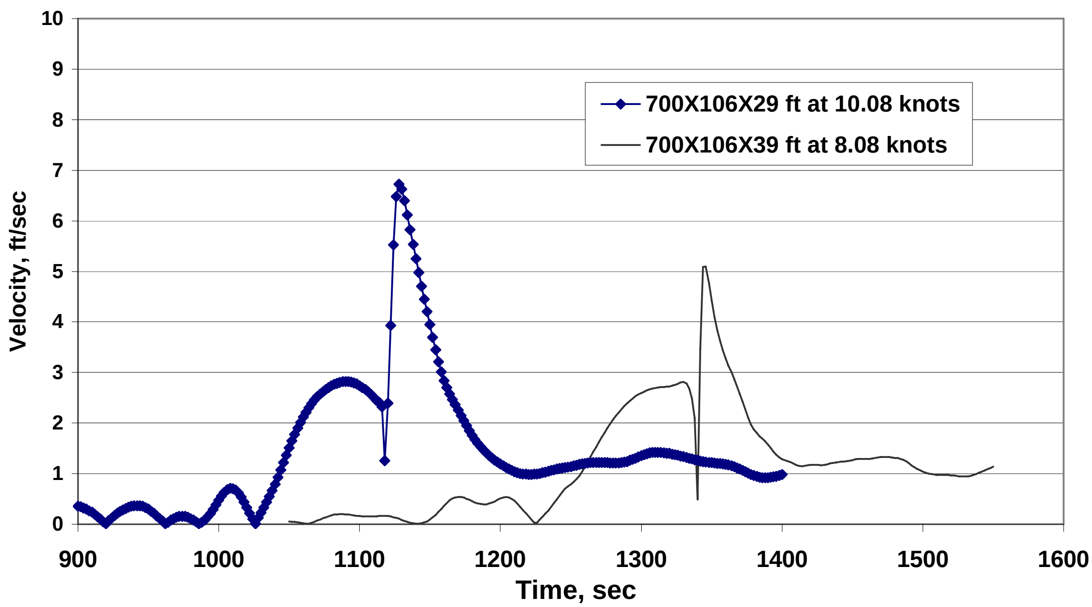

Figure 5. North site, existing channel, 106 ft beam ships.

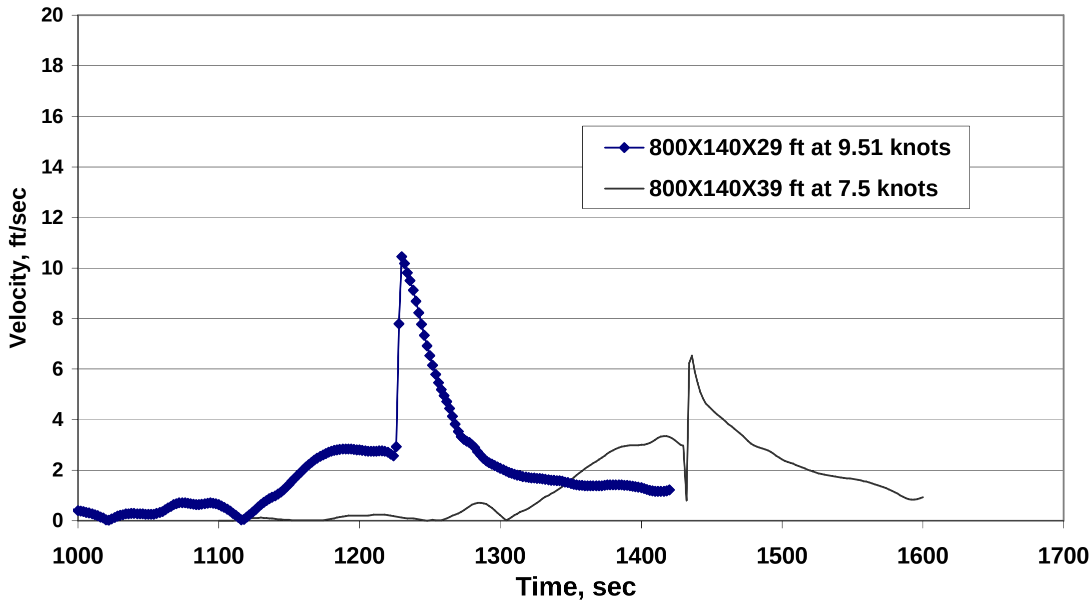

Figure 6. North site, existing channel, 140 ft beam ships.

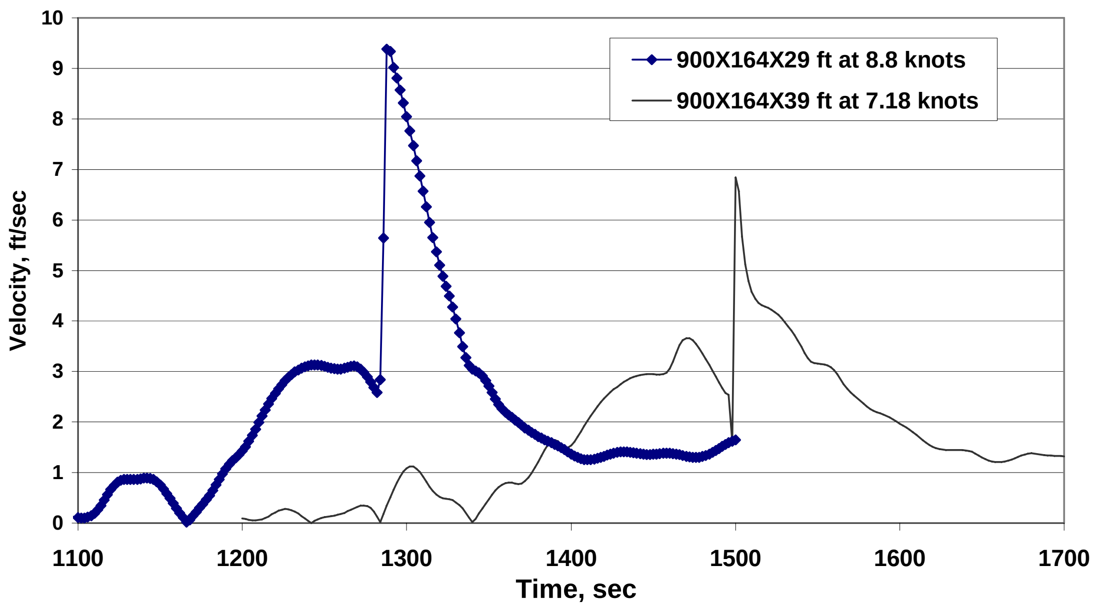

Figure 7. North site, existing channel, 164 ft beam ships.

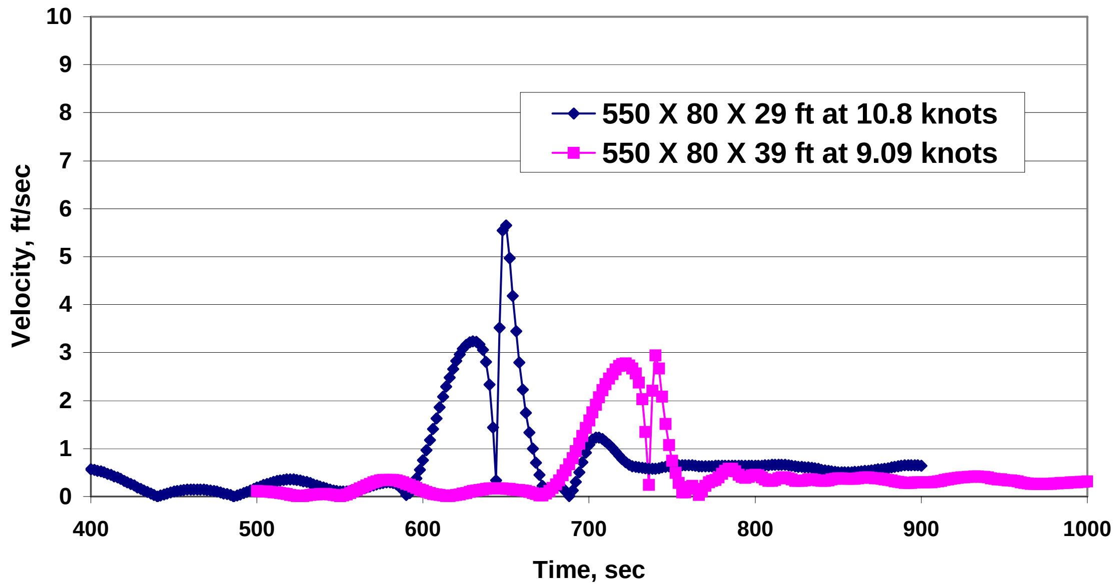

Figure 8. South site, existing channel, 80 ft beam ships.

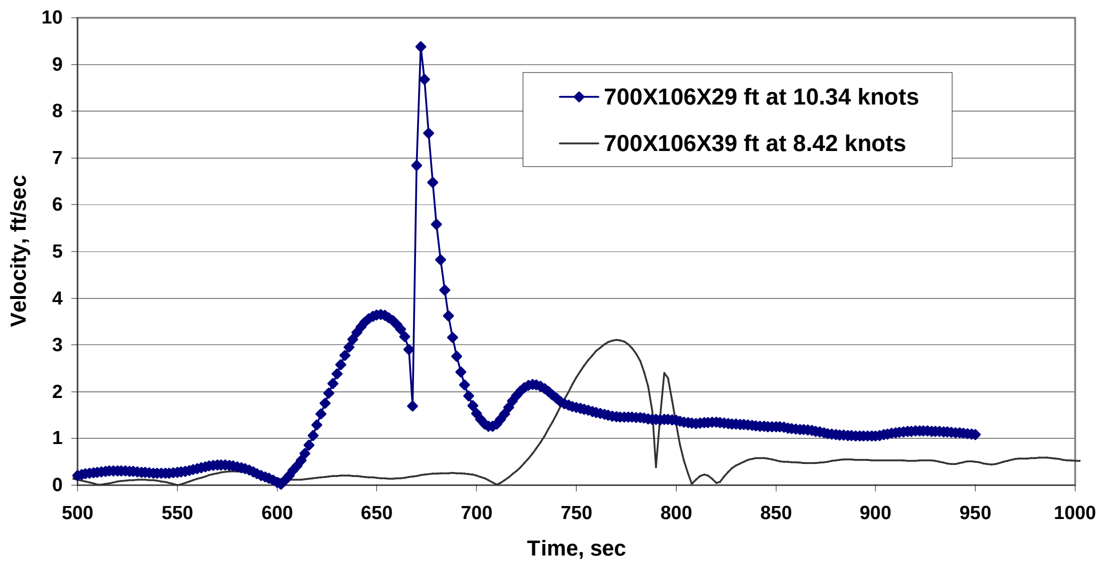

Figure 9. South site, existing channel, 106 ft beam ships.

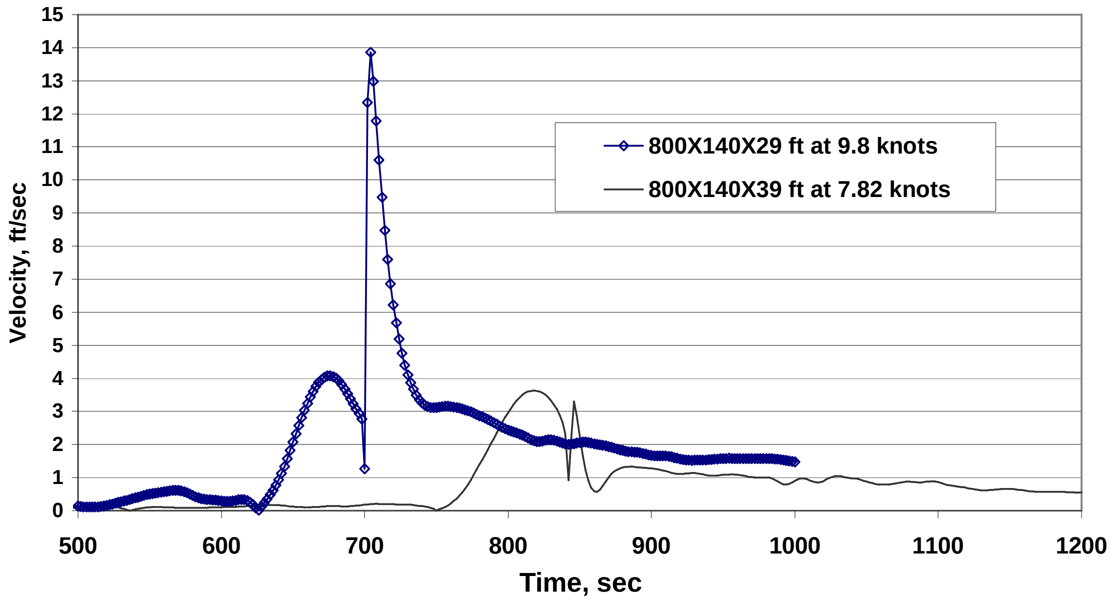

Figure 10. South site, existing channel, 140 ft beam ships.

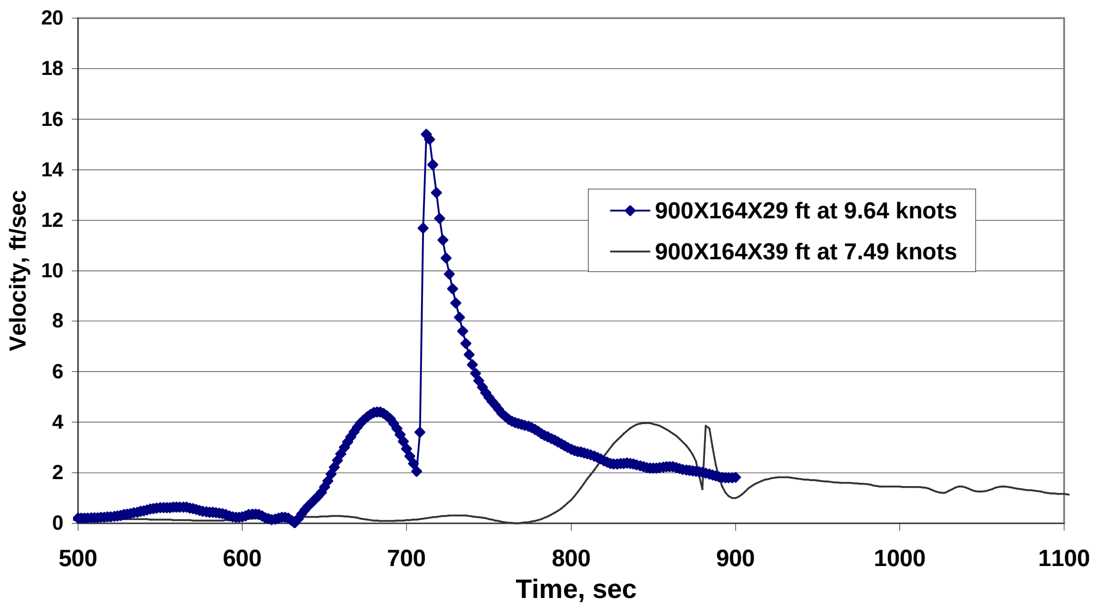

Figure 11. South site, existing channel, 164 ft beam ships.

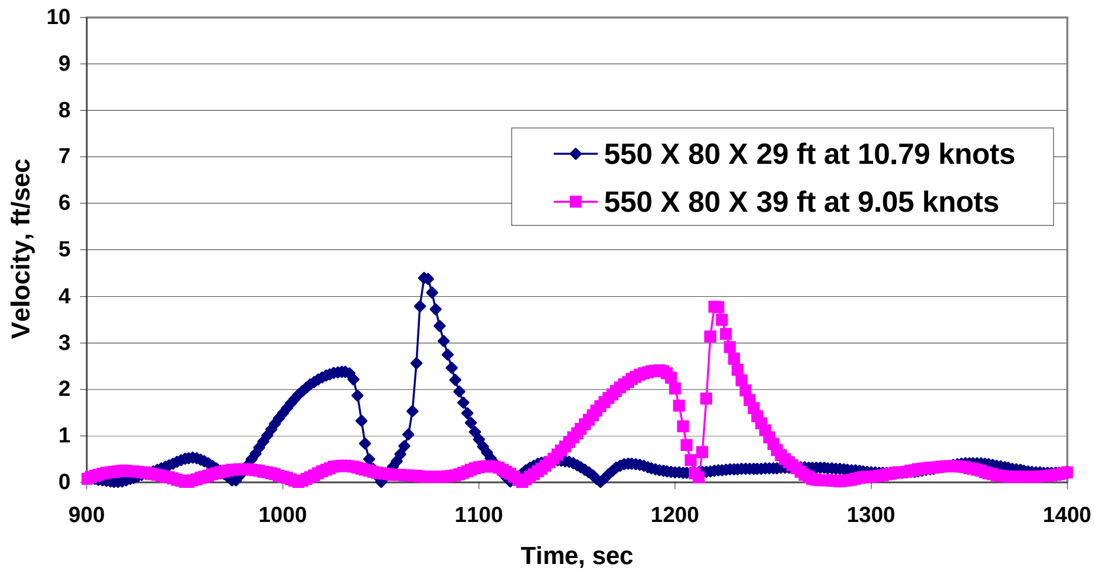

Figure 12. North site, proposed channel, 80 ft beam ship.

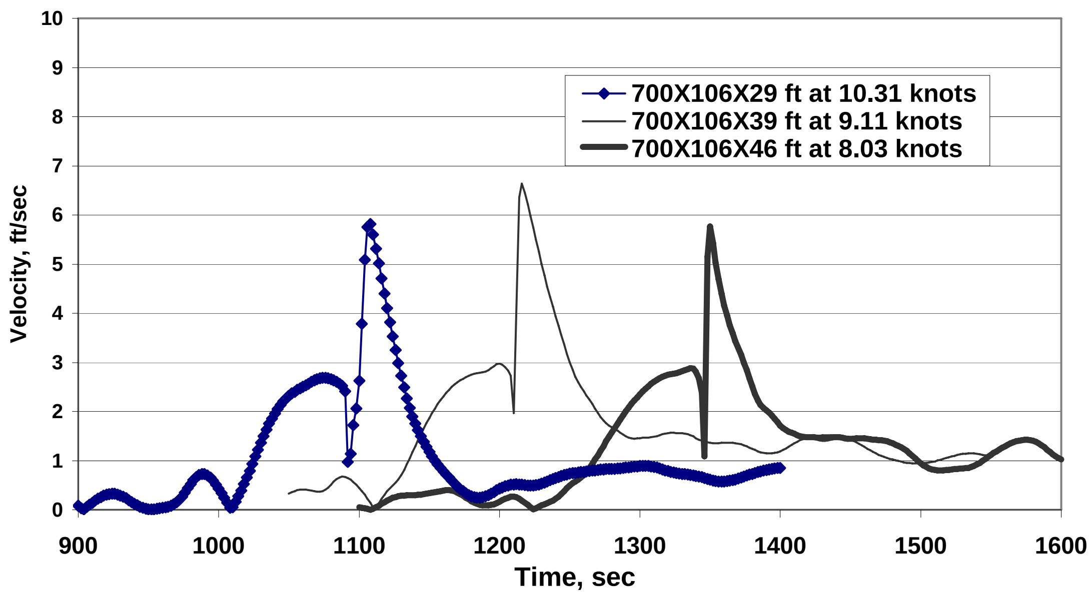

Figure 13. North Site, proposed channel, 106 ft beam ship

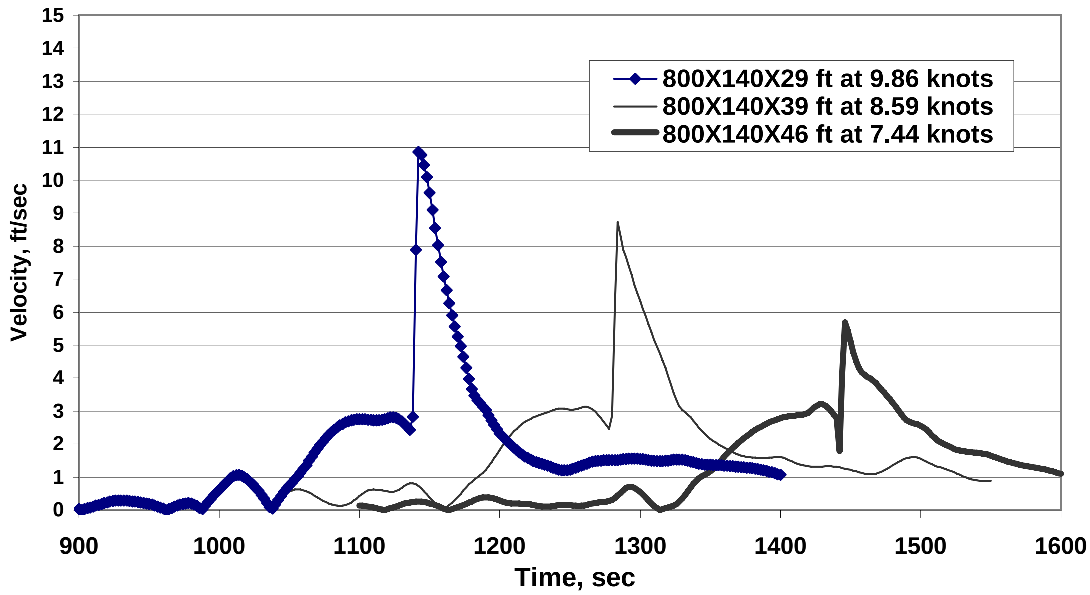

Figure 14. North site, proposed channel, 140 ft beam ships.

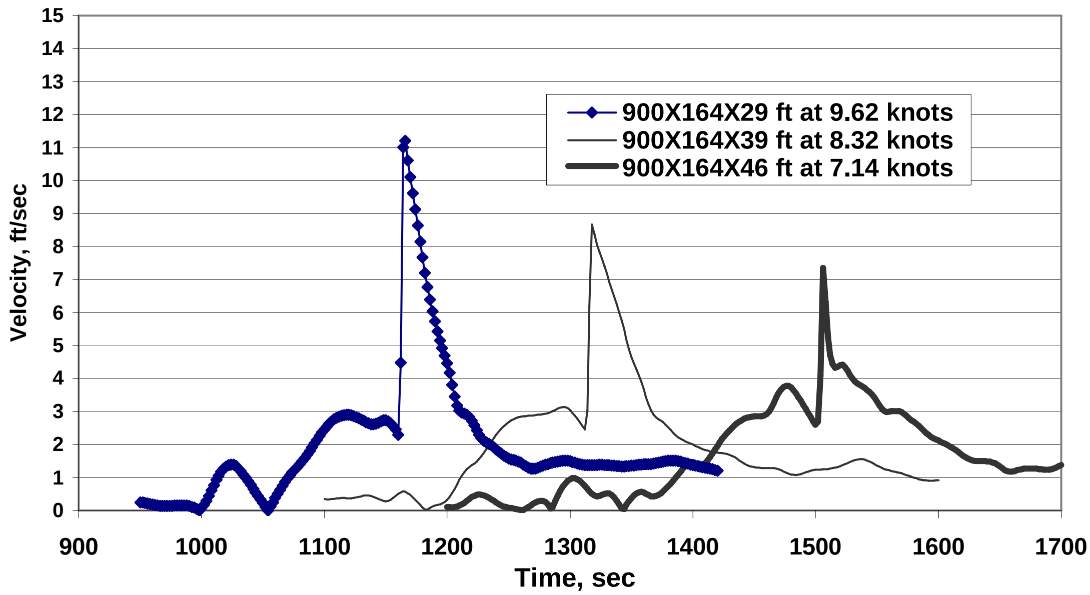

Figure 15. North site, proposed channel, 164 ft beam ship.

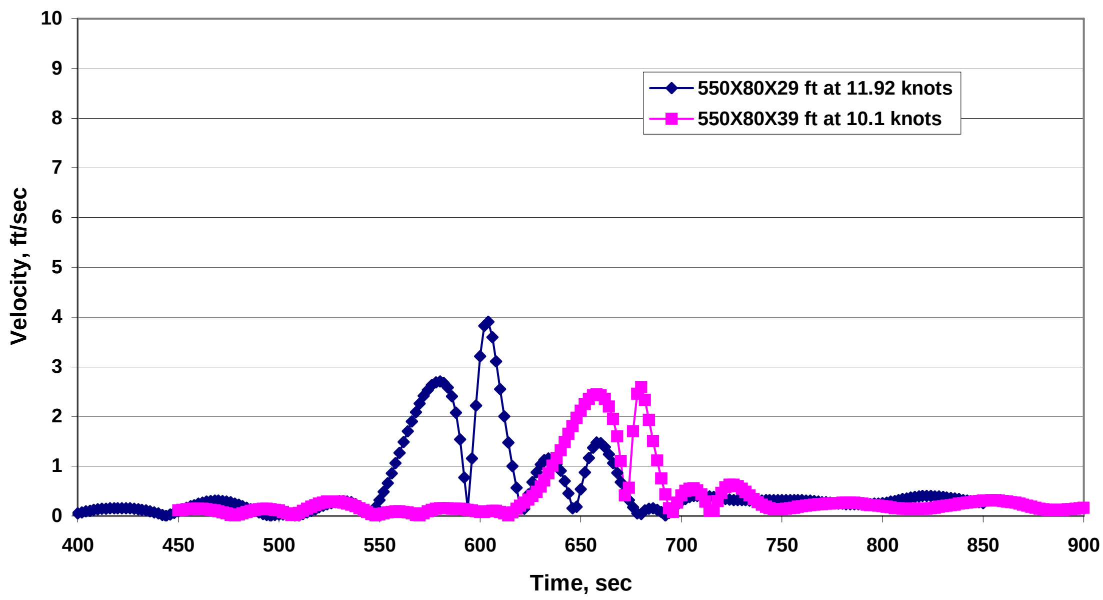

Figure 16. South site, proposed channel, 80 ft beam ship.

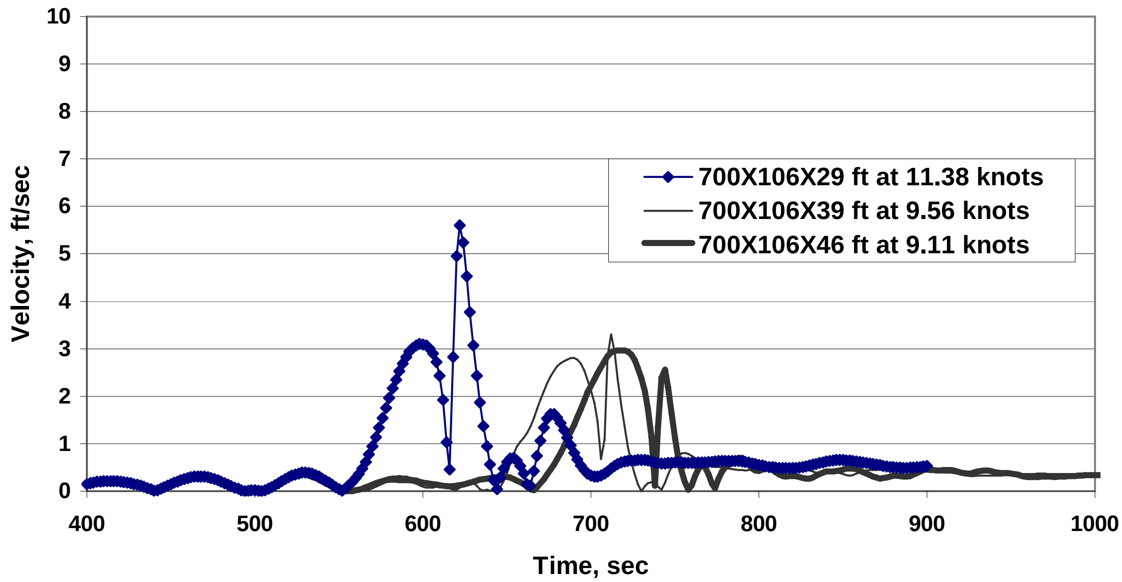

Figure 17. South site, proposed channel, 106 ft beam ship.

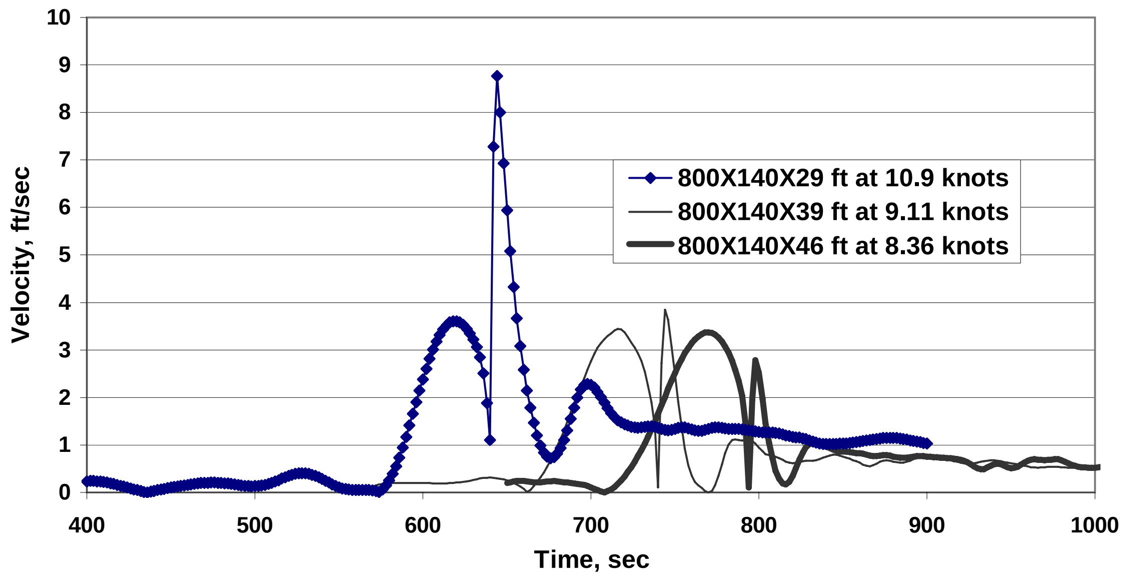

Figure 18. South site, proposed channel, 140 ft beam ship.

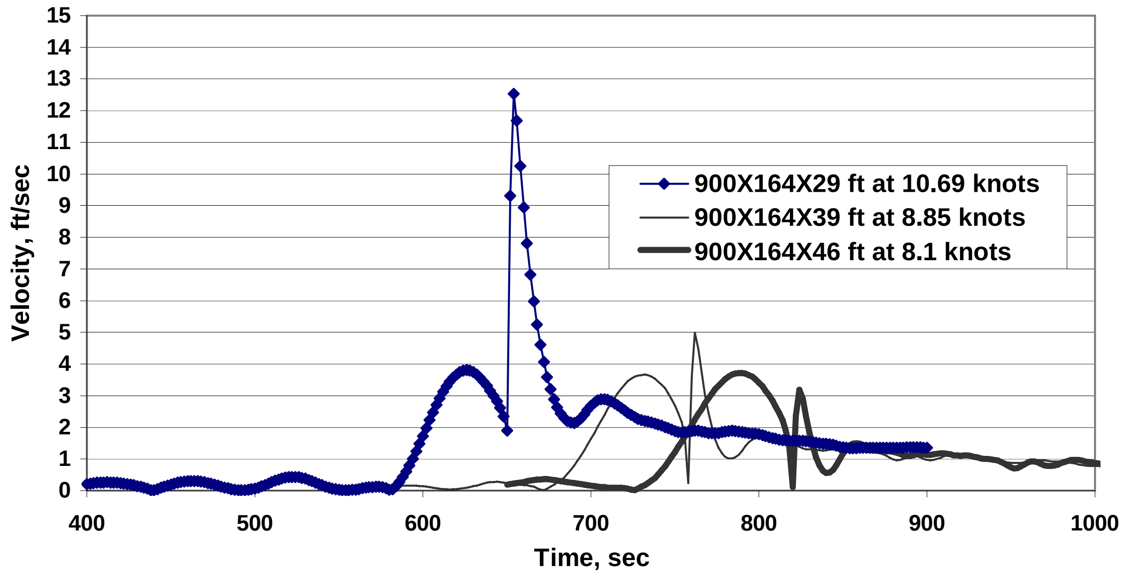

Figure 19. South site, proposed channel, 164 ft beam ship.