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Engineer Research and Development Center
Coastal and Hydraulics Laboratory

US Army Corps
of Engineers
Engineer Research and
Development Center

Desktop Sediment Study for Freeport Project

T. M. Parchure, Ben Brown, Nolan Raphelt, Lynn Vera
and Justo Pena

Sept 2005

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By T. M. Parchure, Ben Brown and Nolan Raphelt

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

Lynn Vera and Justo Pena

US Army Corp of Engineers
2000 Ft. Point Road
Galveston, TX 77550

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Preface

The US Army Engineer District Galveston proposed increasing the length, width and depth of the navigation channel at Freeport Harbor, TX. The proposed modifications varied in different segments of the navigation channel. The impact of these channel modifications on the future shoaling needed to be assessed.

A desktop sedimentation study was conducted at the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. The U.S. Army Engineer District, Galveston, provided funding for this study. Dr. Trimbak M. Parchure, research hydraulic engineer, was the principal investigator for the project. Dr. Parchure prepared this report jointly with Mr. Ben Brown and Nolan Raphelt of CHL and Ms. Lynn Vera and Mr. Justo Pena of U.S. Army Engineer District, Galveston. Mr. Joseph Letter of CHL provided guidance on ADCP data analysis and 3-D numerical modeling. Mr. Thad Pratt and Mr. Chris Callegan collected field data. Mr. Doug Brister of CHL conducted laboratory analysis of bed samples and water samples under the guidance of Dr. Parchure. Dr. Nolan Raphelt processed the ADCP current data and provided results of analysis.

The work was conducted under general supervision of Dr. Robert T. McAdory, Chief, Estuarine Engineering Branch, and Mr. Thomas Richardson, Director, CHL.
At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL James R. Rowen, EN, was Commander and Executive Director.

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Conversion Factors: Non-SI to SI Units of Measurement

Non-Si units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Cubic feet	0.02831685	Cubic meters
Fahrenheit degrees	*	Celsius Degrees
feet	0.3048	Meters
Inches	2.540	Centimeters
knots	0.5151	meters per second
Microns	0.001	Meters
miles (US statute)	1.609344	kilometers (km)
Ounces	28.34952	Grams
Pounds	0.4535924	Kilograms
square miles	2.5900	square km
tons (2000 pounds mass)	907.1847	Kilograms
* **To** obtain Celsius © temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F-32). To obtain Kelvin readings, use: K = (5/9)(F-32) + 273.15.		

Abstract

Freeport Harbor, TX has a deep-draft navigation channel that connects the harbor facilities in the area to the Gulf of Mexico. The present navigation channel has a width of 400 feet and a project depth of 47 feet. Alternatives were considered to modify the navigation channel in terms of deepening it to 60 feet and providing new turning basins. Since such modifications are expected to alter shoaling in the system, the U. S. Army Engineer District, Galveston (SWG) requested the U. S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) to conduct a desktop study and provide an estimate on the quantity of annual dredging in the navigation channel after modifications to the navigation channel.

The desktop study included numerical hydrodynamic modeling, extensive analysis of field and model data and computations for shoaling estimate. It is concluded that the quantity of maintenance dredging in the Freeport navigation channel will increase from the present average of 2.10 million cubic yards per year to 5.05 million cubic yards per year as a result of widening the channel from 400 feet to 600 feet and deepening it from 47 feet to 60 feet.

Key Words: Freeport, Sediment study, Desktop study, Shoaling prediction, Navigation channel shoaling.

1 Project Information

1.1 Freeport Project Description

Freeport Harbor is located about 40 miles southwest of Galveston Harbor on the Texas coast. Index maps showing location of Freeport is shown in Figure 1.1. Details around the harbor are shown in Figure 1.2. The Freeport Harbor has a deep-draft navigation channel that connects the harbor facilities in the area to the Gulf of Mexico. The present navigation channel has two segments. One is the outer straight channel in the sea, which has a length of about five miles from the shoreline, width of 400 feet and a project depth of 47 feet. Sediment dredged from this channel has been historically placed on the spoil areas located on both sides of the channel. The second segment is a winding channel inside the coastline and has harbor facilities. This channel has varying width and depth along its course. Historically, the current Freeport channel was the old Brazos River (Figure 1.2). The northern end of the present channel was disconnected; making it a dead-end channel. Levees are constructed along both banks of the channel. The Gulf Intracoastal Waterway (GIWW) intersects the Freeport navigation channel. Also, Dow Barge Canal joins at the intersection. In the absence of any specific name available from the maps, the area of most complex flow pattern is referred to as the "Junction" in this report, which is the confluence of five tidal waterways, namely east GIWW, west GIWW, north navigation channel, south navigation channel and the Dow barge canal.

A tide gate was constructed in upstream of the Stauffer Turning Basin giving a depth of 16 feet over sill. Road and railway bridges on the upstream channel provide constrictions on the channel and hence restrictions on the navigation.

1.2 Existing Port Facilities

Freeport harbor provides the following facilities for navigation.

- 47-foot deep, 400-foot wide entrance channel east of the jetties
- 45-foot deep, 400-foot wide main channel west of the jetties
- 45-foot deep, 1,000-foot diameter turning basin
- 40-foot deep, 200-foot wide Brazos Harbor Channel, and
- 40-foot deep, 750-foot wide Brazos Harbor turning basin.
- 25-foot deep channel, leading to the Stauffer Turning Basin

The additional two feet depth of the entrance channel east of jetties allows for the ship's vertical motion (squat) due to waves. The tidal range for Freeport Harbor is typically 2 ft.

1.3 Proposed Modifications

The U. S. Army Engineer District, Galveston (CESWG) is presently evaluating several channel modifications to widen and/or deepen portions of the harbor to accommodate larger, and possibly deeper drafted ships. These changes will allow larger tankers to use the harbor as far inland as the Upper Turning Basin and containership traffic to continue into a portion of the channel to Stauffer Turning Basin.

Several alternatives were considered for modifying the navigation channel. These included 1) widening, 2) deepening, 3) widening plus deepening and 4) providing a larger turning basin. Based on the ship simulation studies conducted at ERDC, one "Plan" layout along with the recommended widths and depths have been evolved for conducting the numerical modeling and sedimentation study.

1.4 Sedimentation Problem

The present dredging pattern and quantities would change as a result of the proposed modifications to the navigation channel. The objective of this study is to estimate the shoaling rates in the modified navigation channel.

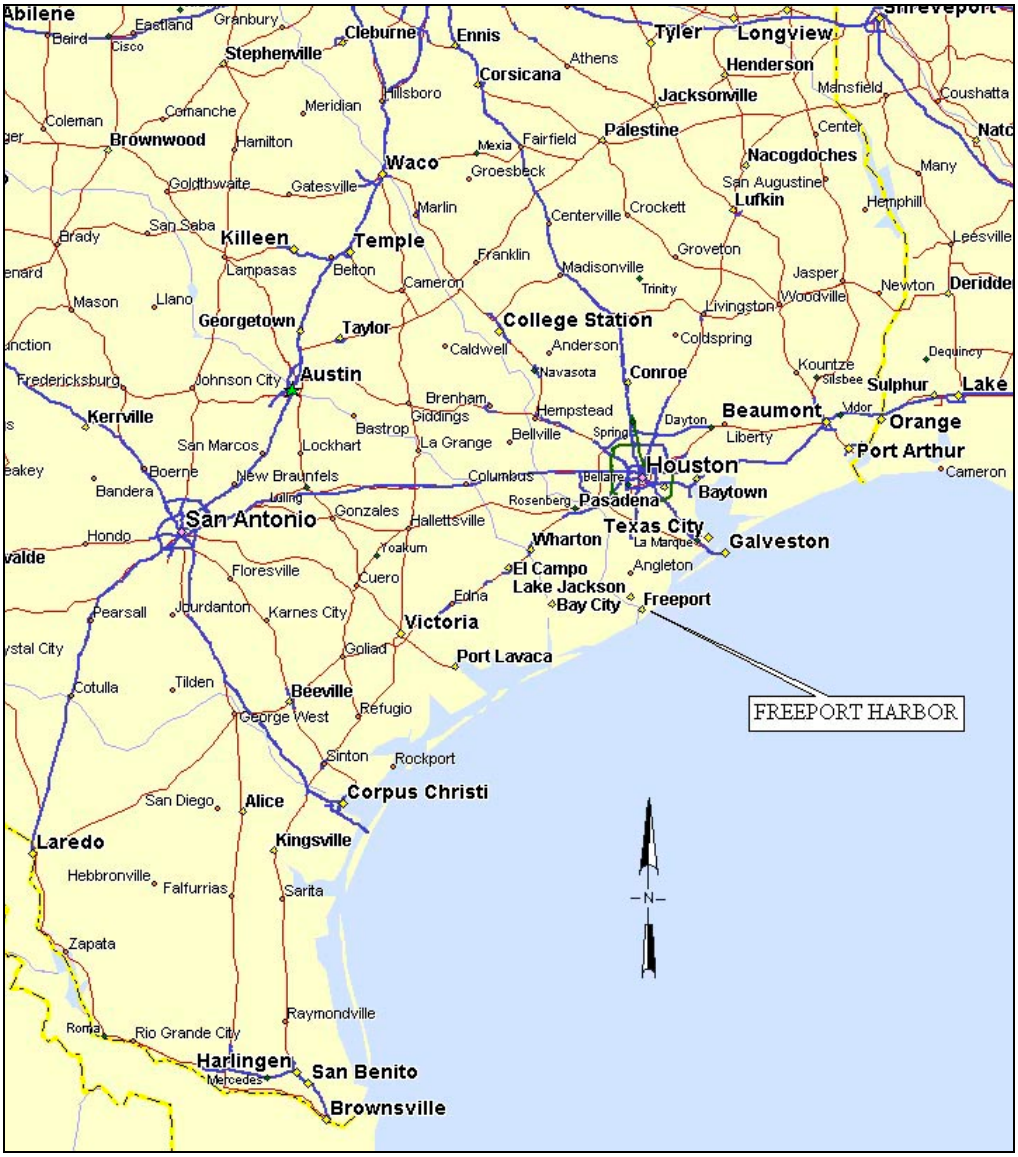


Figure 1.1: Location of Freeport

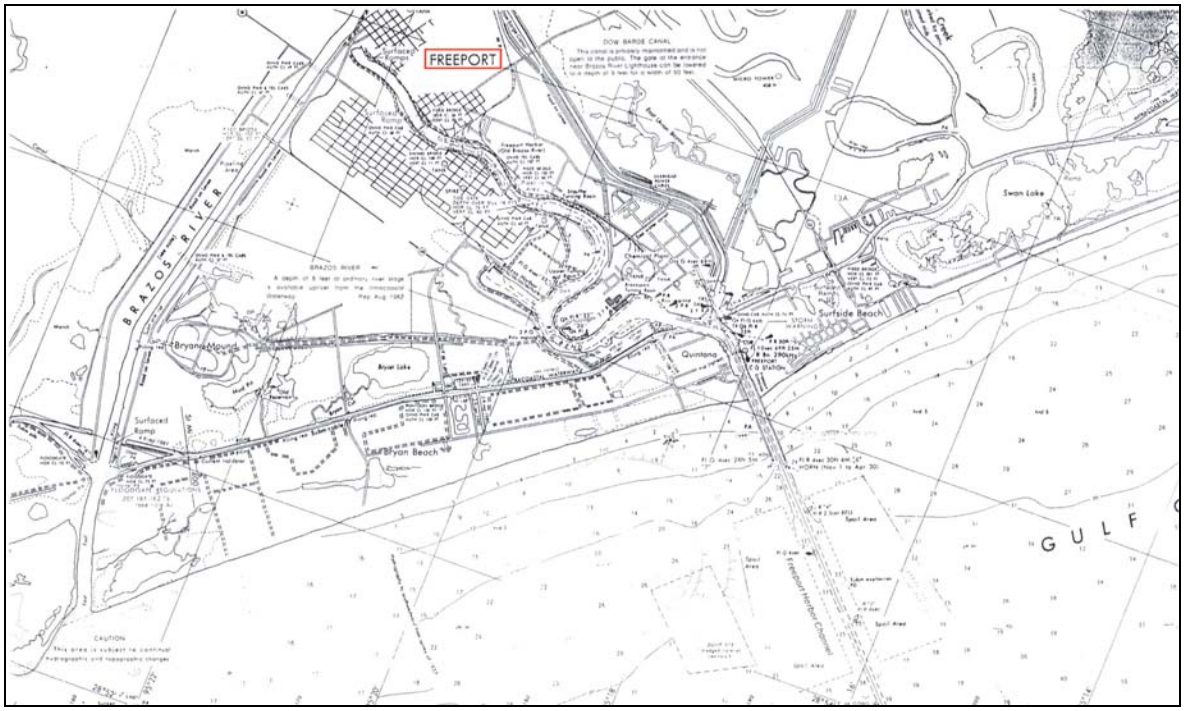


Figure 1.2: Details around Freeport Harbor

2 Desktop Study

2.1 Introduction

A desktop study is an alternative method of obtaining preliminary answers without conducting a full-fledged numerical sediment modeling study. It requires field data on sediments and dredging quantities and results of a hydrodynamic model. Estimation of anticipated shoaling involves an unavoidable subjective element and hence the results need to be considered as a preliminary estimate, which is sometimes adequate for a feasibility study. In view of variation in salinity and currents, results of 3D hydrodynamic model would be necessary.

Desktop studies conducted earlier at ERDC include the following. 1. Parchure et al. (2001), Desktop study for shoaling prediction in Corpus Christi navigation channel. 2. Parchure et al. (2002), Desktop Study for La Quinta Project. 3. Parchure et al. (2005), Desktop Study for sediment-related problems at Sabine Neches Project.

2.2 Objective

The objective of this study is to estimate the shoaling rates in the modified navigation channel.

2.3 Approach

A desktop study is an alternative method of obtaining preliminary answers without conducting a full-fledged numerical sediment transport modeling study. Such a desktop approach requires field data on sediments, dredging quantities, and velocity results from a hydrodynamic model. In view of variations in salinity and currents in the system, velocity results from a three-dimensional (3D) hydrodynamic model will be necessary. From previous work, the velocity profile in the channel, particularly near the intersection with the GIWW, is known to be complex. Determination of the forces (for example, bottom velocities) responsible for sediment accumulation and movement are not easily determined from a depth-averaged approach in a system such as this. Since the overall system is small and the 3D aspects of the velocity are likely dominated by geometric considerations, the development of the 3D model is expected to be straightforward. These desktop methods have been successfully employed to estimate project shoaling rates and quantities in other studies such as the La Quinta Channel Project and the La Quinta Channel Extension Project (both of which used two-dimensional (2D) model currents), as well as in the Sabine-Neches Waterways Channel Deepening Project (which

required 3D model currents), for example. Estimation of anticipated shoaling involves an unavoidable subjective element and hence the results need to be considered as a preliminary estimate, which is sometimes adequate for a feasibility study.

2.4 Scope of Work

The following scope of work was adopted for the study:

1. Dredging data will be analyzed to establish the present siltation pattern.
2. Field sediment samples and water samples will be analyzed in CHL laboratory.
3. Results of laboratory analysis will be plotted and used in the study.
4. Properties of sediment at site will be evaluated.
5. Numerical 3D model will be formulated with appropriate boundary conditions and verified with field data.
6. Numerical model runs will be made for selected base and plan conditions.
7. Velocity data at selected stations will be extracted from the numerical solution files for the existing and plan conditions.
8. Velocity data will be plotted for comparison. Change in the current pattern caused by navigation channel modifications will be assessed. Effect of velocity change on shoaling will be assessed.
9. A draft letter report will be submitted for review and comments from the District.
10. Final report will be prepared later with additional time and cost, if requested by the Galveston District.

2.5 Data Used for the Study

The following data provided to ERDC by the Galveston District were used:

1. Results of analysis of field data collected by ERDC on bed sediment, water samples, water levels and currents in the area.
2. Results of numerical model study.
3. Data on bed sediment and water samples collected in the past.
4. All available data on dredging quantities from various reaches of navigation channel over the past years.

2.6 Proposed Improvements

The Galveston District developed five alternative channel plans, all of which were oriented towards construction of a proposed Liquid Natural Gas (LNG) facility. Freeport LNG has proposed to construct a new LNG terminal at Freeport Harbor. The new terminal would require enlarging and deepening an existing notch in the southwestern corner of the intersection of the deep water navigation channel and the Gulf

Intracoastal Waterway (GIWW) and enlarging the turning basin at the intersection to the north of the proposed location. A ship maneuvering study was conducted at ERDC to test the safety of ship maneuvering and control in Freeport Harbor. The study concluded that ships could maneuver safely in and around the new LNG facility.

Plan 1. The proposed Plan 1 channel is shown in Figure 2.6.1. The Plan 1 channel will be a 62 ft MLT Entrance Channel (east of the jetties) and 60 ft MLT from the western end of the jetties to the Upper Turning Basin. Plan 1 includes deepening a portion of the channel leading to Stauffer Turning Basin to 50 ft MLT.

The Plan 1 Entrance Channel is 600 ft wide and 60 ft deep. The deepening extends the federal channels by approximately three miles, to the Gulf of Mexico's 60 ft contour. The Plan 1 channel is widened 150 ft on the northeast side and 50 ft on the southwest side.

The 600 ft wide Plan 1 channel will have the same footprint as the existing channel from the eastern end of the proposed LNG improvements to the Brazos Port Turning Basin. Plan 1 includes a 1350 ft diameter turning basin at Brazos Port. Construction of this basin will require removal of some of the peninsula between the deep-draft channel and the GIWW. Due to the low shear strength of the soils located in the channel area, the existing slope angles of the cut from the Brazos Port Turning Basin to the Upper Turning Basin will be maintained for the Plan 1 channel cut to 60 ft deep. As a result, the Plan 1 Channel bottom width will be 90 ft narrower (45 ft on both sides) than the existing channel bottom width in this area. The 50 ft MLT portion of the Channel to Stauffer will be widened from 200 ft to 300 ft.

Plan 2. The proposed Plan 2 channels are shown in Figure 2.6.2. The Plan 2 channel will be a 62 ft MLT Entrance Channel (east of the jetties) and 60 ft MLT from the western end of the jetties to the Upper Turning Basin. Plans 1 and 2 are identical inland from the western end of the Brazos Port Turning Basin.

The Plan 2 Entrance Channel is 500 ft wide and 60 ft deep. Plan 2 is widened from the existing channel's centerline, i.e. 50 ft on both sides. The 500 ft wide Plan 2 channel tapers to the same footprint as the existing channel from the eastern end of the proposed LNG improvements to the Brazos Port Turning Basin on the south side of the channel. The northern side of the Plan 2 channel tapers to the existing footprint about 1000 ft east of the proposed LNG improvements. Plan 2 includes an 1100 ft diameter turning basin. Due to the low shear strength of the soils located in the channel area, the existing slope angles of the cut from the Brazos Port Turning Basin to the Upper Turning Basin will be maintained for the Plan 2 channel cut to 60 ft deep. As a result, the Plan 2 Channel bottom width will be 90 ft narrower (45 ft on both sides) than the existing channel bottom width in this area.

Plan 3. The proposed Plan 3 channels are shown in Figure 2.6.3. The Plan 3 channels will not deepen the existing channels. The Entrance Channel is 600 ft wide. Plan 3 channel is widened from the existing channel's centerline by 100 ft on both sides. The 600 ft wide Plan 3 channel will taper to the existing channel footprint at the eastern end of the proposed LNG improvements. The Brazos Port Turning Basin will remain 1000 ft wide.

Plan 4. The proposed Plan 4 channels are shown in Figure 2.6.4. The Plan 4 channels are very similar to the Plan 1 channels. The Plan 4 channels will be deepened in the same manner as in Plan 1 and will have a constant width of 600-ft. The channel widening for the entrance channel will be offset in the same manner as in Plan 1, 150-ft on the north side and 50-ft on the south side. Plan 4 will also have a 1350-ft diameter turning basin at Brazos Point. However, unlike Plan 1, the area northwest of the turning basin will be dredged to 60-ft to allow more area for the turning maneuver. This additional dredged area is proposed in order to accommodate additional turning radius needed by the VLCC and 165K LNG Tankers.

Plan 5. The proposed plan 5 channels are shown in Figure 2.6.5. Plan 5 varies only slightly from plan 4 in that the turning basin at Brazos Point is reduced to 1,100-ft in diameter. As in plan 4, the area northwest of the turning basin is also dredged to allow for extra area during turning maneuvers as well as serve as a bend widener heading into the Big Bend reach of the study. The entrance channel geometry is as the plan 1 channel and can be seen as compared to the existing channel.

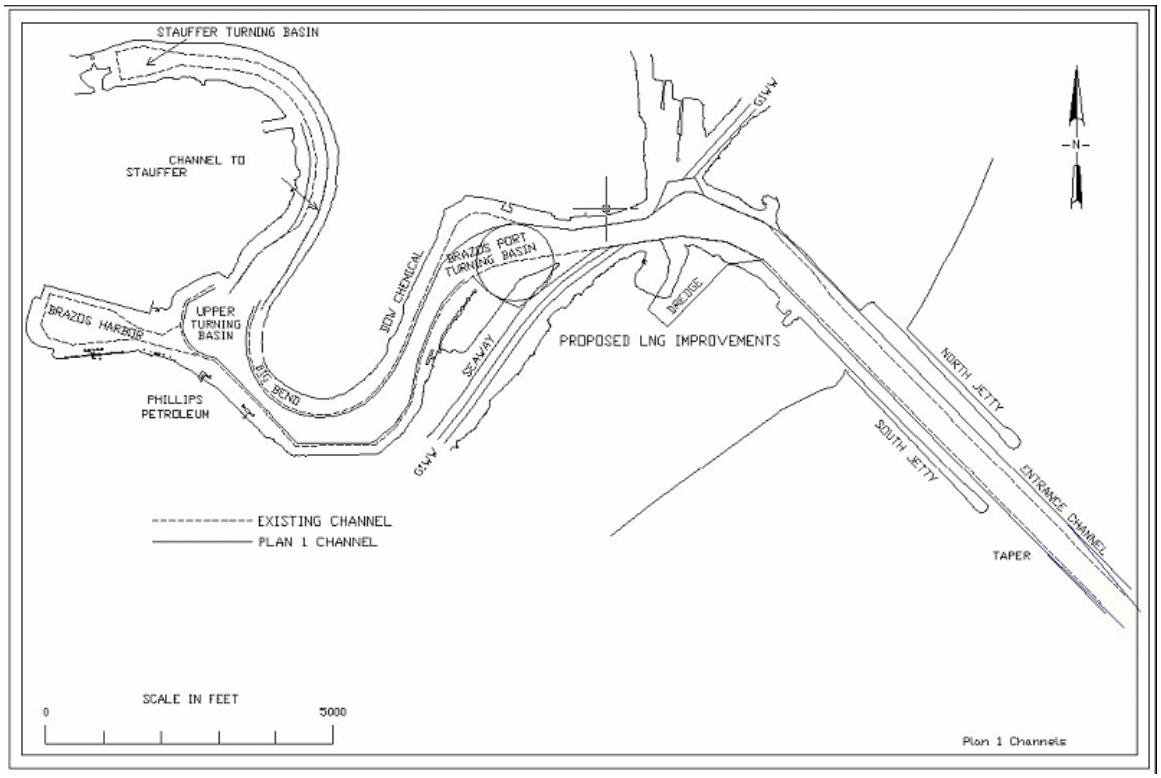


Figure 2.6.1: Proposed improvement layout Plan 1

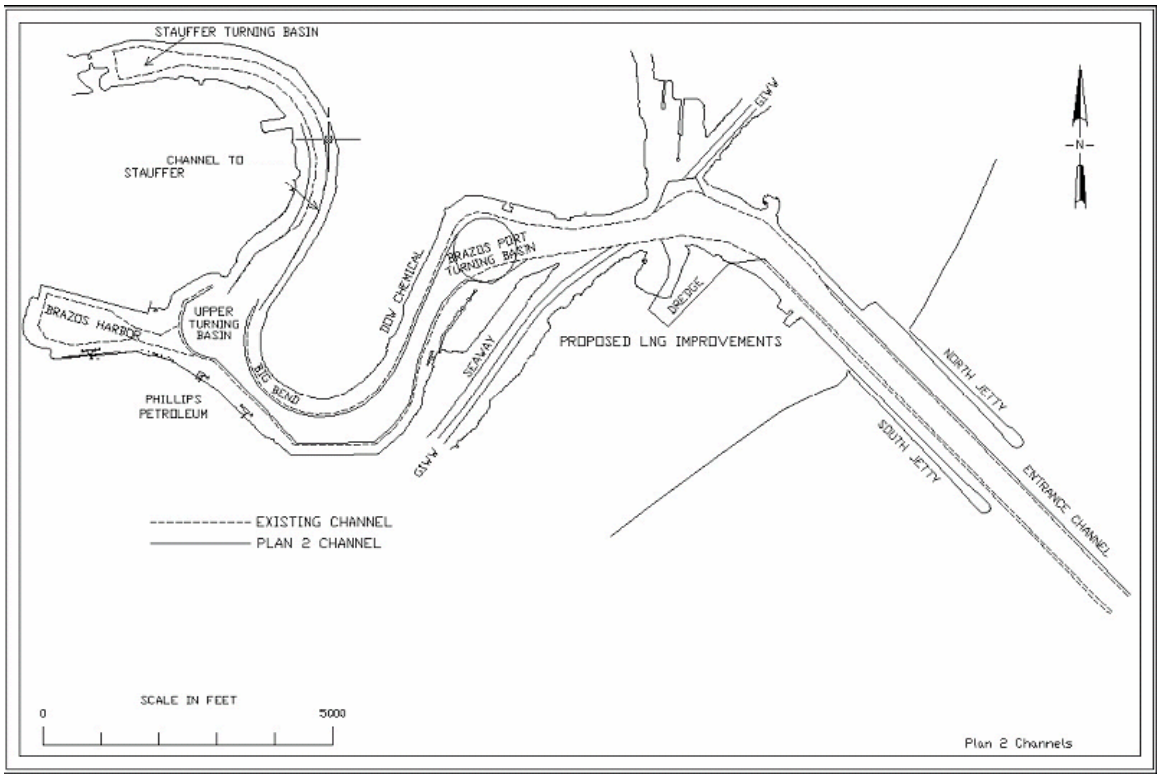


Figure 2.6.2: Proposed improvement layout Plan 2

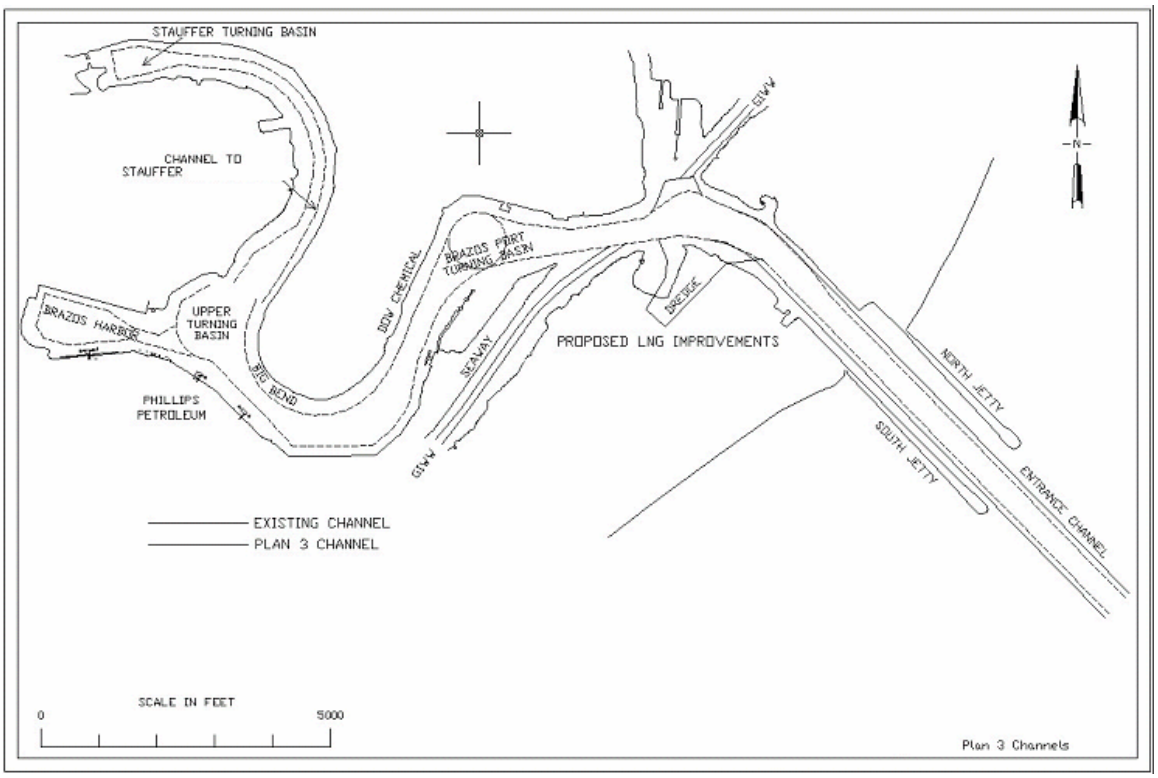


Figure 2.6.3: Proposed improvement layout Plan 3

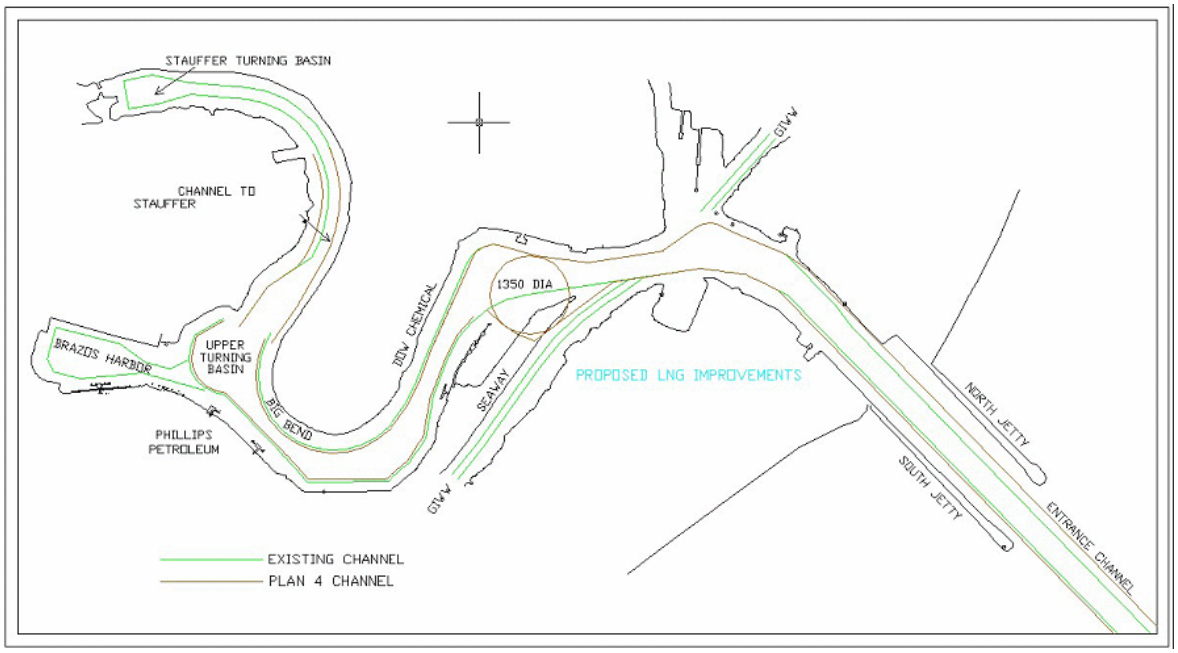


Figure 2.6.4: Proposed improvement layout Plan 4

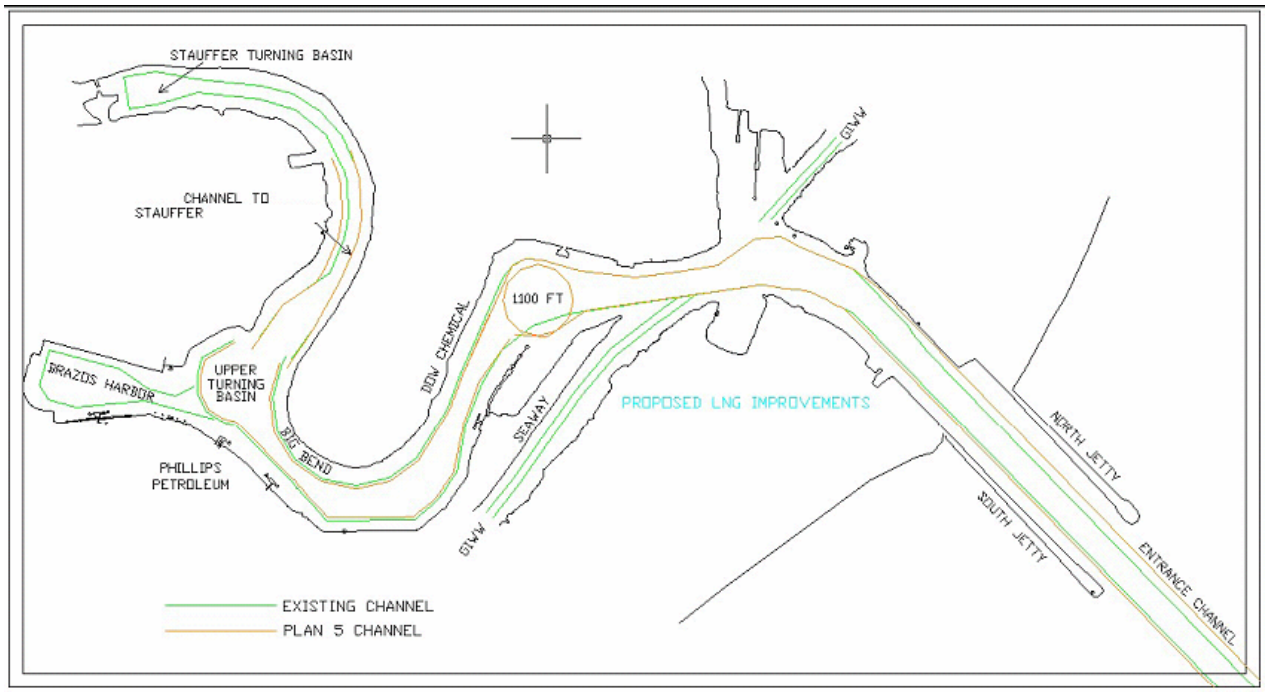


Figure 2.6.5: Proposed improvement layout Plan 5

3 Site Conditions and Field Data Analysis

3.1 Introduction

Field data for several parameters are essential for conducting the desktop study for predicting shoaling in the navigation channel. Except for a scant data on bed sediment properties, such data were not available with the Galveston District. Hence the field data collection team at ERDC collected data on tidal levels, currents, bed sediment, suspended sediment and salinity. These data were analyzed at ERDC and the results are presented in this chapter.

3.2. Tides

Tide gages were installed in the field at the following four locations shown in Figure 3.2.1.

TG 129	Outer Channel
TG 363	East GIWW
TG 367	Inner Harbor
TG 371	West GIWW

Out of these four gages, tide gage installed in the west GIWW did not function well and did not collect any data. Data at other three locations were available over a period of about 1000 hours (about 41 days) starting on October 1, 2003. Thus, the zero hour used for plotting the field tidal data corresponds to zero hour on October 1, 2003. Tidal gage data were collected using an arbitrary local datum for each gage. These data were converted to a common datum, Mean Tidal Level (MTL), using appropriate correlation factors.

Water level elevations at the outer channel location 129 are superimposed on water levels at the Inner Harbor location 367 in Figure 3.2.2. Elevation 0.0 corresponds to the Mean Tidal Level (MTL). Substantial variation on the order of 2 feet is noticed over time in the low water and high water elevations. The spring tidal range varies from 1.5 feet to 3 feet. The neap tidal range varies from 1 to 2 feet. As would be expected, no significant change in tidal elevations or any phase lag is seen between the outer channel and inner harbor since the distance between the two stations is small.

Figure 3.2.3 shows superimposed water levels at Outer Channel station 129 and East GIWW station 363. The high water elevations at east GIWW are lower by about 0.2 to 0.5 feet but the low waters are about the same as those at outer channel. Also the high waters in GIWW show a time lag of few minutes with reference to the time of occurrence of high waters in the outer channel. This trend in magnitudes and phase lag would be expected due to the restricted waterway of GIWW for tidal propagation.

Figure 3.2.4 shows superimposed water levels at East GIWW station 363 and Inner Harbor station 367. Here again the conclusions are the same as above. Figure 3.2.5 shows superposition of water levels at all the three locations.

Figures 3.2.6, 3.2.7 and 3.2.8 show a plot of tidal levels observed at Outer Channel, Inner Harbor and East GIWW respectively for a period of seven days. Figures 3.2.9, 3.2.10 and 3.2.11 show a plot of one tidal cycle (low water to low water) observed at Outer Channel, Inner Harbor and East GIWW respectively.

The following observations are made from the field tidal data:

1. Tidal characteristics at the three field stations do not differ significantly from each other.

2. The tides are predominantly diurnal, with tidal period varying between 22 and 28 hours.

3. Neap tidal range varies from 0.8 ft to 1.5 ft and spring tidal range varies from 2.5 to 3 ft.

4. A large variation between the elevations of high waters and low waters is noticed. The high waters vary between 2.5 and 4.3 ft. The low water elevations vary between 0.4 and 2.7 ft.

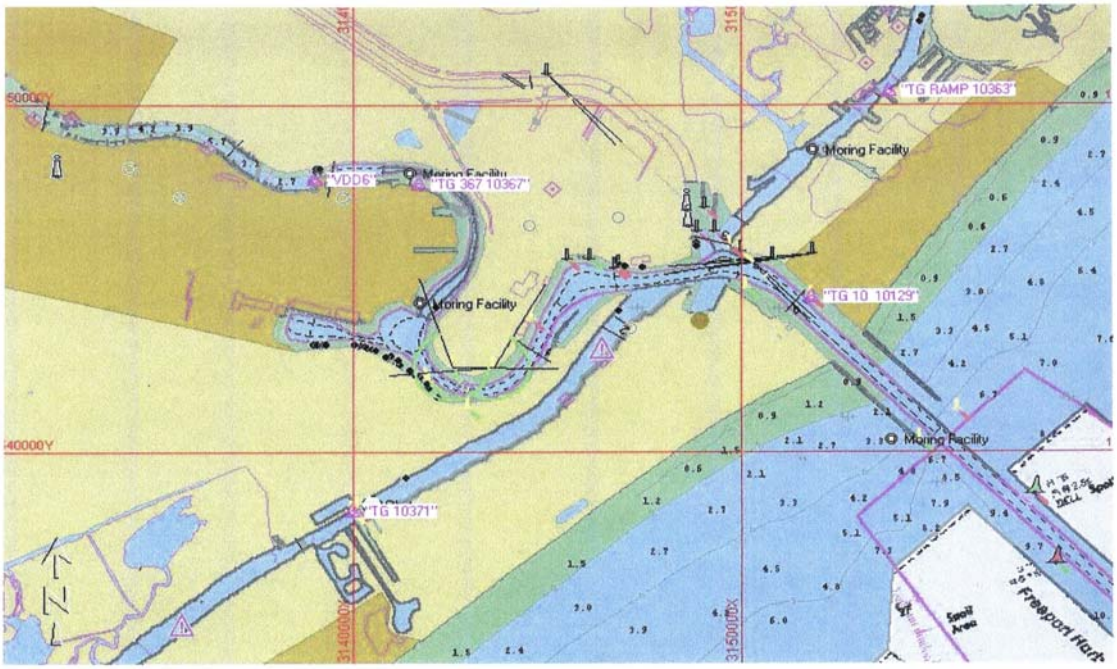


Figure 3.2.1: Tide gage locations at Freeport

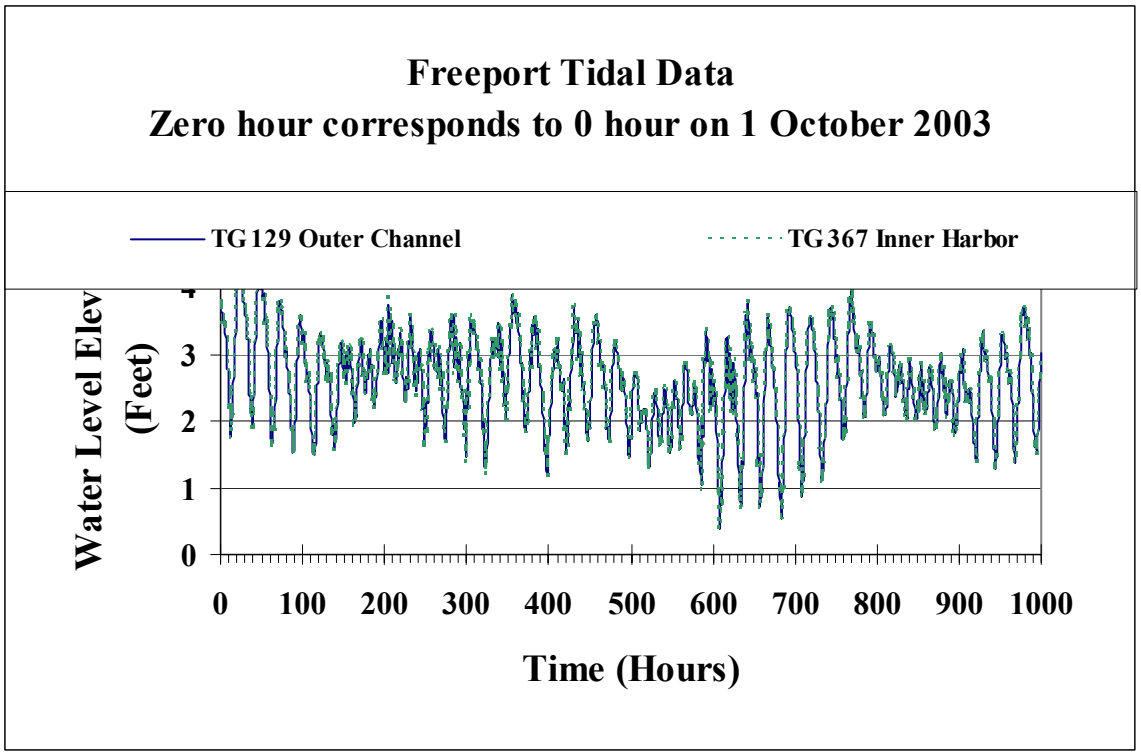


Figure 3.2.2: Superposed tidal elevations observed at stations 129 and 367

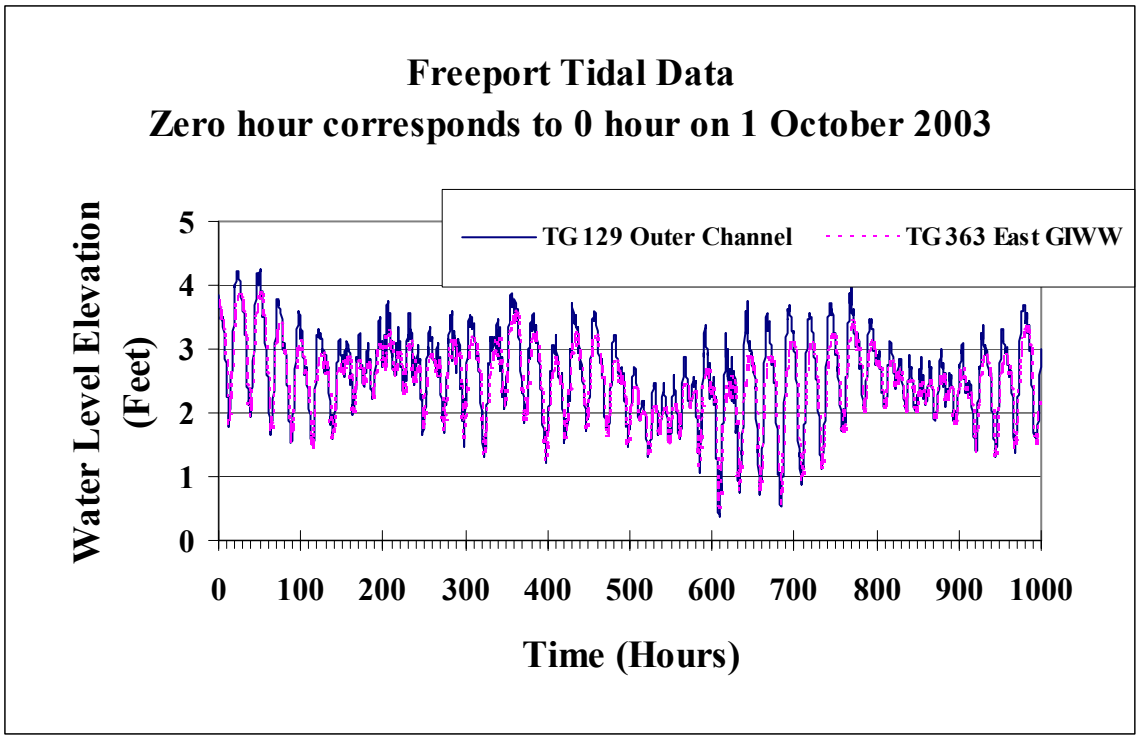


Figure 3.2.3: Superposed tidal elevations observed at stations 129 and 363

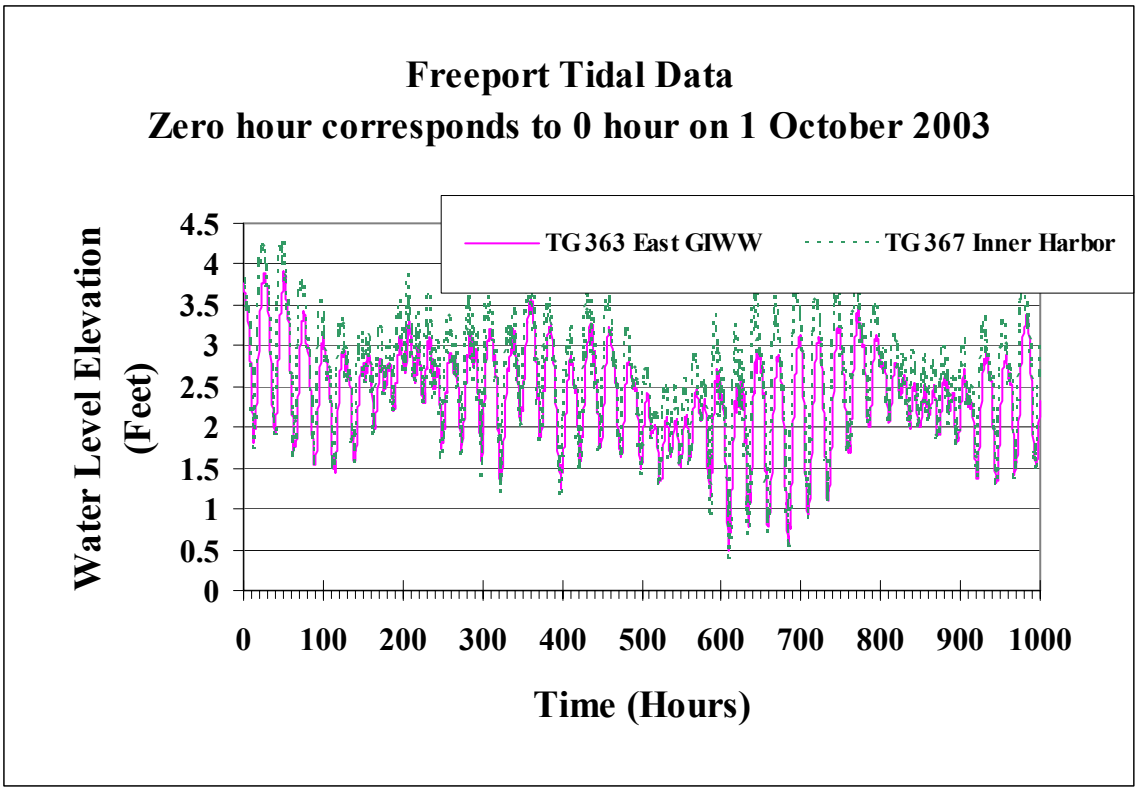


Figure 3.2.4: Superposed tidal elevations observed at stations 363 and 367

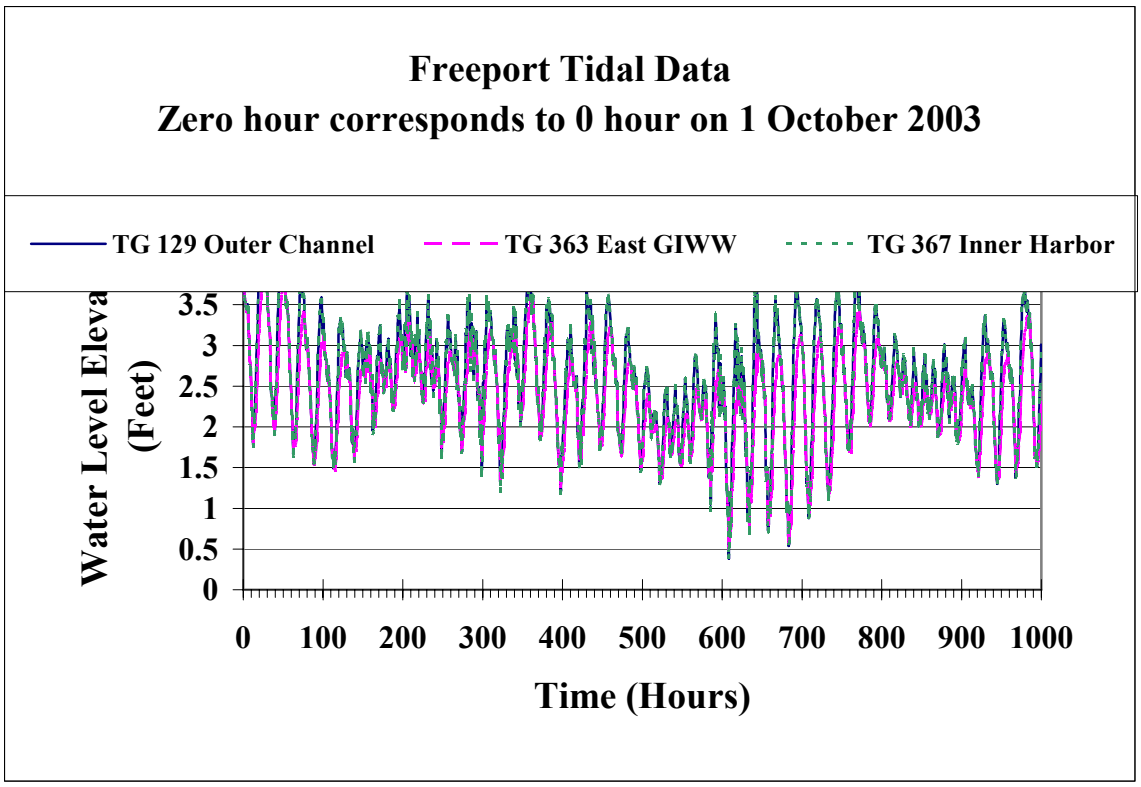


Figure 3.2.5: Superposed tidal elevations observed at stations 129, 363, and 367

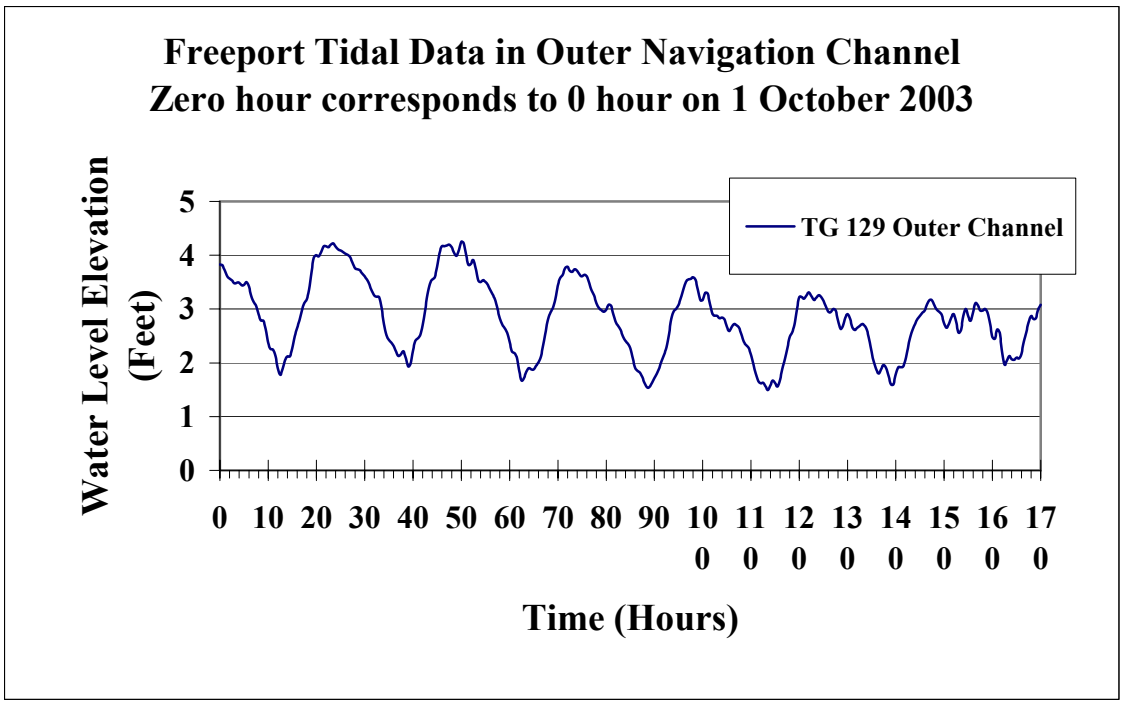


Figure 3.2.6: Tidal levels plotted for Outer Channel Location 129

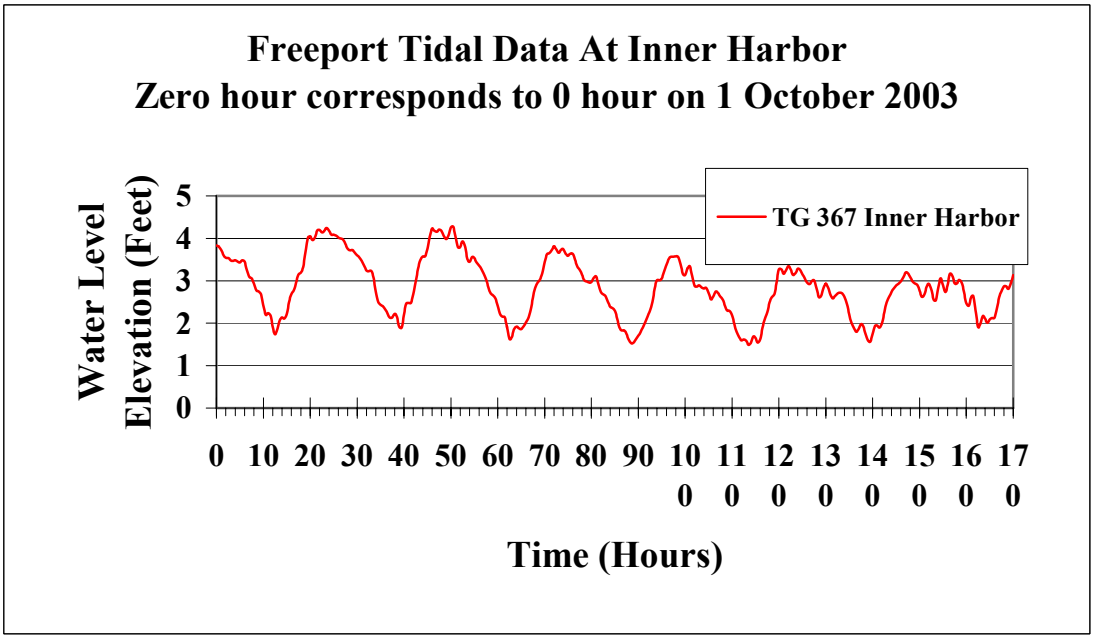


Figure 3.2.7: Tidal levels plotted for Inner Harbor Location 367

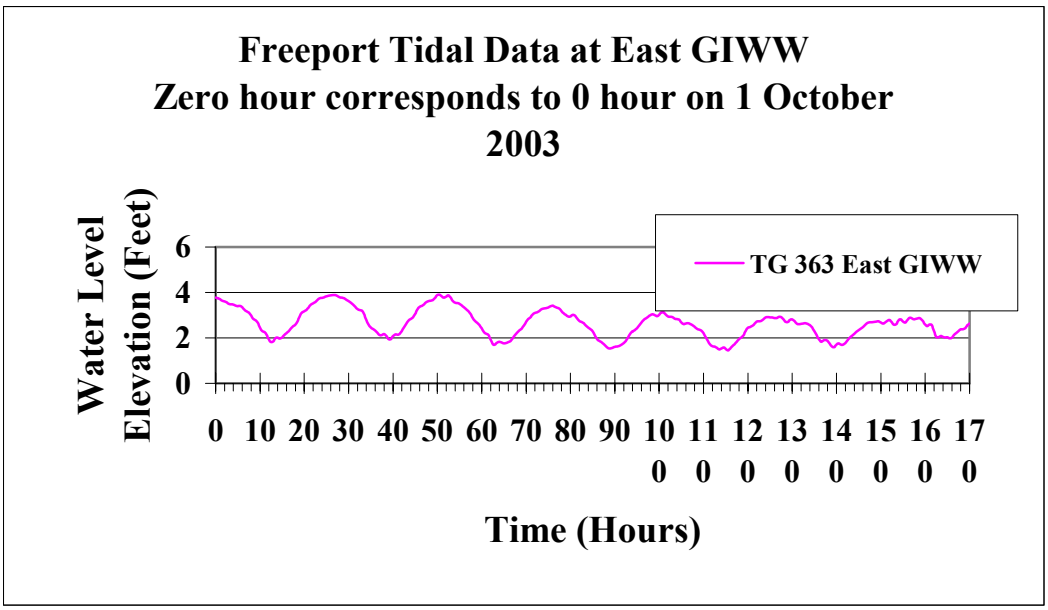


Figure 3.2.8: Tidal levels plotted for East GIWW Location 363

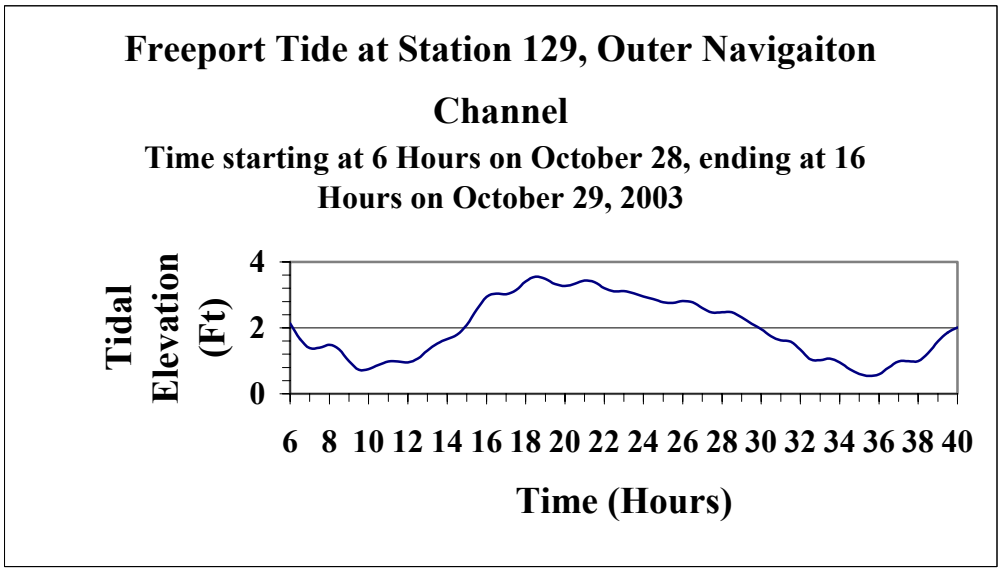


Figure 3.2.9: One tidal cycle plotted for Outer Channel Location 129

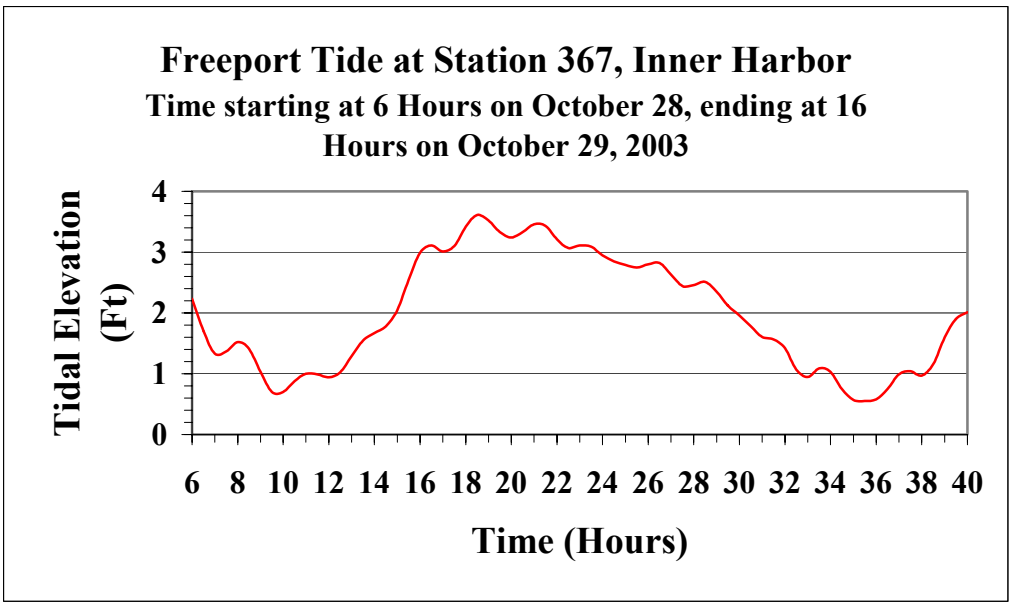


Figure 3.2.10: One tidal cycle plotted for Inner Harbor Location 367

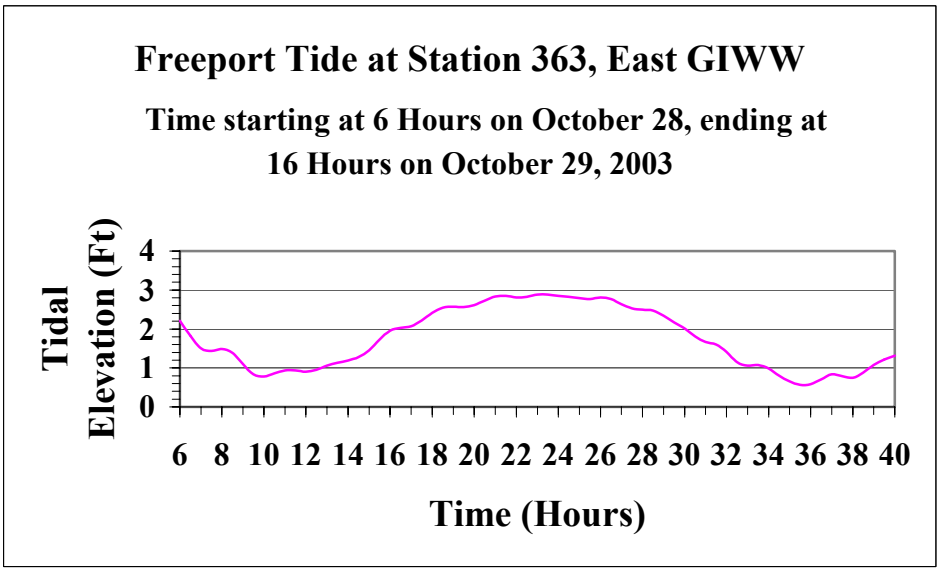


Figure 3.2.11: One tidal cycle plotted for East GIWW Location 363

3.3. Tides

Data received on analysis of few bed sediment samples are given in Table 3.3.1. The bed samples were collected over the years 1987 through 2000 and cover the three reaches, namely outer bar, jetty channel and harbor channel. The following conclusions are drawn from the results of analysis.

1. The amount of sand in the outer bar varied between 1 and 55 percent, in jetty channel it varied between 2 and 38 percent and in the harbor channel it varied between 1 and 17 percent. The average amounts of sand were 17.7, 14.2 and 4.8 in the three reaches respectively.
2. The amount of silt was variable and did not show such distinct variation in the three reaches. The average amounts were 40.7, 38.5 and 42.8 respectively.
3. The average amounts of clay were 41.6, 47.3 and 52.4 respectively. Thus all the reaches had about 50 percent clay.
4. The median diameter in the outer bar area was a little higher than in the other two segments.

Additional bed sediment (BS) samples were collected by ERDC during October – November 2003. Figure 3.3.1 shows locations BS1 through BS 31. These locations may generally be grouped as follows:

Outer Channel	BS1 to BS14
Junction	BS15
West GIWW	BS16, 17, and 31
East GIWW	BS32, 33
Inner channel	BS18 to BS30

Sample collection details such as the sample number, date and time of collection, and water depth are given in Table 3.3.2. These sediment samples were analyzed to determine the percentages of sand and silt plus clay, bulk density, percentage moisture content and percentage of total organic matter. Wet sieving method was used to separate the fraction smaller than 64 microns, which represents particle sizes in the range of silt and clay. The results of laboratory analysis are given in Table 3.3.3. Since most of the samples contained high percentage of fines, the finer fractions were also analyzed with Laser Particle Size Analyzer for obtaining their size distribution. The results are given in Appendix 1.

Percentage of total organic contents in each sample is plotted in Figure 3.3.2. Percentage of moisture content in each sample is plotted in Figure 3.3.3. Bulk Density of each sample is plotted in Figure 3.3.4. Percentage of total silt plus clay in each sample is plotted in Figure 3.3.5. Average values of these sediment parameters are given in Table 3.3.4 for the Outer Channel and Inner Navigation Channel for comparison.

The following conclusions are drawn from the results of analysis of bed sediment data:

1. The average composition of sediment in the outer channel is as follows.
   Sand: 26.14 % Silt plus clay: 73.86 %

2. The average composition of sediment in the inner channel is as follows.
   Sand: 17.15 % Silt plus clay: 82.85 %

3. The entire navigation channel consists of a very high quantity (about 78 %) of silt plus clay.

4. The bulk density of sediment samples varied from 1.2 to 1.6 g/cm^3, with the average value of about 1.32 g/cm^3.

5. The average total organic contents in bed sediment in the outer and inner navigation channel are 5.86 % and 7.25 % respectively.

Table 3.3.1: Bed sediment data collected at Freeport during 1987 - 2000

	Outer Bar					*Jetty Channel*					*Freeport Harbor Channel*				
Date	**Station**	**% Sand**	**% Silt**	**% Clay**	**d50**	**Station**	**% Sand**	**% Silt**	**% Clay**	**d50**	**Station**	**% Sand**	**% Silt**	**% Clay**	**d50**
Sep-87	-	-	-	-		-	-	-	-		113+00	17.3	53.8	28.9	0.007
-	-	-	-	-	-	-	-	-	-	-	164+00	1.0	70.2	28.8	0.007
Mar-88	-50+00	39.1	56.9	4.0	?	50+00	38.1	48.6	13.3						
Apr-89	-50+00	33.0	48.0	19.0	0.063	50+00	27.9	47.4	24.7	0.046					
Jul-93	0+00	49.2	35.6	15.2	0.093	50+00	12.1	38.4	49.5	0.005					
	-50+00	31.4	33.1	35.5	0.019										
	-100+00	14.6	63.7	21.7	0.045										
Feb-95	0+00	3.0	50.5	46.5	0.050	50+00	6.0	49.6	44.4	0.012	75+00	2.9	71.3	25.8	0.051
	-50+00	1.6	72.5	25.9	0.054						112+00	0.8	59.2	40.0	0.04
	-100+00	0.8	61.4	37.8	0.050						125+00	1.1	77.7	21.2	0.057
Jan-97	-50+00	27.1	11.6	61.3		50+00	17.5	34.0	48.5	0.006	175+00	9.6	64.0	26.4	0.055
	-100+00	5.8	40.9	53.3	0.004										
Sep-97	0+00	1.2	34.5	64.3	0.002	50+00	1.8	40.2	58.0	0.003	75+00	2.9	37.3	59.8	0.003
	-50+00	11.1	28.7	60.2	0.003										
	-100+00	1.4	25.8	72.8	0.002										
Jul-98	0+00	4.8	37.3	57.9	0.003	50+00	3.6	28.2	68.2	0.002	75+00	9.2	25.4	65.4	0.003
	-50+00	54.9	7.4	37.7	0.062						112+00	0.2	14.6	85.2	0.002
	-100+00	4.3	43.6	52.1	0.004		-	-	-		125+00	1.4	24.6	74.0	0.002
		-	-	-	-		-	-	-	-	175+00	0.5	26.4	73.1	0.002
May-00		-	-	-		60+00	6.7	21.2	72.1	0.002	75+00	7.2	25.3	67.5	0.002
		-	-	-			-	-	-		85+00	10.6	27.1	62.3	0.003
		-	-	-	-		-	-	-	-	95+00	2.4	21.9	75.7	0.002
Average:		17.7	40.7	41.6	0.032		14.2	38.5	47.3	0.011		4.8	42.8	52.4	0.017

Table 3.3.2: Freeport Bed Sample Collection Details

General Area	Range Sta. #	Date of Collection	Time of Collection (CST)	Depth (ft.)
Outer Channel				
	BS 01	11/19/03	085623	56.0
	BS 02	11/19/03	085201	57.0
	BS 03	11/19/03	084702	50.0
	BS 04	11/19/03	084320	50.0
	BS 05	11/19/03	083413	50.0
	BS 06	11/19/03	083033	52.0
	BS 07	11/19/03	082556	50.0
	BS 08	11/19/03	082118	50.0
	BS 09	11/19/03	081641	50.0
	BS 10	11/19/03	081249	48.0
	BS 11	11/19/03	080823	50.0
	BS 12	10/16/03	115400	52.0
	BS 13	10/16/03	120023	17.0
	BS 14	10/16/03	120546	52.0
Junction	BS 15	10/16/03	121307	52.0
West GIWW	BS 16	10/16/03	122246	20.0
	BS 17	10/16/03	122955	11.0
Inner Channel	BS 18	10/16/03	124006	53.0
	BS 19	10/16/03	124537	51.0
	BS 20	10/16/03	125113	52.0
	BS 21	10/16/03	125600	52.0
	BS 22	10/16/03	130000	14.0
	BS 23	10/16/03	130503	53.0
	BS 24	10/16/03	131045	39.0
	BS 25	10/16/03	131635	24.0
	BS 26	10/16/03	132154	18.0
	BS 27	10/16/03	132443	15.0
	BS 28	10/16/03	133006	21.0
	BS 29	10/16/03	133453	21.0
	BS 30	10/16/03	134019	21.0
West GIWW	BS 31	10/16/03	140126	19.0
East GIWW	BS 32	10/16/03	141204	20.0
	BS 33	10/16/03	141755	20.0

Table 3.3.3: Freeport Bed Sample Analysis

General Area	Sample#	Bulk Density (g/cm^3)	% Sand	% Silt & Clay	% Moisture	% Organics
Outer Channel	BS 01	1.317	18.14	81.86	144.21	5.55
	BS 02	1.252	20.91	79.09	170.92	6.19
	BS 03	1.353	5.69	94.31	172.98	6.77
	BS 04	1.275	10.91	89.09	147.16	7.24
	BS 05	1.227	8.03	91.97	166.43	6.76
	BS 06	1.218	5.32	94.68	195.84	6.66
	BS 07	1.339	27.94	72.06	187.26	7.80
	BS 08	1.300	30.26	69.74	114.70	5.23
	BS 09	1.319	24.83	75.17	126.68	5.46
	BS 10	1.377	41.66	58.34	114.40	5.66
	BS 11	1.361	56.37	43.63	95.50	4.10
	BS 12	1.313	35.36	64.64	122.08	5.40
	BS 13	1.509	58.71	41.29	56.18	2.57
	BS 14	1.316	21.83	78.17	151.18	6.63
Average =		1.320	26.14	73.86	140.39	5.86
Junction	BS 15	1.444	43.13	56.87	84.22	4.41
West GIWW	BS 16	1.380	21.03	78.97	110.27	6.83
	BS 17	1.501	10.59	89.41	94.81	7.85
Inner Channel	BS 18	1.210	0.87	99.13	225.28	11.17
	BS 19	1.200	0.21	99.79	223.78	10.61
	BS 20	1.201	0.68	99.32	223.02	9.23
	BS 21	1.189	0.83	99.17	229.88	8.91
	BS 22	1.478	39.57	60.43	57.95	3.46
	BS 23	1.208	6.55	93.45	221.65	10.81
	BS 24	1.247	10.00	90.00	149.84	7.80
	BS 25	1.572	52.37	47.63	56.24	3.37
	BS 26	1.577	62.44	37.56	55.19	4.26
	BS 27	shell grab	shell	grab	--------	--------
	BS 28	1.310	10.66	89.34	145.85	7.60
	BS 29	1.249	9.94	90.06	129.22	5.89
	BS 30	1.423	11.73	88.27	61.48	3.84
Average =		1.322	17.15	82.85	148.28	7.25
West GIWW	BS 31	1.305	18.89	81.11	100.46	5.70
East GIWW	BS 32	shell grab	shell	grab		
	BS 33	shell grab	shell	grab		

Table 3.3.4: Average values of sediment parameters in Outer Channel and Inner Channel

General Area	Sample#	Bulk Density (g/cm^3)	% Sand	% Silt & Clay	% Moisture	% Organics
Outer Channel	Average =	1.320	26.14	73.86	140.39	5.86
Inner Channel	Average =	1.322	17.15	82.85	148.28	7.25

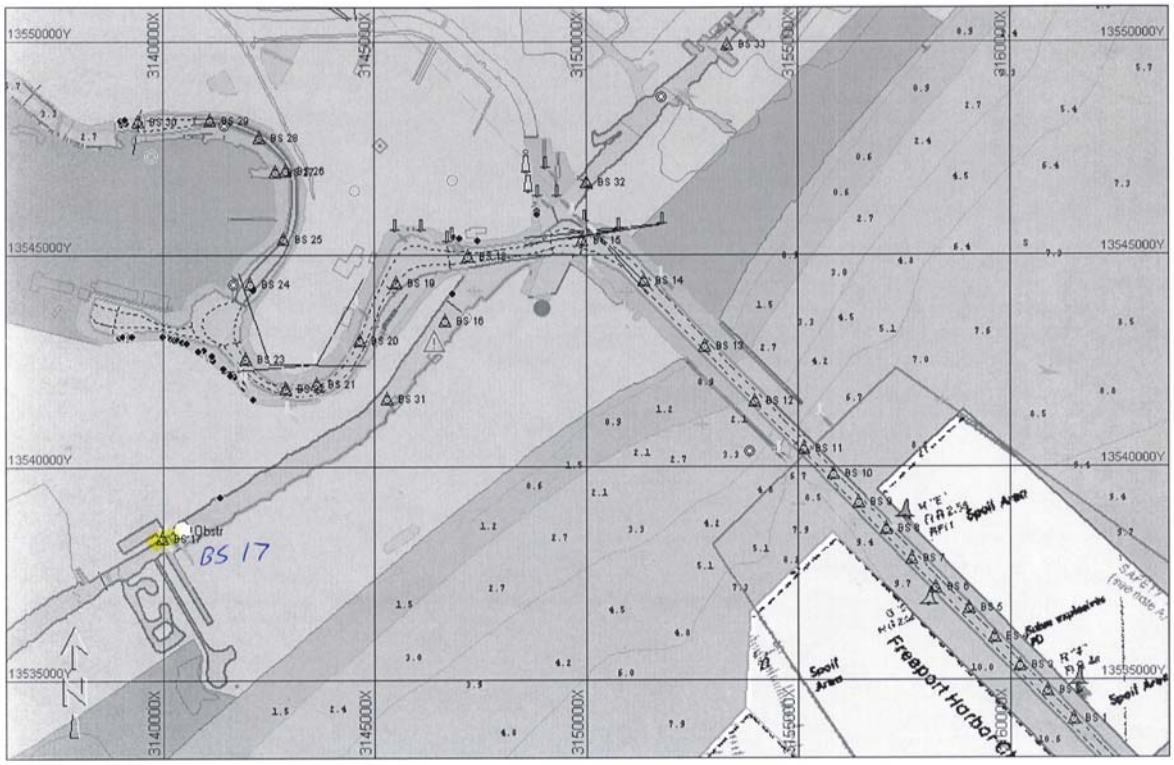


Figure 3.3.1: Locations of bed sediment samples, Map 2

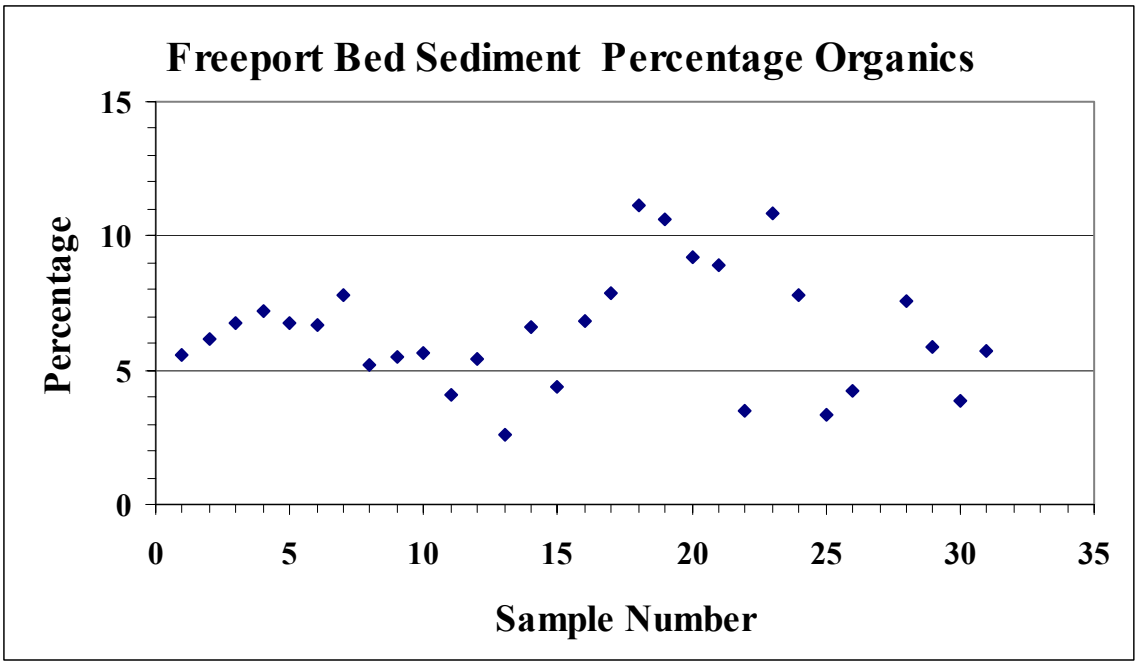


Figure 3.3.2: Percentage of organic matter in bed samples at Freeport Harbor

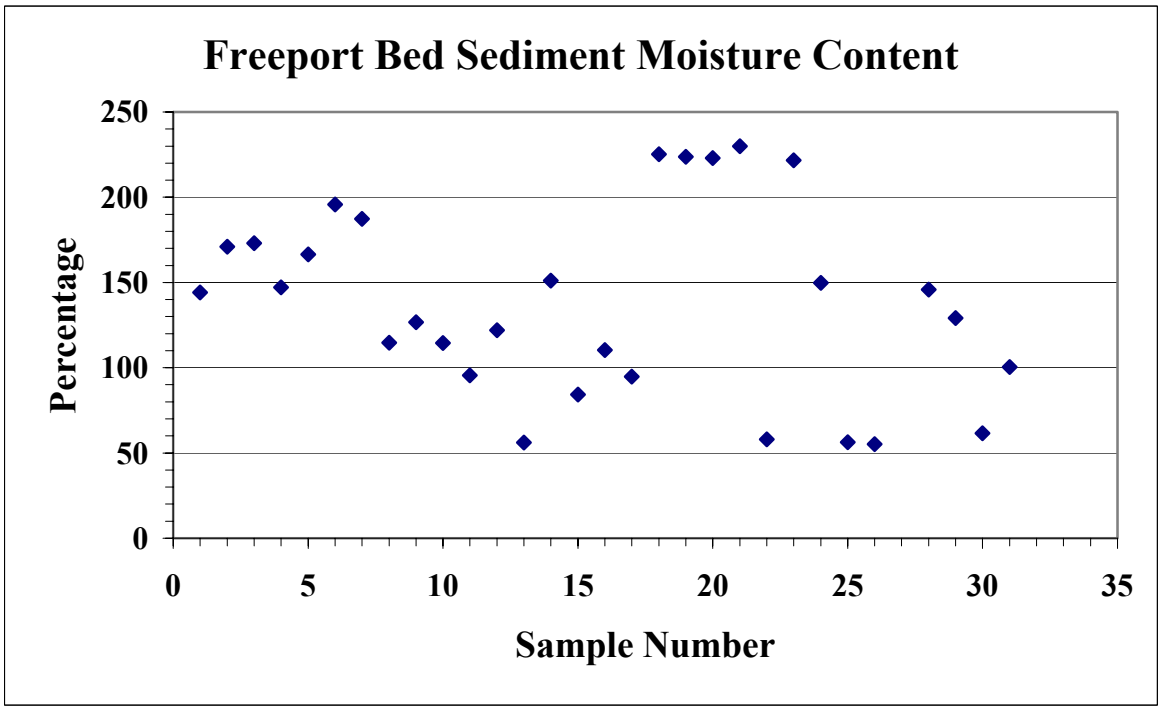


Figure 3.3.3: Percentage of moisture content in bed samples at Freeport Harbor

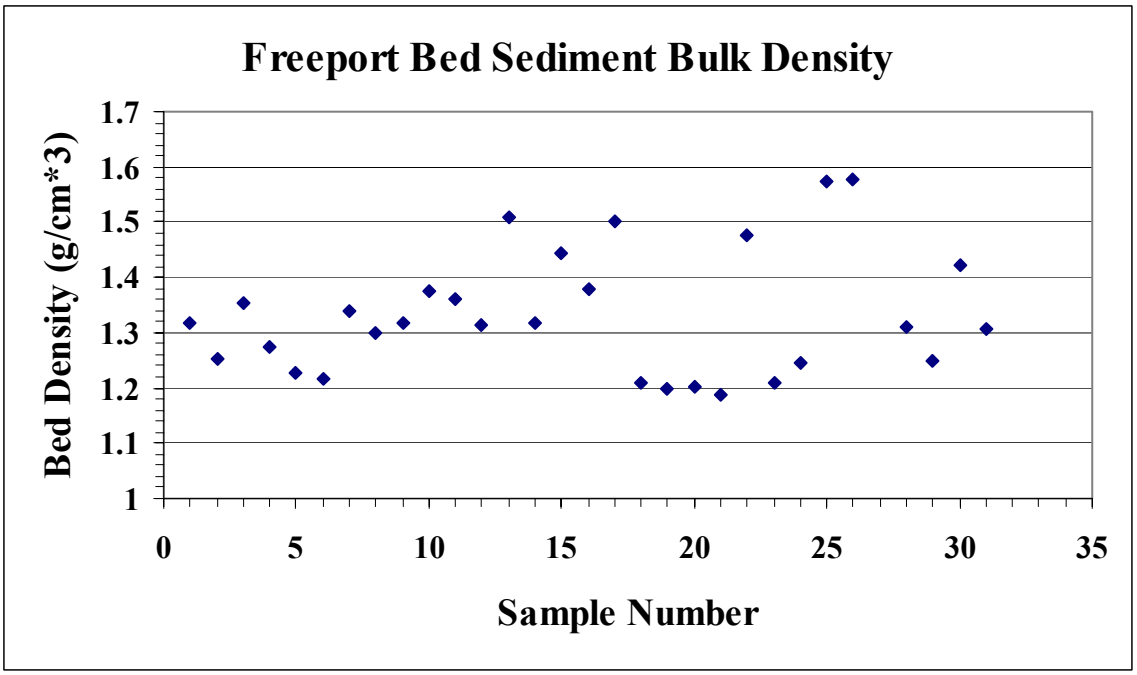


Figure 3.3.4: Bulk density of bed samples at Freeport Harbor

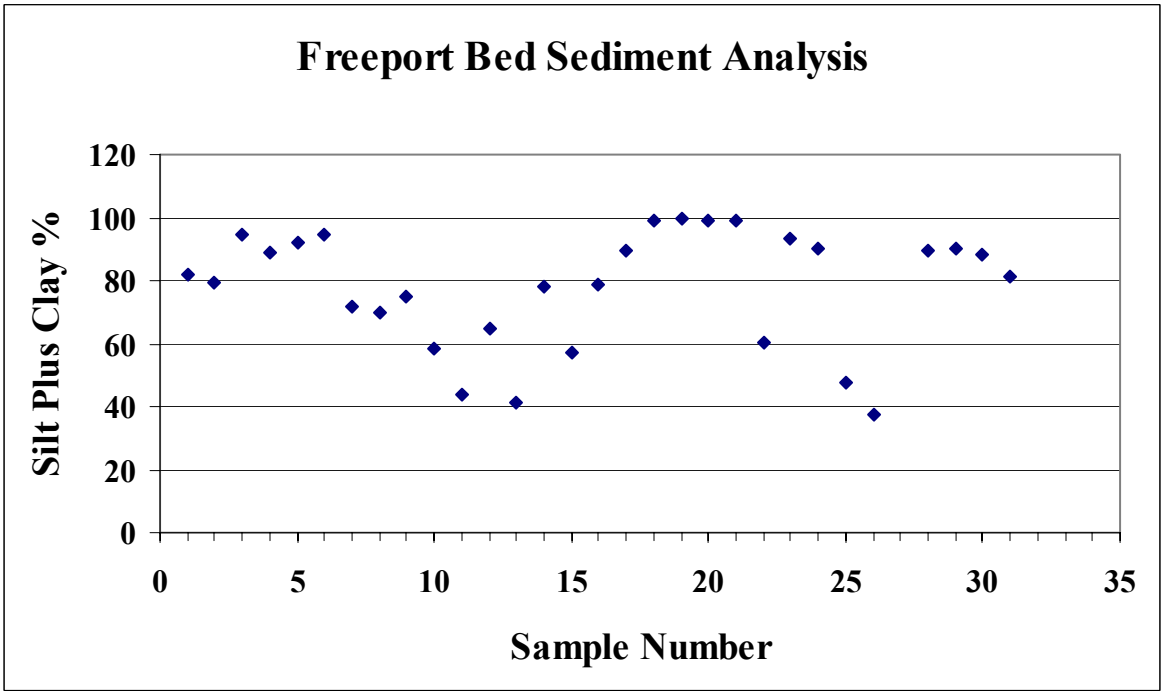


Figure 3.3.5: Percentage of silt plus clay in bed samples at Freeport Harbor

3.4 Suspended Sediment and Salinity

Data on suspended sediment concentration were not available with the Galveston District. Hence these were collected by ERDC in three data sets. Several water samples were collected in the field and were analyzed at ERDC laboratory to determine concentration of suspended sediment and salinity.

Large volumes of water samples were collected in the field by using Niskin samplers. Particle size distribution of suspended matter for these samples was determined by using Laser Particle Size Analyzer. Results of laboratory analysis are given in Appendix 1. The median diameters were as follows:

Sample No.	Median Diameter (micron)
1	52.08
2	85.93
3	58.18
4	67.70
5	50.65
6	46.49
7	73.18
8	91.81

3.4.1. Data Set 1

Water samples were collected at the same 33 locations where bed samples were collected. These were analyzed for salinity and suspended sediment concentration. The results are given in Table 3.4.1. Although these samples were not synoptic and they were also not collected at the same water depth, the results of analysis still show the expected spatial variation in salinity. Salinity values written next to the sample locations are shown in Figures 3.4.1, 3.4.2 and 3.4.3. The following conclusions are drawn from the results of analysis:

1. There is significant variation in salinity values, ranging mostly from 31.5 to 20 along the navigation channel from south to north.
2. Salinity values of 31.5 ppt were observed in the seaward part of navigation channel. From there it decreased along the navigation channel to 26 ppt in the vicinity of junction area.
3. Salinity decreased to 24 ppt in the Big Bend area.
4. From the Big Bend to the end of channel it decreased to about 20 ppt. Some local deviations in this predominant trend were present.

5. The northern end of Freeport channel is not connected to the Brazos River and there is no freshwater input at this location. The channel does not have its own well-defined catchment area. Hence local groundwater runoff during rains is the most likely source of freshwater input along the Freeport navigation channel.
6. Salinity in the east GIWW was 18.55 ppt.
7. Salinity in the west GIWW was 4.87 ppt. The western location was about twice as far as the eastern location from the junction. Hence the salinity there was much lower.
8. The GIWW appears to be a significant source of fresh water input to the Freeport navigation channel.

Spatial variation in suspended sediment concentration is not very significant and does not indicate any specific trend. The values ranged mostly from 10 to 80 mg/l. The two high values at locations 16 and 17 may be in error.

3.4.2. Data Set 2

In addition to the above data set, water samples were collected at 6 locations, which are shown in Figure 3.4.4. Stations 0 and 1 are located in the navigation channel reach between the junction and the shoreline. Station 2 is in the eastern GIWW and station 3 in the western GIWW. Stations 4 and 5 are located in the navigation channel west of the junction. Station 4 is at the Big Bend and station 5 is at the Stauffer Turning Basin.

Data Set 2 consisted of samples collected near surface, mid-depth, and near bed at Stations 1, 2, 3, and 4 so as to enable determination of salinity and suspension concentration variation as a function of water depth. These samples were collected over duration of about 26 hours starting at around 8 am on October 29, 2003. The results of analysis on both parameters for samples collected under Set 2 are presented in the following Tables:

Table 3.4.2: Station 1 (navigation channel south)
Table 3.4.3: Station 2 (east GIWW)
Table 3.4.4: Station 3 (west GIWW)
Table 3.4.5: Station 4 (Big Bend)

The vertical variation of salinity as a function of water depth is plotted in Figures 3.4.5 through 3.4.8 for stations 1 through 4 respectively. The following conclusions are drawn on the measured salinity:

1. As would be expected, salinity near surface was lower than salinity near bed because water with higher salt content is heavier due to higher specific gravity.
2. Greater variation in salinity magnitudes near bed is most likely to be a result of local fresh water input from rain, surface runoff or river discharge.
3. Station 1 is closer to ocean. Salinity at this station varied from 31 / 32 ppt near bed to 27 / 28 ppt near surface.
4. Station 2 in the east GIWW is not very far from the junction and showed a trend similar to that at Station 1. Salinity at this station varied from 31 / 32 ppt near bed to 28 / 29 ppt near surface.
5. Station 3 is closer to the Brazos River and hence susceptible to impact of fresh water from the river. Salinity at this location varied from 29 / 30 ppt near bed to 28 / 29 ppt near surface.
6. Station 4 located at Big Bend showed a variation in near bed salinity between 26 and 30 ppt.

The vertical variation of suspension concentration as a function of water depth is plotted in Figures 3.4.9 through 3.4.12 for stations 1 through 4 respectively. The following conclusions are drawn on the measured suspended sediment concentrations:

1. Mid-depth and near-surface suspension concentrations were about the same at stations 1, 2, and 4. The magnitudes varied between 40 and 8 mg/l.
2. Near-bed suspension concentration values showed greater fluctuations. This may be due to bed sediment entering water sample during collection or due to instantaneous high resuspension caused by local disturbance.

3.4.3. Data Set 3

Data Set 3 consisted of samples taken at five stations with the use of automated system, which were programmed to activate sample collection mechanism twice a day at fixed water depth, at 1200 hours and 2400 hours. Subscripts A and B were assigned to the station numbers when water samples were collected at more than one water depth. Data collection under set 3 was continued for duration of about 12 days and samples were collected at 3 feet and 7 feet above bed.

The results of analysis on both parameters for samples collected under Set 3 are presented in the following Tables:

Table 3.4.6: Station Zero, navigation channel south, 3 feet above bed
Table 3.4.7: Station 2A, east GIWW, 3 feet above bed
Table 3.4.8: Station 2B, east GIWW, 7.5 feet above bed
Table 3.4.9: Station 3, west GIWW, 3 feet above bed
Table 3.4.10: Station 4, Big Bend, 3 feet above bed

Table 3.4.11: Station 5A, navigation channel north, 3 feet above bed
Table 3.4.12: Station 5B, navigation channel north, 7 feet above bed

Salinity measurements are plotted in figures 3.4.13 through 3.4.19. These cover about 12 days and thus represent long-term measurements. The following conclusions are drawn:

1. Salinity at 3 feet above bed at Station 0 varied between 15 and 30 ppt.
2. Salinity at 3 feet and 7.5 feet above bed at Station 2 did not show significant difference. The magnitude varied between 20 and 32 ppt.
3. At Station 3, salinity varied from 5 ppt to 24 ppt at 3 feet above bed.
4. At Station 4, salinity at 3 feet above bed varied from 16 to 30 ppt.
5. At Station 5, salinity at 3 feet above bed, salinity varied from 21 to 31 ppt and at 7 feet above bed it varied from 20 to 26 ppt.

Suspended sediment concentration measurements are plotted in figures 3.4.20 through 3.4.26. These cover about 12 days and thus represent long-term measurements. The following conclusions are drawn:

1. No specific spatial or temporal trend was noticed in suspension concentration.
2. Excluding some peak values, the concentrations mostly ranged between 10 and 80 mg/l at Stations 0, 2, 4 and 5.
3. Higher concentrations varying between 50 and 150 mg/l were measured at Station 3, which is located in the western GIWW. This may be due to sediment load brought by the Brazos River.

Salinity was also plotted for different cross sections. These are shown in Figures 3.4.27 through 3.4.34.

Table 3.4.1: Data Set 1, Freeport Water Samples Collected on October 16 and 19, 2003
Note: The water sample locations listed below are the same as the bed sample locations shown in Figures 3.3.1, 3.3.2, and 3.3.3

Sampling Date	Time	Range Sta. #	Depth Ft.	Susp. Conc. mg/l	Salinity ppt
11/19/03	085623	WS 01	28.0	29	31.51
11/19/03	085201	WS 02	28.5	30	31.55
11/19/03	084702	WS 03	25.0	31	31.39
11/19/03	084320	WS 04	25.0	31	31.32
11/19/03	083413	WS 05	25.0	41	31.04
11/19/03	083033	WS 06	26.0	38	30.64
11/19/03	082556	WS 07	25.0	40	30.81
11/19/03	082118	WS 08	25.0	39	30.42
11/19/03	081641	WS 09	25.0	43	29.98
11/19/03	081249	WS 10	24.0	66	29.79
11/19/03	080823	WS 11	25.0	81	28.49
10/16/03	115400	WS 12	26.0	35	25.25
10/16/03	120023	WS 13	8.5	40	21.03
10/16/03	120546	WS 14	26.0	58	26.00
10/16/03	121307	WS 15	26.0	39	25.90
10/16/03	122246	WS 16	10.0	158	18.06
10/16/03	122955	WS 17	5.5	329	4.87
10/16/03	124006	WS 18	26.5	66	22.96
10/16/03	124537	WS 19	25.5	36	23.53
10/16/03	125113	WS 20	26.0	20	22.96
10/16/03	125600	WS 21	26.0	10	22.84
10/16/03	130000	WS 22	7.0	27	17.50
10/16/03	130503	WS 23	26.5	14	24.18
10/16/03	131045	WS 24	19.5	19	21.48
10/16/03	131635	WS 25	12.0	19	20.40
10/16/03	132154	WS 26	9.0	10	20.64
10/16/03	132443	WS 27	7.5	8	20.63
10/16/03	133006	WS 28	10.5	9	20.50
10/16/03	133453	WS 29	10.5	8	20.14
10/16/03	134019	WS 30	10.5	12	20.14
10/16/03	140126	WS 31	9.5	79	16.59
10/16/03	141204	WS 32	10.0	73	19.07
10/16/03	141755	WS 33	10.0	50	18.55

Table 3.4.2: Data Set 2, Depth variation of salinity and suspended sediment concentration at Station 1 (navigation channel south)

Sampling Date	Time CST	Range Sta. #	Depth ft	Susp. Sed. Conc. mg/l	Salinity ppt
10/29/03	0802	1	39.0	22	28.70
10/29/03	0803	1	21.0	22	28.67
10/29/03	0804	1	3.0	22	28.60
10/29/03	0906	1	37.0	31	28.88
10/29/03	0907	1	20.0	27	28.88
10/29/03	0908	1	3.0	27	28.87
10/29/03	1005	1	37.0	28	29.26
10/29/03	1006	1	20.0	30	28.74
10/29/03	1007	1	3.0	30	28.70
10/29/03	1105	1	37.0	44	29.39
10/29/03	1106	1	20.0	38	28.47
10/29/03	1107	1	3.0	37	27.96
10/29/03	1204	1	37.0	35	29.04
10/29/03	1205	1	20.0	42	28.07
10/29/03	1206	1	3.0	38	27.22
10/29/03	1304	1	40.0	48	29.79
10/29/03	1305	1	21.5	35	28.23
10/29/03	1306	1	3.0	39	27.06
10/29/03	1404	1	37.0	39	30.94
10/29/03	1405	1	20.0	25	29.26
10/29/03	1406	1	3.0	32	27.02
10/29/03	1505	1	39.0	46	31.10
10/29/03	1506	1	21.0	20	30.14
10/29/03	1507	1	3.0	22	27.07
10/29/03	1619	1	47.0	36	31.09
10/29/03	1621	1	22.0	22	30.78
10/29/03	1621	1	3.0	14	26.97
10/29/03	1711	1	41.0	83	31.05
10/29/03	1713	1	22.0	40	30.80
10/29/03	1713	1	3.0	15	27.43
10/29/03	1810	1	37.0	49	30.85
10/29/03	1814	1	20.0	18	29.40
10/29/03	1809	1	3.0	14	27.73
10/29/03	1914	1	44.0	75	30.73
10/29/03	1915	1	23.5	15	29.80
10/29/03	1916	1	3.0	12	28.21
10/29/03	2029	1	44.0	37	30.69

10/29/03	2032	1	23.5	11	29.87
10/29/03	2032	1	3.0	12	28.39
10/29/03	2128	1	44.0	71	31.48
10/29/03	2129	1	23.5	8	30.00
10/29/03	2130	1	3.0	9	28.32
10/29/03	2228	1	44.0	44	31.36
10/29/03	2230	1	23.5	7	30.62
10/29/03	2231	1	3.0	9	28.86
10/29/03	2337	1	44.0	29	31.89
10/29/03	2339	1	23.5	5	30.83
10/29/03	2340	1	3.0	7	29.06
10/30/03	0121	1	41.0	16	32.06
10/30/03	0122	1	22.0	10	31.22
10/30/03	0123	1	3.0	6	29.24
10/30/03	0220	1	41.0	14	31.84
10/30/03	0221	1	22.0	5	31.00
10/30/03	0222	1	3.0	12	29.47
10/30/03	0323	1	39.0	19	31.79
10/30/03	0324	1	21.0	11	31.10
10/30/03	0325	1	3.0	23	28.83
10/30/03	0421	1	41.0	10	31.76
10/30/03	0422	1	22.0	8	31.50
10/30/03	0423	1	3.0	20	28.76
10/30/03	0535	1	41.0	10	31.95
10/30/03	0536	1	22.0	11	30.83
10/30/03	0537	1	3.0	21	27.68
10/30/03	0624	1	41.0	13	32.05
10/30/03	0625	1	22.0	12	30.57
10/30/03	0626	1	3.0	20	28.02
10/30/03	0729	1	43.0	62	31.59
10/30/03	0731	1	23.0	16	29.88
10/30/03	0732	1	3.0	19	29.48
10/30/03	0834	1	42.0	18	31.57
10/30/03	0835	1	22.5	22	29.80
10/30/03	0836	1	3.0	21	29.23
10/30/03	0941	1	42.0	32	30.62
10/30/03	0942	1	22.5	33	29.68
10/30/03	0943	1	3.0	33	29.26

Table 3.4.3: Data Set 2, Depth variation of salinity and suspended sediment concentration at Station 2 (east GIWW)

Sampling Date	Time CST	Range Sta. #	Depth ft	Susp. Sed. Conc. mg/l	Salinity ppt
10/29/03	0815	2	46.0	36	29.79
10/29/03	0816	2	24.5	39	29.69
10/29/03	0817	2	3.0	23	29.01
10/29/03	0918	2	45.0	337	29.49
10/29/03	0919	2	24.0	67	29.36
10/29/03	0920	2	3.0	42	29.06
10/29/03	1038	2	46.0	84	29.29
10/29/03	1039	2	24.5	61	29.08
10/29/03	1040	2	3.0	46	28.93
10/29/03	1118	2	46.0	87	29.51
10/29/03	1119	2	24.5	87	28.89
10/29/03	1120	2	3.0	40	28.34
10/29/03	1216	2	46.0	58	29.86
10/29/03	1217	2	24.5	45	28.79
10/29/03	1218	2	3.0	32	28.15
10/29/03	1318	2	46.0	59	31.11
10/29/03	1319	2	24.5	35	29.32
10/29/03	1320	2	3.0	28	27.86
10/29/03	1415	2	47.0	51	31.22
10/29/03	1416	2	25.0	25	30.08
10/29/03	1417	2	3.0	19	27.91
10/29/03	1515	2	47.0	49	31.06
10/29/03	1516	2	25.0	23	30.47
10/29/03	1517	2	3.0	17	27.78
10/29/03	1633	2	49.0	66	31.09
10/29/03	1635	2	25.0	19	30.49
10/29/03	1635	2	3.0	14	27.97
10/29/03	1722	2	48.0	93	31.14
10/29/03	1724	2	25.0	18	30.84
10/29/03	1722	2	3.0	12	28.03
10/29/03	1826	2	51.0	55	31.17
10/29/03	1828	2	26.5	12	30.67
10/29/03	1829	2	3.0	37	27.18
10/29/03	1927	2	50.0	38	31.18
10/29/03	1928	2	26.5	7	30.67
10/29/03	1929	2	3.0	10	28.27
10/29/03	2042	2	50.0	37	31.47

10/29/03	2044	2	26.5	14	31.01
10/29/03	2045	2	3.0	10	28.51
10/29/03	2141	2	51.0	44	31.62
10/29/03	2143	2	26.5	8	31.01
10/29/03	2144	2	3.0	8	28.80
10/29/03	2246	2	51.0	21	31.99
10/29/03	2248	2	26.5	7	31.19
10/29/03	2249	2	3.0	9	28.48
10/29/03	2350	2	51.0	20	32.01
10/29/03	2352	2	27.0	19	31.12
10/29/03	2353	2	3.0	7	28.85
10/30/03	0133	2	49.0	14	32.03
10/30/03	0134	2	26.0	7	31.25
10/30/03	0135	2	3.0	8	29.22
10/30/03	0235	2	49.0	14	31.95
10/30/03	0236	2	26.0	11	30.91
10/30/03	0237	2	3.0	14	29.27
10/30/03	0336	2	50.0	20	32.01
10/30/03	0337	2	26.5	12	31.35
10/30/03	0338	2	3.0	15	29.04
10/30/03	0434	2	50.0	14	31.93
10/30/03	0435	2	26.5	12	31.21
10/30/03	0436	2	3.0	17	28.66
10/30/03	0546	2	49.0	12	32.18
10/30/03	0547	2	26.0	11	31.43
10/30/03	0548	2	3.0	24	27.51
10/30/03	0634	2	48.0	15	32.21
10/30/03	0635	2	25.5	12	31.40
10/30/03	0636	2	3.0	25	26.73
10/30/03	0742	2	51.0	48	32.05
10/30/03	0744	2	27.0	50	30.90
10/30/03	0744	2	3.0	22	27.67
10/30/03	0845	2	50.0	80	31.18
10/30/03	0847	2	26.5	22	30.48
10/30/03	0848	2	3.0	21	28.98
10/30/03	0957	2	49.0	80	30.48
10/30/03	0959	2	26.0	65	30.18
10/30/03	1000	2	3.0	33	29.47

Table 3.4.4: Data Set 2, Depth variation of salinity and suspended sediment concentration at Station 3 (west GIWW)

Sampling Date	Time CST	Range Sta. #	Depth ft	Susp. Sed. Conc. mg/l	Salinity ppt
10/29/03	0825	3	15.0	71	24.99
10/29/03	0826	3	9.0	64	28.22
10/29/03	0827	3	3.0	57	23.91
10/29/03	0927	3	15.0	32	29.33
10/29/03	0928	3	9.0	33	28.71
10/29/03	0929	3	3.0	35	22.56
10/29/03	1014	3	15.0	27	29.24
10/29/03	1015	3	9.0	30	28.63
10/29/03	1016	3	3.0	33	22.42
10/29/03	1127	3	15.0	39	29.32
10/29/03	1128	3	9.0	27	28.98
10/29/03	1129	3	3.0	36	21.05
10/29/03	1225	3	15.0	58	29.01
10/29/03	1226	3	9.0	39	28.52
10/29/03	1227	3	3.0	34	21.44
10/29/03	1326	3	15.0	41	28.39
10/29/03	1327	3	9.0	105	27.45
10/29/03	1328	3	3.0	33	21.42
10/29/03	1423	3	15.0	34	27.86
10/29/03	1424	3	9.0	26	27.58
10/29/03	1425	3	3.0	27	23.14
10/29/03	1523	3	15.0	22	29.00
10/29/03	1524	3	9.0	17	27.84
10/29/03	1525	3	3.0	24	23.95
10/29/03	1643	3	18.0	44	29.73
10/29/03	1644	3	10.0	14	28.94
10/29/03	1645	3	3.0	16	25.13
10/29/03	1731	3	17.0	52	29.61
10/29/03	1732	3	10.0	14	29.00
10/29/03	1733	3	3.0	12	28.13
10/29/03	1840	3	17.5	30	30.04
10/29/03	1842	3	10.0	12	28.97
10/29/03	1843	3	3.0	11	28.09
10/29/03	1941	3	18.0	23	30.13
10/29/03	1942	3	10.5	30	29.48
10/29/03	1943	3	3.0	36	29.14
10/29/03	2055	3	18.0	18	30.45

10/29/03	2056	3	10.5	12	29.32
10/29/03	2057	3	3.0	9	28.68
10/29/03	2155	3	18.0	14	30.32
10/29/03	2156	3	10.5	9	29.39
10/29/03	2157	3	3.0	9	28.63
10/29/03	2259	3	18.0	13	30.31
10/29/03	2300	3	10.5	8	29.60
10/29/03	2301	3	3.0	11	28.80
10/30/03	0044	3	15.0	32	29.13
10/30/03	0045	3	9.0	21	28.79
10/30/03	0046	3	3.0	22	28.82
10/30/03	0148	3	17.0	33	28.92
10/30/03	0149	3	10.0	47	28.34
10/30/03	0150	3	3.0	60	27.73
10/30/03	0247	3	17.0	32	29.22
10/30/03	0248	3	10.0	44	28.37
10/30/03	0249	3	3.0	40	27.75
10/30/03	0349	3	17.0	34	29.04
10/30/03	0350	3	10.0	41	27.91
10/30/03	0351	3	3.0	42	27.04
10/30/03	0500	3	17.0	20	29.32
10/30/03	0501	3	10.0	31	28.07
10/30/03	0502	3	3.0	39	25.06
10/30/03	0600	3	17.0	30	29.42
10/30/03	0601	3	10.0	32	27.77
10/30/03	0602	3	3.0	38	24.61
10/30/03	0643	3	15.0	19	29.63
10/30/03	0644	3	9.0	43	26.08
10/30/03	0645	3	3.0	45	24.05
10/30/03	0752	3	17.0	55	29.84
10/30/03	0753	3	10.0	39	28.11
10/30/03	0754	3	3.0	45	23.70
10/30/03	0912	3	17.0	1686	27.28
10/30/03	0913	3	10.0	266	26.61
10/30/03	0914	3	3.0	72	23.43
10/30/03	1008	3	18.0	305	29.65
10/30/03	1009	3	10.5	332	27.06
10/30/03	1010	3	3.0	424	24.10

Table 3.4.5: Data Set 2, Depth variation of salinity and suspended sediment concentration at Station 4 (Big Bend)

Sampling Date	Time CST	Range Sta. #	Depth ft	Susp. Sed. Conc. mg/l	Salinity ppt
10/29/03	0841	4	47.0	66	32.17
10/29/03	0842	4	25.0	26	30.27
10/29/03	0843	4	3.0	10	28.19
10/29/03	0940	4	45.0	106	32.20
10/29/03	0941	4	24.0	30	30.12
10/29/03	0942	4	3.0	16	28.04
10/29/03	1026	4	45.0	44	32.32
10/29/03	1027	4	24.0	19	30.03
10/29/03	1028	4	3.0	17	28.22
10/29/03	1139	4	46.0	86	32.29
10/29/03	1140	4	24.5	15	29.65
10/29/03	1141	4	3.0	21	27.82
10/29/03	1239	4	47.0	35	32.52
10/29/03	1240	4	25.0	14	29.62
10/29/03	1241	4	3.0	25	26.80
10/29/03	1338	4	45.0	31	32.41
10/29/03	1339	4	24.0	17	29.50
10/29/03	1340	4	3.0	24	25.89
10/29/03	1435	4	47.0	25	32.55
10/29/03	1436	4	25.0	17	29.47
10/29/03	1437	4	3.0	19	26.19
10/29/03	1535	4	46.0	22	32.26
10/29/03	1536	4	24.5	17	30.32
10/29/03	1537	4	3.0	17	26.19
10/29/03	1658	4	48.0	17	32.06
10/29/03	1700	4	25.0	15	30.62
10/29/03	1701	4	3.0	12	26.32
10/29/03	1744	4	49.0	86	32.22
10/29/03	1746	4	26.0	13	30.69
10/29/03	1745	4	3.0	11	26.65
10/29/03	1856	4	48.0	17	31.72
10/29/03	1857	4	25.5	10	30.59
10/29/03	1858	4	3.0	10	27.57
10/29/03	1959	4	49.0	16	31.51
10/29/03	2001	4	26.0	12	30.64
10/29/03	2002	4	3.0	10	28.07
10/29/03	2110	4	48.0	13	31.54

10/29/03	2111	4	25.5	10	30.67
10/29/03	2113	4	3.0	13	28.40
10/29/03	2211	4	51.0	11	31.31
10/29/03	2213	4	26.5	10	29.93
10/29/03	2214	4	3.0	8	28.86
10/29/03	2313	4	49.0	12	31.27
10/29/03	2314	4	26.0	10	30.61
10/29/03	2315	4	3.0	6	29.22
10/30/03	0059	4	48.0	29	31.73
10/30/03	0100	4	25.5	7	30.54
10/30/03	0101	4	3.0	6	29.59
10/30/03	0203	4	48.0	20	31.90
10/30/03	0204	4	25.5	8	30.52
10/30/03	0205	4	3.0	5	29.71
10/30/03	0302	4	48.0	20	31.88
10/30/03	0303	4	25.5	8	30.47
10/30/03	0304	4	3.0	7	29.79
10/30/03	0404	4	48.0	19	31.92
10/30/03	0405	4	25.5	13	30.71
10/30/03	0406	4	3.0	6	29.65
10/30/03	0513	4	48.0	15	31.95
10/30/03	0514	4	25.5	7	30.98
10/30/03	0515	4	3.0	3	29.81
10/30/03	0612	4	46.0	407	30.02
10/30/03	0613	4	24.5	11	30.85
10/30/03	0614	4	3.0	7	29.89
10/30/03	0654	4	48.0	26	31.94
10/30/03	0655	4	25.5	7	30.92
10/30/03	0656	4	3.0	6	29.83
10/30/03	0813	4	48.0	216	31.72
10/30/03	0814	4	25.5	25	30.43
10/30/03	0815	4	3.0	22	30.24
10/30/03	0925	4	47.0	47	31.73
10/30/03	0926	4	25.0	28	30.25
10/30/03	0927	4	3.0	27	30.24
10/30/03	1026	4	46.0	46	31.57
10/30/03	1028	4	24.5	22	30.72
10/30/03	1029	4	3.0	38	27.33

Table 3.4.6: Data Set 3, Water samples collected at Freeport at Station Zero, 3 feet above bed

Sampling Date	Sampling Time (CST)	Susp. Conc. (mg/l)	Salinity ppt
10/16/03	1200	25	19.03
10/16/03	2400	35	15.33
10/17/03	1200	51	14.70
10/17/03	2400	17	20.02
10/18/03	1200	34	17.20
10/18/03	2400	16	20.69
10/19/03	1200	12	20.71
10/19/03	2400	9	21.16
10/20/03	1200	12	22.33
10/20/03	2400	10	21.39
10/21/03	1200	12	21.18
10/21/03	2400	15	20.11
10/22/03	1200	22	18.36
10/22/03	2400	16	21.36
10/23/03	1200	19	24.80
10/23/03	2400	19	25.64
10/24/03	1200	16	29.20
10/24/03	2400	30	27.83
10/25/03	1200	22	26.84
10/25/03	2400	21	23.69
10/26/03	1200	23	28.60
10/26/03	2400	26	28.48
10/27/03	1200	23	25.20
10/27/03	2400	18	26.35

Table 3.4.7: Data Set 3, Water samples collected at Freeport at Station 2A, 3 feet above bed

Sampling Date	Sampling Time (CST)	Susp. Conc. (mg/l)	Salinity ppt
10/16/03	1200	36	21.57
10/16/03	2400	21	23.55
10/17/03	1200	46	21.25
10/17/03	2400	27	24.74
10/18/03	1200	43	20.55
10/18/03	2400	10	25.34
10/19/03	1200	30	21.89
10/19/03	2400	12	25.29
10/20/03	1200	21	22.37
10/20/03	2400	9	24.78
10/21/03	1200	18	22.34
10/21/03	2400	20	24.57
10/22/03	1200	100	22.97
10/22/03	2400	33	27.61
10/23/03	1200	34	29.26
10/23/03	2400	33	30.54
10/24/03	1200	25	31.92
10/24/03	2400	40	30.49
10/25/03	1200	43	32.11
10/25/03	2400	71	29.04
10/26/03	1200	80	29.43
10/26/03	2400	59	25.95
10/27/03	1200	80	27.30
10/27/03	2400	56	29.24

Table 3.4.8: Data Set 3, Water samples collected at Freeport at Station 2B, 7.5 feet above bed

Sampling Date	Sampling Time (CST)	Susp. Conc. (mg/l)	Salinity ppt
10/16/03	1200	25	22.76
10/16/03	2400	43	19.96
10/17/03	1200	30	24.46
10/17/03	2400	45	20.41
10/18/03	1200	15	24.54
10/18/03	2400	31	21.52
10/19/03	1200	16	25.08
10/19/03	2400	25	22.08
10/20/03	1200	14	24.70
10/20/03	2400	24	22.39
10/21/03	1200	26	24.20
10/21/03	2400	32	22.33
10/22/03	1200	24	26.61
10/22/03	2400	32	29.04
10/23/03	1200	28	29.67
10/23/03	2400	28	31.24
10/24/03	1200	39	30.10
10/24/03	2400	52	31.66
10/25/03	1200	70	29.30
10/25/03	2400	67	29.08
10/26/03	1200	67	25.99
10/26/03	2400	75	27.26
10/27/03	1200	41	28.97
10/27/03	2400	42	21.35

Table 3.4.9: Data Set 3, Water samples collected at Freeport at Station 3, 3 feet above bed

Sampling Date	Sampling Time (CST)	Susp. Conc. (mg/l)	Salinity ppt
10/16/03	1200	147	6.05
10/16/03	2400	162	6.45
10/17/03	1200	311	3.71
10/17/03	2400	155	8.01
10/18/03	1200	181	6.06
10/18/03	2400	no sample	no sample
10/19/03	1200	81	8.88
10/19/03	2400	56	15.58
10/20/03	1200	105	12.34
10/20/03	2400	76	15.61
10/21/03	1200	77	13.52
10/21/03	2400	126	15.29
10/22/03	1200	115	13.81
10/22/03	2400	153	15.75
10/23/03	1200	94	17.56
10/23/03	2400	89	19.77
10/24/03	1200	117	23.85
10/24/03	2400	83	19.02
10/25/03	1200	73	18.87
10/25/03	2400	77	15.50
10/26/03	1200	87	18.37
10/26/03	2400	52	16.85
10/27/03	1200	46	20.41
10/27/03	2400	116	22.78

Table 3.4.10: Data Set 3, Water samples collected at Freeport at Station 4, 3 feet above bed

Sampling Date	Sampling Time (CST)	Susp. Conc. (mg/l)	Salinity ppt
10/16/03	1200	20	18.65
10/16/03	2400	12	19.16
10/17/03	1200	21	16.41
10/17/03	2400	11	18.93
10/18/03	1200	26	17.74
10/18/03	2400	13	19.24
10/19/03	1200	18	18.46
10/19/03	2400	11	21.20
10/20/03	1200	12	21.25
10/20/03	2400	8	22.08
10/21/03	1200	8	22.66
10/21/03	2400	6	22.99
10/22/03	1200	13	24.60
10/22/03	2400	19	26.17
10/23/03	1200	16	28.05
10/23/03	2400	14	28.84
10/24/03	1200	17	30.47
10/24/03	2400	12	30.43
10/25/03	1200	20	29.26
10/25/03	2400	24	27.19
10/26/03	1200	33	25.81
10/26/03	2400	22	26.26
10/27/03	1200	32	24.97
10/27/03	2400	17	28.16

Table 3.4.11: Data Set 3, Water samples collected at Freeport at Station 5A, 3 feet above bed

Sampling Date	Sampling Time (CST)	Susp. Conc. (mg/l)	Salinity ppt
10/16/03	1200	16	21.08
10/16/03	2400	15	22.94
10/17/03	1200	9	20.89
10/17/03	2400	14	24.28
10/18/03	1200	7	22.09
10/18/03	2400	20	23.95
10/19/03	1200	9	22.58
10/19/03	2400	12	23.47
10/20/03	1200	26	24.05
10/20/03	2400	17	23.12
10/21/03	1200	14	24.02
10/21/03	2400	12	23.89
10/22/03	1200	11	25.13
10/22/03	2400	12	26.70
10/23/03	1200	21	27.91
10/23/03	2400	19	29.53
10/24/03	1200	19	30.45
10/24/03	2400	20	30.91
10/25/03	1200	19	29.98
10/25/03	2400	17	29.84
10/26/03	1200	16	29.07
10/26/03	2400	31	29.72
10/27/03	1200	41	28.58
10/27/03	2400	22	29.35

Table 3.4.12: Data Set 3, Water samples collected at Freeport at Station 5B, 7 feet above bed

Sampling Date	Sampling Time (CST)	Susp. Conc. (mg/l)	Salinity ppt
10/16/03	1200	12	20.69
10/16/03	2400	15	20.84
10/17/03	1200	9	20.27
10/17/03	2400	11	22.23
10/18/03	1200	7	21.84
10/18/03	2400	13	22.24
10/19/03	1200	6	22.15
10/19/03	2400	8	22.34
10/20/03	1200	15	23.21
10/20/03	2400	12	22.52
10/21/03	1200	4	23.04
10/21/03	2400	4	22.90
10/22/03	1200	5	23.90
10/22/03	2400	8	26.01

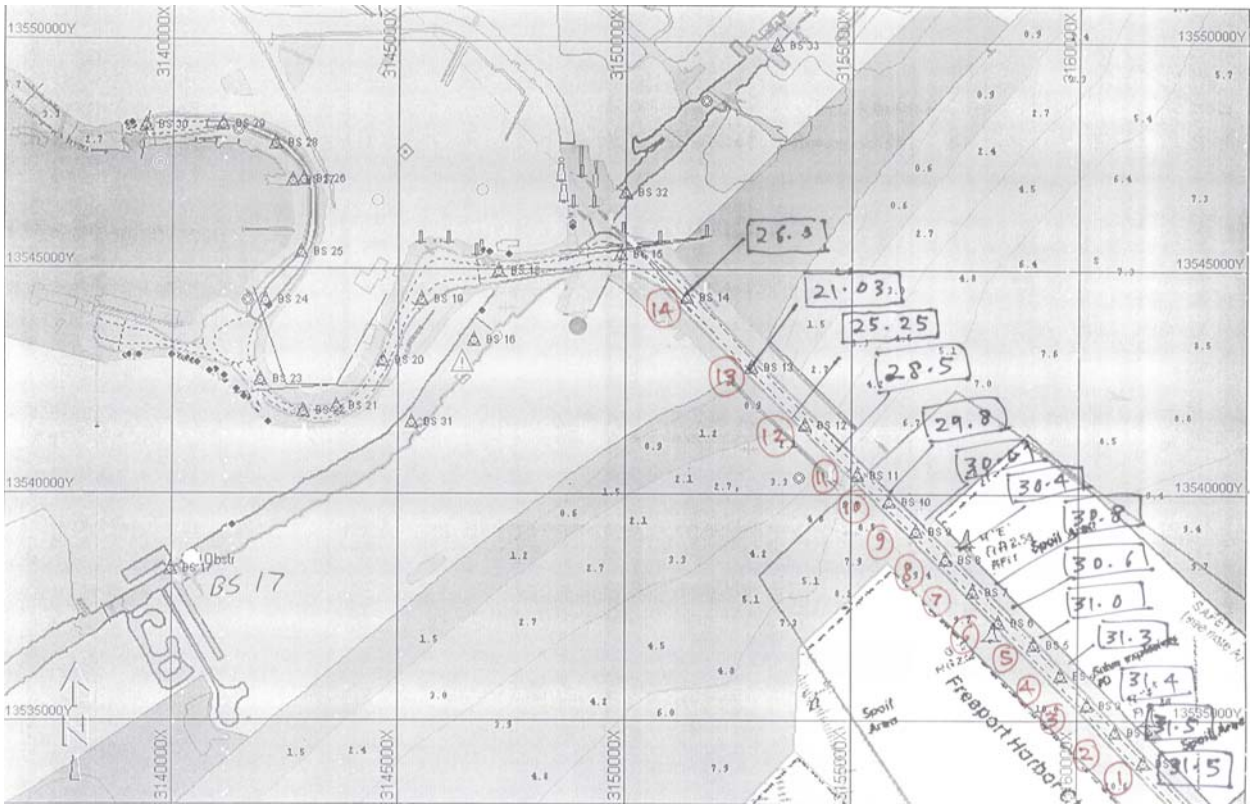


Figure 3.4.1: Map 1 showing locations of water sample collection and measured salinity values

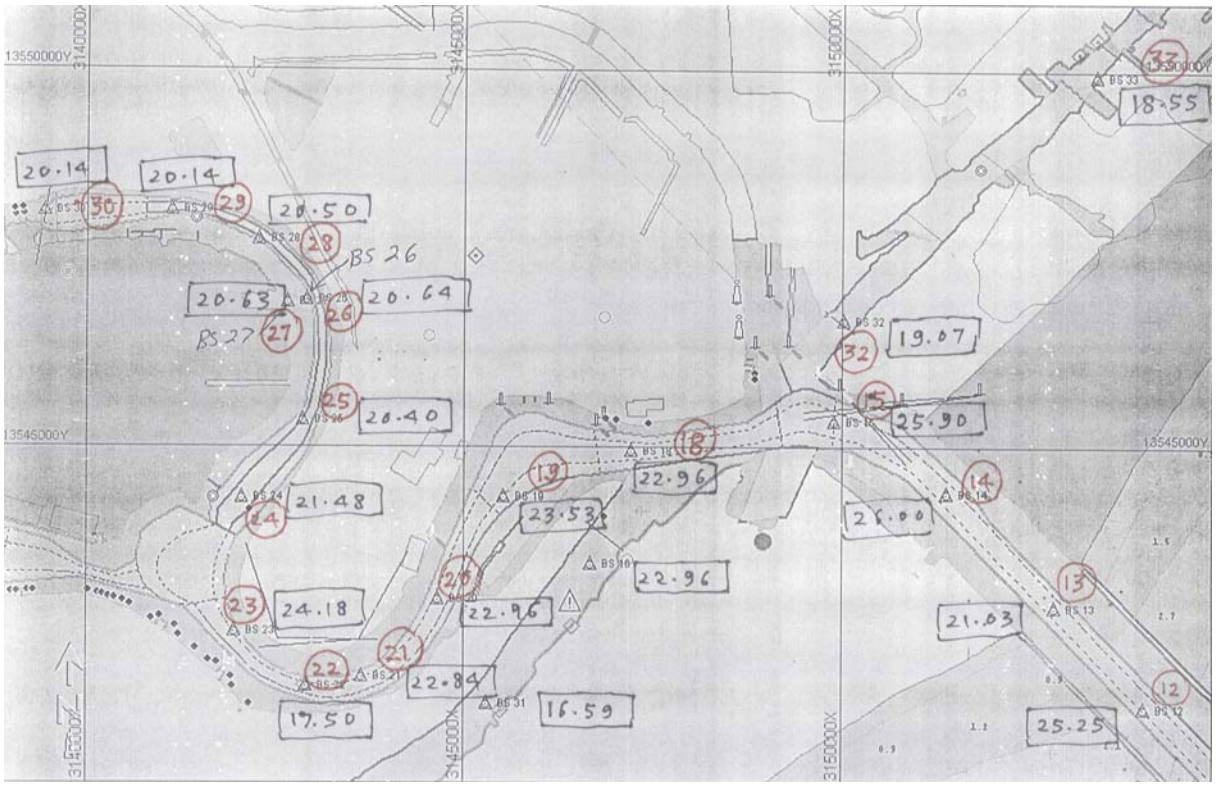


Figure 3.4.2: Map 2 showing locations of water sample collection and measured salinity values

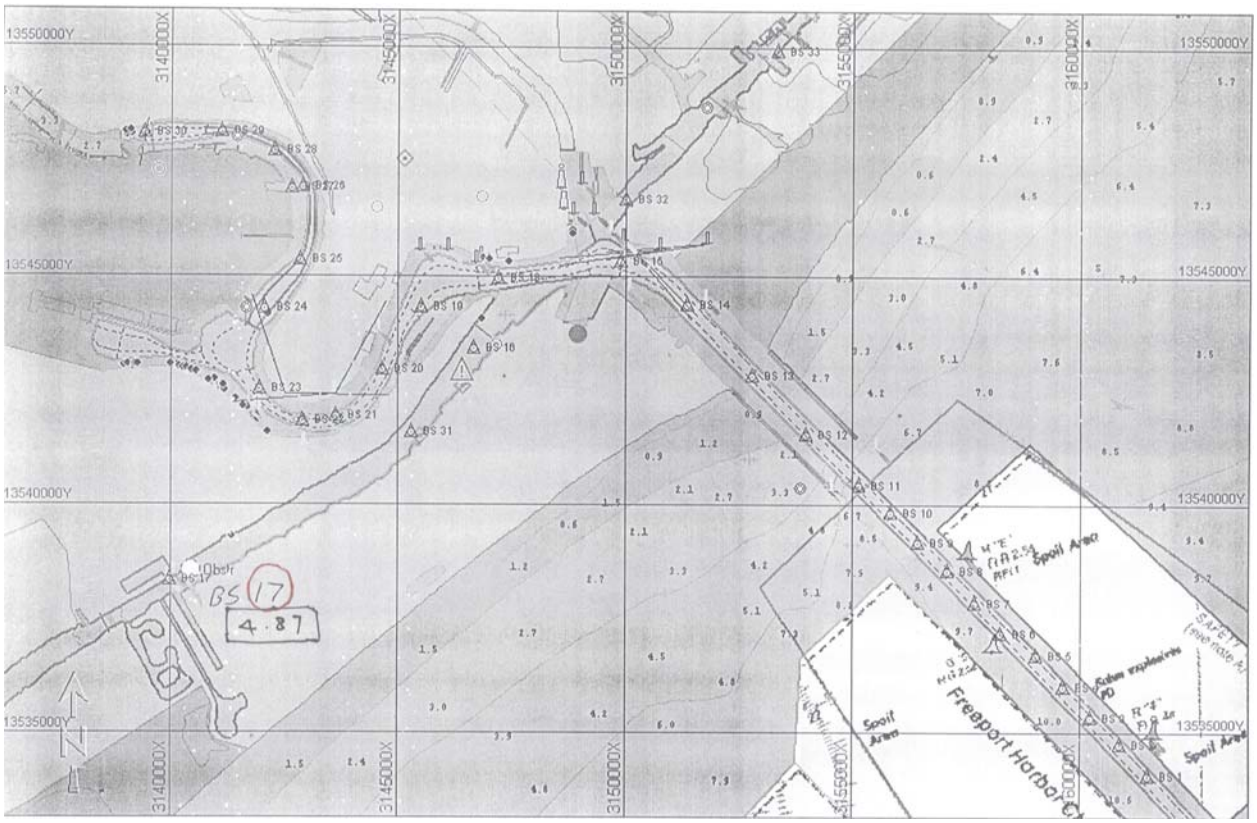


Figure 3.4.3: Map 3 showing locations of water sample collection and observed salinity values

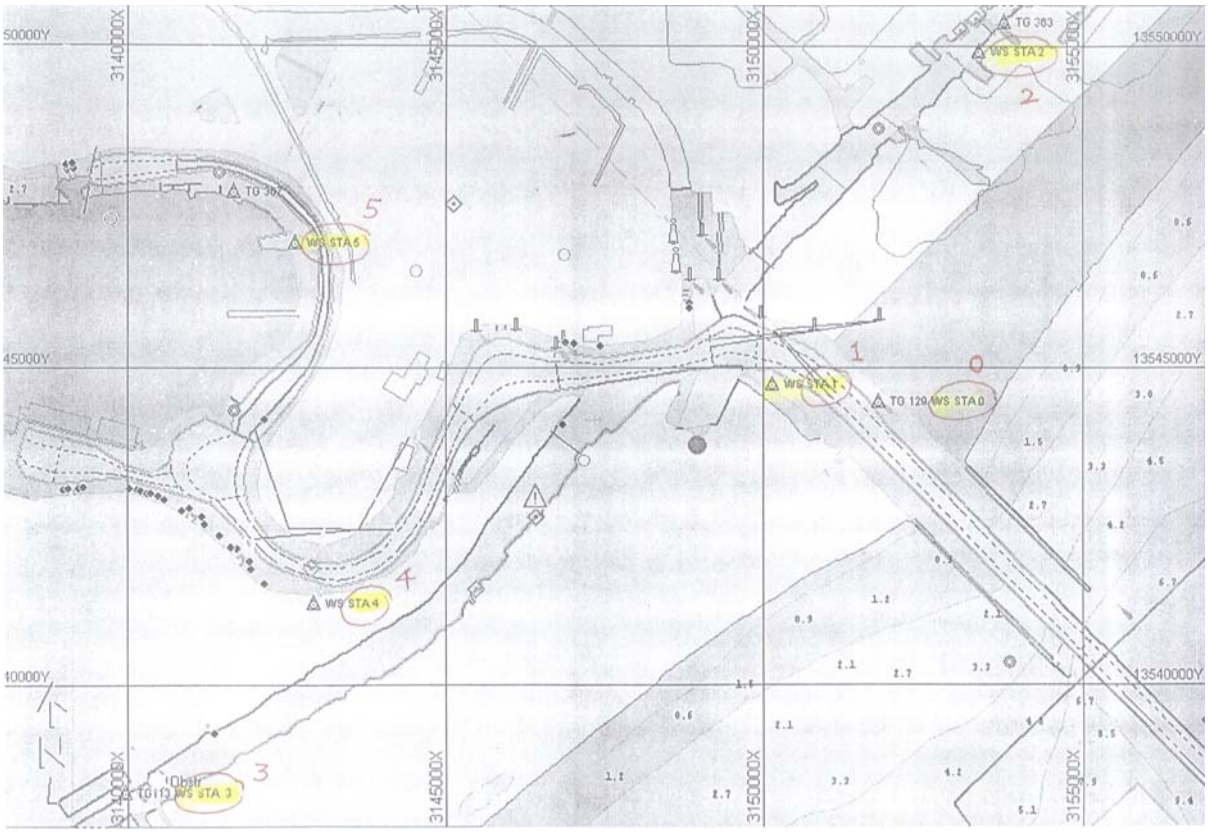


Figure 3.4.4: Map 4 showing locations of water sample collection and measured salinity values

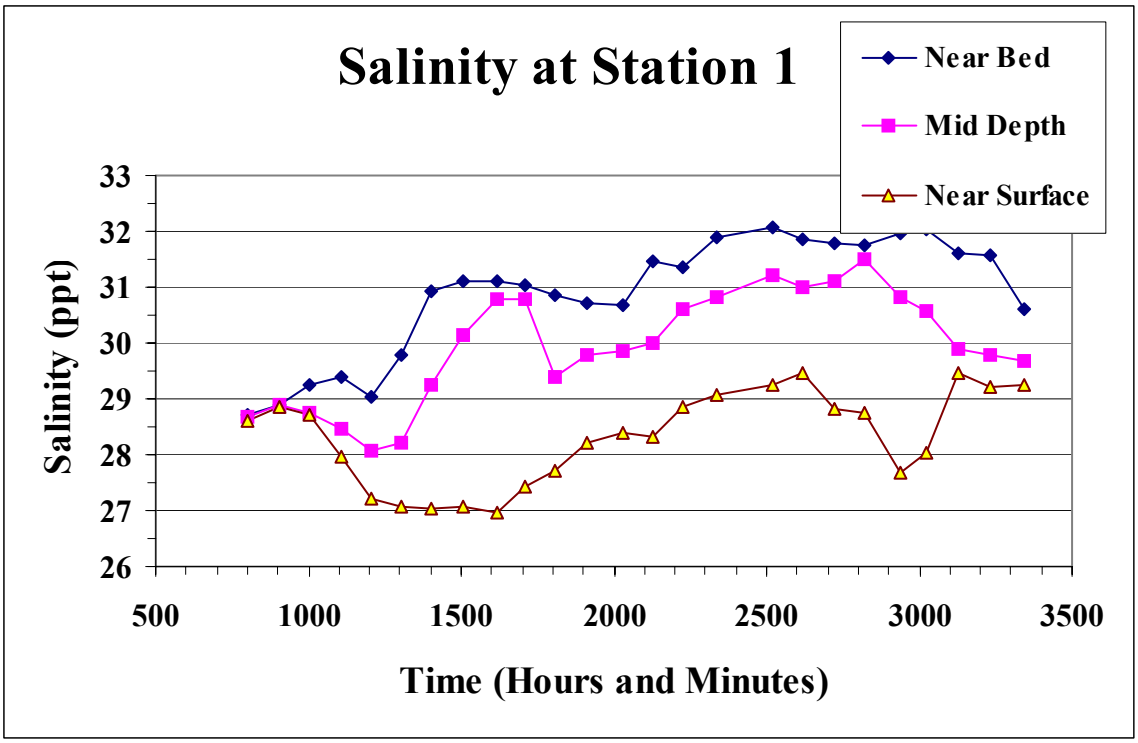


Figure 3.4.5: Depth-variation of salinity at Station 1, navigation channel south

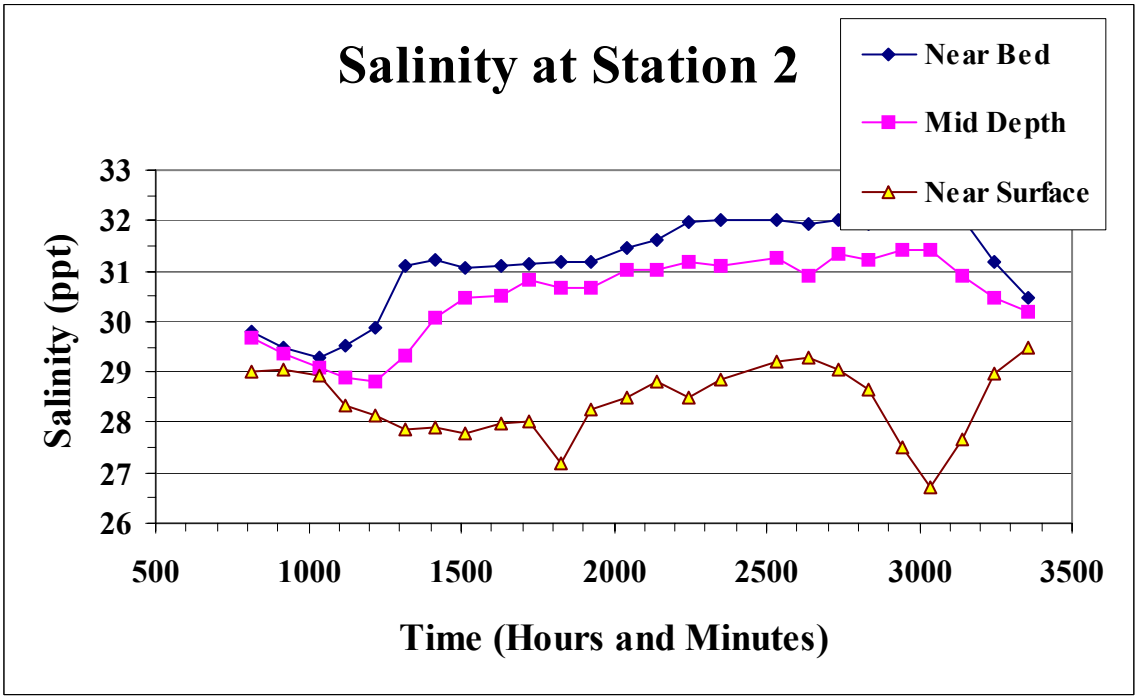


Figure 3.4.6: Depth-variation of salinity at Station 2, east GIWW

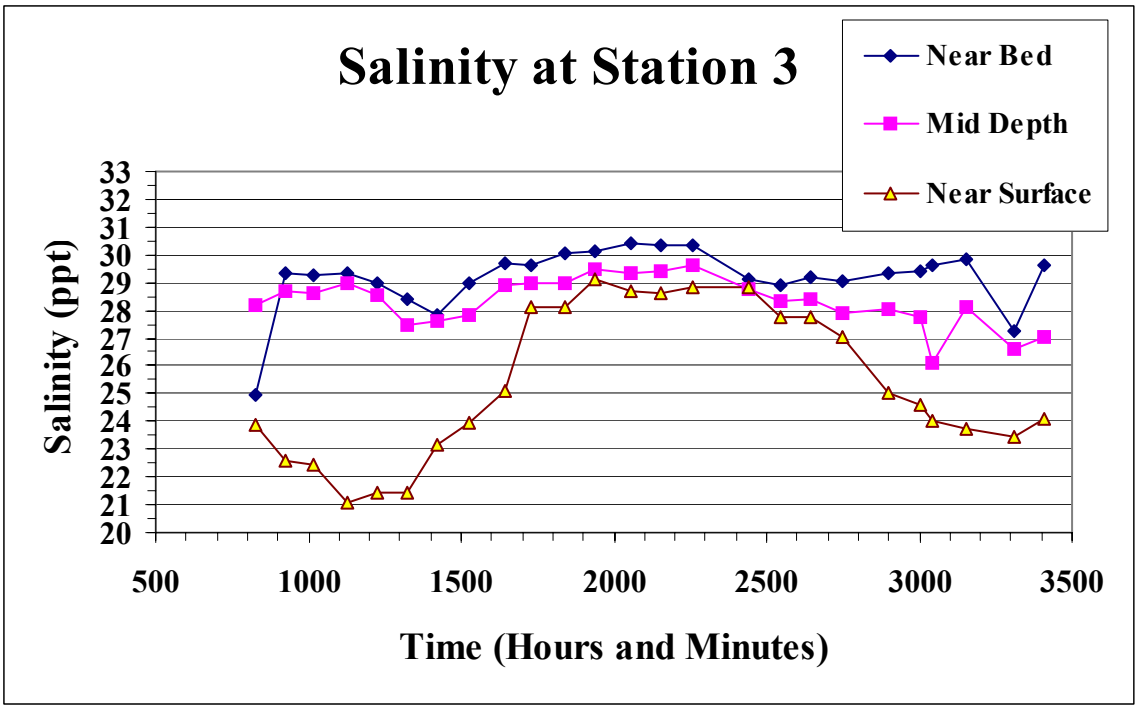


Figure 3.4.7: Depth-variation of salinity at Station 3, west GIWW

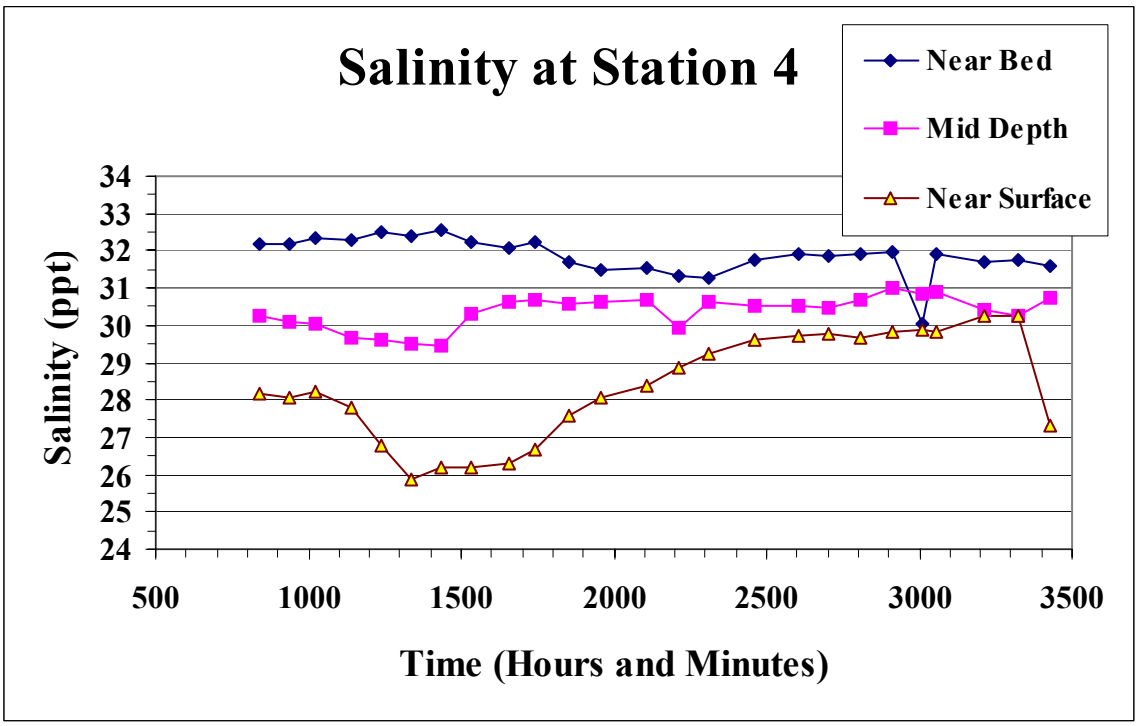


Figure 3.4.8: Depth-variation of salinity at Station 4, Big Bend

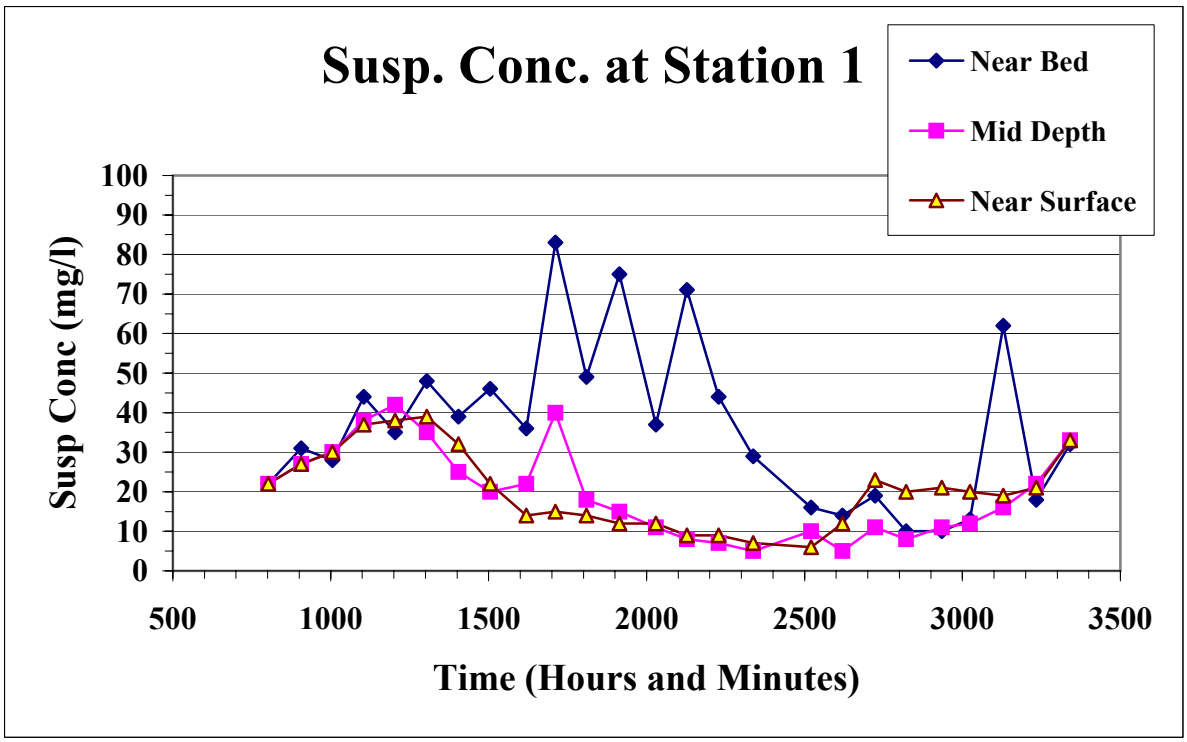


Figure 3.4.9: Depth-variation of suspended sediment concentration at Station 1, navigation channel south

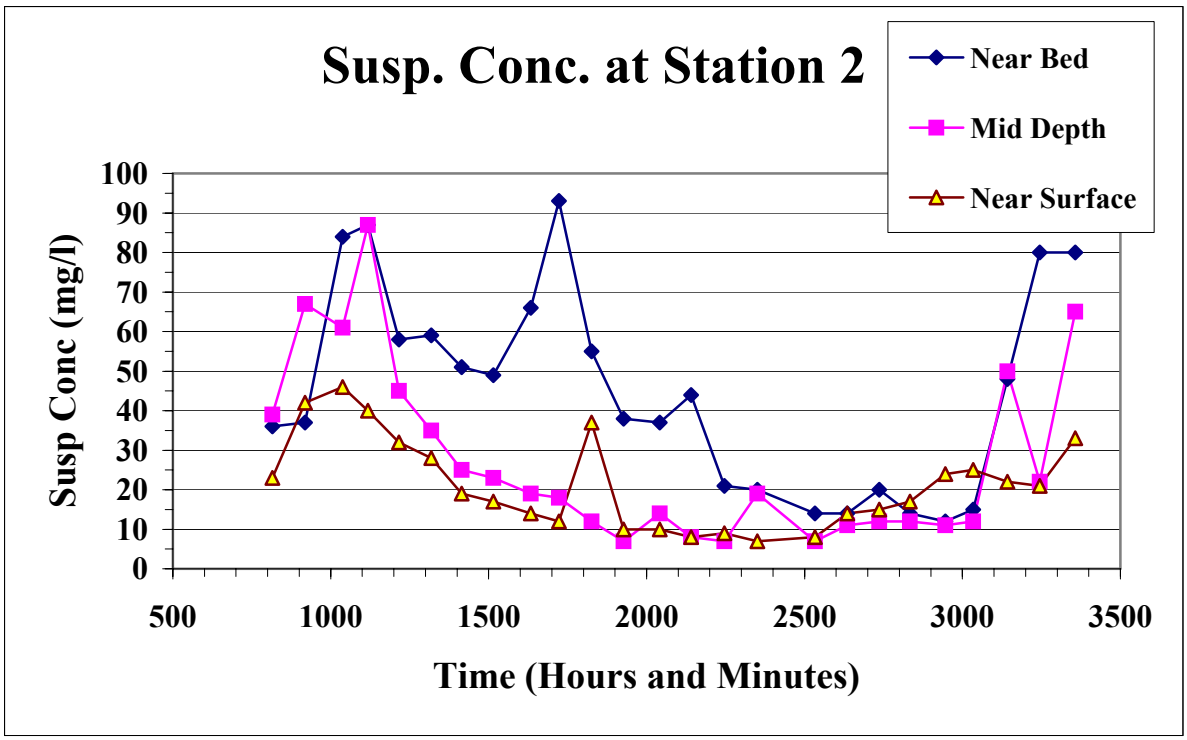


Figure 3.4.10: Depth-variation of suspended sediment concentration at Station 2, east GIWW

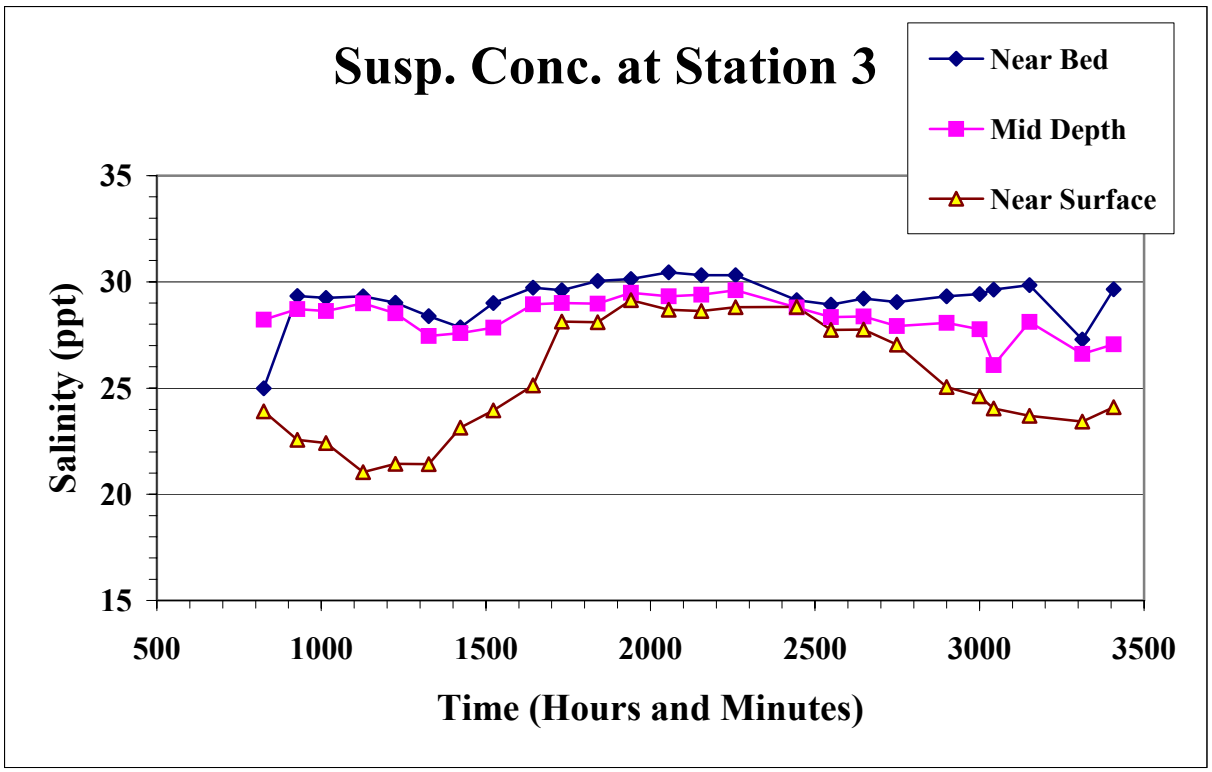


Figure 3.4.11: Depth-variation of suspended sediment concentration at Station 3, west GIWW

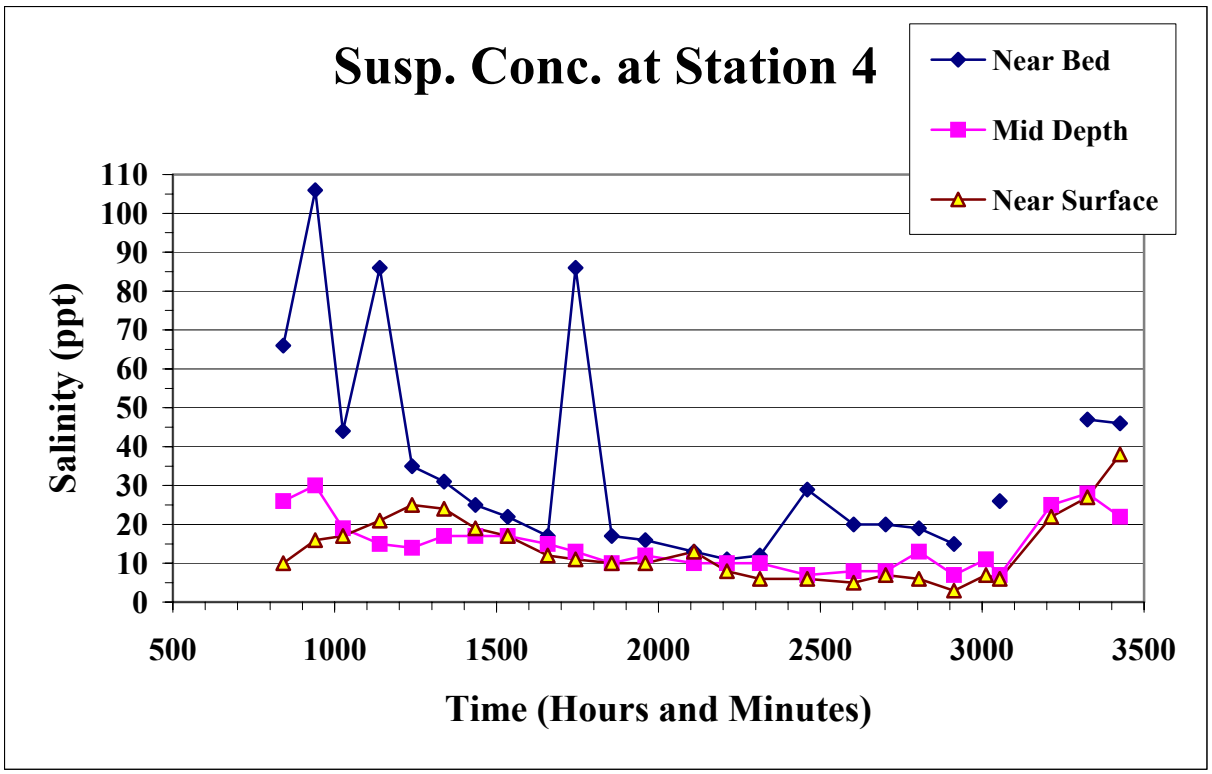


Figure 3.4.12: Depth-variation of suspended sediment concentration at Station 4, Big Bend

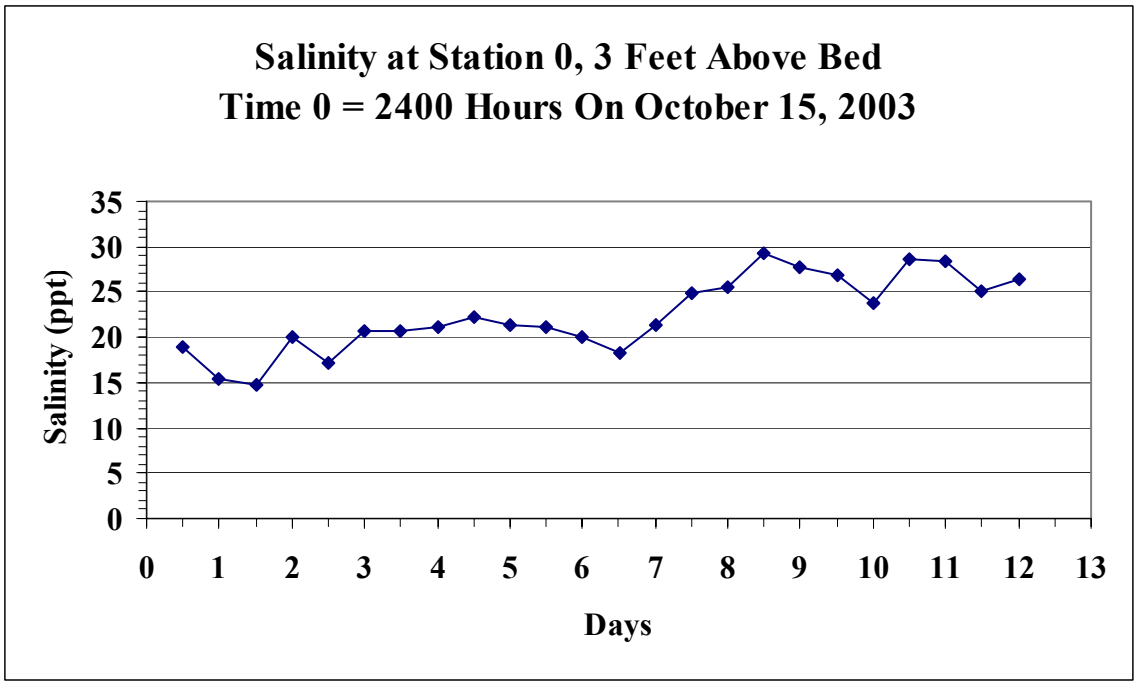


Figure 3.4.13: Salinity at Station 0, navigation channel south

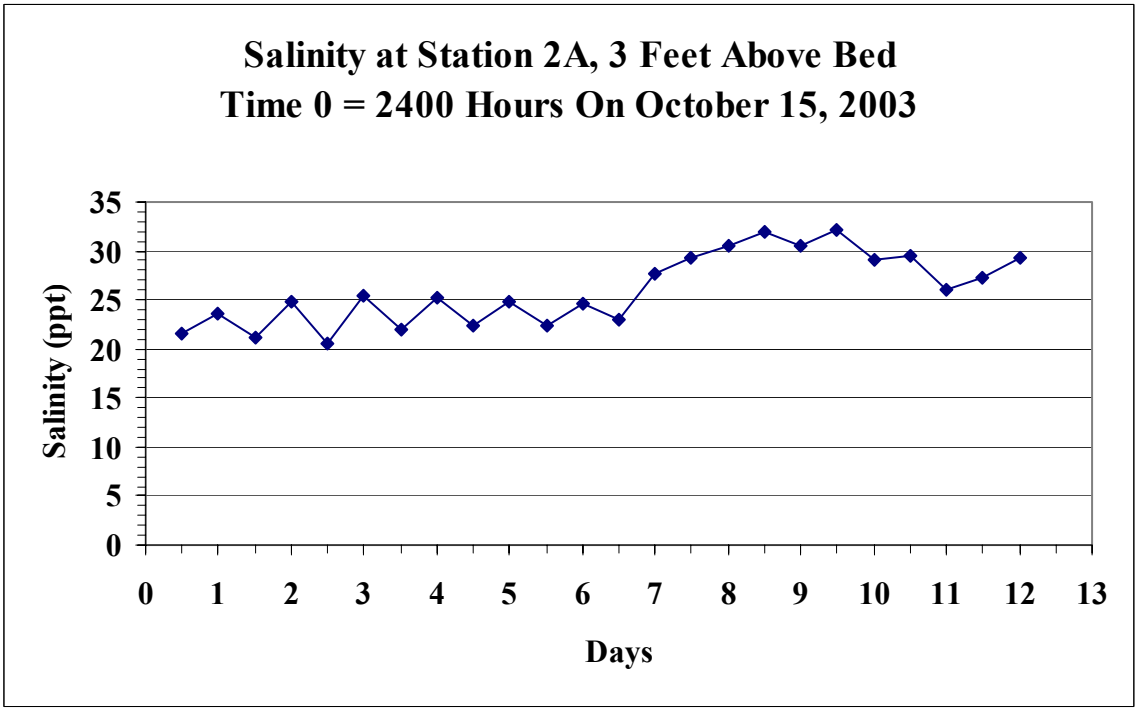


Figure 3.4.14: Salinity at Station 2A, east GIWW

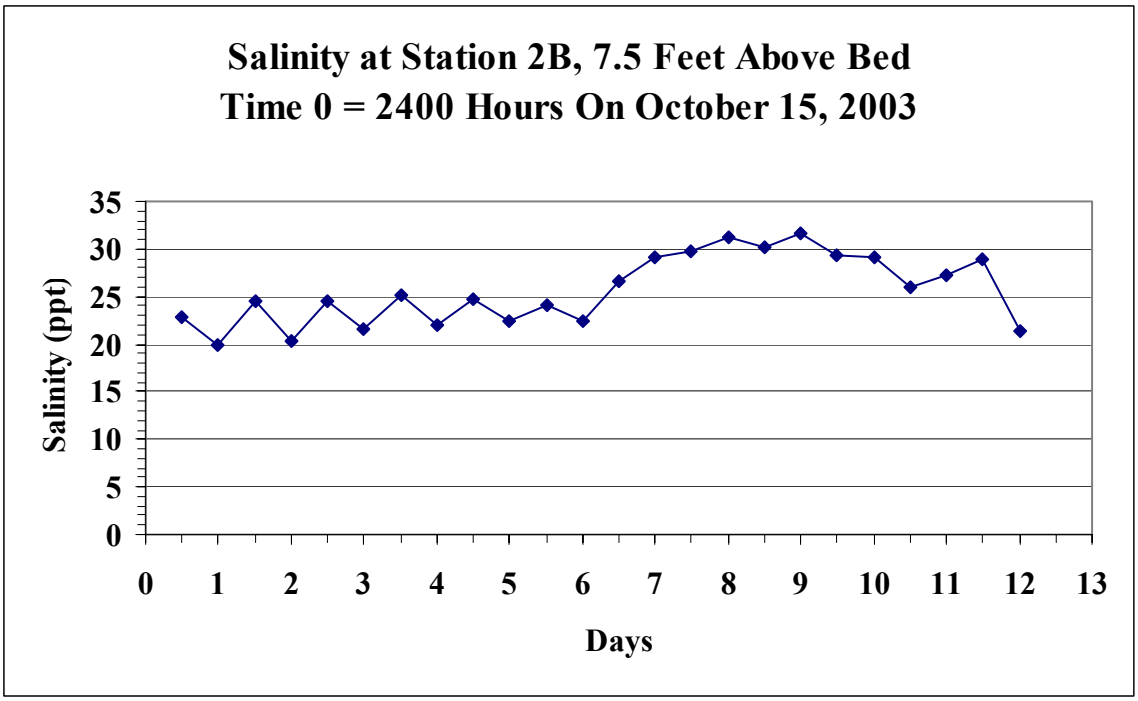


Figure 3.4.15: Salinity at Station 2B, east GIWW

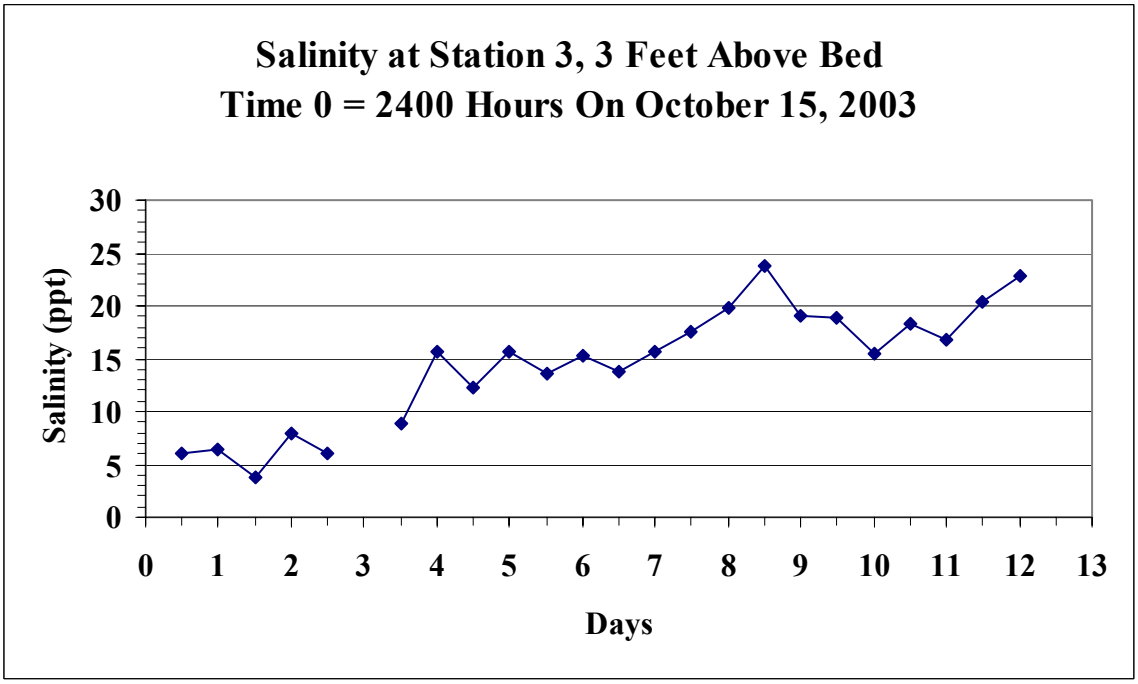


Figure 3.4.16: Salinity at Station 3, west GIWW

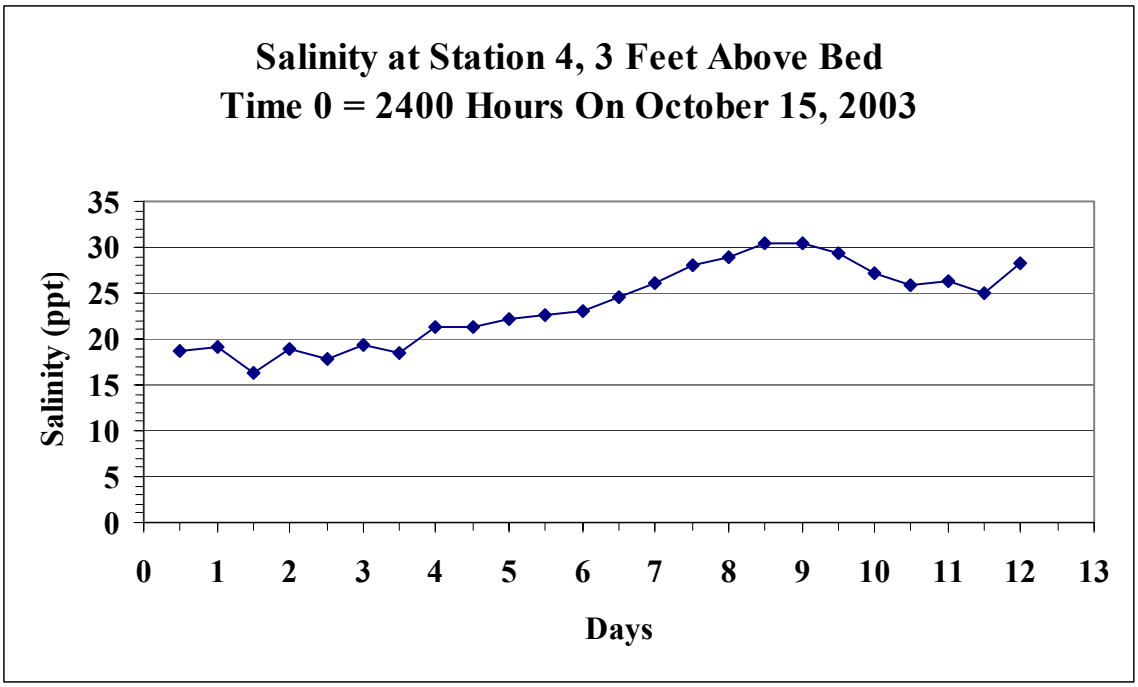


Figure 3.4.17: Salinity at Station 4, Big Bend

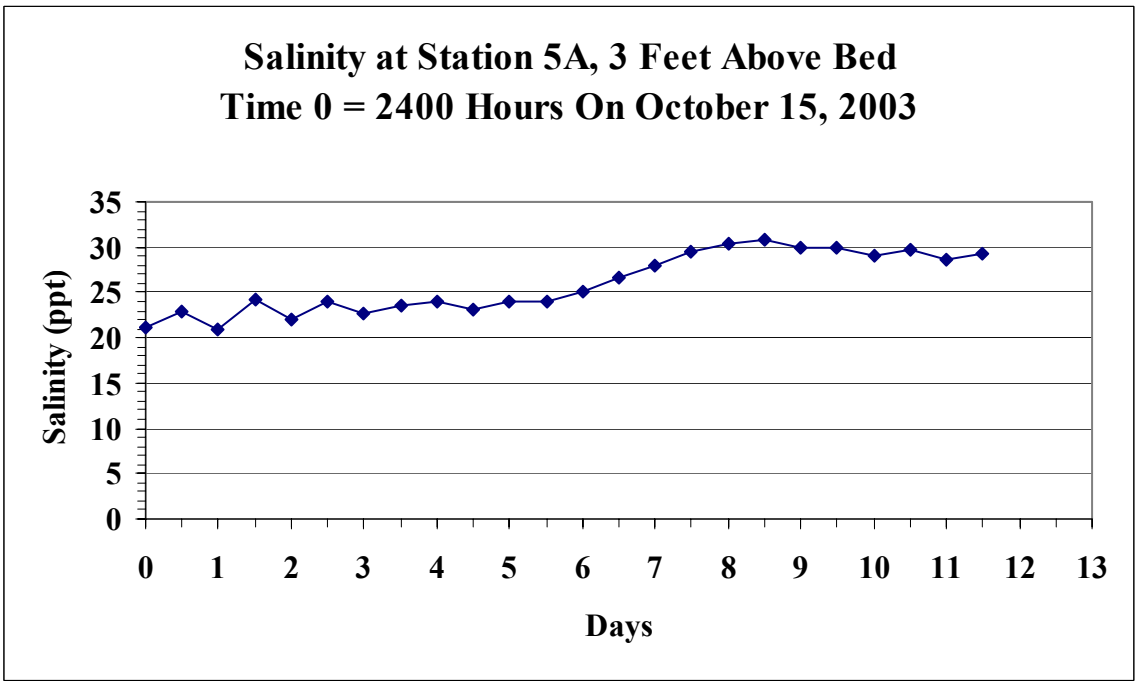


Figure 3.4.18: Salinity at Station 5A, navigation channel north

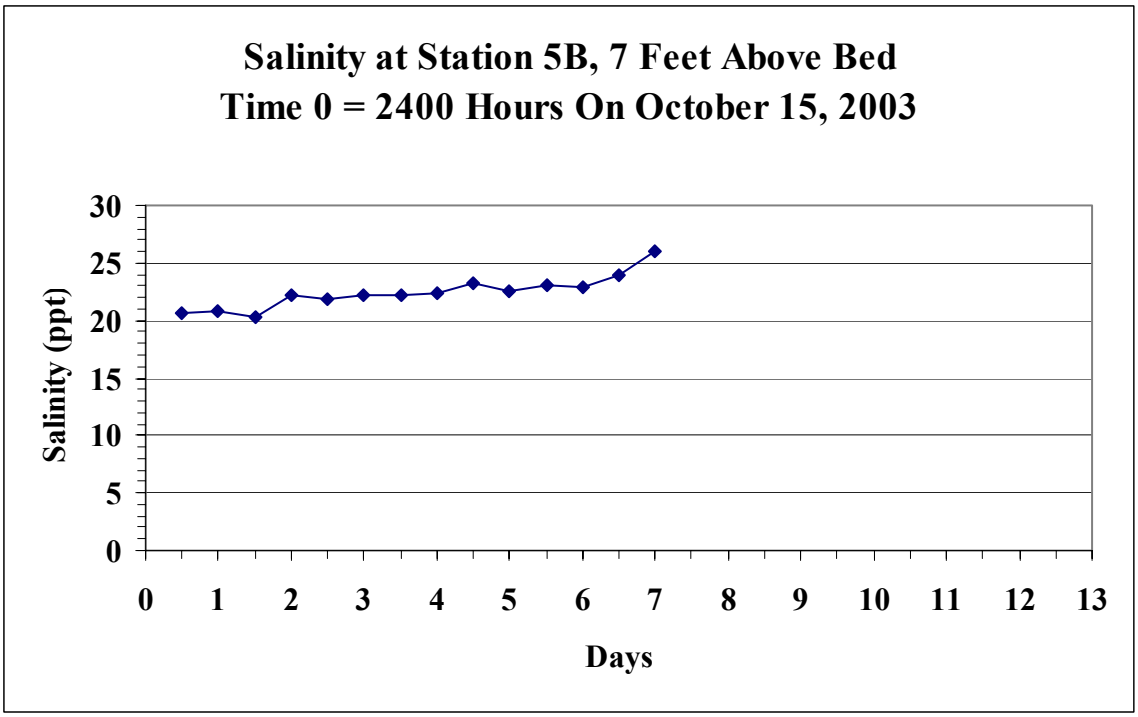


Figure 3.4.19: Salinity at Station 5B, navigation channel north

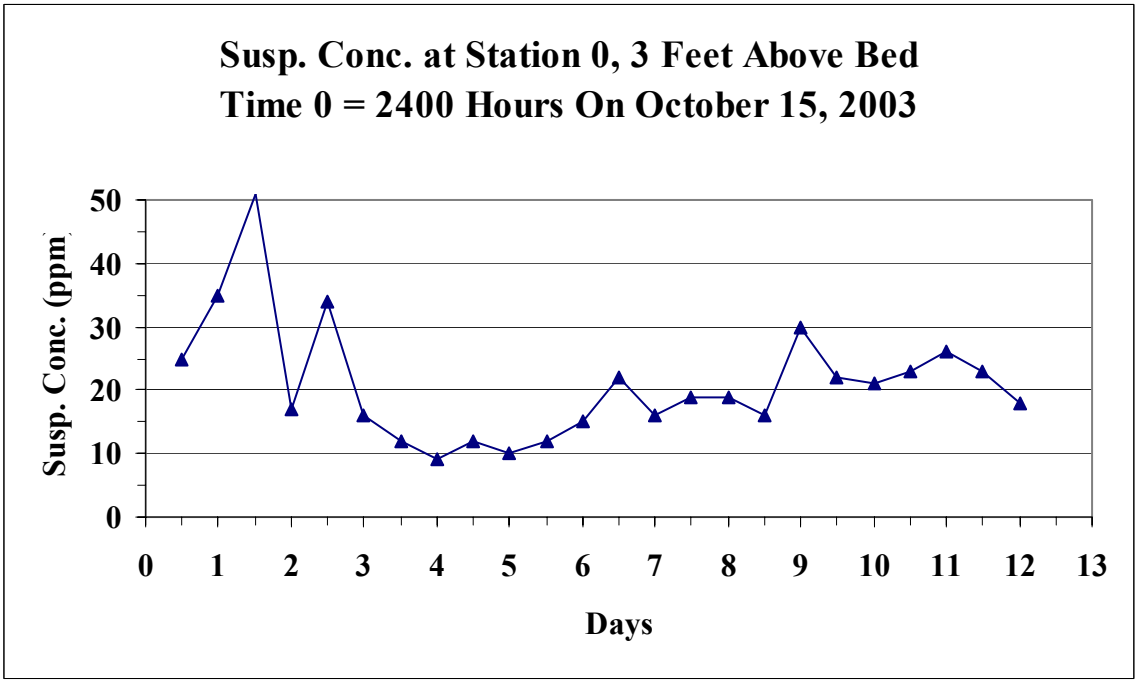


Figure 3.4.20: Suspended sediment concentration at Station 0, navigation channel south

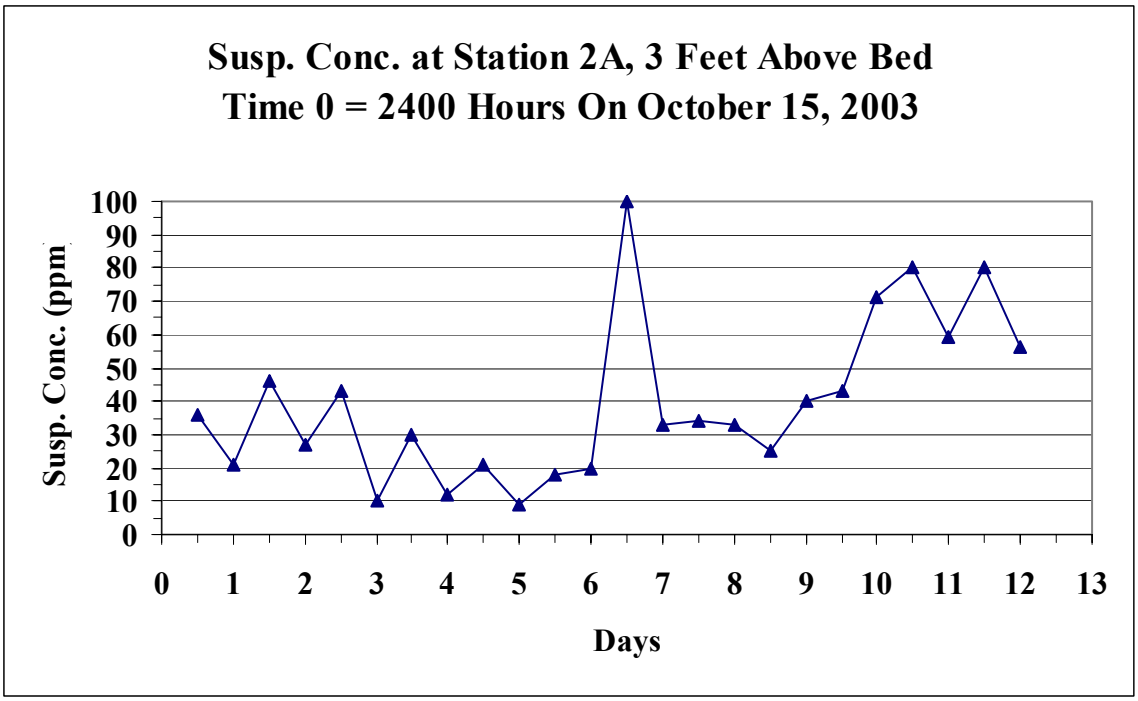


Figure 3.4.21: Suspended sediment concentration at Station 2A, east GIWW

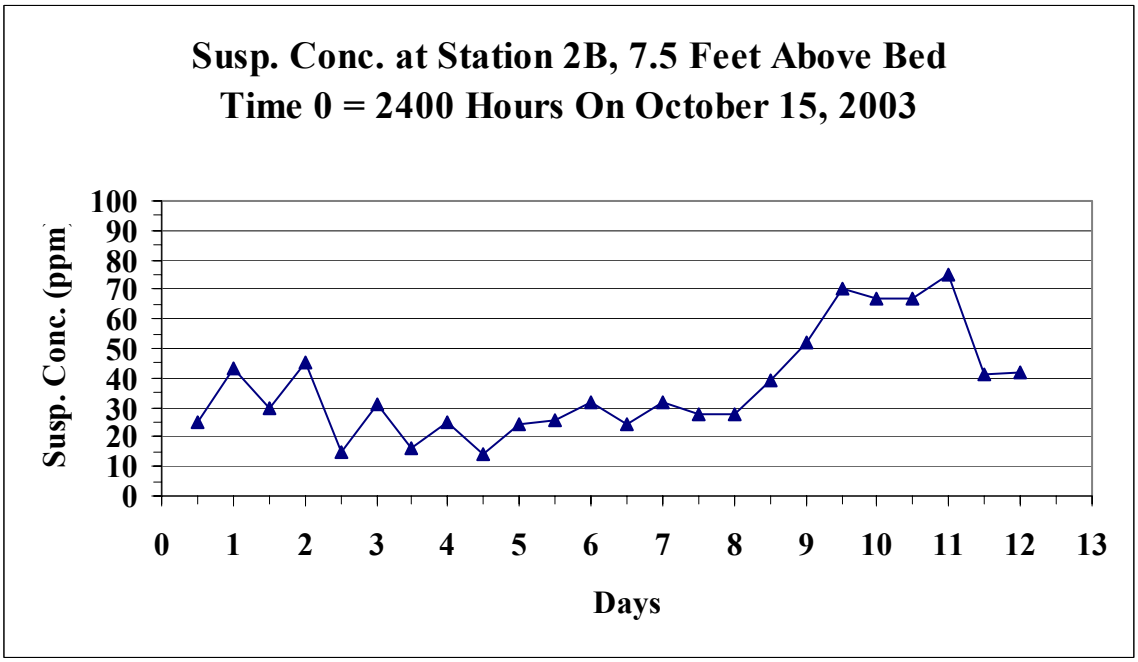


Figure 3.4.22: Suspended sediment concentration at Station 2B, east GIWW

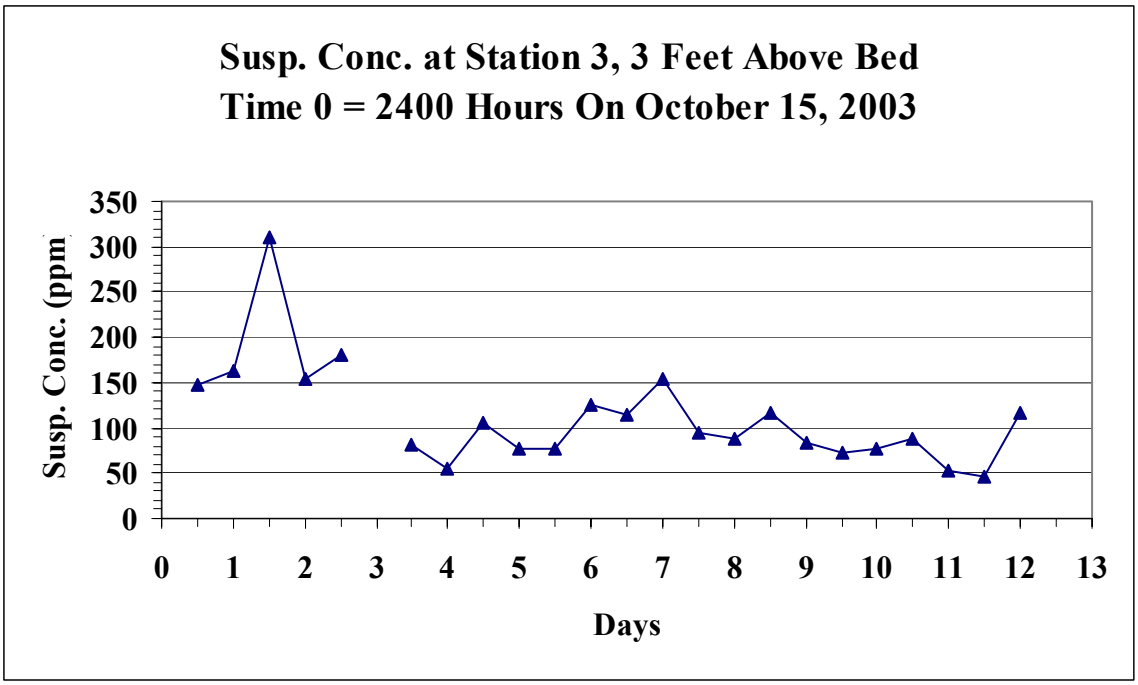


Figure 3.4.23: Suspended sediment concentration at Station 3, west GIWW

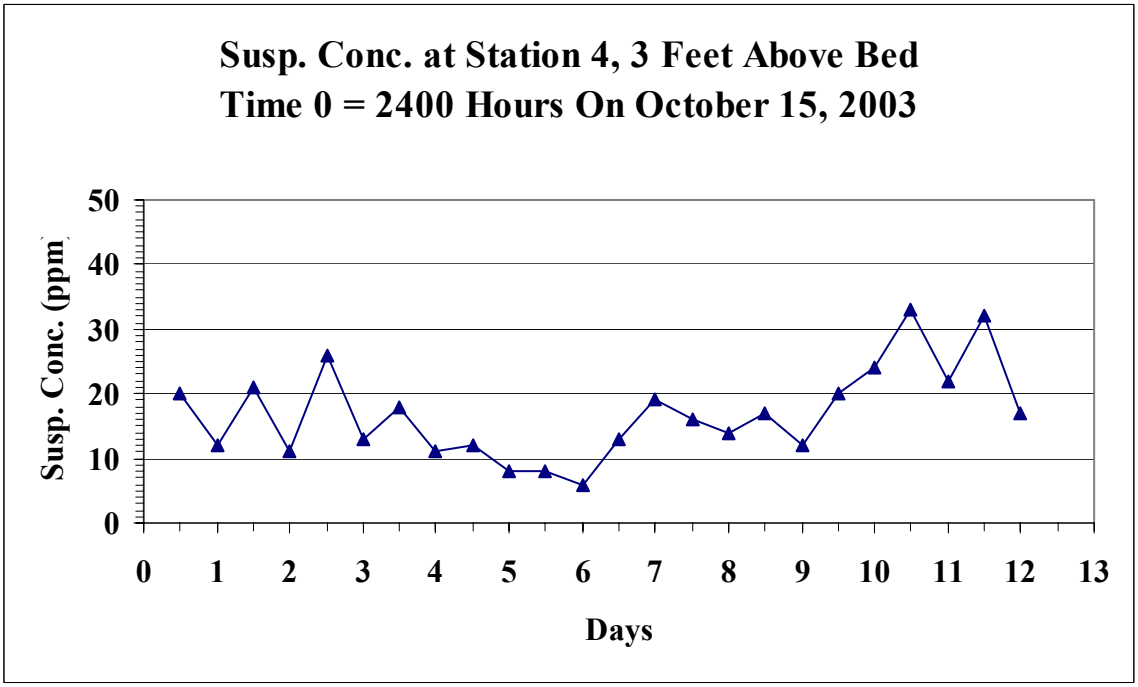


Figure 3.4.24: Suspended sediment concentration at Station 4, Big Bend

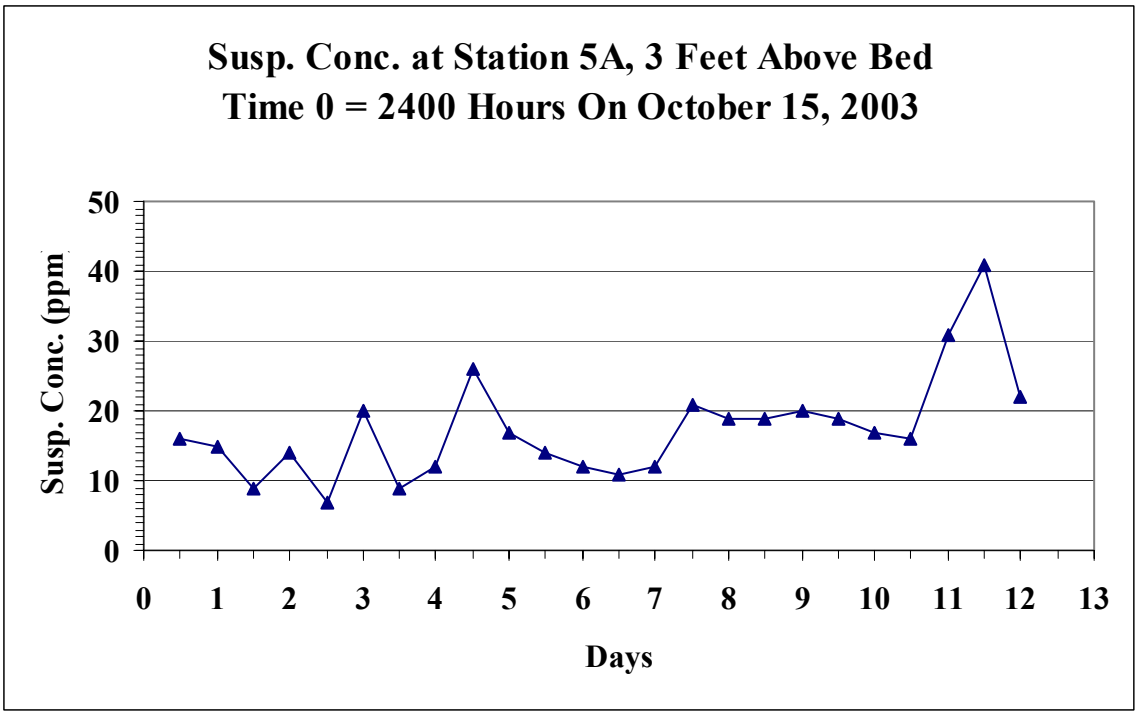


Figure 3.4.25: Suspended sediment concentration at Station 5A, navigation channel north

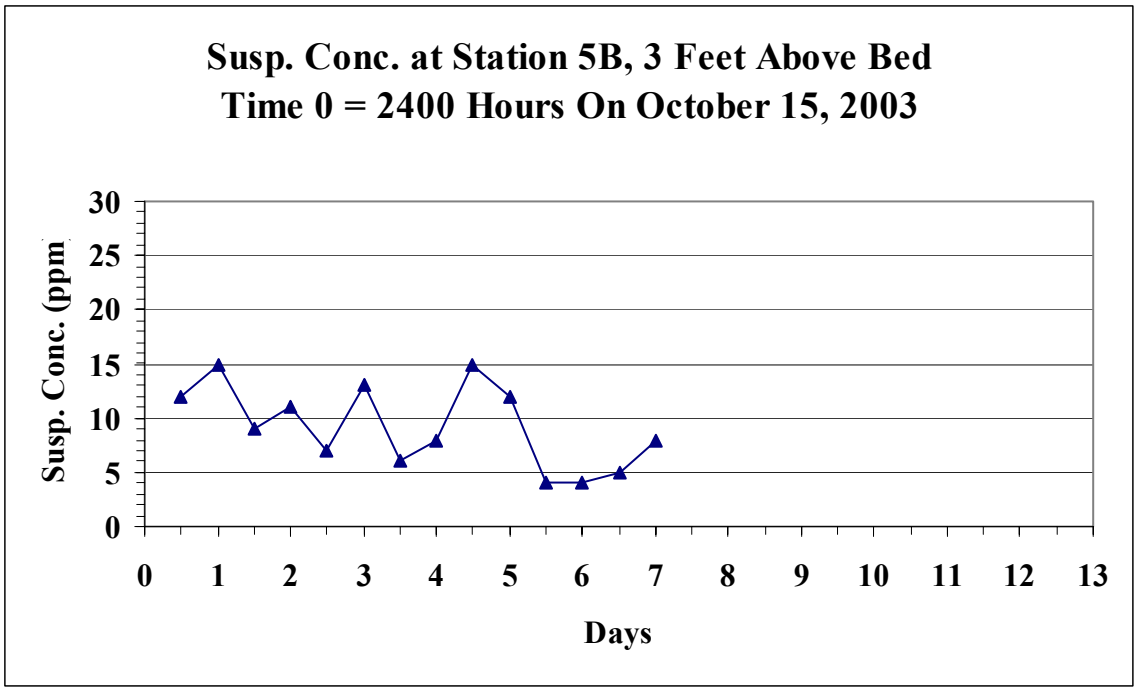
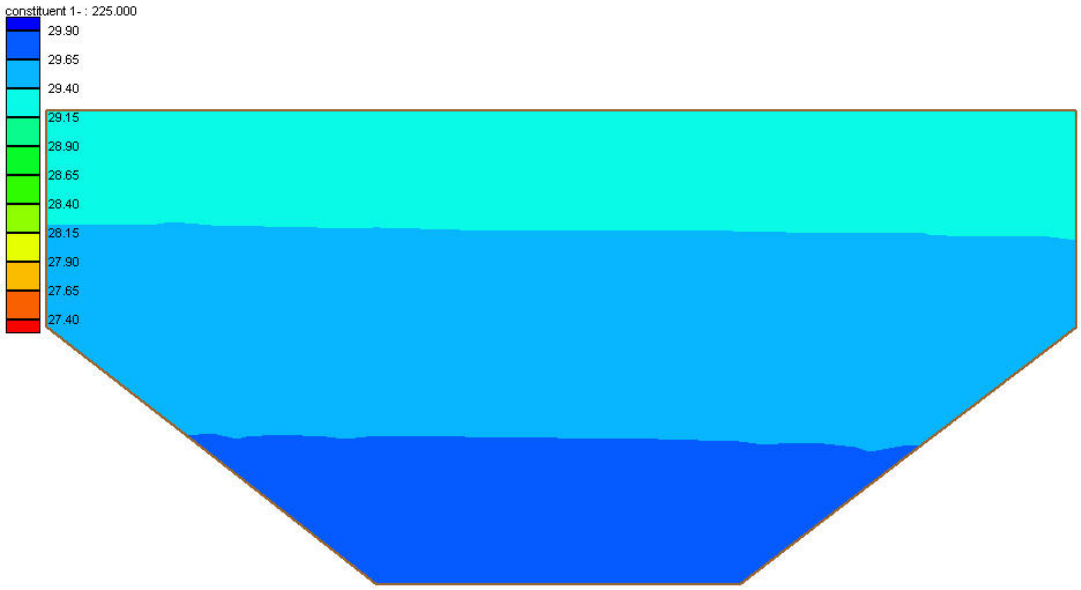
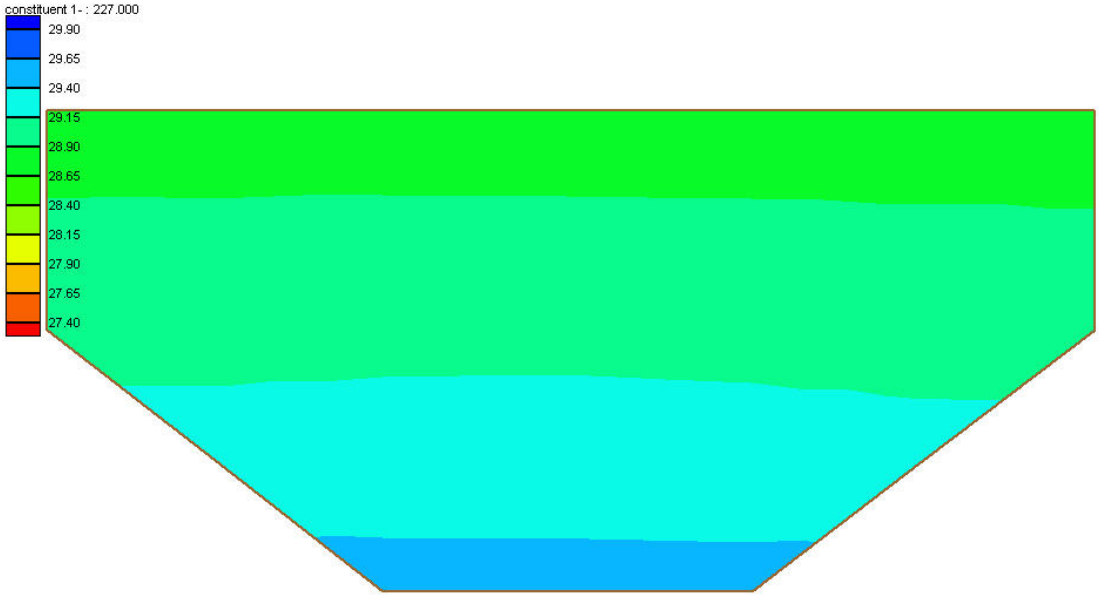


Figure 3.4.26: Suspended sediment concentration at Station 5B, navigation channel north



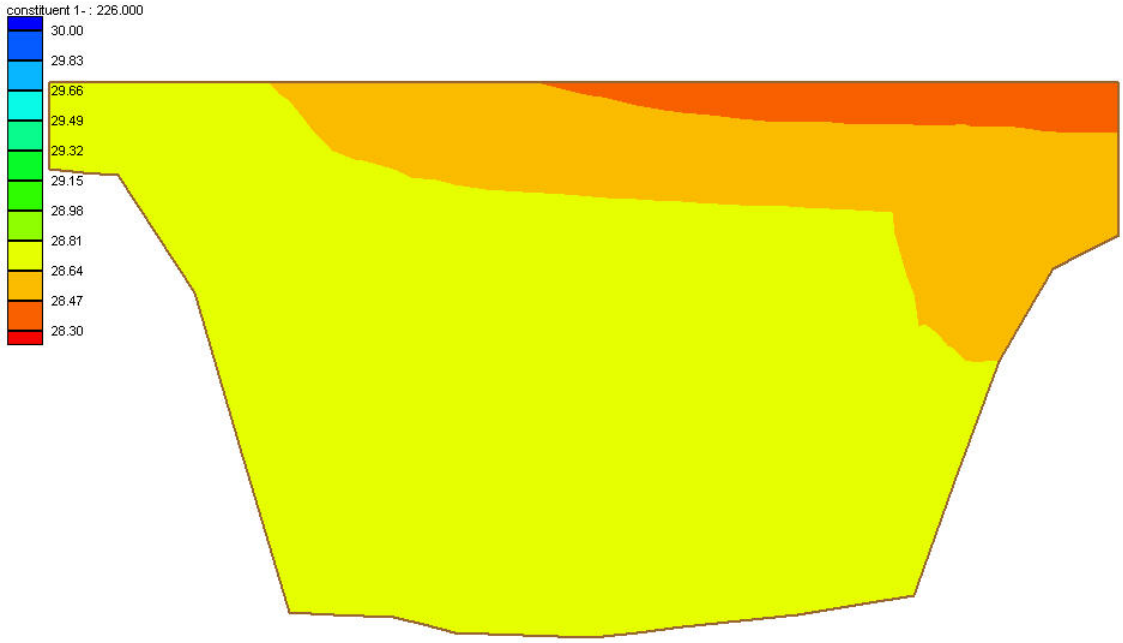
L1d1h12

Figure 3.4.27: Salinity at Transect 1 on day 1 hour 12



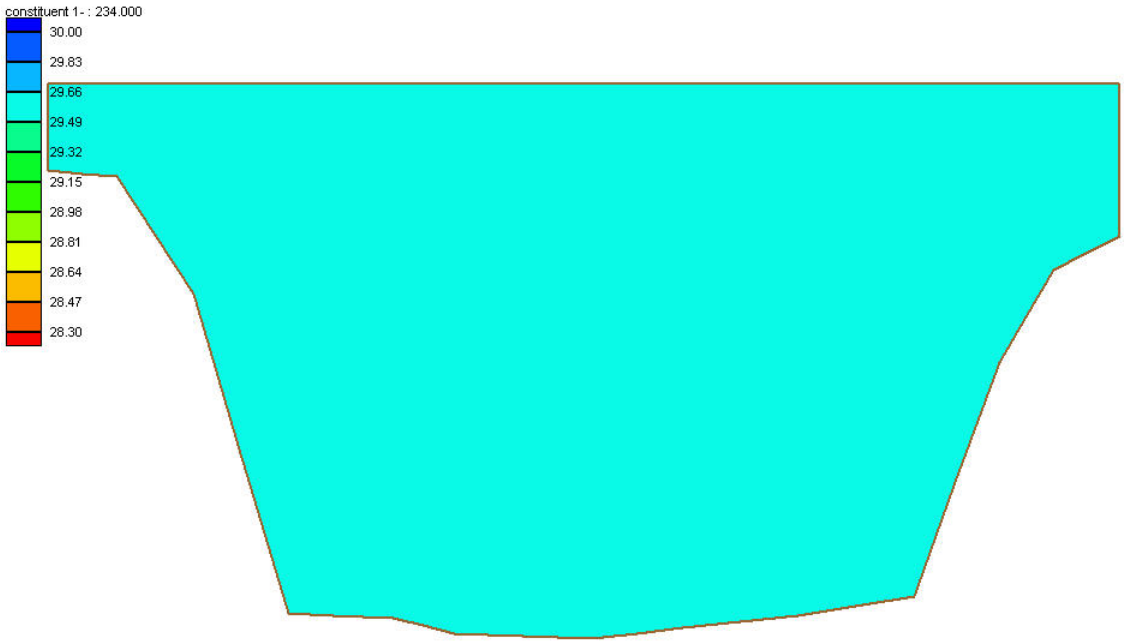
L1d1h14

Figure 3.4.28: Salinity at Transect 1 on day 1 hour 14



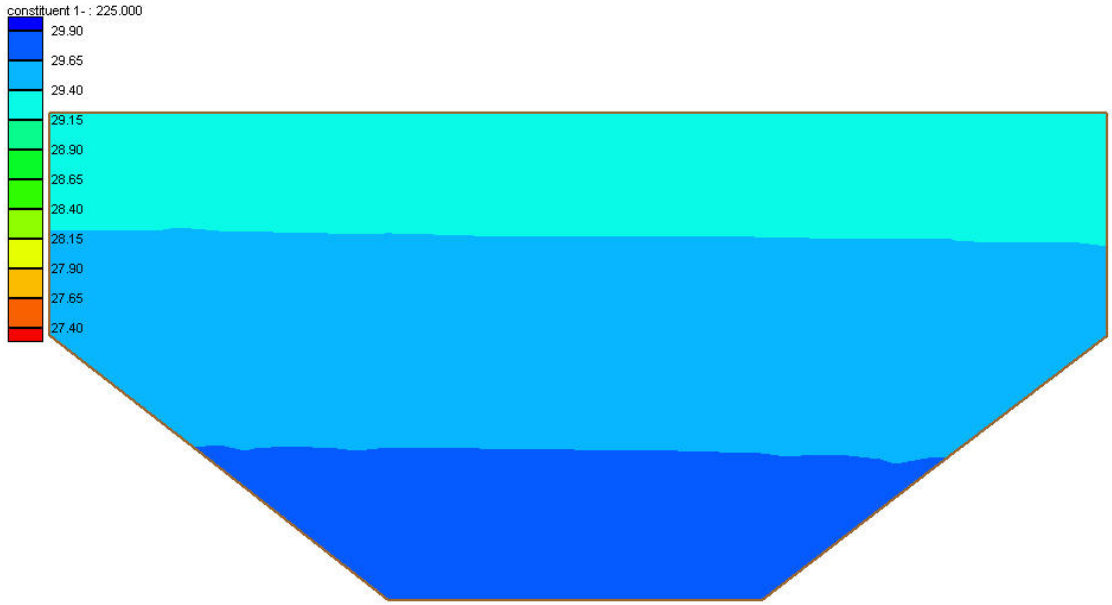
L2d1h16

Figure 3.4.29: Salinity at Transect 2 on day 1 hour 16



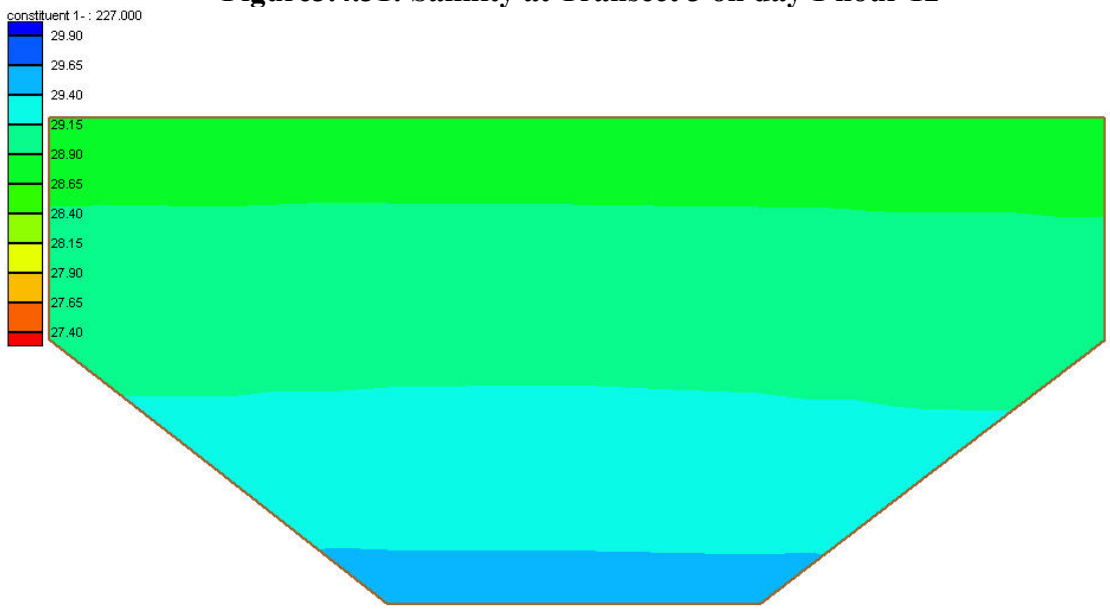
L2d1h21

Figure 3.4.30: Salinity at Transect 2 on day 1 hour 21



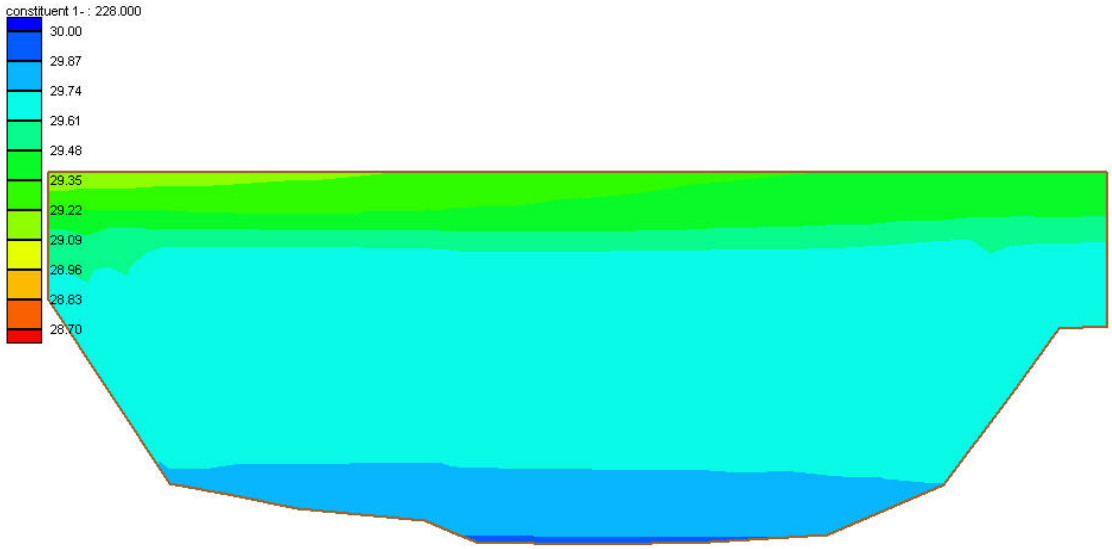
L3d1h12

Figure3.4.31: Salinity at Transect 3 on day 1 hour 12



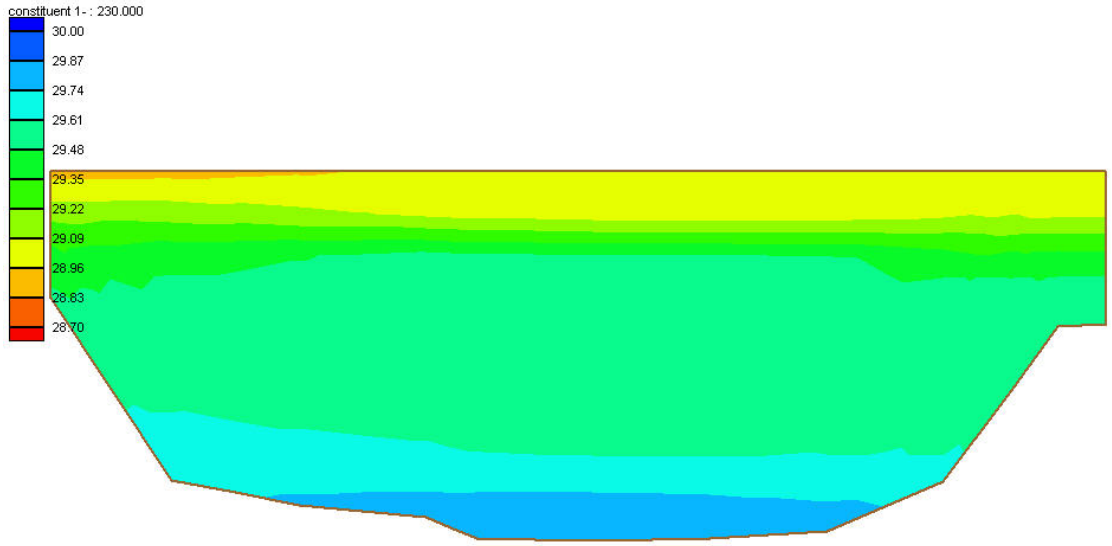
L3d1h14

Figure3.4.32: Salinity at Transect 3 on day 1 hour 14



L4d1h15

Figure 3.4.33: Salinity at Transect 4 on day 1 hour 15



L4d1h17

Figure3.4.34: Salinity at Transect 4 on day 1 hour 17

3.5. Currents

Acoustic Doppler Current Profiler (ADCP) was used for collecting current data in the field. This equipment is carried on a boat, which traverses bank to bank within a channel. Data on current magnitude and direction are recorded at several stations across the width and depth of channel section as the boat travels. The data are processed in office by using software called "HYPAS", which has been specially developed at ERDC for this purpose.

The area of intersection of Freeport navigation channel and GIWW is the area of complex flow pattern. Hence current direction and magnitude were measured at four transects located on four sides of this junction as shown in Figure 3.5.1. The locations may be described as follows:

Transect 1	North of the junction in the Dow barge canal
Transect 2	East of junction in the navigation channel
Transect 3	South of junction in the west GIWW
Transect 4	West of junction in the navigation channel.

ADCP data were collected over a period of 25 hours starting at 7000 hours on October 28, 2003. The total ADCP current data are voluminous and have been given to the Galveston District on a CD. The data can be plotted for any location on the transect. Since field data need to be compared with the model data, one location on each of the four transects was selected for purposes of presenting an illustration of field current observations. Figure 3.5.2 shows locations of these four nodes. They were as follows:

Transect 1	Node # 4522	Transect 2	Node # 4000
Transect 3	Node # 4189	Transect 4	Node # 5196

Appendix 2 contains plots of ADCP field current observations at the above listed four nodes. Hourly depth-variation of current magnitudes and directions at each node is shown in these plots.

ADCP data were plotted for each transect showing the velocity distribution. Illustrations of such plots for each of the four transects are shown in Figures 3.5.3 through 3.5.6. More plots are given in Figures 4.5.6 through 4.5.13 under Chapter 4. Such plots have been used for numerical model validation for currents.

The depth-averaged magnitudes and directions of observed velocities were also plotted at each transect as a function of distance from the corresponding bank line. Data were available for each hour. Illustrative plots for Transects 1, 2, 3, and 4 for are given in Figures 3.5.7 through 3.5.10.

The following observations are made on the current measurements in the field:

1. ADCP is a sensitive device for measuring field currents at a large number of locations across the width and depth of transect selected for measurements.

2. The voluminous data can be analyzed only with the help of software developed for this purpose. The sign assigned to magnitudes indicates current direction. Plus sign indicates flood tide and minus sign indicates ebb.

3. The data provide instantaneous values of velocities. Since the total time required to complete measurement along one transect is small relative to the duration of tidal cycle period, the data are considered synoptic.

4. Depth-averaged values along transect result in values that fluctuate around the zero current. Small magnitudes in the range of +0.2 ft/s to –0.2 ft/s may be ignored because these could be a result of local turbulence.

5. Although hourly depth-averaged values showed large variation between +2 ft/s and –2 ft/s, the predominant variation was between +1 ft/s and –1 ft/s for flood and ebb respectively.

6. Higher velocity magnitudes noticed in some cases is an indication of non-uniform velocity distribution across a section.

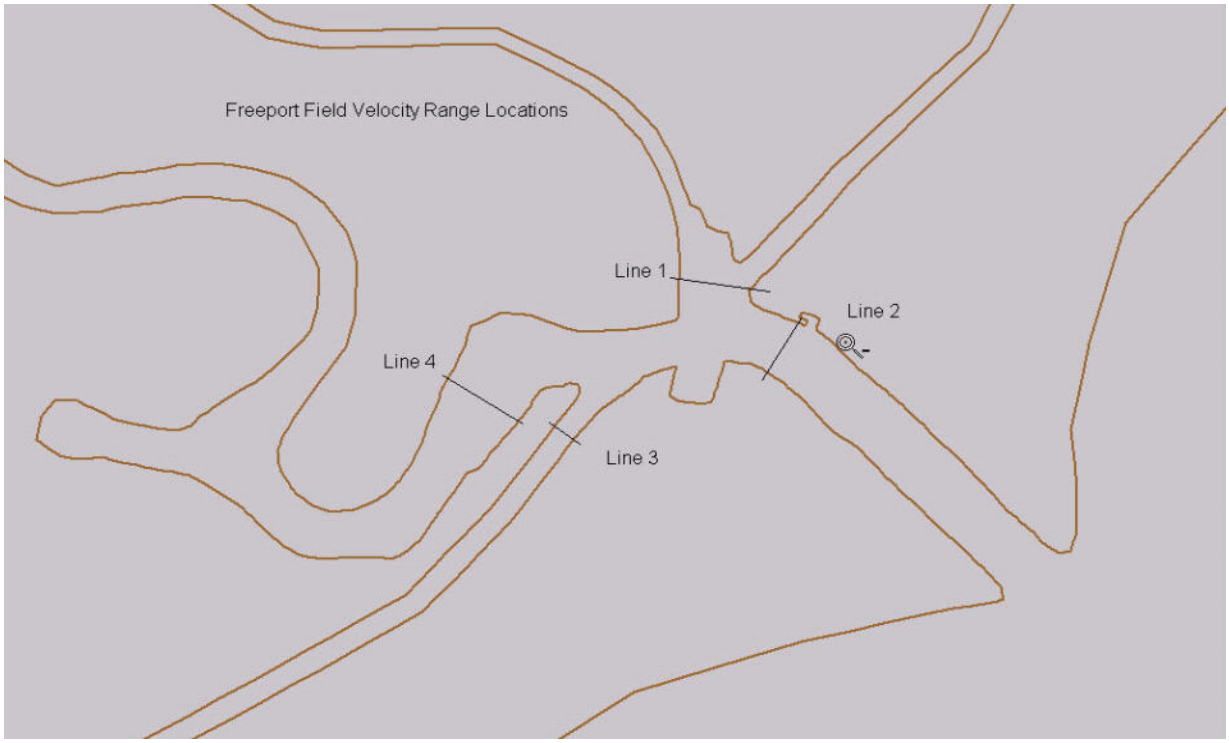


Figure 3.5.1. Locations of transects for current measurements

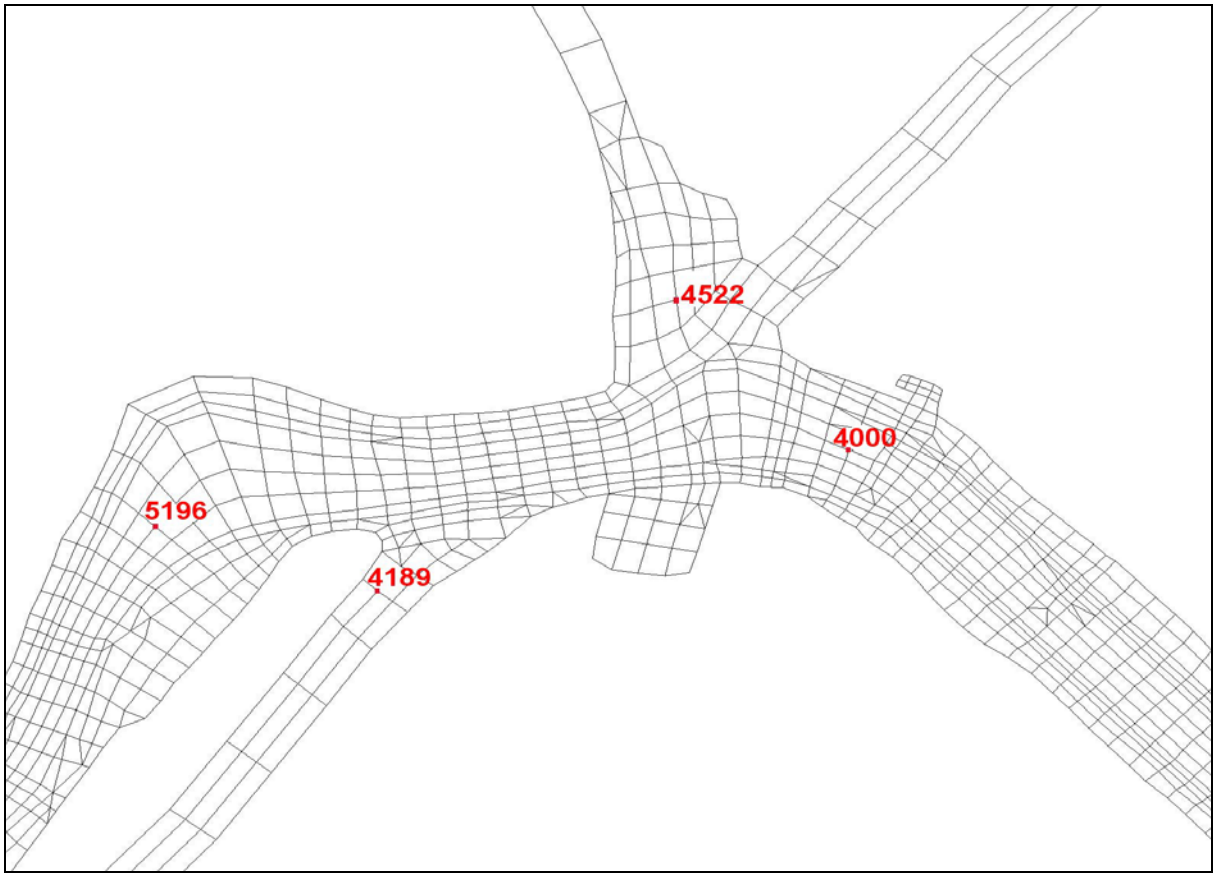
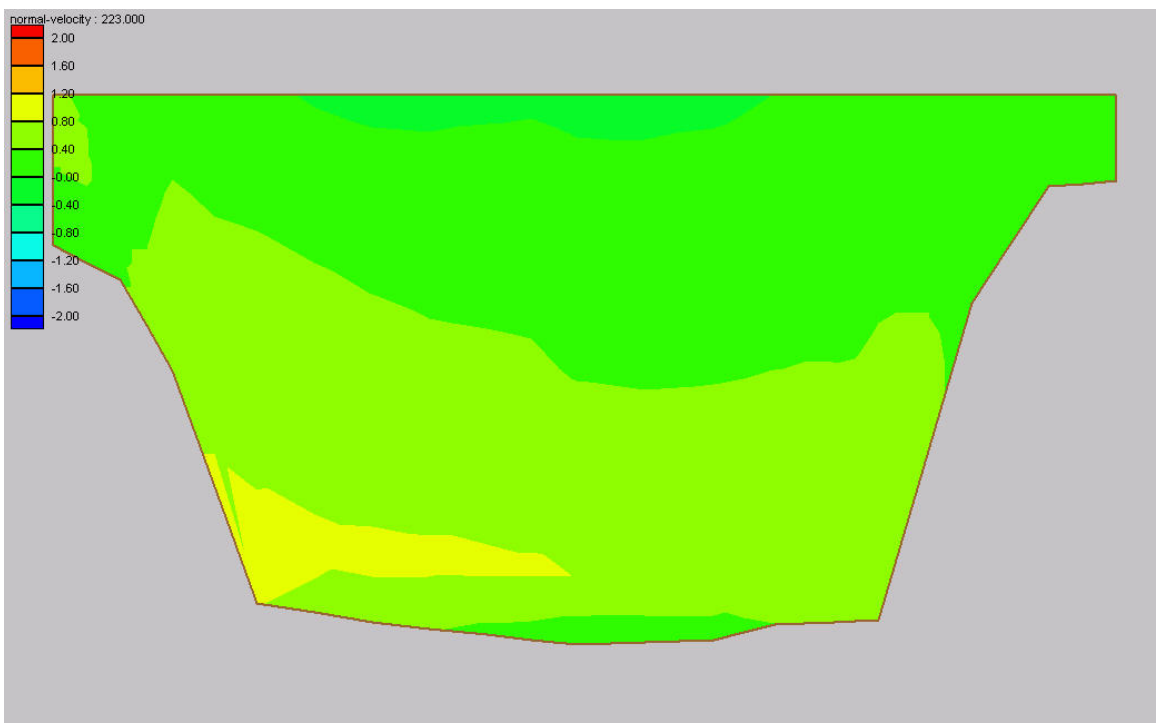


Figure 3.5.2: Locations of nodes on each transect for presenting illustrations of observed velocities

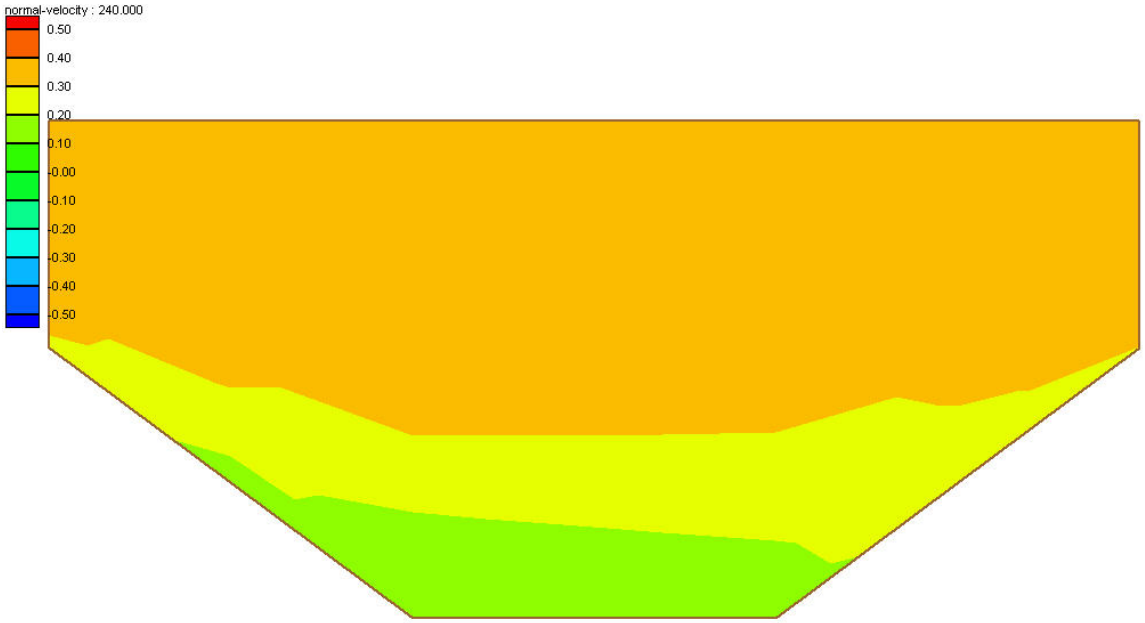
L1d2h5_M

Figure 3.5.3: Velocity contours at Transect 1 at day 2, hour 5



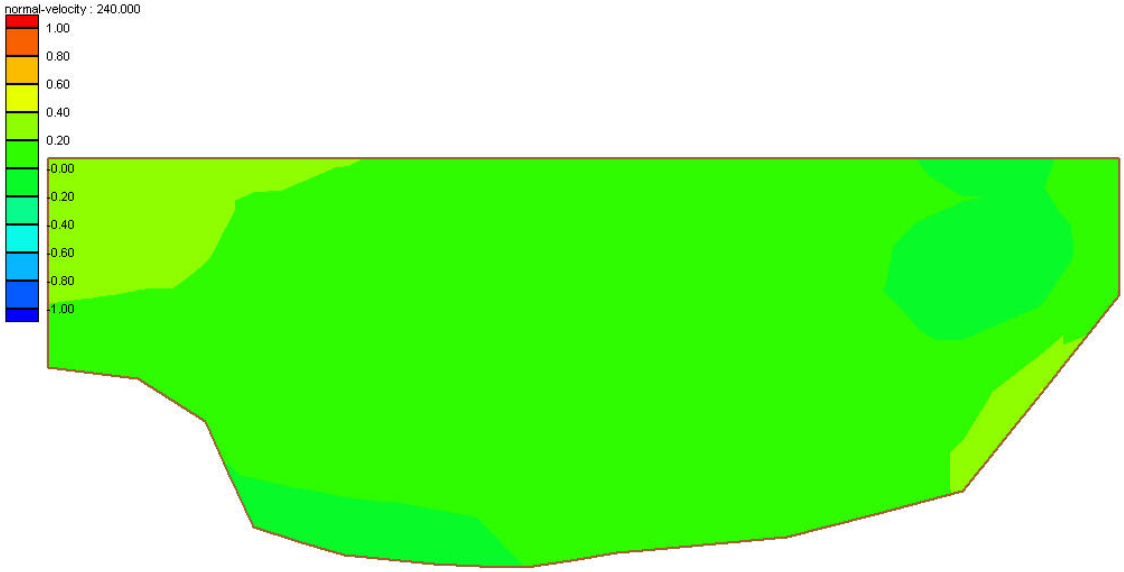
L2d1h10_M

Figure 3.5.4: Velocity contours at Transect 2 at day 1, hour 10



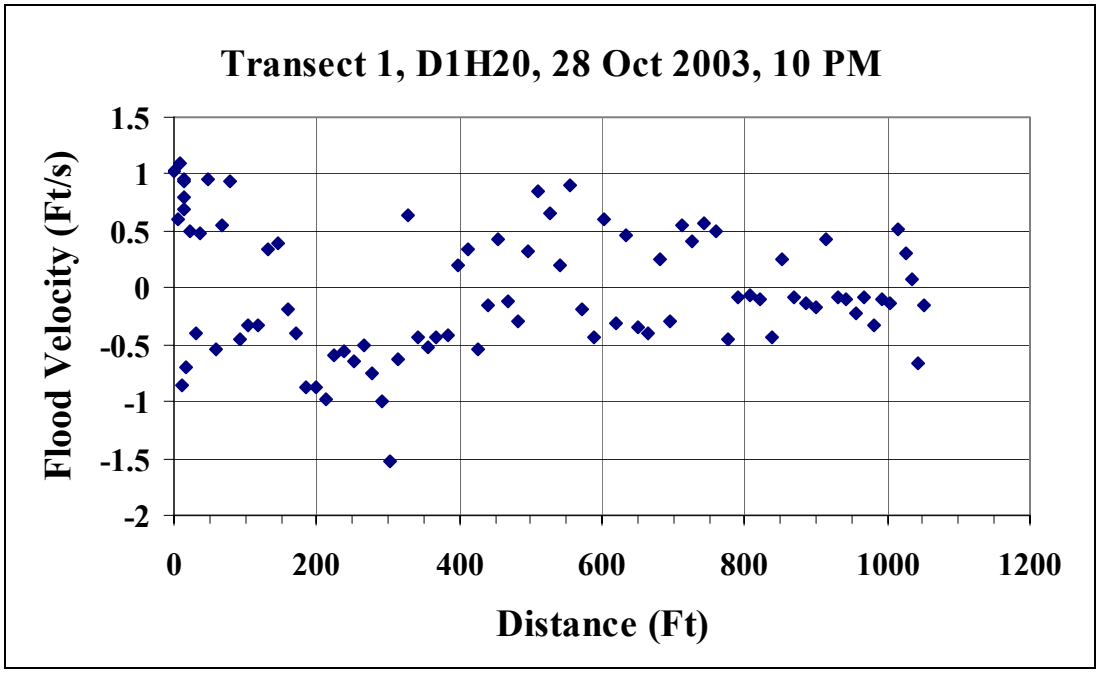
L3d2h4_M

Figure 3.5.5: Velocity contours at Transect 3 at day 2, hour 4



L4d2h4_M

Figure 3.5.6: Velocity contours at Transect 4 at day 2, hour 4



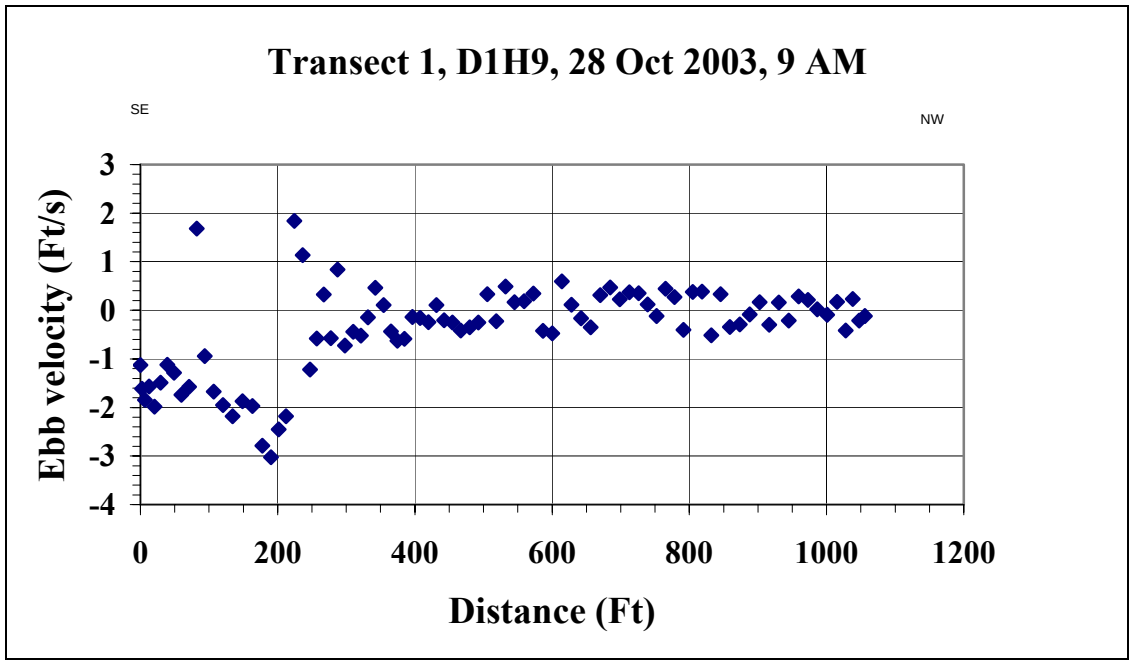
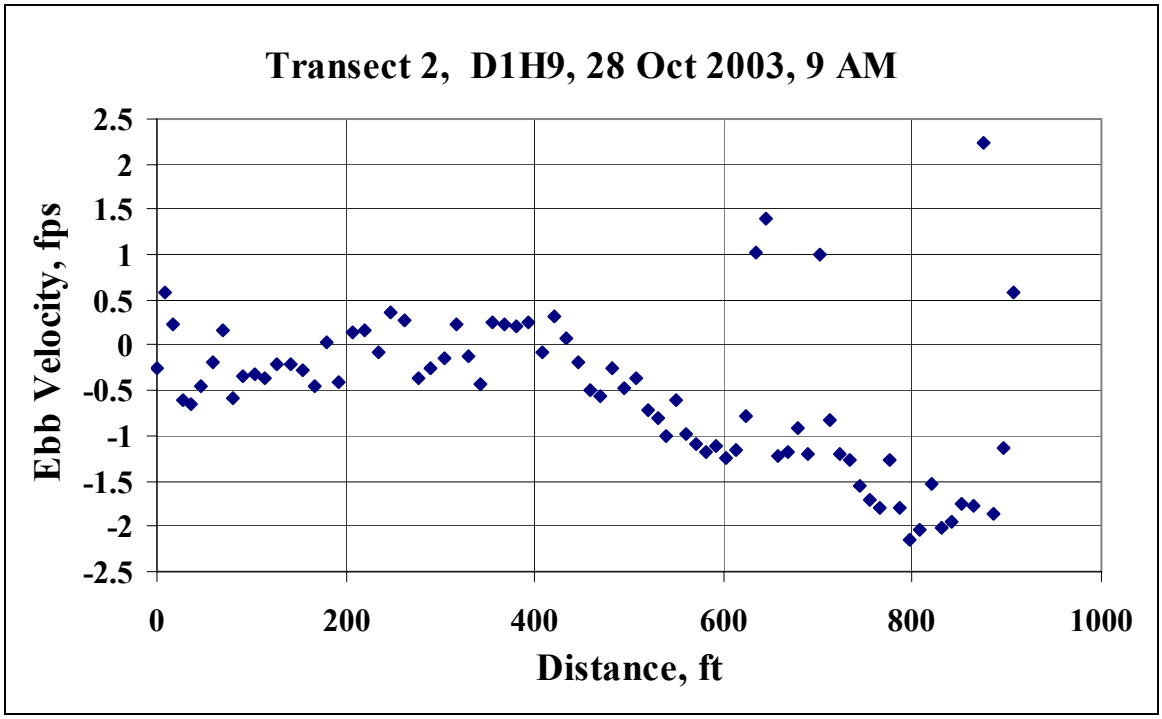


Figure 3.5.7: Depth-averaged ADCP velocity observed at Transect 1



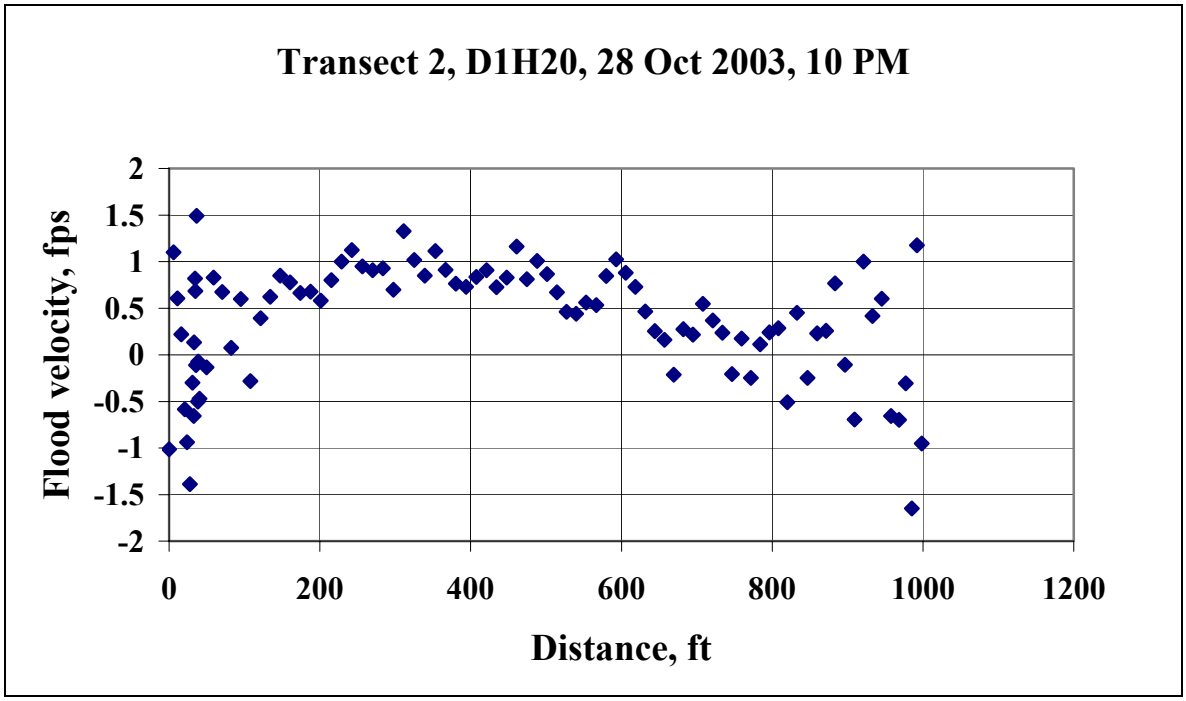
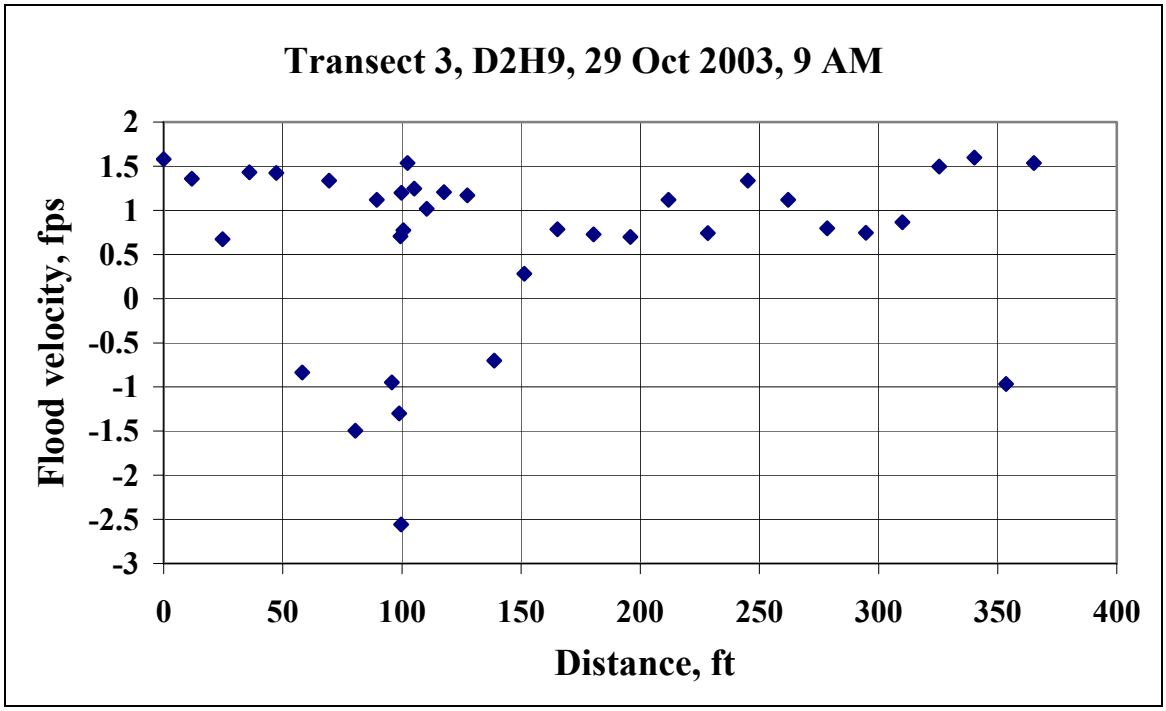


Figure 3.5.8: Depth-averaged ADCP velocity observed at Transect 2



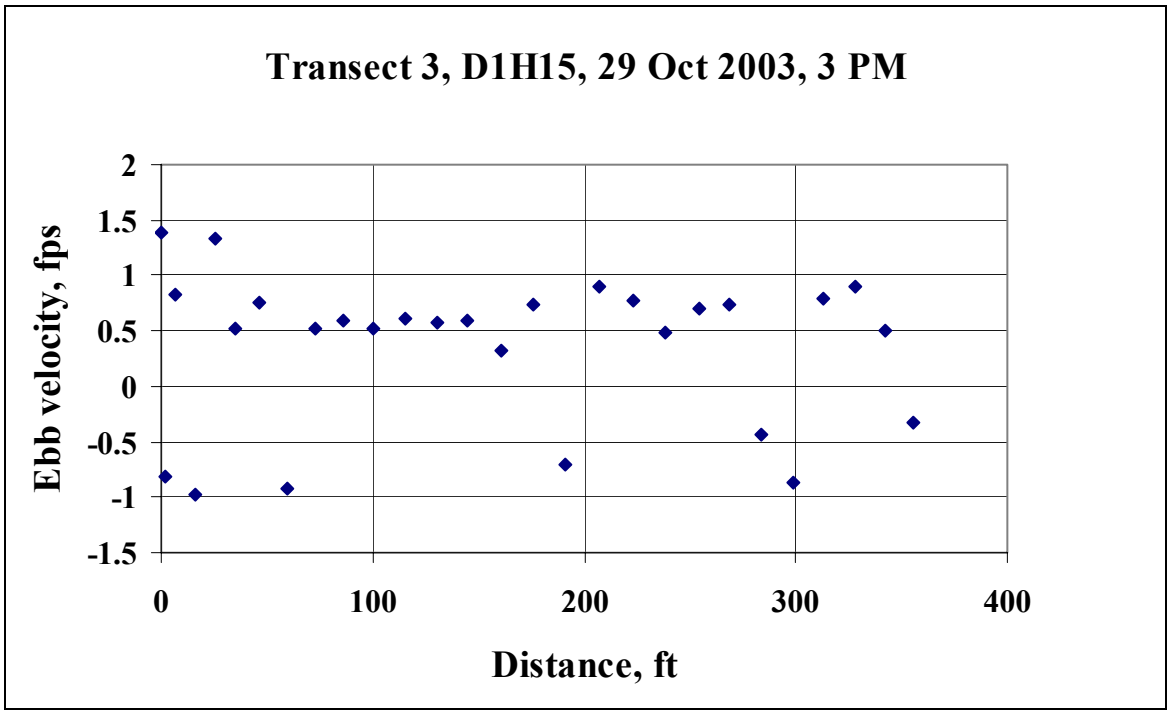
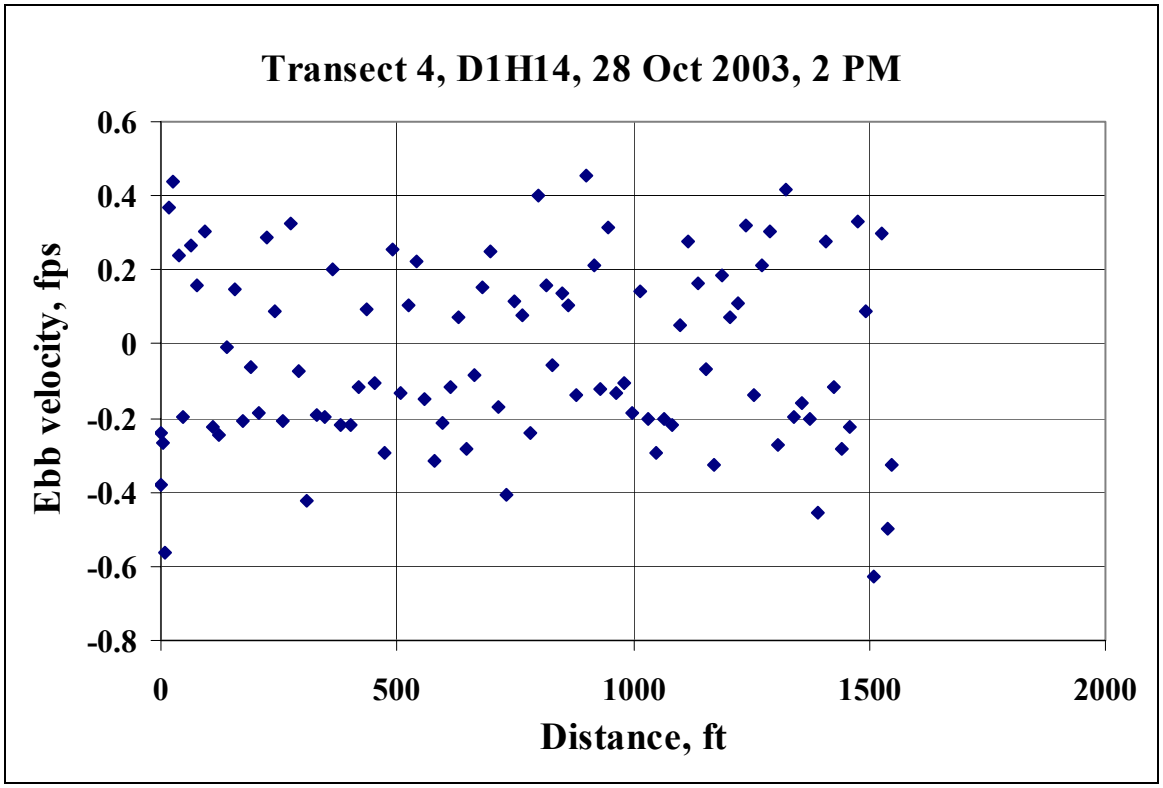


Figure 3.5.9: Depth-averaged ADCP velocity observed at Transect 3



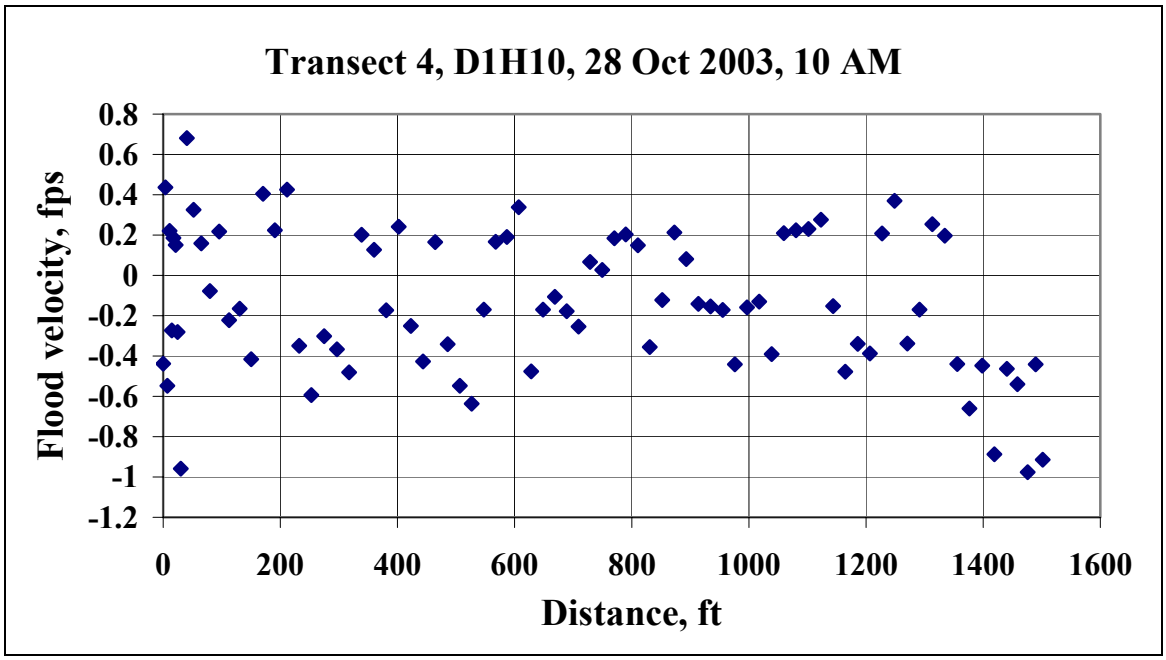


Figure 3.5.10: Depth-averaged ADCP velocity observed at Transect 4

3.6 Dredging

The Galveston District supplied dredging data collected over the past several years. These included total quantity of sediment removed from the navigation channel for new works as well as for maintenance of navigable depth. These data were available separately for the following three main reaches of the channel: 1) Outer Bar Channel, 2) Jetty Channel, and 3) Harbor Channel. Each operation of maintenance dredging has been termed in this report as a dredging cycle for convenience of reference. It is obvious that the quantity of sediment removed is equal to the amount of shoaling in the channel between the end of previous dredging operation to the beginning of the next operation. However, shoaling of channel continues to take place even while the dredging operation is in progress. Hence dredging cycle was considered as the time between the end of the previous dredging operation to the end of the next dredging operation.

The duration of dredging work varied for each cycle. The timing of dredging was different for each of the three reaches. Also, the time interval between the consecutive dredging cycles was variable. Hence it was difficult to determine the annual quantities of dredging. The data were therefore analyzed to determine the duration of each dredging cycle in days and the quantity of shoaling per day was worked out for each cycle. Average shoaling rate per year was worked out from the average daily rate for all the cycles combined.

An Index Map showing the three reaches is given in Figure 3.6.1. Details of the entire navigation channel split into 8 segments are shown in Figures 3.6.2 through 3.6.9 (Maps 1 through 8). For the development Plan 4, reach 1 for the outer channel needs to be subdivided into two reaches, namely present outer channel and proposed extension. The reference distances used by the project and lengths of different reaches under present condition and Plan 4 condition are given in Table 3.6.1.

The results of analysis on shoaling per day were received from the Galveston District in file named Sediment Study Task1.xls dated 15 June 2005. These are given in Tables 3.6.2, 3.6.3 and 3.6.4 respectively for the three reaches. Histograms of results are plotted in Figures 3.6.10 through 3.6.14. Worked out daily and annual average rates of shoaling in each of the three reaches of the channel are given in Table 3.6.5. The average annual shoaling rate for the entire channel works out to about 2.11 million cubic yards.

Table 3.6.1: Reaches of Freeport navigation channel

Reach #	Name	From	To	Length (feet)	Length (Miles)
Present Condition					
1 A	Outer Bar Channel	0+00	- 260+00	26,000	4.92
2	Jetty Channel	0+00	+ 50+00	5,000	0.95
3	Harbor Channel	+ 50+00	+ 257+86	20,186	3.82
			Total	51,186	9.69
Plan 4 Condition					
1 A	Outer Bar Channel Present	0+00	- 260+00	26,000	4.92
1 B	Outer Bar Channel Proposed Extension	- 260+00	- 430+00	17,000	3.22
2	Jetty Channel	0+00	+ 50+00	5,000	0.95
3	Harbor Channel	+ 50+00	+ 257+86	20,186	3.82
			Total	68,186	12.91
	New Outer Channel	0+00	- 430+00	43,000	8.14

Table 3.6.2: Freeport maintenance dredging in Outer Bar Channel

Dredging Cycle Number	From	To	Duration (Days)	Dredging Quantity Cu. Yd	Shoaling Per Day Cu. Yd
1	16-May-71	14-May-72	364	751,374	2,064
2	14-May-72	27-May-73	378	561,996	1,487
3	27-May-73	22-Jan-74	240	704,996	2,937
4	22-Jan-74	27-Dec-74	339	653,763	1,929
5	27-Dec-74	07-Dec-75	345	1,355,958	3,930
6	07-Dec-75	04-Oct-78	1032	625,478	606
7	04-Oct-78	02-Feb-80	486	712,546	1,466
8	02-Feb-80	02-Jan-81	335	711,066	2,123
9	02-Jan-81	05-Aug-82	580	1,131,000	1,950
10	05-Aug-82	25-Oct-83	446	932,986	2,092
11	25-Oct-83	29-Nov-84	401	966,615	2,411
12	29-Nov-84	20-Sep-85	295	666,295	2,259
13	20-Sep-85	18-Aug-86	332	776,551	2,339
14	18-Aug-86	23-Jul-87	339	855,152	2,523
15	23-Jul-87	03-Sep-88	408	650,873	1,595
16	03-Sep-88	24-Sep-89	386	871,641	2,258
17	24-Nov-92	04-Sep-93	284	1,415,742	4,985
18	04-Sep-93	27-Nov-94	449	2,021,652	4,503
19	27-Nov-94	16-Jan-96	415	2,065,161	4,976
20	16-Jan-96	05-Aug-96	202	1,360,769	6,736
21	05-Aug-96	21-Apr-97	259	1,765,840	6,818
22	21-Apr-97	10-Dec-97	233	764,389	3,281
23	10-Dec-97	11-Dec-98	366	2,021,965	5,524
24	11-Dec-98	21-Nov-99	345	1,042,746	3,022
25	21-Nov-99	12-Sep-00	296	625,361	2,113
26	12-Sep-00	30-Jan-01	140	1,804,766	12,891
27	30-Jan-01	29-Aug-02	576	1,826,667	3,171
28	29-Aug-02	21-Oct-03	418	384,624	920
			Average	1,072,428	3,318

Table 3.6.3: Freeport maintenance dredging in Jetty Channel

Dredging Cycle Number	From	To	Duration (Days)	Dredging Quantity Cu. Yd	Shoaling Per Day Cu. Yd
1	16-May-71	14-May-72	364	409,841	1,126
2	14-May-72	27-May-73	378	306,544	811
3	27-May-73	22-Jan-74	240	384,544	1,602
4	22-Jan-74	27-Dec-74	339	356,598	1,052
5	27-Dec-74	07-Dec-75	345	739,614	2,144
6	07-Dec-75	04-Oct-78	1032	341,170	331
7	04-Oct-78	02-Feb-80	486	388,662	800
8	02-Feb-80	02-Jan-81	335	387,854	1,158
9	02-Jan-81	05-Aug-82	580	257,500	444
10	05-Aug-82	25-Oct-83	446	176,803	396
11	25-Oct-83	29-Nov-84	401	219,520	547
12	29-Nov-84	20-Sep-85	295	237,453	805
13	20-Sep-85	18-Aug-86	332	149,158	449
14	18-Aug-86	23-Jul-87	339	161,134	475
15	23-Jul-87	03-Sep-88	408	193,067	473
16	03-Sep-88	24-Sep-89	386	128,321	332
17	24-Nov-92	27-Nov-94	733	577,615	788
18	27-Nov-94	16-Jan-96	415	608,865	1,467
19	16-Jan-96	05-Aug-96	202	408,231	2,021
20	05-Aug-96	21-Apr-97	259	618,630	2,389
21	21-Apr-97	10-Dec-97	233	160,431	689
22	10-Dec-97	11-Dec-98	366	667,471	1,824
23	11-Dec-98	21-Nov-99	345	512,869	1,487
24	21-Nov-99	30-Jan-01	436	581,869	1,335
25	30-Jan-01	29-Aug-02	576	531,000	922
			Average	380,191	1,035

Table 3.6.4: Freeport maintenance dredging in Harbor Channel

Dredging Cycle Number	From	To	Duration (Days)	Dredging Quantity Cu. Yd	Shoaling Per Day Cu. Yd
1	07-Nov-47	28-Jun-50	964	730,573	758
2	28-Jun-50	19-Apr-53	1026	784,460	765
3	21-Jun-61	01-Nov-63	863	394,999	458
4	01-Nov-63	20-Apr-65	536	645,888	1,205
5	20-Apr-65	08-Nov-66	567	1,021,285	1,801
6	08-Nov-66	05-Aug-69	1001	1,321,844	1,321
7	05-Aug-69	02-Dec-71	849	859,034	1,012
8	02-Dec-71	26-Jan-74	786	535,000	681
9	26-Jan-74	01-Jul-75	521	573,034	1,100
10	01-Jul-75	05-Jan-77	554	169,908	307
11	05-Jan-77	08-Feb-77	34	714,816	21,024
12	08-Feb-77	06-May-80	1183	1,463,443	1,237 *
13	06-May-80	08-Jan-83	977	1,125,098	1,152
14	08-Jan-83	14-Aug-85	949	1,279,346	1,348
15	14-Aug-85	20-Aug-88	1102	761,668	691
16	24-Jun-92	24-Nov-92	153	438,085	2,863
17	24-Nov-92	24-Mar-93	120	461,269	3,844
18	24-Mar-93	27-Nov-95	978	1,310,393	1,340
19	23-Feb-98	09-Mar-99	379	1,670,551	4,408
20	09-Mar-99	19-Apr-02	1137	823,168	724
			Average	854,193	2,402
	* Average, ignoring quantity under #11				1,422

Table 3.6.5: Dredging quantities in different reaches of Freeport navigation channel

Reach #	Name	Length (feet)	Length (Miles)	Avg. Daily Rate Cu. Yd.	Avg. Annual Rate Cu. Yd.
Present Condition					
1 A	Outer Bar Channel	26,000	4.92	3318	1,211,070
2	Jetty Channel	5,000	0.95	1035	377,775
3	Harbor Channel	20,186	3.82	1422	519,030
	Total	51,186	9.69		2,107,875

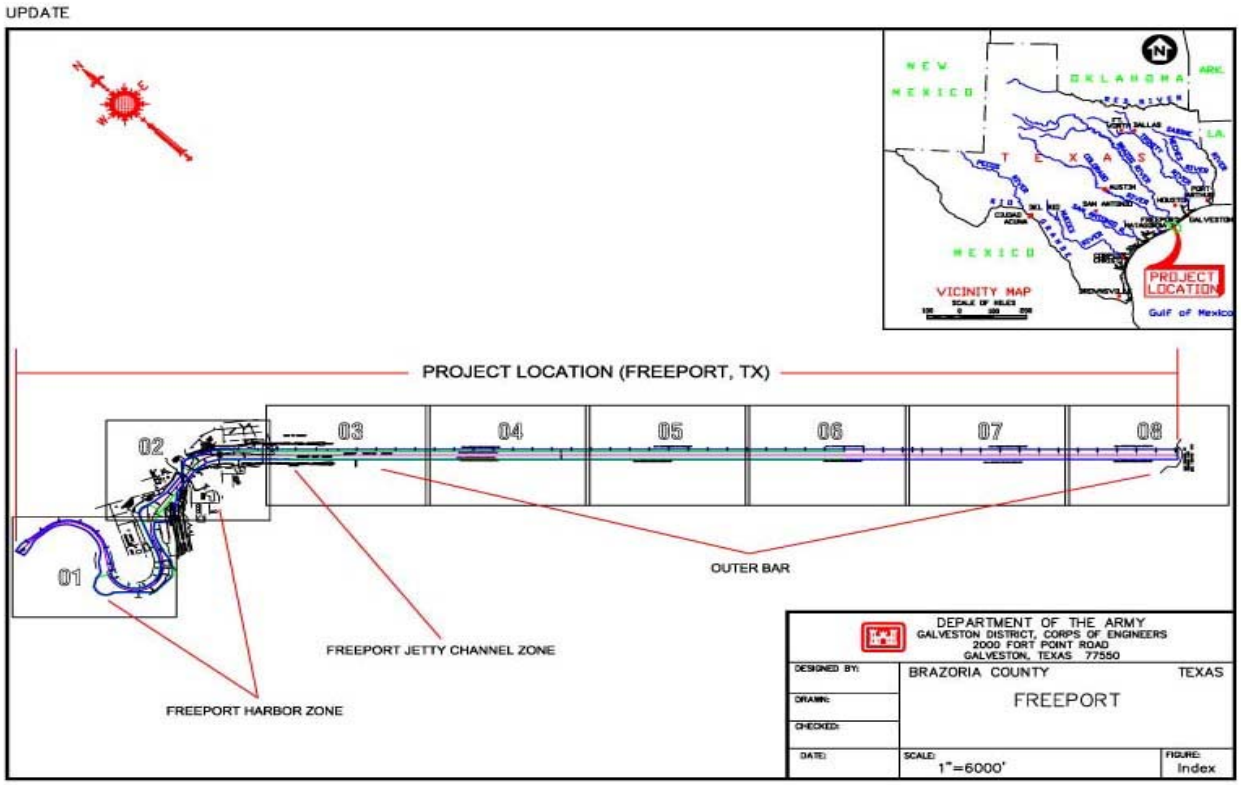


Figure 3.6.1: Freeport navigation channel, Index Map

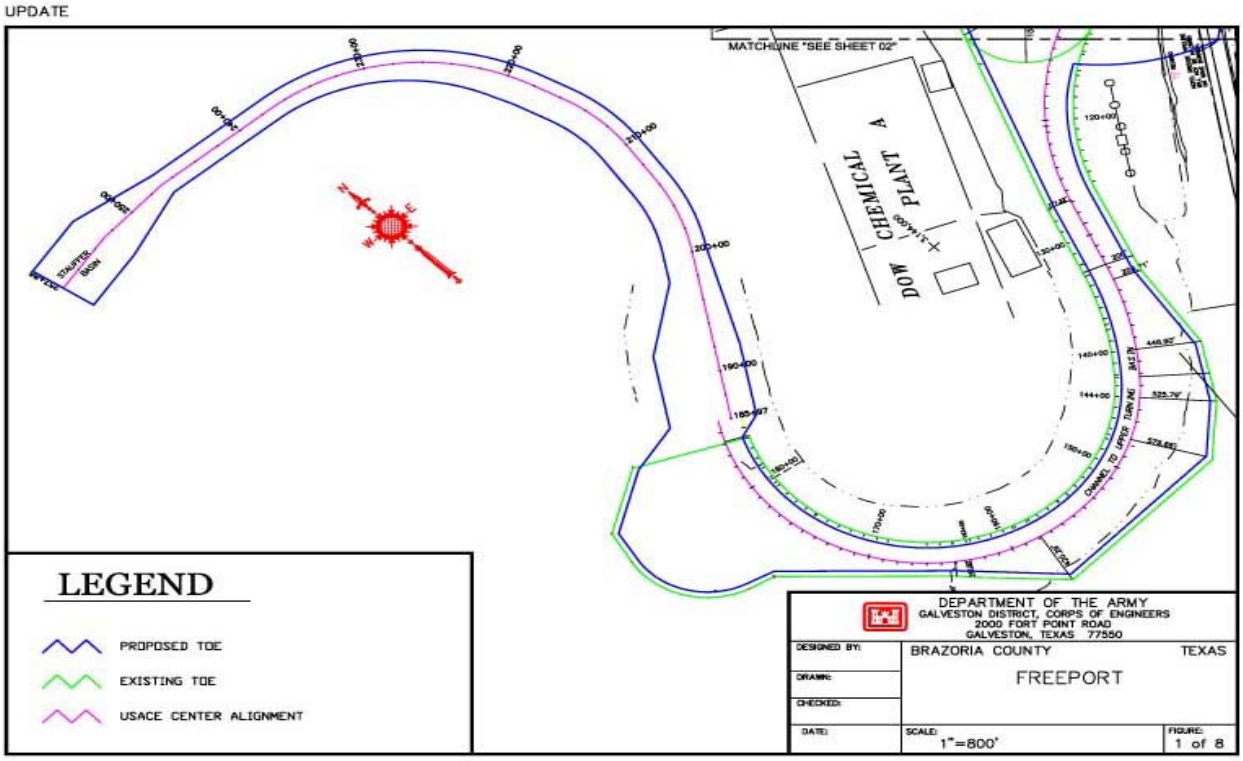


Figure 3.6.2: Freeport navigation channel, Map 1

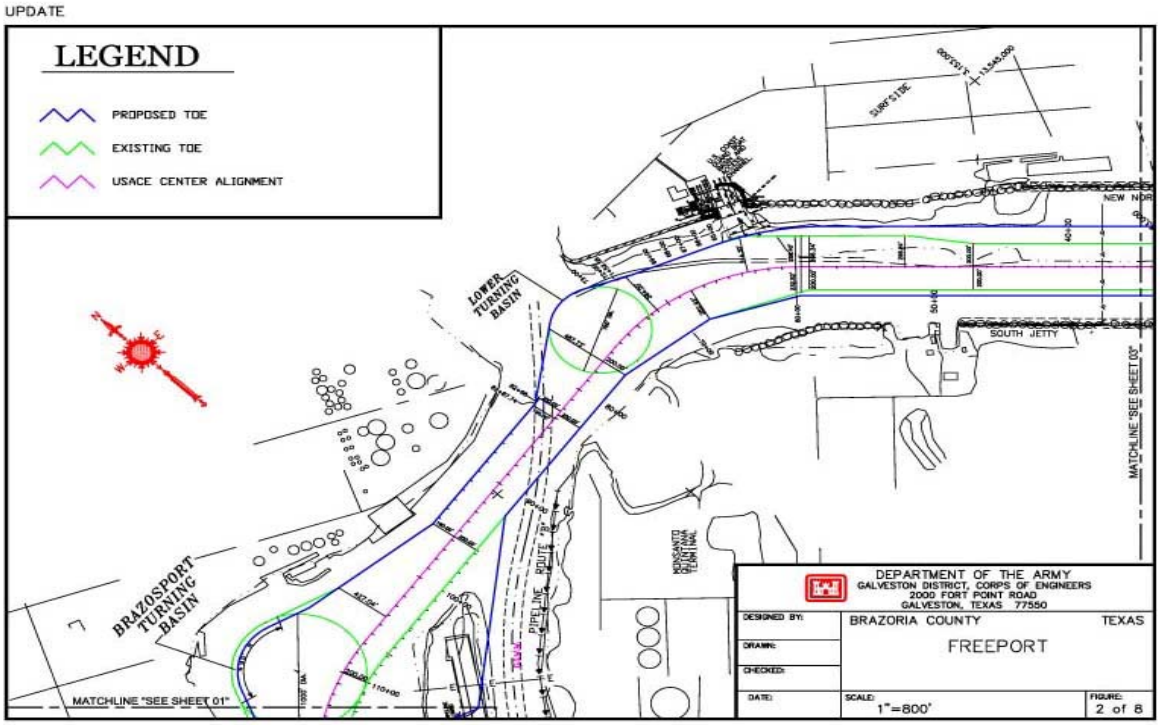


Figure 3.6.3: Freeport navigation channel, Map 2

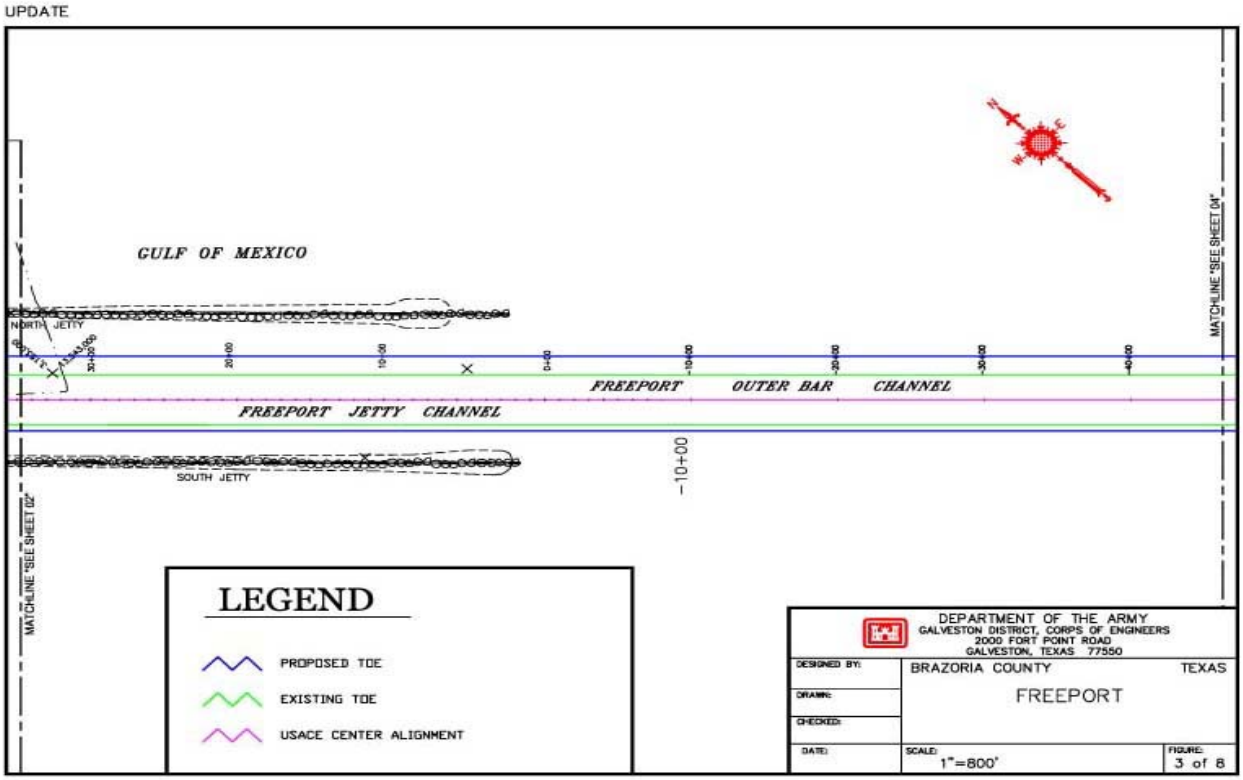


Figure 3.6.4: Freeport navigation channel, Map 3

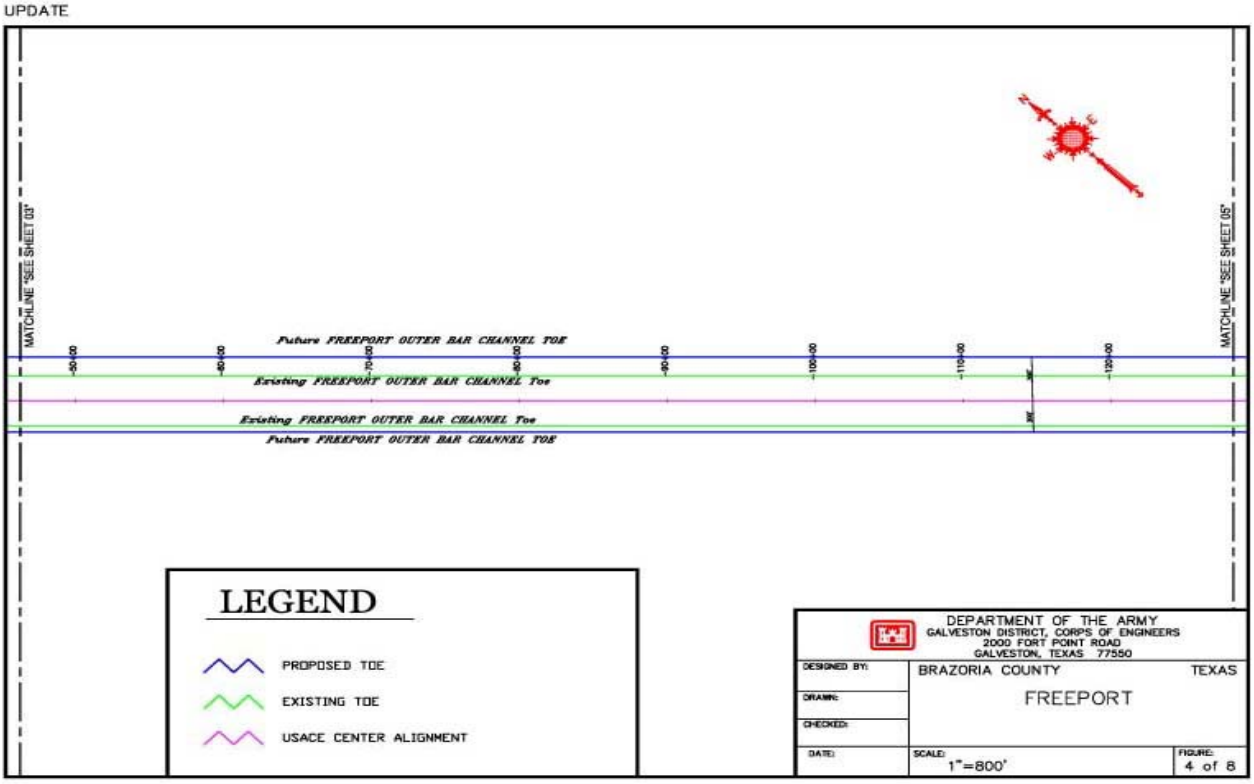


Figure 3.6.5: Freeport navigation channel, Map 4

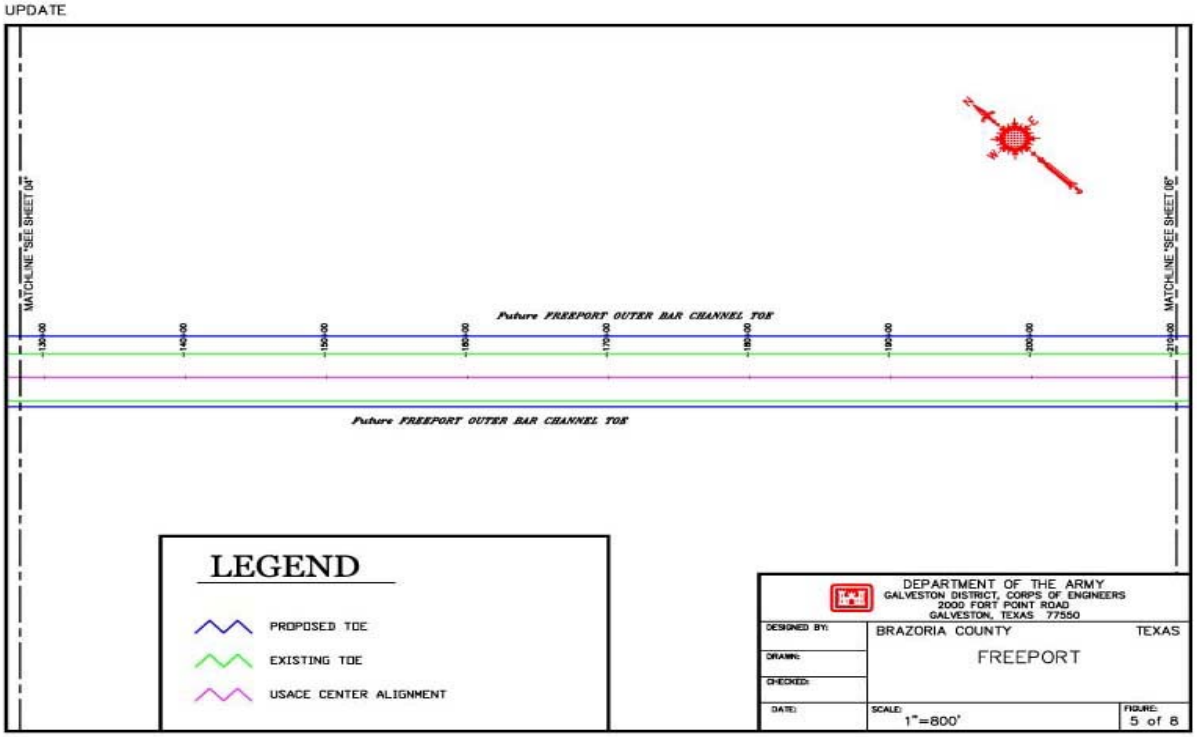


Figure 3.6.6: Freeport navigation channel, Map 5

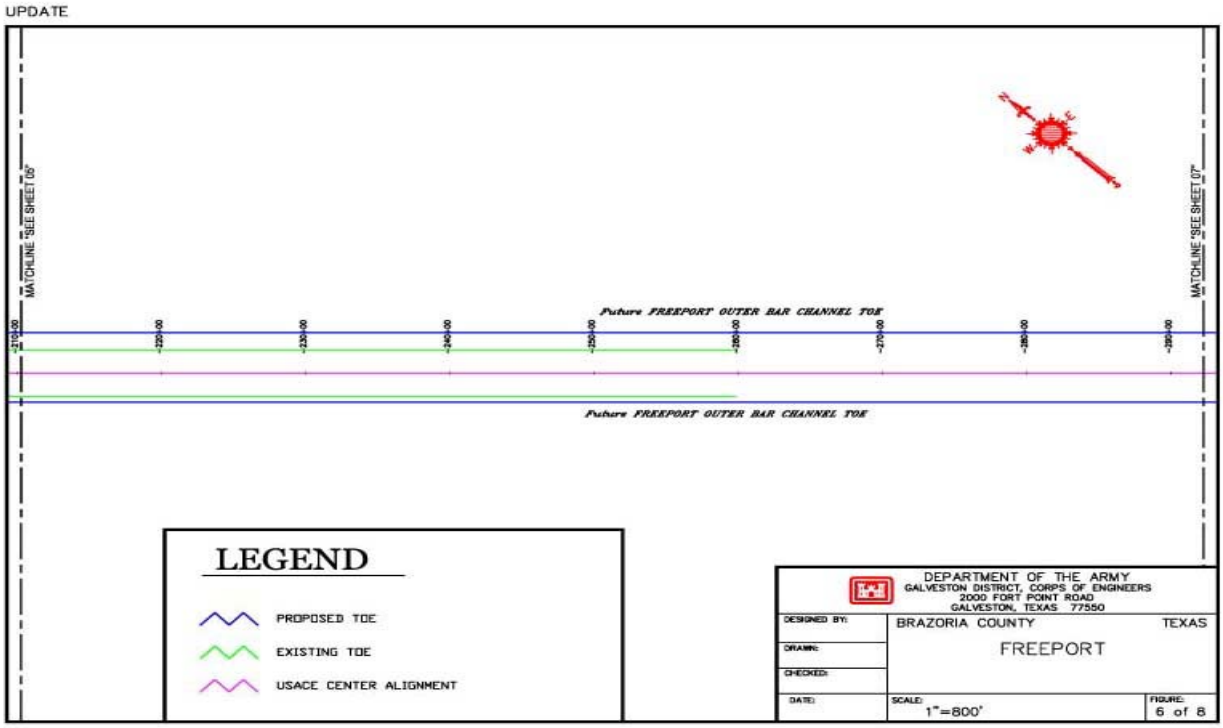


Figure 3.6.7: Freeport navigation channel, Map 6

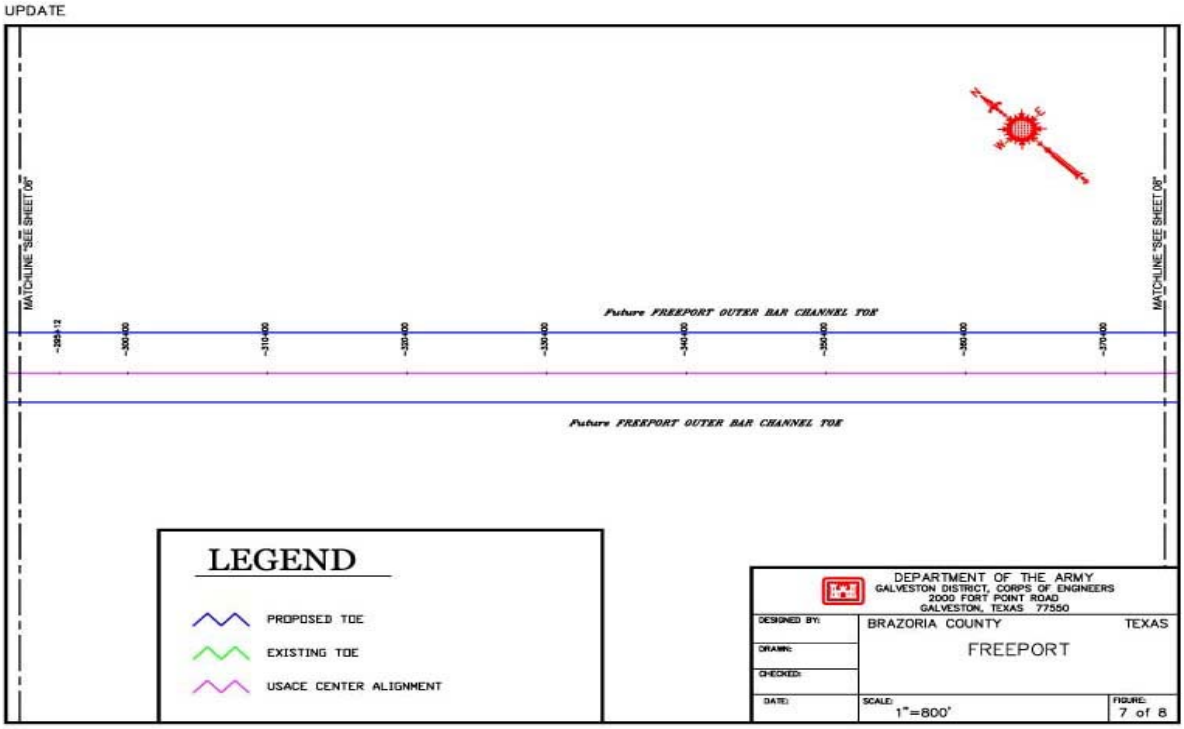


Figure 3.6.8: Freeport navigation channel, Map 7

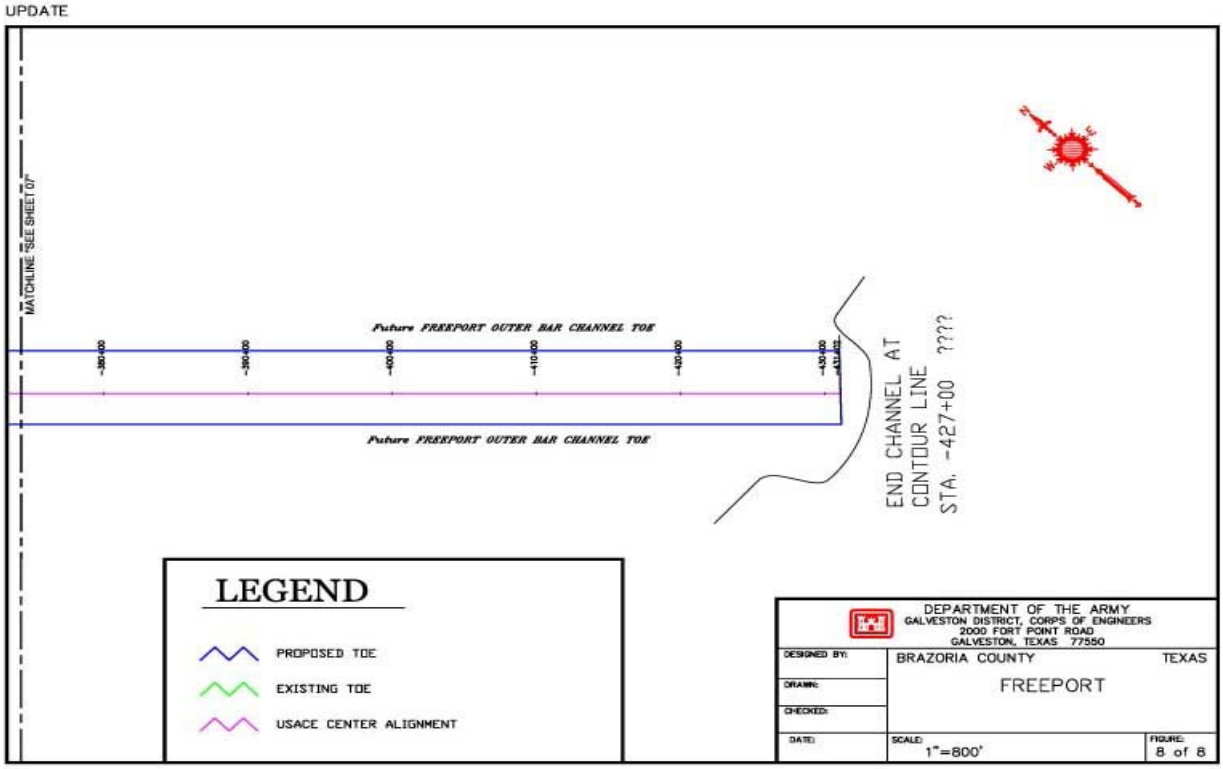


Figure 3.6.9: Freeport navigation channel, Map 8

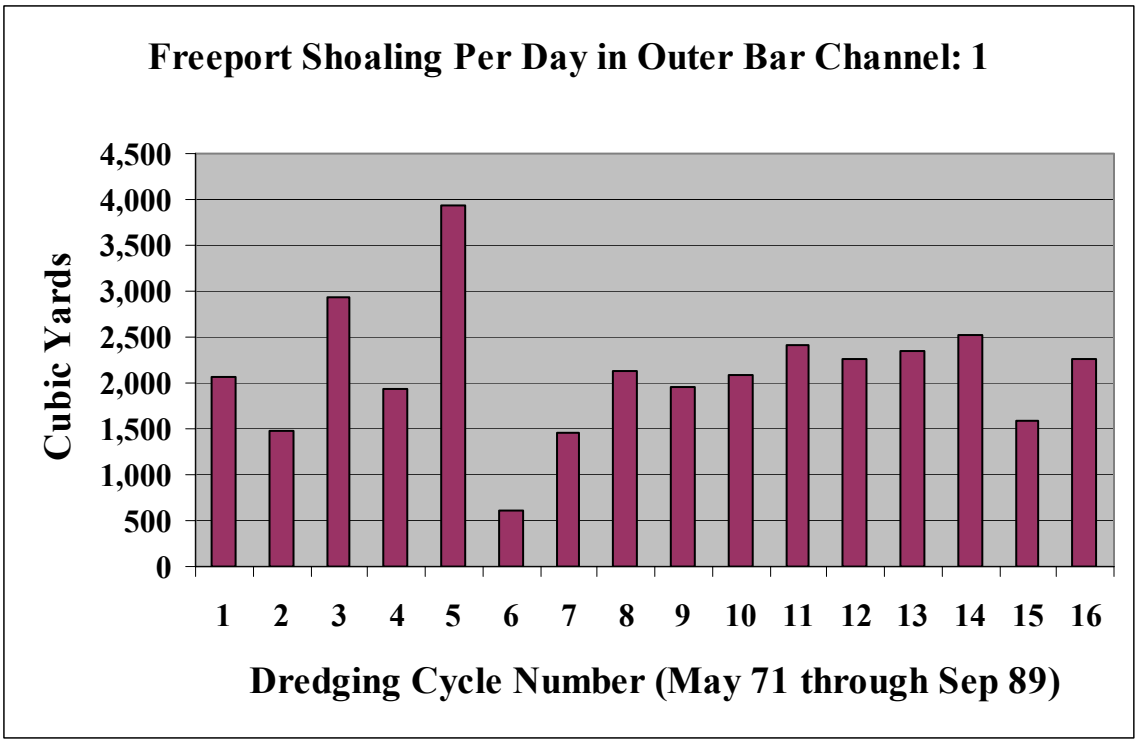


Figure 3.6.10: Freeport annual shoaling in Outer Bar Channel-1

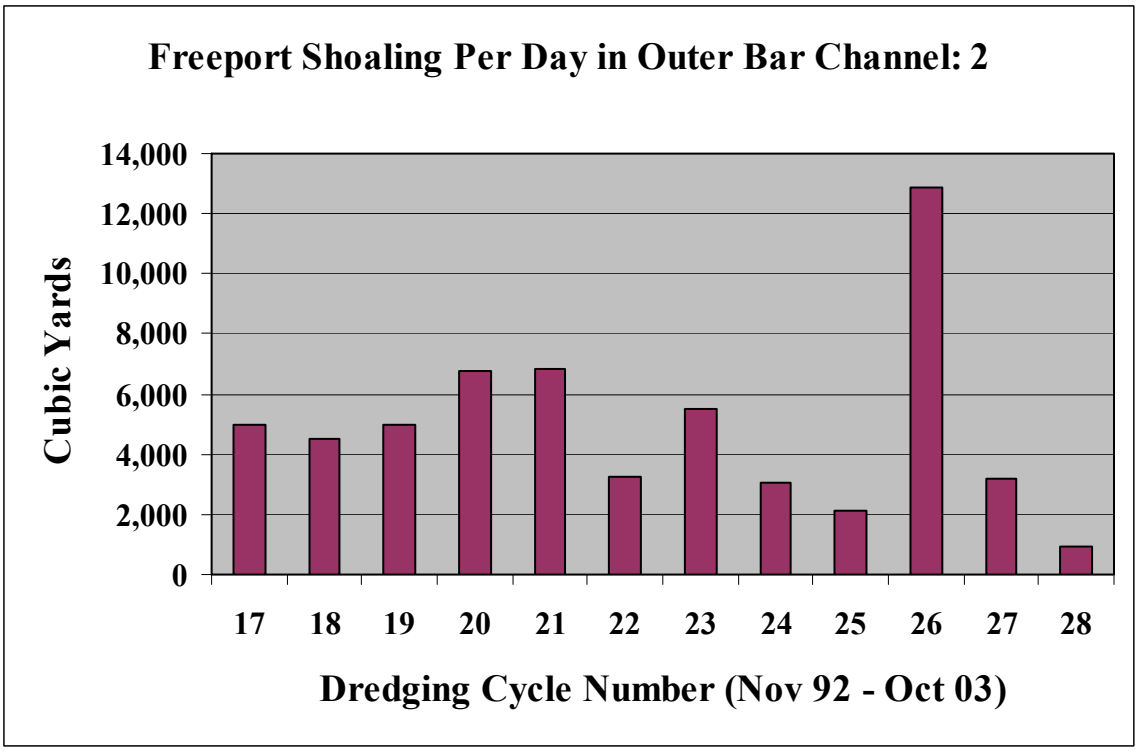


Figure 3.6.11: Freeport annual shoaling in Outer Bar Channel-2

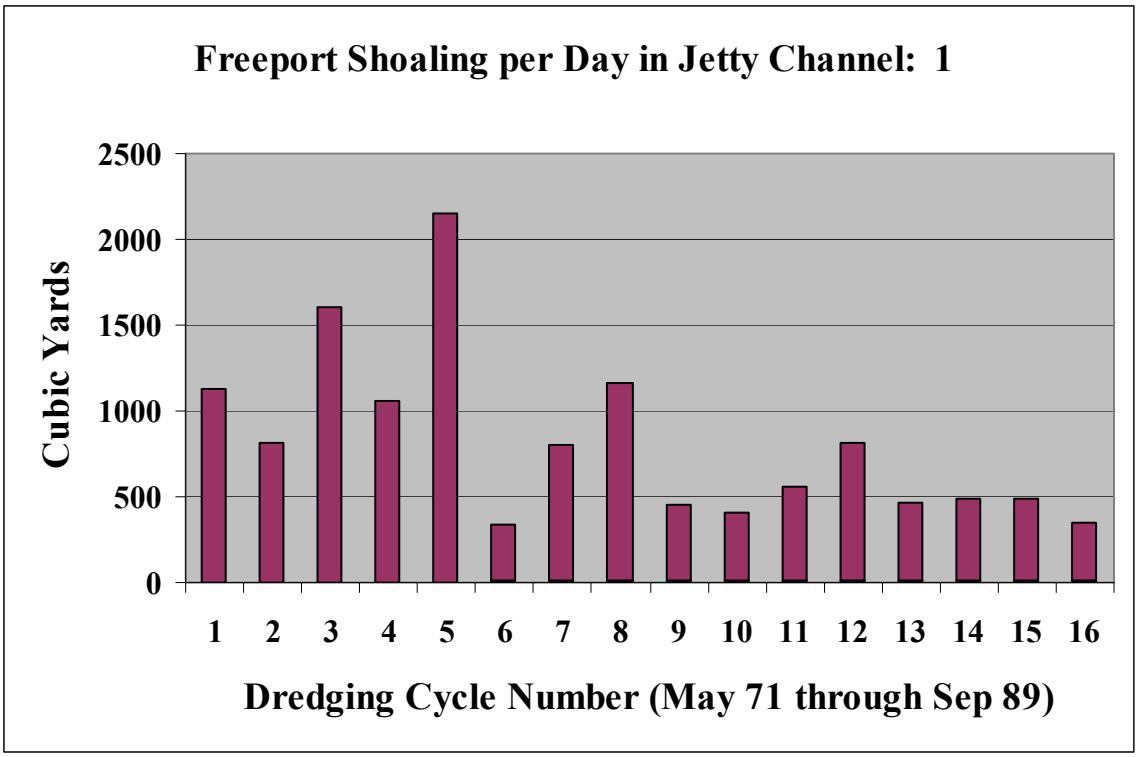


Figure 3.6.12: Freeport annual shoaling in Jetty Channel-1

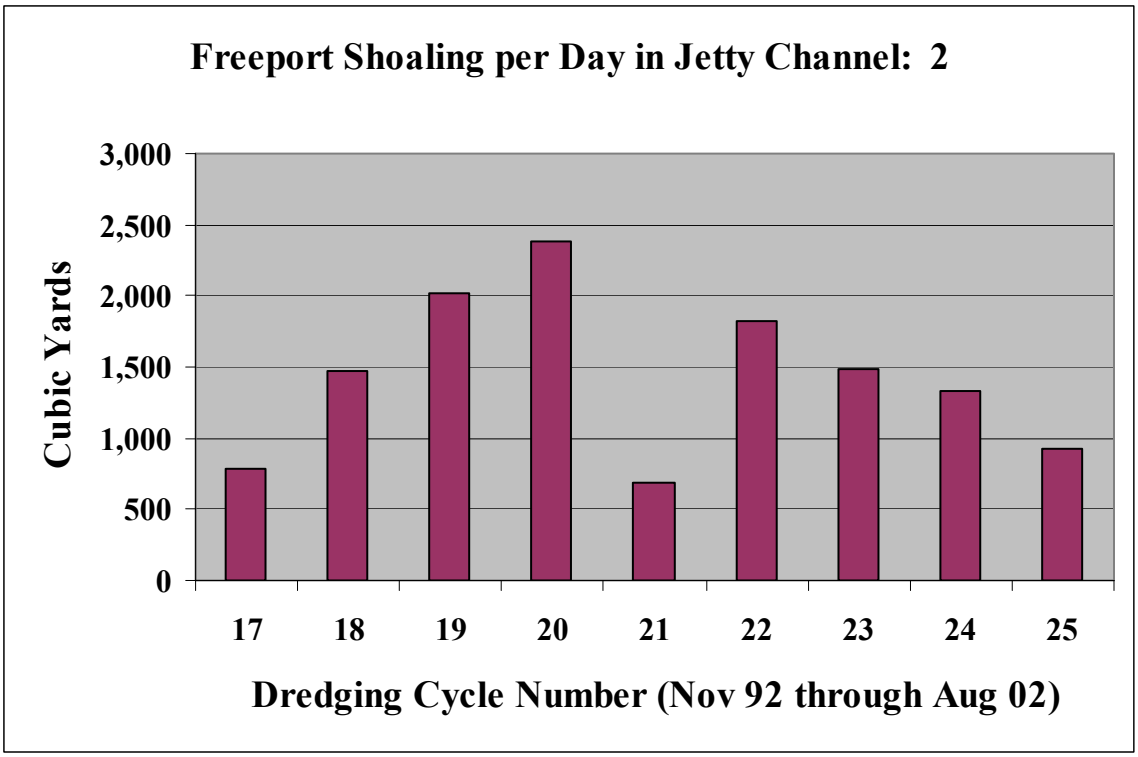


Figure 3.6.13: Freeport annual shoaling in Jetty Channel-2

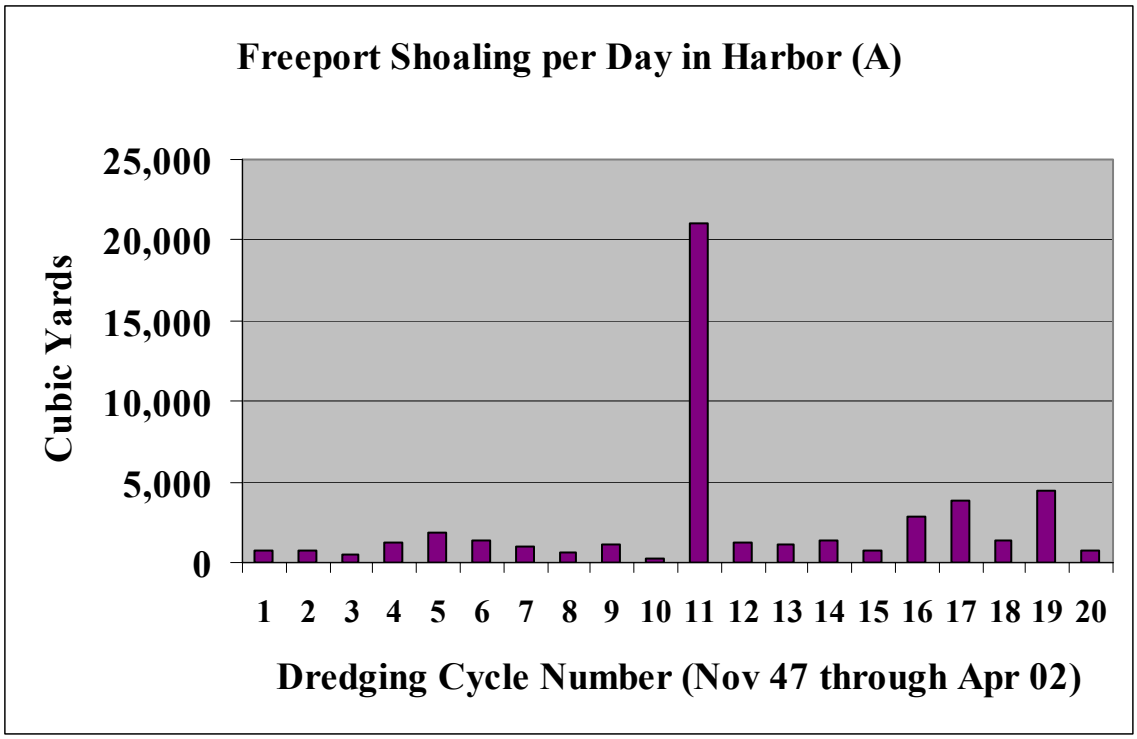


Figure 3.6.14: Freeport annual shoaling in Harbor Channel-(A)

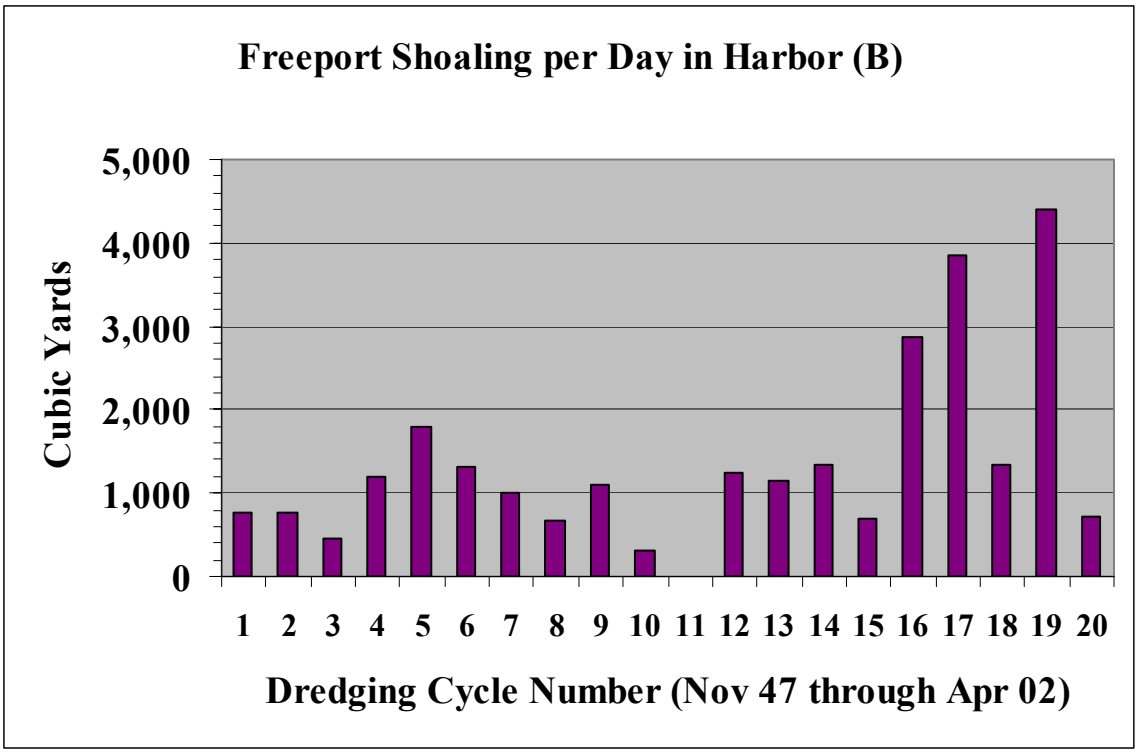


Figure 3.6.15: Freeport annual shoaling in Harbor Channel-(B)

4 Numerical Modeling

4.1 Justification for 3D Freeport Model Study

The main problem to be examined consisted of prediction of shoaling in the navigation channel after its modification from the existing conditions. In general, the following factors need to be taken into account while deciding whether a two-dimensional or a three-dimensional numerical scheme should be used for solving a problem.

1. Geographical features of the area: River, Lake, Estuary, Tidal Inlet, etc.
2. Presence or absence of parameters causing vertical density gradients in water column: Salt water, Suspended sediment, Fluid mud, Temperature.
3. Reversed flow directions over vertical across density interface.
4. Type and particle size distribution of bed sediment and suspended sediment.
5. Influence of salt water: Depositional properties of fine sediment are substantially influenced by the presence of salt water.
6. Type of problem: Salinity intrusion, Surface flow / circulation pattern, Shoaling and erosion

In the absence of any field data and in-depth study before undertaking the modeling task, the situation at Freeport appeared as follows:

a. The main waterway channel is in the form of a tidal creek with a dead end with no fresh water input from river flow or tributary flow from upstream of the creek.
b. There is a direct, deep and wide connection to the sea.
c. The harbor is located not too far inland.
d. The type of sediment, cohesive or non-cohesive, could not be predicted.

These site conditions were expected to offer salt water prevailing over the entire length of the channel without any strong vertical velocity or salinity gradients. Complete stratification with fresh water at top, and salt water below with simultaneous current flowing in opposite directions at any channel section was not expected to occur.

After the results of field data were available, the site conditions were found to be different from expected as follows:

a. Substantial spatial and vertical variation in salinity in the study area. It was apparent that GIWW, which intersects the Freeport navigation channel as well as the rivers in the vicinity, brings down substantial fresh water flow into the hydraulic system of Freeport Harbor.
b. Presence of high percentage of fine sediments all over the area.
c. Reversal of current direction over depth.

It was apparent that the vertical structure of currents that is responsible for sediment dynamics was so different that vertically averaged currents of a 2-D numerical model would not be able to adequately simulate it. Hence 3-D numerical modeling was considered essential.

4.2 Sediment Modeling

Under many situations a full-fledged numerical sediment modeling is recommended for important projects. However, every sediment modeling requires results of a satisfactorily verified hydrodynamic model as the first step. Since fine sediment dynamics is significantly influenced by salinity, a three-dimensional sediment model including salinity simulation becomes essential. This first step requires field data on several parameters such as bathymetry, tides, currents, and salinity. The task of verification of numerical sediment model requires additional data on suspended sediment, bed sediment, and historical data on capital and maintenance dredging quantities. Collection of field data for a project covering reaches extending over several miles and conducting their laboratory analysis is quite expensive and time consuming. Hence the Galveston District proposed conducting a desktop study on the prediction of shoaling quantities in the navigation channel for the Freeport project.

Field data collected specifically for use of desktop study were analyzed in detail and results are presented in this report. This information on various parameters such as tides, currents, dredging quantities, bed sediment and suspended sediment would be very valuable in providing representative site-specific input to the numerical sediment model study that may be conducted at a later stage.

4.3 Hydrodynamic Model Study

Two-dimensional (2D) hydrodynamic model study was conducted at ERDC for generating current data needed for the ship simulator study done at ERDC. Letter et al., (2005) have submitted to Galveston District a draft report on the 2D study. The 2D model was converted to a three dimensional (3D) hydrodynamic numerical model in support of the present desktop sediment study on Freeport Harbor reported here.

The 3D finite-element code RMA-10 available with CHL was used to run the model and obtain results. The RMA-10 code has been used successfully at CHL for several navigation studies. Details of this model are given in Appendix 3. Because the model used a finite-element mesh, it could reproduce with adequate resolution the complex geometries of ship channels, turning basins, etc. The model extended from the Gulf of Mexico to inland area up to the dead end of Freeport navigation channel. The offshore boundary was located in about 94 feet water depth in sea, which is well beyond the maximum contemplated Plan channel depth of 60-ft including over-dredging. It included portions of the Gulf Intracoastal Waterway (GIWW) going east and west from its intersection with the Freeport channel. The GIWW west included a segment beyond its intersection with the Brazos River. The Brazos River and Dow Barge Canal were partly reproduced from their mouths landwards in truncated form.

4.4 Model Mesh and Boundary Conditions

The base geometry and bathymetry for the primary Freeport study area was derived from the 2003 Fall survey conducted by the CHL under the guidance of the SWG. All coordinates were converted with the North American Datum Conversion (NADCON). The National Ocean Service/National Oceanic and Atmospheric Administration (NOAA) nautical chart number 11322 was used extensively for defining bathymetry in areas away from the navigation channels. US Geological Survey (USGS) Quad Sheets, aerial orthographic photos, and latest surveys supplied by the Galveston District were also used. Attempt was made to accurately simulate the real geographic boundaries as far as possible, while formulating the model grid. The bathymetry data are referenced to mean low tide (MLT). The bathymetry of the model ranges from –94 ft in the Gulf to 0.04 ft in the shallows. An arbitrary datum of 100.00 was used as reference datum for running the model so as to avoid negative values for water depths as well as for the water surface elevation due to tides on both sides of Mean Low Tide (MLT). All parts of the computational domain remain submerged during the periods of simulation. The lowest water surface elevation in the boundary condition file was approximately +0.5 ft MLT. Time step of 30-minute duration was used to run the model.

The 2D model mesh required modification so as to include sufficient resolution in the areas of interest. Higher resolution was provided in the study areas by adopting smaller size elements. Larger size elements were provided in the areas of less interest in order to keep smaller number of grid elements. Such schematization is inevitable for most numerical models involving large geographic areas. Higher resolution in the navigation channels enabled representing the velocity distribution across the deeper channel section as well as side banks, and any cross currents. The mesh and bathymetry for existing conditions were modified appropriately for the plan conditions. Although GIWW is a

tidal waterway extending over several miles, it had to be truncated in the model at both ends. Arbitrary labyrinths were provided in the numerical model at the east and west ends for absorbing and releasing tidal volumes during flood and ebb phases of tidal propagation. The model boundaries, model grid and the bathymetry are shown in Figures 4.4.1 and 4.4.2.

User specified coefficients for the hydrodynamic model included varying Manning's n values and eddy viscosity for different parts of the model. Both were controlled by the element material type (IMAT) descriptor. By grouping elements into 10 different IMAT categories, the roughness and viscosity values were easily assigned. The Peclet number assigned on the PE card can be used as an indicator of numerical stability. A value of 20 or less is typically recommended for numerical stability. A Peclet number of 10 was used for the entire computational domain, and for all hydrodynamic runs. Manning's n values were assigned using the automatic assignment of roughness by depth card.

The same boundary conditions that were used for the 2D study were also used for the 3D study. The boundary conditions included two parameters, namely a) fresh water discharges at appropriate locations and b) tides at the ocean boundary. Wind was not included as a separate parameter because its effect was included in the tides and currents used as boundary conditions for validation and running of the model. Field data on the amount of fresh water entering the GIWW from Brazos River were not available. Similarly, fresh water discharge from the east GIWW was not known. Hence the following fresh water discharge values were arbitrarily adopted for initial testing: GIWW East: 10,000 cu ft/sec, and Brazos River: 19,000 cu ft/sec. The numerical model became unstable and could not be operated with these values. Hence both the values were arbitrarily adjusted to lower values (5,000 and 10,000 respectively) by running some trials on the model until satisfactory conditions were reproduced.

Raw data on water surface elevations indicated considerable fluctuations. It was also noted that the observed velocities generally had a low magnitude on the order of less than 1 ft/s and the current magnitude as well as direction had considerable noise (erratic rapid fluctuations) presumably due to tidal water level fluctuations. It is also believed that local turbulence in the system and local meteorological effects may also be additional factors. Often times, it is neither practical nor necessary to reproduce the small fluctuations in water levels and velocities for purposes of the type of problem in hand. Hence a specially developed program was run to filter and smooth out the observed short-term water levels fluctuations. The filter applied was a band pass filter, which passed periods between 4 and 200 hours. This procedure had a disadvantage in the form of slightly reduced tidal ranges in the time series. Figure 4.4.3 shows a superposition of tidal water levels plotted with raw data and filtered water level data. Effect of filtering out frequencies outside 3-200 and 4-200 is shown in this figure.

Smoothing of water levels also resulted in smoothing the model velocities. Node 5111 located in the Brazos Port turning basin area was selected to evaluate the effect of filtering. Figure 4.4.4 shows location of node 5111. Figure 4.4.5 shows superposition of model velocities at this node plotted with raw tides and filtered tides. This figure shows a 1000-hour-long time series with a vertical range for velocity varying from +0.8 to –0.6 ft/s. Figures 4.4.6 and 4.4.7 show a similar comparison for durations of 300 hours (from 500 to 800) and 100 hours (from 600 to 700) respectively. It may be noted that the occurrence of high and low peaks of smoothed velocity time series coincided well with those of the velocities obtained with raw water level variations in most cases. The currents generated by use of the filtered tidal signal are much less erratic, but the peak current velocities are somewhat lower than with the unfiltered results. Figure 4.4.8 shows the time series of filtered tidal water levels used as boundary condition for running the numerical model.

4.5 Model Mesh and Boundary Conditions

Water Levels

Field data collected by ERDC for this study during October and November 2003 were used to validate the hydrodynamic conditions. The 3D model was run for two conditions. Under condition 1, the model was run with salinity uncoupled (su) and fresh water inflow was low (l-Inf). Under condition 2, the model was run with salinity coupled (sc) and fresh water inflow was zero (0-Inf). The objective of keeping zero fresh water inflow was to obtain the maximum salt-water intrusion from the sea.

Figure 4.5.1 shows three tide gage locations, namely TG363, TG129, and TG367, where field data were collected for water surface verification of the numerical model. Numerical model nodes for the Base condition mesh were identified corresponding to these locations of tide gages, which are also shown in Figure 4.5.1.

Superposed water levels at these three locations for field and model are presented in Figures 4.5.2, 4.5.3, and 4.5.4. Each figure shows three water levels, namely 1) field data, 2) model data with salinity uncoupled and low fresh water discharge (M-su-l-Inf), and 3) model data with salinity coupled and zero fresh water inflow (M-sc-0-Inf). Figure 4.5.2 shows such comparison at a location near entrance corresponding to node 3378 and tide gage 129. Figures 4.5.3 and 4.5.4 present data for GIWW east (TG 363) and Stauffer area (TG 367) respectively. It is noted that at all the three locations, the field data, and model data for salt uncoupled are in excellent agreement. Model data with salt-coupled shows good agreement with field data in terms of the occurrences of high and low waters but the model magnitudes of high and low waters are higher than field values at entrance and at GIWW east. All the three water levels were in good agreement for the location near Stauffer (node 7163, TG 367). In summary, water level validation with salt

uncoupled is very good but with salt coupled it is not as good. The reason for this was that the hydrodynamic numerical model was only cursorily validated for salinity in accordance with the agreed scope of work. It may be noted that one location, namely GIWW East, where the agreement was not as good, is outside the area of interest. Since the model data matched well with the field data for the inner navigation channel, the model was considered validated for water surface elevations.

Velocity

A common method of presenting results of velocity validation is to show superposed curves of velocities for field and model, as has been done for water level validation. This is mostly done when current data are collected by using current meters deployed at single location and single depth in a cross section. Even when multiple current meters are used, the data are always limited. In the present case, current data were collected using ADCP. The locations of the ADCP transects are shown in Figure 4.5.5. One transect is across the entrance channel, southeast of Bolivar Roads (line 2). The second is a composite range across the east GIWW and the DOW channel (line 1). The third is in the western GIWW (line 2) and the fourth in the navigation channel west of the turning basin (line 4). Voluminous data are available at several locations along each transect as well as at several water depths. The model data are however limited by the number of nodes and the number of layers used in a cross section. Hence, comparison of currents using superposed lines is inadequate. A different method has been adopted in this report. Both the field and model data are plotted over a cross section and a visual comparison of velocity distribution for the field and model was made over the entire cross-section as a whole. Illustrative cross sections showing velocity distribution for the field at four transects are shown in Figures 4.5.6 through 4.5.13. Corresponding cross sections showing velocity distribution in the numerical model at four transects are shown in Figures 4.5.14 through 4.5.21. Since the model data matched fairly well with the field as shown in these sections, the model was considered validated for velocity.

Salinity

Water samples at three depths were collected at the same four transects, which provided depth-variation of salinity in the field. Model salinity could be obtained for the number of layers provided in the model. Salinity was plotted for the corresponding cross sections in the field and model. The agreement between the two was not as good because the numerical model was only cursorily validated with the field data. However, the order of magnitude match was considered acceptable for validation for salinity.

4.6 Model Mesh and Boundary Conditions

The model was run on the ERDC High Performance Computing (HPC) SGI Origin 3000 (Ruby) parallel processing super computer. Model was run with a starting time of zero hour corresponding to the field zero hour on October 1, 2003. The 3D solution files for water level and current data were stored for use of the desktop sedimentation study. The base condition mesh was then modified to the "Plan" condition to include the proposed channel modifications (Layout 4) as determined by the ship simulator studies and accepted by the Galveston District for implementation. Model was run for the Plan conditions using the same boundary conditions as used for the Base conditions.

Hydrodynamic model provided data on water levels and currents at every node used in the model. Several nodes in the area of interest were selected for extracting this information from the solution files for both the Base and Plan conditions for use of the desktop sedimentation study. List of selected nodes is given in Table 4.6.1. Locations of selected nodes are shown in Figures 4.6.1, 4.6.2, and 4.6.3. The mesh for the Plan condition was different from that of the base condition. Hence, several grid numbers changed after incorporating Plan condition. Corresponding node numbers for the same locations corresponding to Base are given in Table 4.6.1. Grid numbers selected for extracting data from numerical model for the Plan condition are shown in Figure 4.6.4.

4.7 Model Mesh and Boundary Conditions

Out of the several nodes that were selected for extracting data from the numerical model solution files, 10 nodes were selected (Table 4.7.1) for comparing the results of Base versus Plan. Locations of these are also shown in Figures 4.6.1 and 4.6.2. The 3D model provided velocities at surface, mid-depth and bottom at all nodes. Plots showing comparison of model velocities over vertical (surface, mid-depth and bottom) at these 10 nodes are given in Appendix 4. Plots showing superposition of Base and Plan time series of model velocities at these 10 nodes are given in Appendix 5. Table 4.7.2 provides a summary of model Base and Plan velocities at surface, mid-depth and bed for flood and Table 4.7.3 provides velocities for ebb.

Summary of plots given in Appendix 4 is given in Table 4.7.4 and 4.7.5, which describe velocity variation with water depth obtained in numerical model for the Base and Plan conditions respectively. Table 4.7.6 provides a summary of results on all the parameters, namely, 1. Base and Plan, 2. Flood and ebb, and 3. Surface, Mid-depth and Bottom velocities. The following observations are made:

Outer Channel: Peak Plan flood velocities are smaller than peak Base flood velocities by 0.05 ft/s. Peak Plan ebb velocities are greater than peak Base ebb velocities by 0.07 ft/s. Since Plan ebb is slightly stronger than Base ebb, this should slightly improve flushing of sediment out to the sea.

Jetty Channel: Same as above.

Bolivar Roads Area: Both flood and ebb Plan velocities are smaller than Base velocities by 0.03 ft/s. This would increase sediment deposition.

Big Bend: Both flood and ebb Plan velocities are smaller than Base velocities by 0.02 ft/s. This would increase sediment deposition.

All other areas: Either no difference or the Plan velocities are smaller than Base by about 0.01 ft/s. Hence, deposition will be slightly higher.

The Base peak velocities have a small magnitude, which is on the order of 0.1 ft/s. Although the absolute change in velocities is small, between 0.01 and 0.05 ft/s, the relative change with reference to the present conditions is significant.

4.8 Model Mesh and Boundary Conditions

Current data for Base and Plan conditions were available from numerical model at all the nodes. These data were used for plotting flow pattern in the form of schematic vector diagrams in the area of interest. Schematic flow patterns are shown in the following illustrative figures for the corresponding conditions:

Figure 4.8.1: Flow pattern during Base condition ebb
Figure 4.8.2: Flow pattern during Plan 4 condition ebb
Figure 4.8.3: Flow pattern during Base condition flood
Figure 4.8.4: Flow pattern during Plan 4 condition flood

It is seen that there is no significant difference in the flow pattern for Plan in comparison with the Base condition.

4.9 Comparison of Water Levels and Velocities

Model water levels at Node 407 located at the end of the existing navigation channel in the sea are plotted in Figure 4.9.1 for 0 to 260 hours. The neap tides have a range of about 0.8 to 1.5 feet whereas the spring tides have a range of about 2.5 feet. Spring tides occurring during 120 hours to 230 hours are plotted in Figure 4.9.2. Model velocities at Node 407 are plotted in Figure 4.9.3 for 0 to 260 hours. The same velocity data are plotted in Figure 4.9.4 with a magnified scale over 120 hours to 230 hours. It is noted that the velocity during spring tides varied from –0.05 to 0.17 ft/s.

The following three nodes were selected for examining water surface elevations in the model: Node 407 located at the end of the existing navigation channel in the sea, Node 6389 located at Big Bend, which is about half way from the throat section, and Node 7329 located near Stauffer, which is located towards the end of navigation channel. Superposed water levels at 707 and 6389 are shown in Figure 4.9.5 and Superposed water levels at 707 and 7329 are shown in Figure 4.9.6. It is noted that there is no change in tidal characteristics at all these three locations. This because the existing total length of navigation channel is short compared to the tidal length at site.

4.10 Concluding Remarks from Numerical Model Study

Tides

1. The numerical model was adequately verified for tidal elevations and tidal current velocities but only cursorily verified for salinity.

2. The neap tides have a range of about 0.8 to 1.5 feet whereas the spring tides have a range of about 2.5 feet.

3. Tidal characteristics were examined for the Base condition at three nodes in the model corresponding to the following locations in the field. 1. At the end of the existing navigation channel in the sea, 2. At Big Bend, and 3. Near Stauffer. Tidal characteristics at these three locations did not differ significantly from each other.

4. No significant change in tidal characteristics was noticed between Base and Plan as a result of channel widening to 600 feet and deepening from 47 feet to 60 feet.

Currents

4. Current velocity in the GIWW East was high. It varied from 3 ft/s at bottom to 5 ft/s at surface for flood and from3.5 ft/s at surface to 2.1 ft/s at bottom for ebb.

5. Current velocities in the navigation channel at the throat section at the shoreline and in the Bolivar Roads area was also high. The variation in surface velocity was 0.7 ft/s to 0.9 ft/s.

6. At all the other locations within the navigation channel, the magnitude of surface current velocity during flood and ebb mostly varied from 0.05 to 0.17 ft/s.

7. Superposition of velocities at surface, mid-depth and bottom showed no significant variation over water depth in the outer channel in the sea as well as in the inner channel upstream of the Big Bend area.

8. The area between the Big Bend and the Bolivar Roads showed simultaneous surface and bottom velocity in opposite directions. This is the result of salinity-induced and fresh-water-induced density flows.

Salinity

9. No significant change in salinity values was noticed along the navigation channel as a result of channel deepening from 47 feet to 60 feet.

Flow Pattern

10. Schematic flow pattern diagrams showed no significant difference in the flow pattern for Plan in comparison with the Base condition.

Table 4.6.1: List of nodes selected for extracting model velocity data from numerical model solution files

Base	Base Node #	Data Plotted	Plan	Plan Node #	Comments
Map 1			Map 1	141	New nodes under Plan due to navigation channel extension
				214	
				307	
				420	
	707	*		707	Same node numbers for base and plan, Map 1
	874			874	
	1574	*		1574	
	1586			1586	
	1887			1887	
	2220	*		2220	
Map 2	2232		Map 4	2232	Some node numbers different Map 2 for Base, Map 4 for Plan
	2577			2577	
	3106			3106	
	3543			3543	
	4068	*		4091	
	4622			4906	
	4345			4535	
	4680	*		4972	
	4919			5283	
	5010			5425	
	4664			4956	
	5082			5537	
	5245			5753	
	4232			4540	
	4104			4255	
	3973			3976	
	3845			3848	
	3682			3682	
	4841	*		5361	
	5277			5464	
	5669	*		5677	
	6003			6173	
	6389	*		6624	
	6679			7026	
	7100	*		7502	
	7157			7554	
	7197			7599	
	7272			7672	
	7329	*		7731	
Map 3	3572		Map 3	3572	Same node numbers for base and plan, Map 3
	3461			3461	
	3339			3339	

	3145			3145	
	2326			2326	
	1825			1825	
	2179			2179	
	2852			2852	
	1148			1148	
	3065			3065	
	2861			2861	
	3204			3204	

Table 4.7.1: Nodes selected for plotting model data, Base versus Plan (Appendix 4)

Map #	#	Base Node #	Data Plotted	Map #	Plan Node #	Location
Map 1	1	707	*		707	End of existing Outer channel in sea
	2	1574	*		1574	Half way between entrance and end of channel
	3	2220	*		2220	Inlet throat section
Map 2	4	4068	*	Map 4	4091	Bolivar Roads
	5	4680	*		4972	GIWW East
	6	4841	*		5361	Brazos Port Turning Basin
	7	5669	*		5677	Dow Channel Berths
	8	6389	*		6624	Big Bend
	9	7100	*		7502	North of Upper Turning Basin
	10	7329	*		7731	Stauffer Turning Basin

Table 4.7.2: Summary of model velocities for Flood: Base and Plan (Reference Appendix 5)

S. #	Node # Base/ Plan	Location	Depth	Peak Flood Avg Vel (ft/s)	Peak Flood Avg Vel (ft/s)
				Base	**Plan**
1	707	End of existing Outer channel in sea	Surface	0.12	0.05
	707		Mid-Depth	0.12	0.05
			Bottom	0.12	0.05
2	1574	Half way between entrance and end of channel	Surface	0.10	0.05
	1574		Mid-Depth	0.10	0.05
			Bottom	0.10	0.05
3	2220	Inlet throat section	Surface	0.90	0.70
	2220		Mid-Depth	0.90	0.70
			Bottom	0.90	0.70
4	4068	Bolivar Roads	Surface	1.0	0.75
	4091		Mid-Depth	1.0	0.75
			Bottom	0.7	0.55
5	4680	GIWW East	Surface	5.0	5.0
	4972		Mid-Depth	4.5	4.5
			Bottom	3.0	3.0
6	4841	Brazos Port Turning Basin	Surface	0.17	0.05
	5361		Mid-Depth	0.07	0.055
			Bottom	0.01	0.05
7	5669	Dow Channel Berths	Surface	0.085	0.08
	5677		Mid-Depth	0.08	0.08
			Bottom	0.05	0.075
8	6389	Big Bend	Surface	0.08	0.055
	6624		Mid-Depth	0.075	0.06
			Bottom	0.06	0.055
9	7100	North of Upper Turning Basin	Surface	0.075	0.04
	7520		Mid-Depth	0.09	0.04
			Bottom	0.075	0.04
10	7329	Stauffer Turning Basin	Surface	0.13	0.12
	7731		Mid-Depth	0.13	0.125
			Bottom	0.11	0.10

Table 4.7.3: Summary of model velocities for Ebb: Base and Plan

S. #	Node # Base/ Plan	Location	Depth	Avg Vel (ft/s)	Avg Vel (ft/s)
			Bottom	-0.04	-0.12
				Base	**Plan**
1	707	End of existing Outer channel in sea	Surface	-0.05	-0.12
	707		Mid-Depth	-0.04	-0.12
			Bottom	-0.04	-0.12
2	1574	Half way between entrance and end of channel	Surface	-0.05	-0.10
	1574		Mid-Depth	-0.05	-0.10
			Bottom	-0.05	-0.10
3	2220	Inlet throat section	Surface	-0.80	-0.60
	2220		Mid-Depth	-0.80	-0.60
			Bottom	-0.80	-0.60
4	4068	Bolivar Roads	Surface	-0.80	-0.60
	4091		Mid-Depth	-0.90	-0.60
			Bottom	-0.80	-0.50
5	4680	GIWW East	Surface	- 3.5	- 3.5
	4972		Mid-Depth	- 3.2	- 3.2
			Bottom	- 2.1	- 2.1
6	4841	Brazos Port Turning Basin	Surface	-0.05	-0.04
	5361		Mid-Depth	-0.055	-0.035
			Bottom	-0.14	-0.03
7	5669	Dow Channel Berths	Surface	-0.06	-0.06
	5677		Mid-Depth	-0.065	-0.055
			Bottom	-0.075	-0.05
8	6389	Big Bend	Surface	-0.05	-0.035
	6624		Mid-Depth	-0.05	-0.04
			Bottom	-0.05	-0.035
9	7100	North of Upper Turning Basin	Surface	-0.045	-0.03
	7502		Mid-Depth	-0.06	-0.03
			Bottom	-0.045	-0.03
10	7329	Stauffer Turning Basin	Surface	-0.10	-0.10
	7731		Mid-Depth	-0.10	-0.10
			Bottom	-0.08	-0.075

Table 4.7.4: Summary of depth variation in model velocities for Base (Reference: Appendix 4)

S. #	Node # Base	Location	Comment
1	707	End of existing Outer channel in sea	No velocity variation along water depth
2	1574	Half way between entrance and end of channel	No velocity variation along water depth
3	2220	Inlet throat section	No velocity variation along water depth
4	4068	Bolivar Roads	Mid-depth velocity higher than surface and bottom. Flood by 0.3 ft/s. Ebb by 0.1 ft/s.
5	4680	GIWW East	Surface and Mid-depth velocity higher than bottom. Flood by 1 to 1.5 ft/s. Ebb by 1.5 to 2 ft/s.
6	4841	Brazos Port Turning Basin	Simultaneous bottom velocity in opposite direction to surface. Surface and Mid-depth velocity higher than bottom
7	5669	Dow Channel Berths	Simultaneous bottom velocity in opposite direction to surface. Surface and Mid-depth velocity higher than bottom
8	6389	Big Bend	Velocity over water depth mostly the same, with occasional exceptions.
9	7100	North of Upper Turning Basin	Velocity over water depth mostly the same.
10	7329	Stauffer Turning Basin	Surface and Mid-depth velocity slightly higher than bottom for flood and ebb.

Table 4.7.5: Summary of depth variation in model velocities for Plan (Reference: Appendix 4)

S. #	Node # Plan	Location	Comment
1	707	End of existing Outer channel in sea	No velocity variation along water depth
2	1574	Half way between entrance and end of channel	No velocity variation along water depth
3	2220	Inlet throat section	No velocity variation along water depth
4	4091	Bolivar Roads	Mid-depth velocity higher than surface and bottom. Flood by 0.3 ft/s. Ebb by 0.1 ft/s.
5	4972	GIWW East	Surface and Mid-depth velocity higher than bottom. Both Flood and Ebb by 1.5 to 2 ft/s.
6	5361	Brazos Port Turning Basin	No velocity variation along water depth
7	5677	Dow Channel Berths	No velocity variation along water depth
8	6624	Big Bend	No velocity variation along water depth
9	7502	North of Upper Turning Basin	(Data appears doubtful)
10	7731	Stauffer Turning Basin	Surface and Mid-depth velocities slightly higher than bottom

Table 4.7.6: Summary of model velocities for Base and Plan (Reference Appendix 5)

S. #	Node Base	Node Plan	Location	Depth	Comments (Flood)	Comments (Ebb)
1	707	707	End of existing Outer channel in sea	Surface	Plan flood velocity smaller than Base velocity by 0.05 ft/s.	Plan ebb velocity greater than Base velocity by 0.07 ft/s.
				Mid-Depth	Plan flood velocity smaller than Base velocity by 0.05 ft/s.	Plan ebb velocity greater than Base velocity by 0.07 ft/s.
				Bottom	Plan flood velocity smaller than Base velocity by 0.05 ft/s.	Plan ebb velocity greater than Base velocity by 0.07 ft/s.
2	1574	1574	Half way between entrance and end of channel	Surface	Plan flood velocity smaller than Base velocity by 0.05 ft/s.	Plan ebb velocity greater than Base velocity by 0.05 ft/s.
				Mid-Depth	Plan flood velocity smaller than Base velocity by 0.05 ft/s.	Plan ebb velocity greater than Base velocity by 0.05 ft/s.
				Bottom	Plan flood velocity smaller than Base velocity by 0.05 ft/s.	Plan ebb velocity greater than Base velocity by 0.05 ft/s.
3	2220	2220	Inlet throat section	Surface	Plan flood velocity smaller than Base velocity by 0.02 ft/s.	Plan ebb velocity smaller than Base velocity by 0.02 ft/s.
				Mid-Depth	Plan flood velocity smaller than Base velocity by 0.02 ft/s.	Plan ebb velocity smaller than Base velocity by 0.02 ft/s.
				Bottom	Plan flood velocity smaller than Base velocity by 0.02 ft/s.	Plan ebb velocity smaller than Base velocity by 0.02 ft/s.
4	4068	4091	Bolivar Roads	Surface	Plan flood velocity smaller than Base velocity by 0.03 ft/s.	Plan ebb velocity smaller than Base velocity by 0.03 ft/s.
				Mid-Depth	Plan flood velocity smaller than Base velocity by 0.03 ft/s.	Plan ebb velocity smaller than Base velocity by 0.03 ft/s.
				Bottom	Plan flood velocity smaller than Base velocity by 0.03 ft/s.	Plan ebb velocity smaller than Base velocity by 0.03 ft/s.
5	4680	4972	GIWW East	Surface	Plan flood velocity does not differ from Base velocity.	Plan ebb velocity does not differ from Base velocity.
				Mid-Depth	Plan flood velocity does not differ from Base velocity.	Plan ebb velocity does not differ from Base velocity.
				Bottom	Plan flood velocity does not differ from Base velocity.	Plan ebb velocity does not differ from Base velocity.
6	4841	5361	Brazos Port Turning Basin	Surface	Plan flood velocity smaller than Base velocity by 0.1 ft/s.	Plan ebb velocity does not differ from Base velocity.
				Mid-Depth	Peak plan flood velocity smaller than peak base by 0.02 ft/s	Peak plan ebb velocity smaller than peak base by 0.02 ft/s
				Bottom	Simultaneous Plan bottom velocity in opposite direction to Base.	Simultaneous Plan bottom velocity in opposite direction to Base.
7	5669	5677	Dow Channel Berths	Surface	Plan flood velocity does not differ from Base velocity.	Plan ebb velocity does not differ from Base velocity.
				Mid-Depth	Plan flood velocity does not differ significantly from Base velocity.	Plan ebb velocity does not differ significantly from Base velocity.
				Bottom	Peak plan flood velocity smaller than peak base by 0.01 ft/s	Peak plan ebb velocity smaller than peak base by 0.01 ft/s
8	6389	6624	Big Bend	Surface	Peak plan flood velocity smaller than peak base by 0.02	Peak plan ebb velocity smaller than peak base by 0.02 ft/s

					ft/s	
				Mid-Depth	Peak plan flood velocity smaller than peak base by 0.02 ft/s	Peak plan ebb velocity smaller than peak base by 0.02 ft/s
				Bottom	Peak plan flood velocity smaller than peak base by 0.02 ft/s	Peak plan ebb velocity smaller than peak base by 0.02 ft/s

9	7100	7520	North of Upper Turning Basin	Surface	(Data appears doubtful)	(Data appears doubtful)
				Mid-Depth	Peak plan flood velocity smaller than peak base by 0.04 ft/s	Peak plan ebb velocity smaller than peak base by 0.03 ft/s
				Bottom	(Data appears doubtful)	(Data appears doubtful)
10	7329	7731	Stauffer Turning Basin	Surface	Plan flood velocity does not differ from Base velocity.	Plan ebb velocity does not differ from Base velocity.
				Mid-Depth	Plan flood velocity does not differ from Base velocity.	Plan ebb velocity does not differ from Base velocity.
				Bottom	Plan flood velocity does not differ from Base velocity.	Plan ebb velocity does not differ from Base velocity.

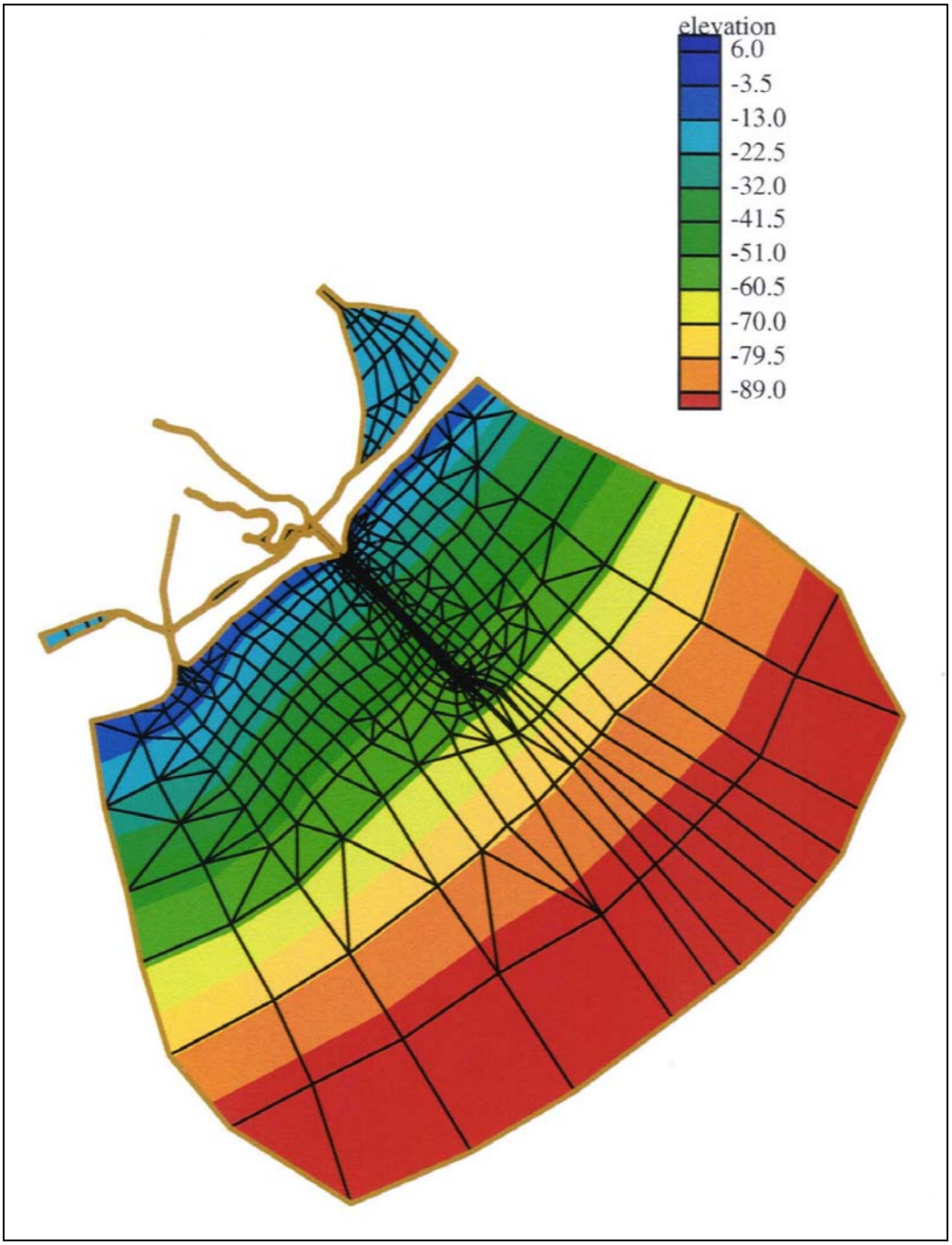


Figure 4.1.1: Numerical model grid and bathymetry used for study

Note: Elevations are with reference to Mean Low Tide (MLT). An arbitrary datum of 100.00 corresponding to the MLT is used for the numerical model.

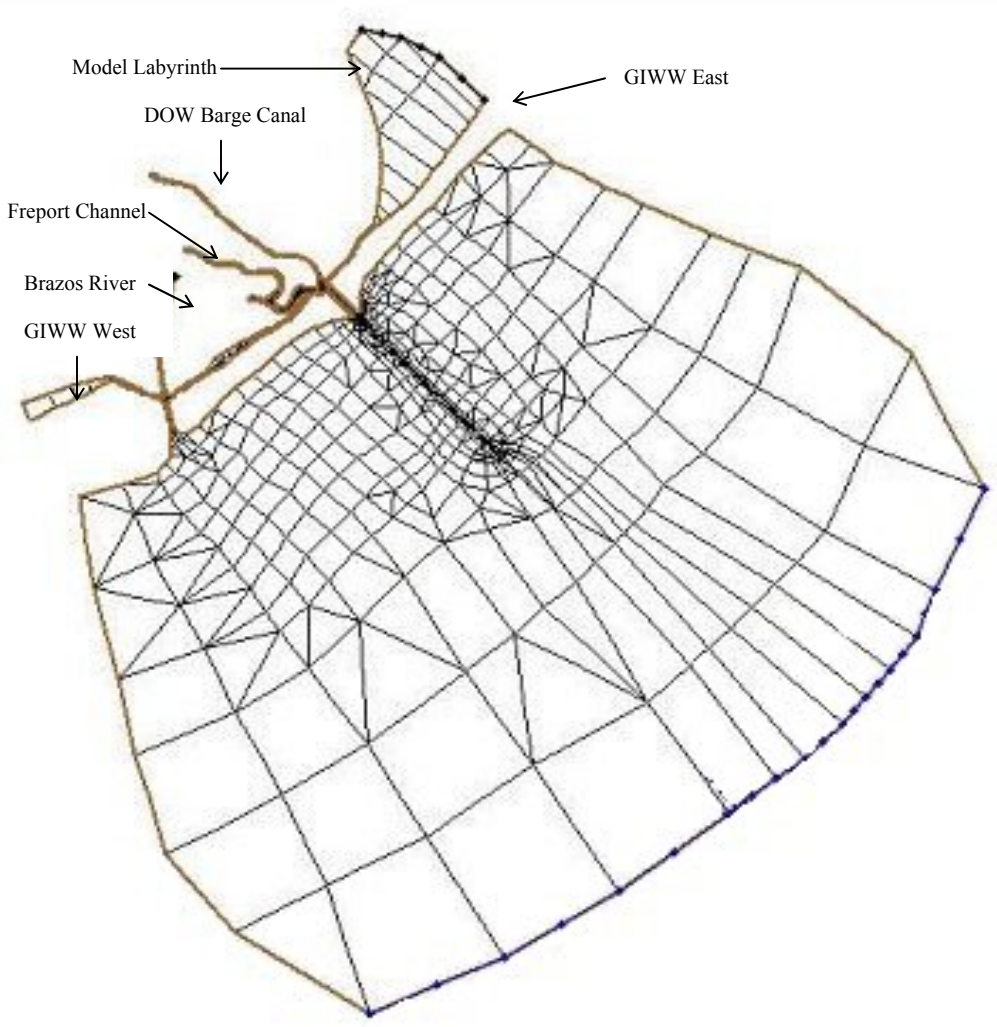


Figure 4.4.2: Model boundaries and computational mesh

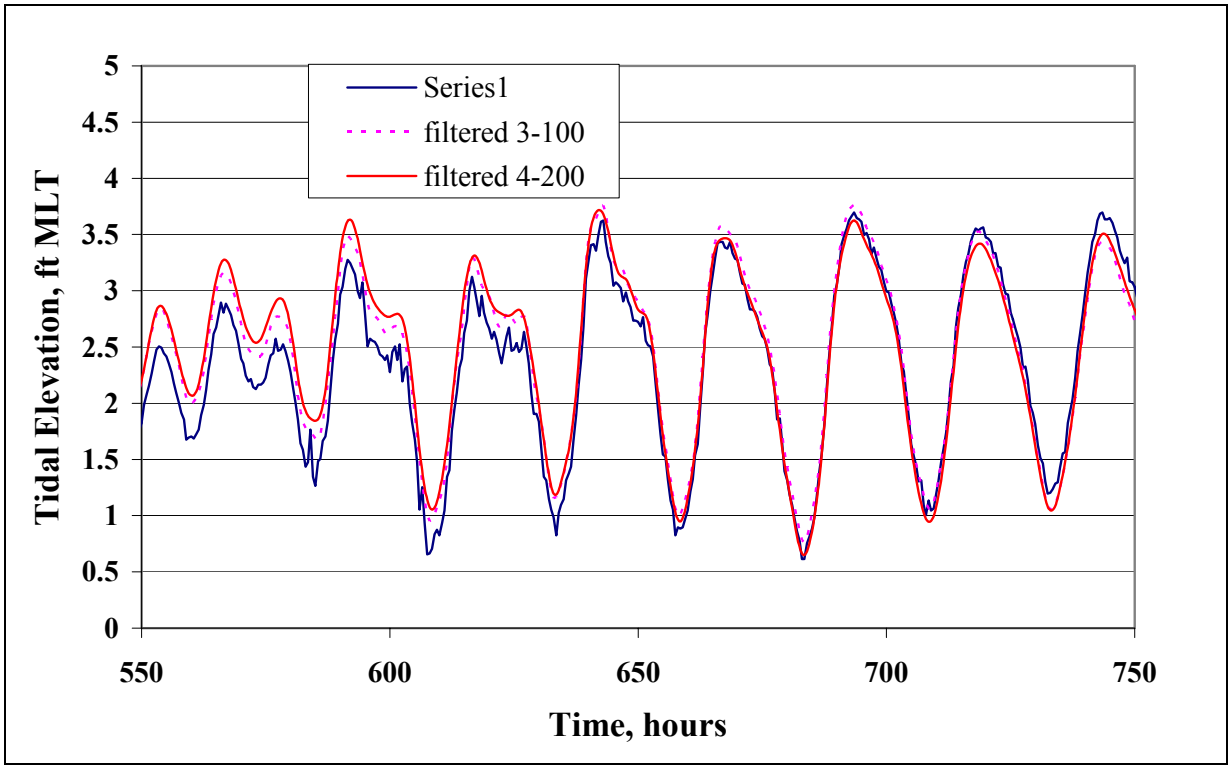


Figure 4.4.3: Effect of filtering raw tidal level data

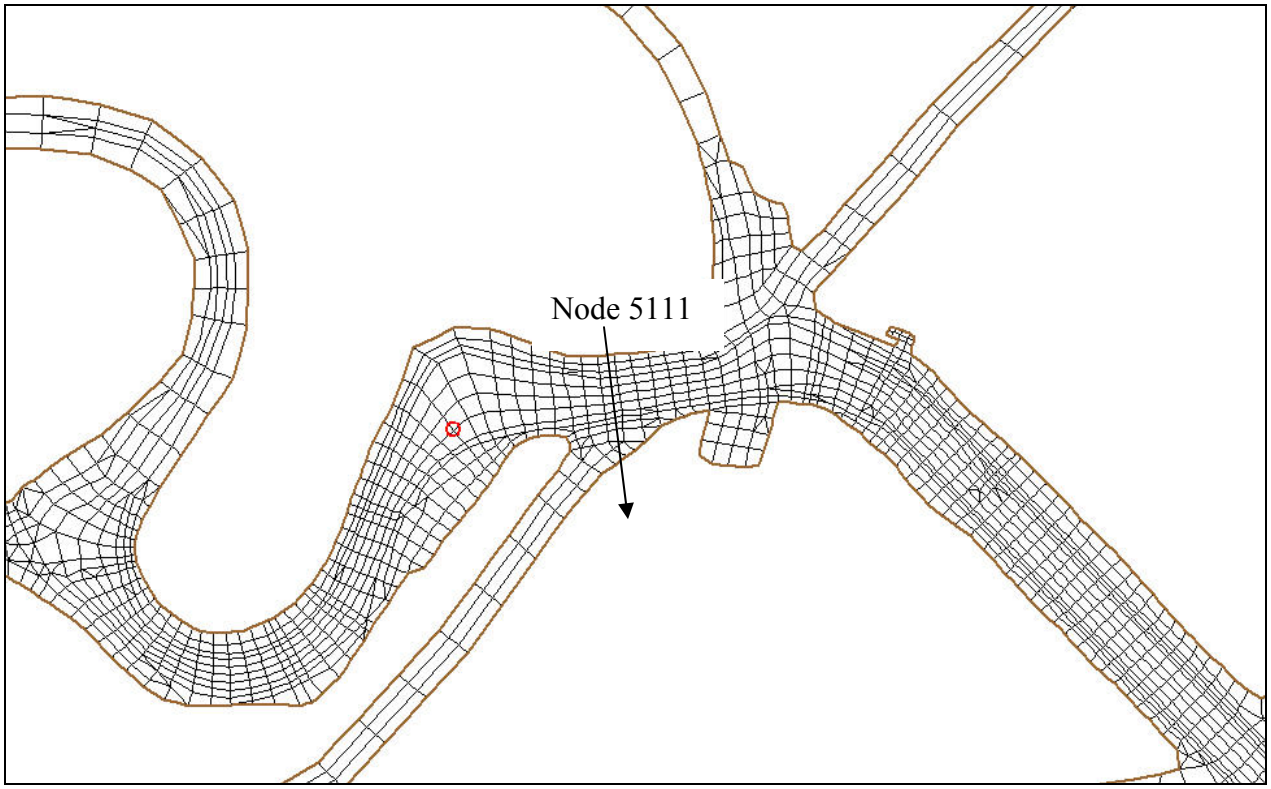


Figure 4.4.4: Location of Node 5111

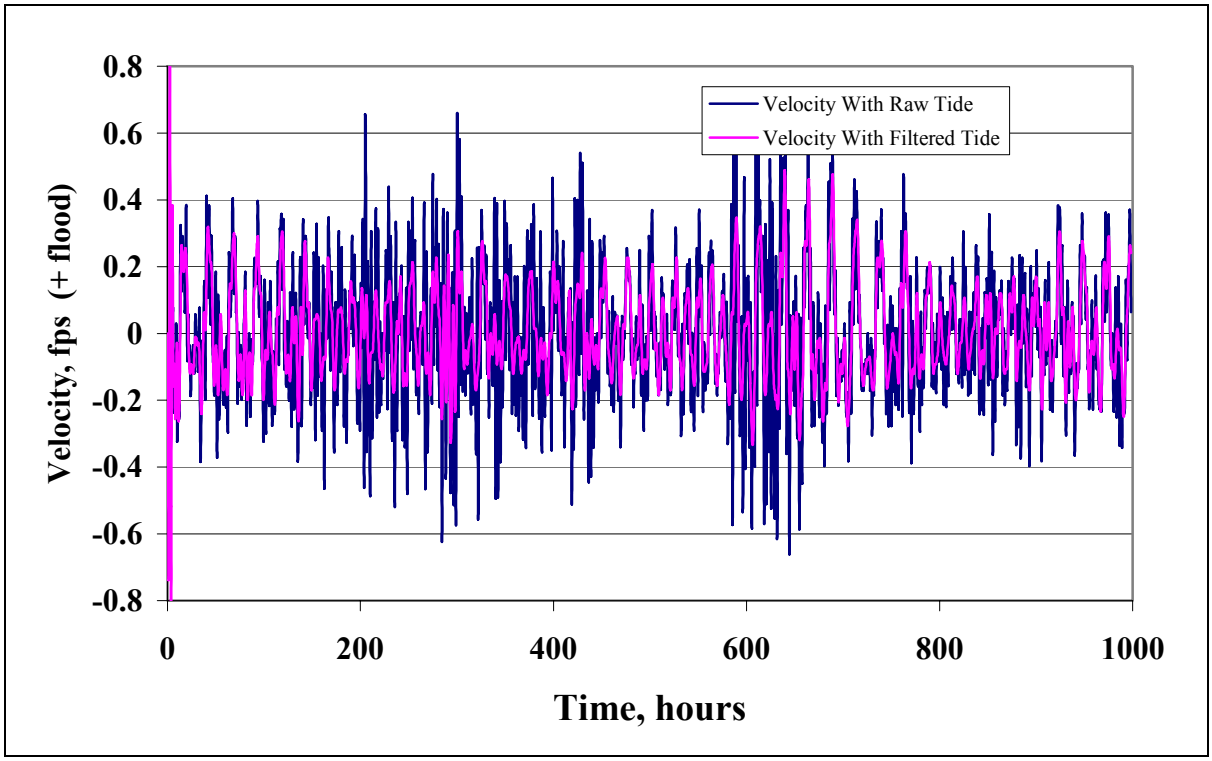


Figure 4.4.5: Effect of filtered boundary condition tide on model current velocities at Node 5111, 1000-hour time series

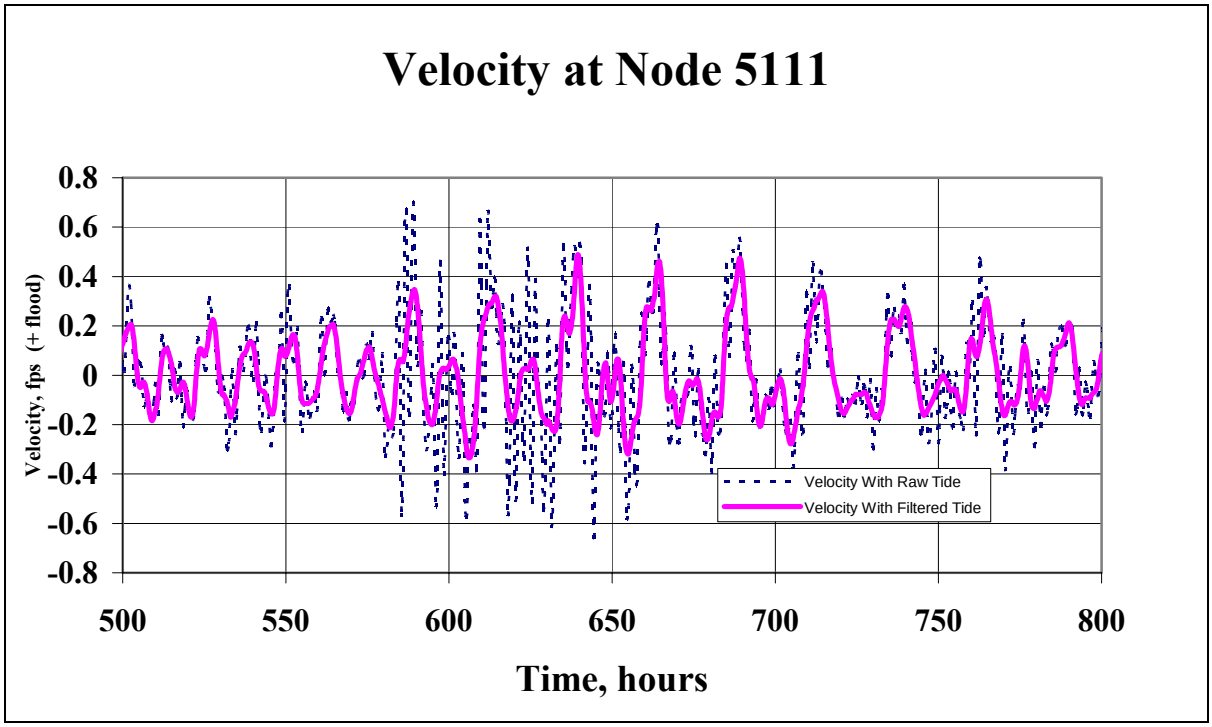


Figure 4.4.6: Effect of filtered boundary condition tide on model current velocities at Node 5111, 300-hour time series

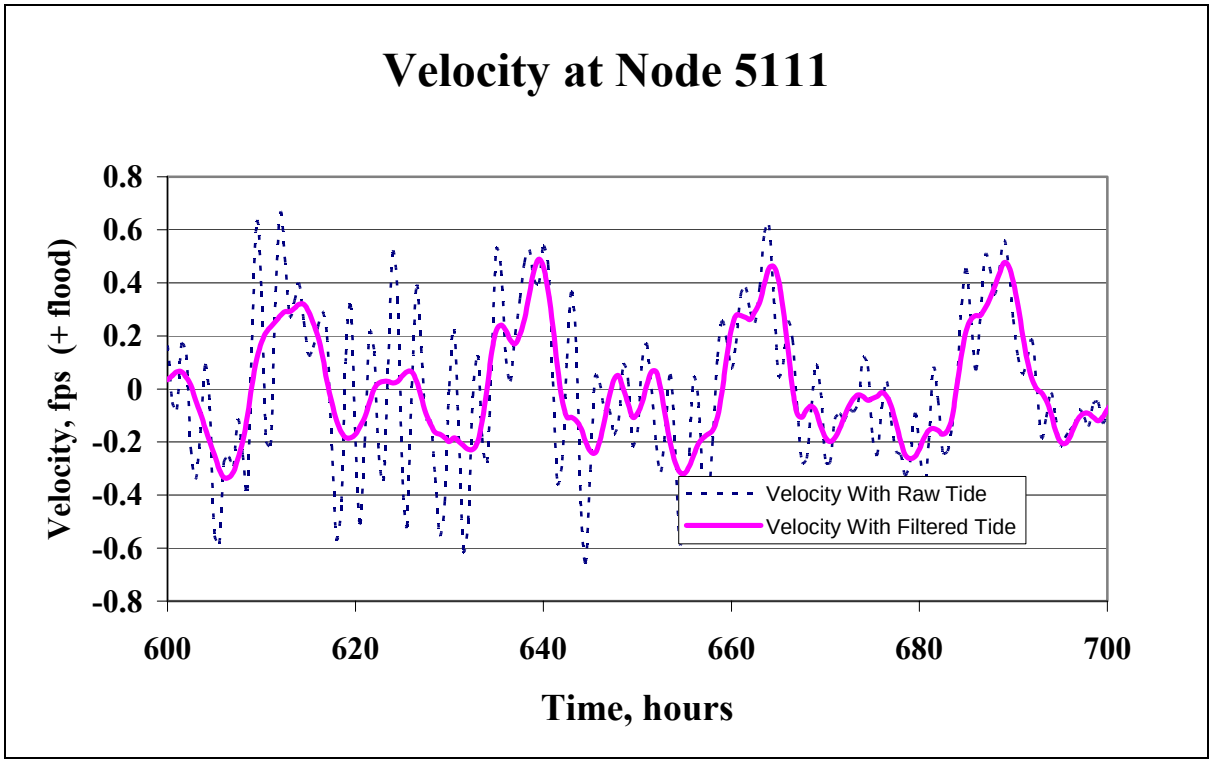


Figure 4.4.7: Effect of filtered boundary condition tide on model current velocities at Node 5111, 100-hour time series

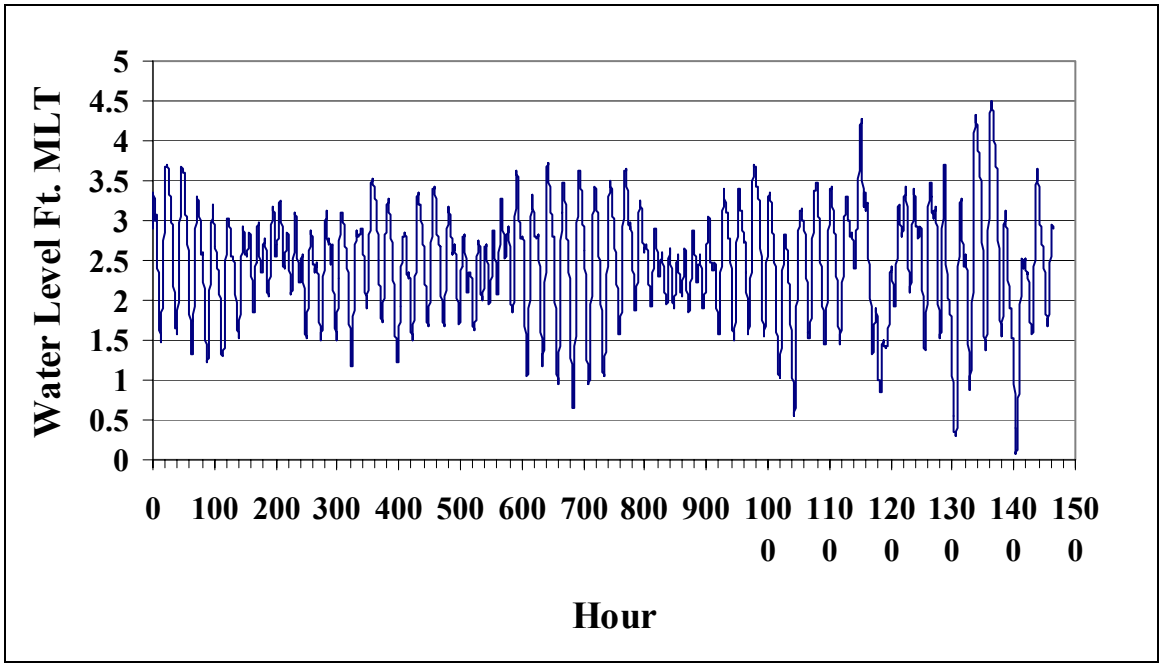


Figure 4.4.8: Time series of tidal water levels used as boundary condition

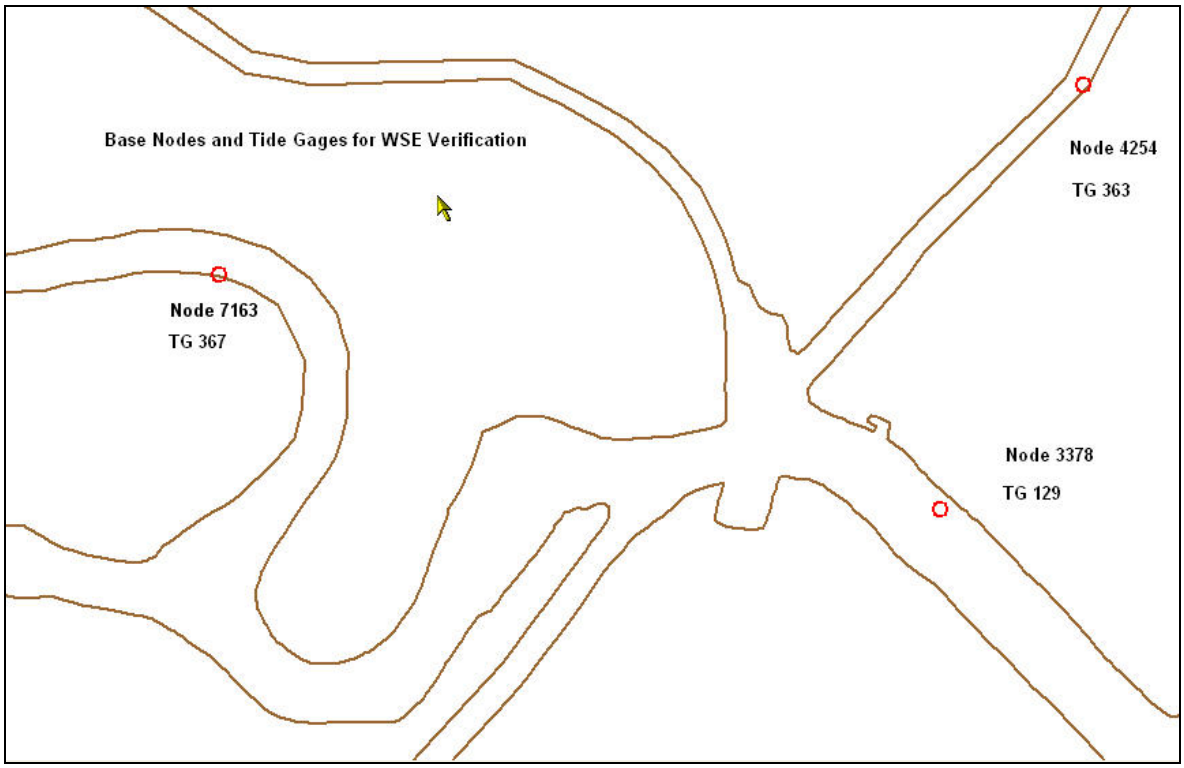


Figure 4.5.1: Base nodes and tide gage locations for water surface elevation verification of numerical model

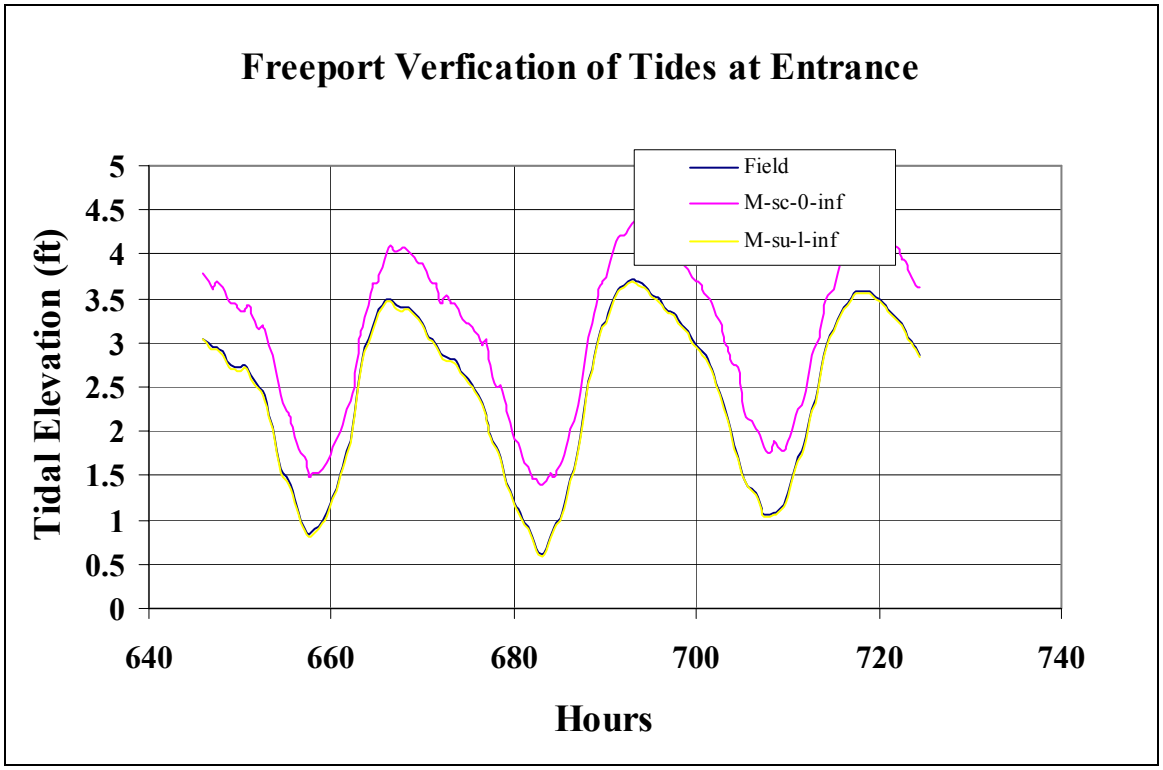


Figure 4.5.2: Verification of field and model tidal elevations at entrance

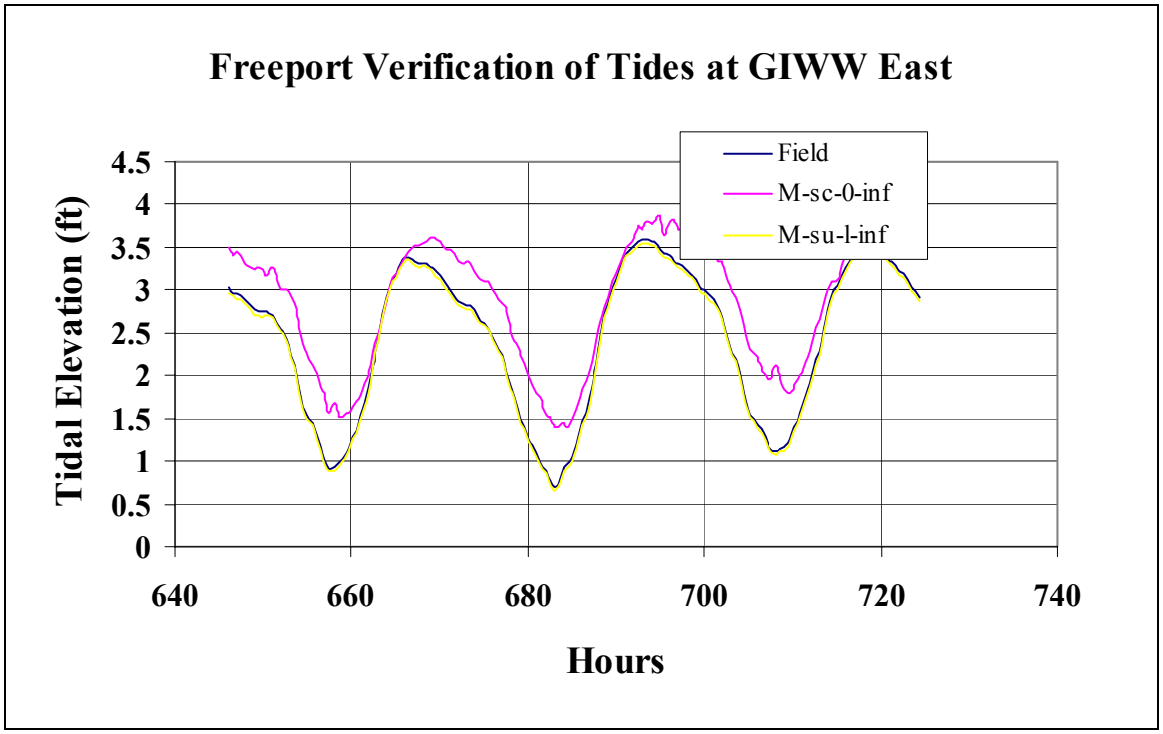


Figure 4.5.3: Verification of field and model tidal elevations at GIWW East

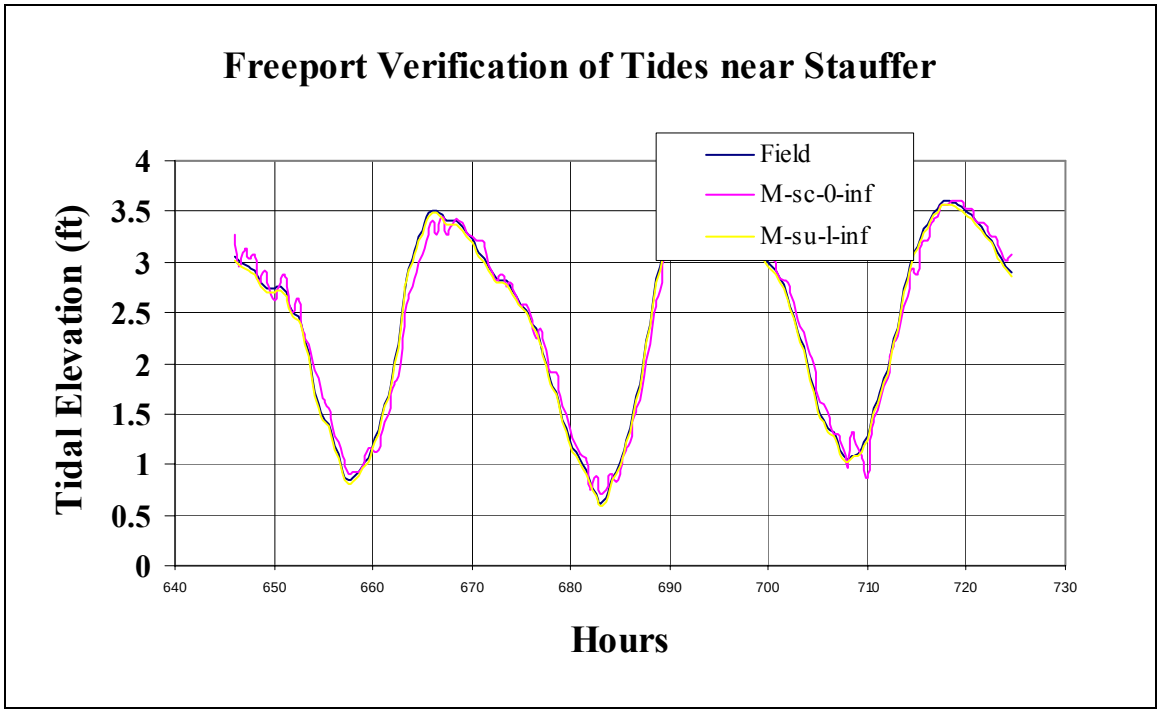


Figure 4.5.4: Verification of field and model tidal elevations near Stauffer

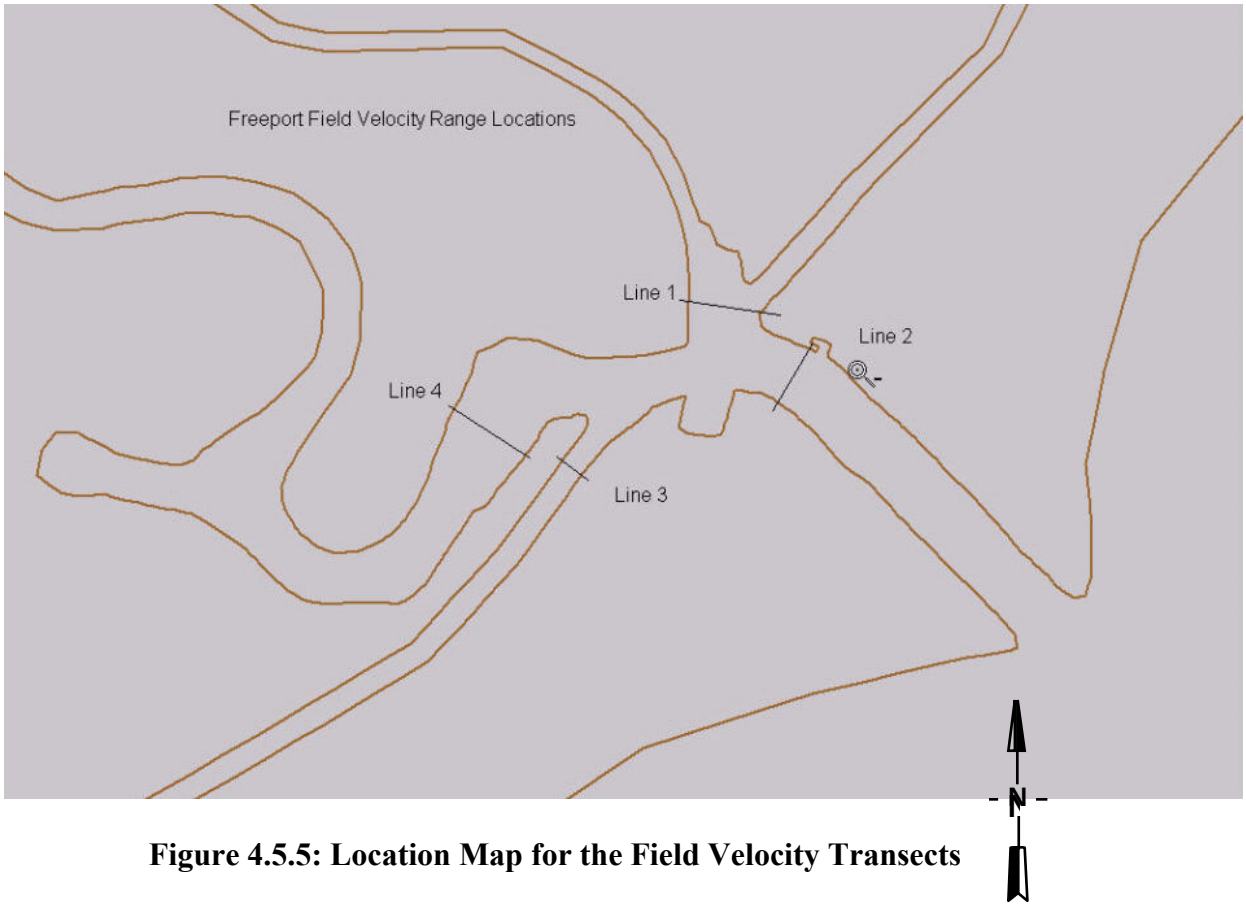


Figure 4.5.5: Location Map for the Field Velocity Transects

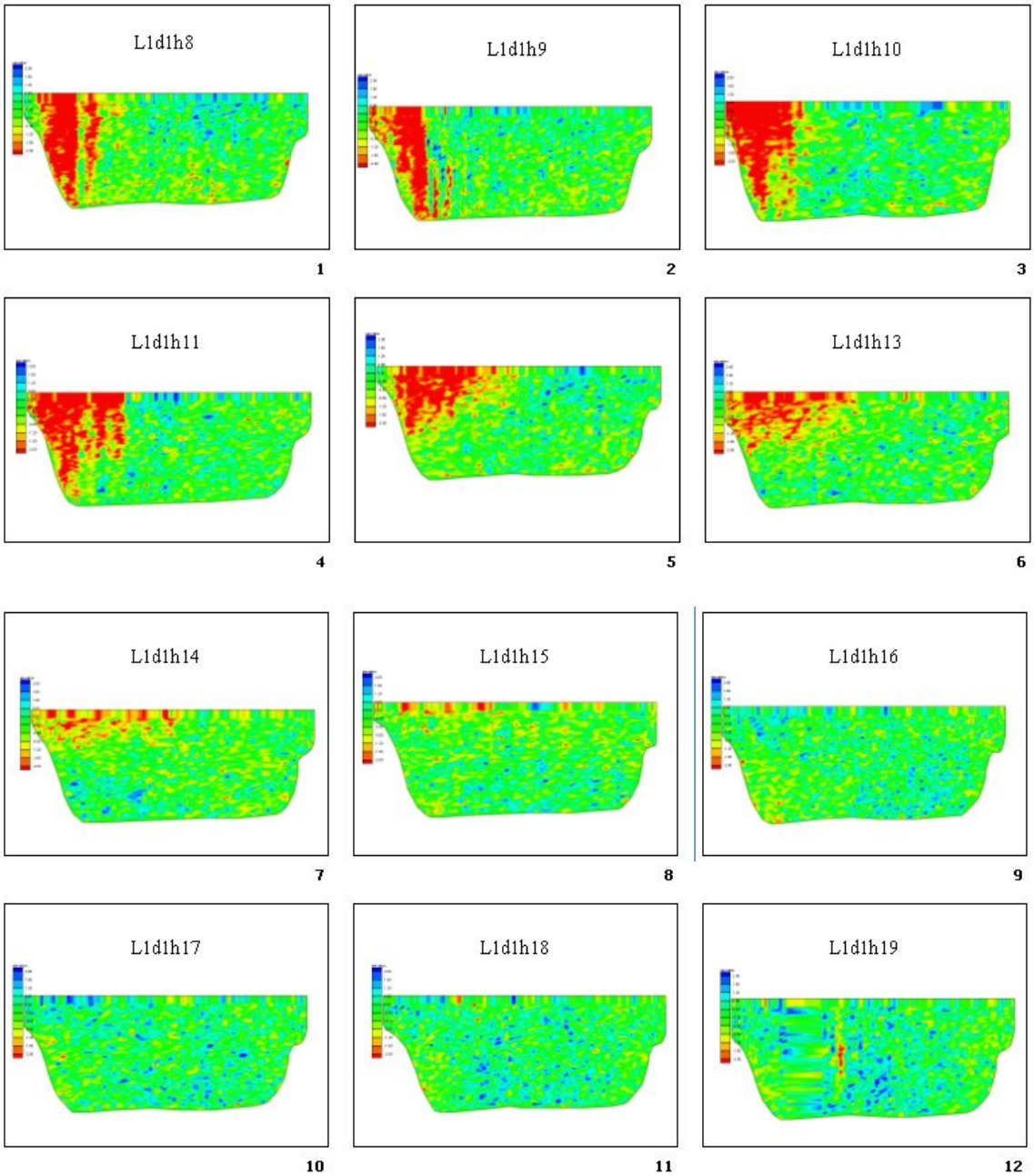


Figure 4.5.6: Velocity distribution in field at Transect 1, Plots 1-12

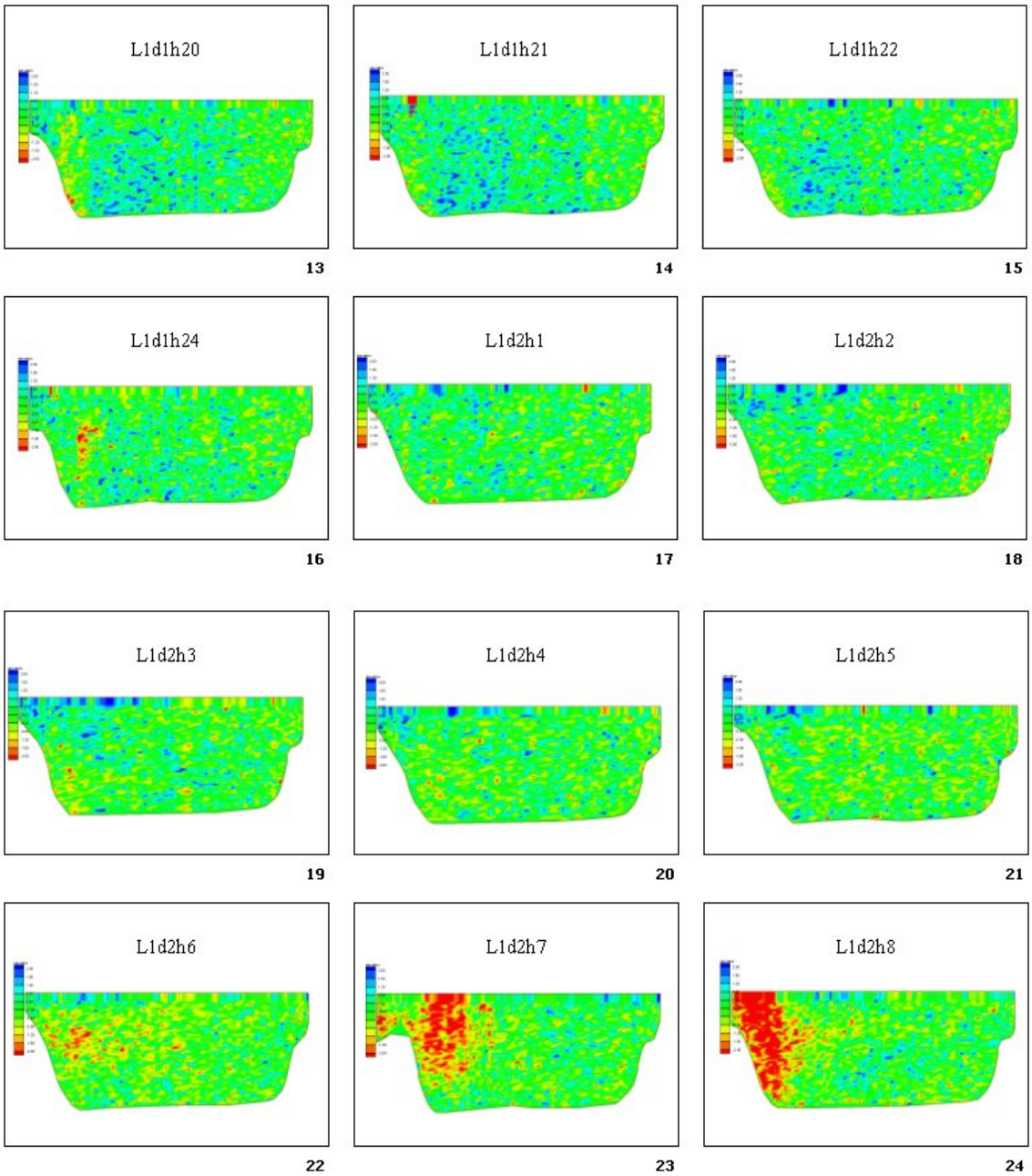


Figure 4.5.7: Velocity distribution in field at Transect 1, Plots 13-24

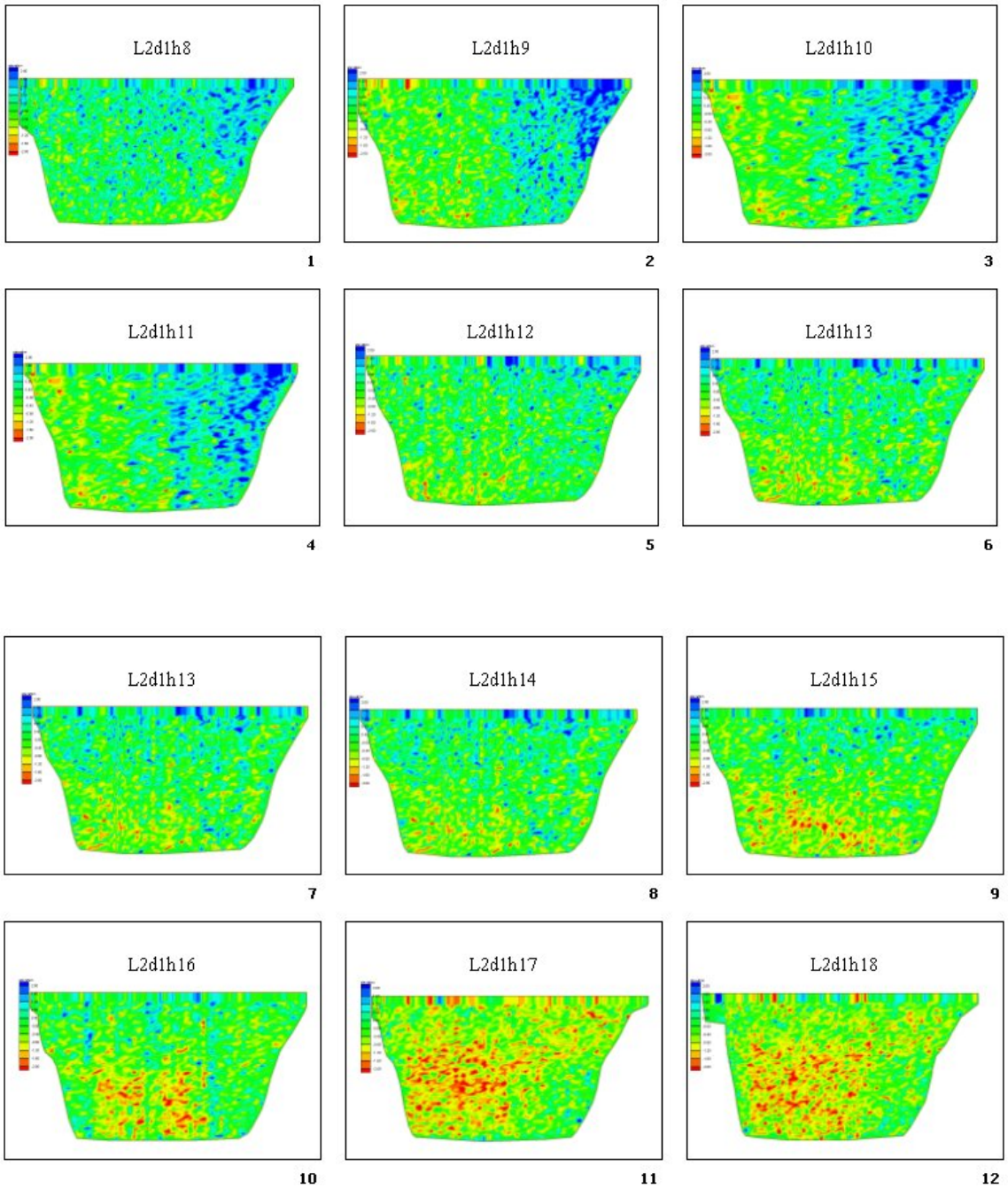


Figure 4.5.8: Velocity distribution in field at Transect 2, Plots 1-12

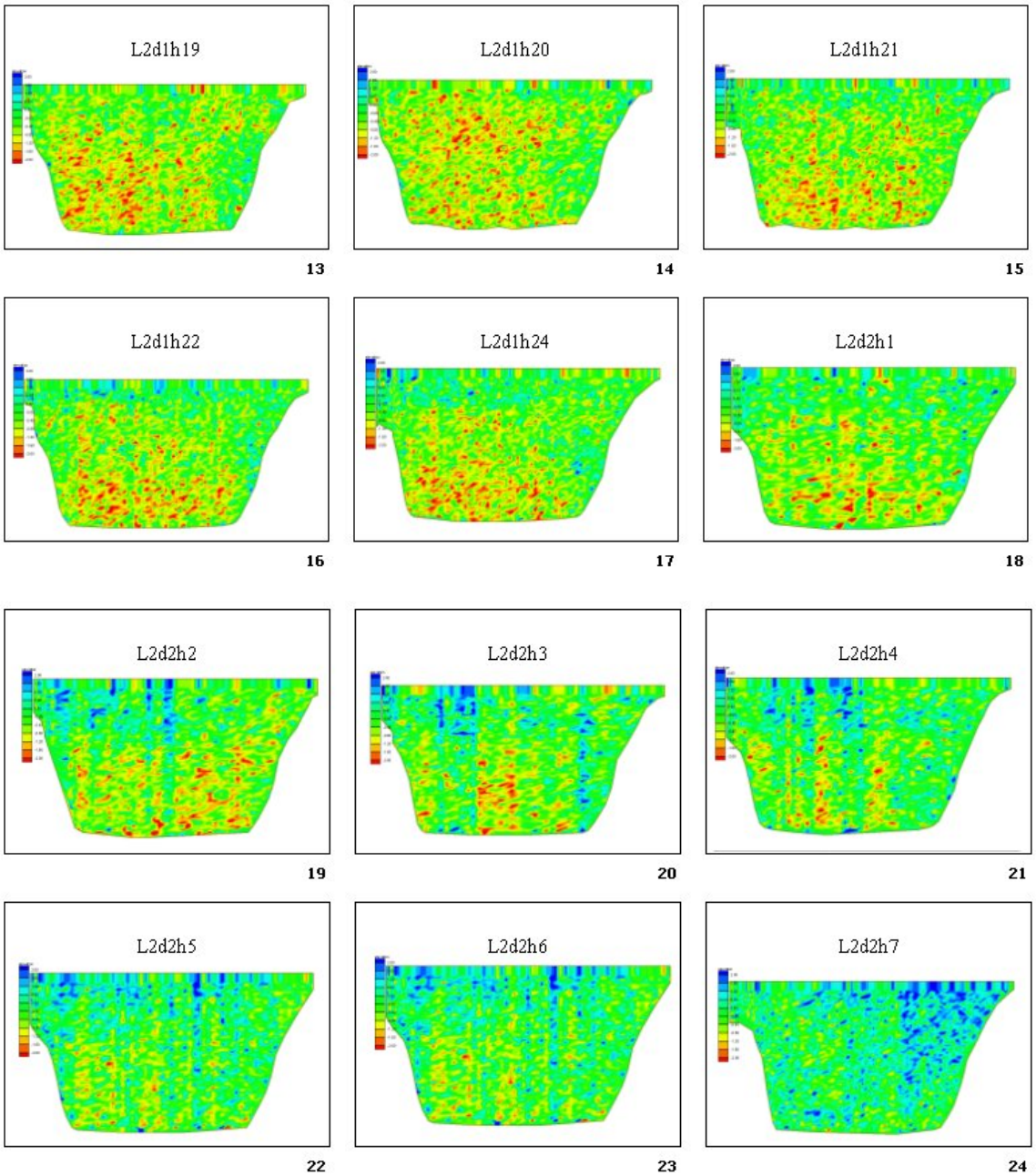


Figure 4.5.9: Velocity distribution in field at Transect2, Plots 13-24

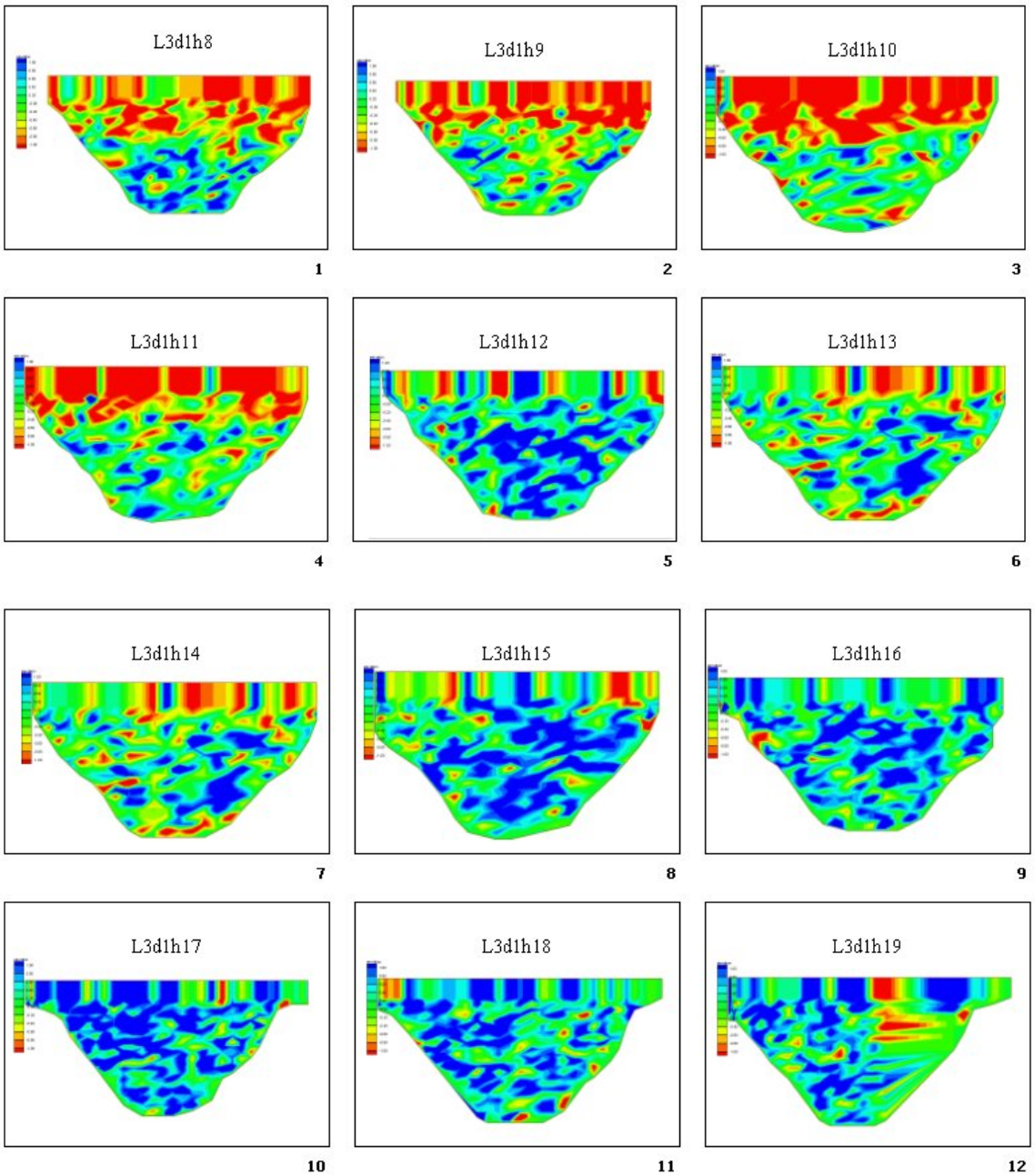


Figure 4.5.10: Velocity distribution in field at Transect3, Plots 1-12

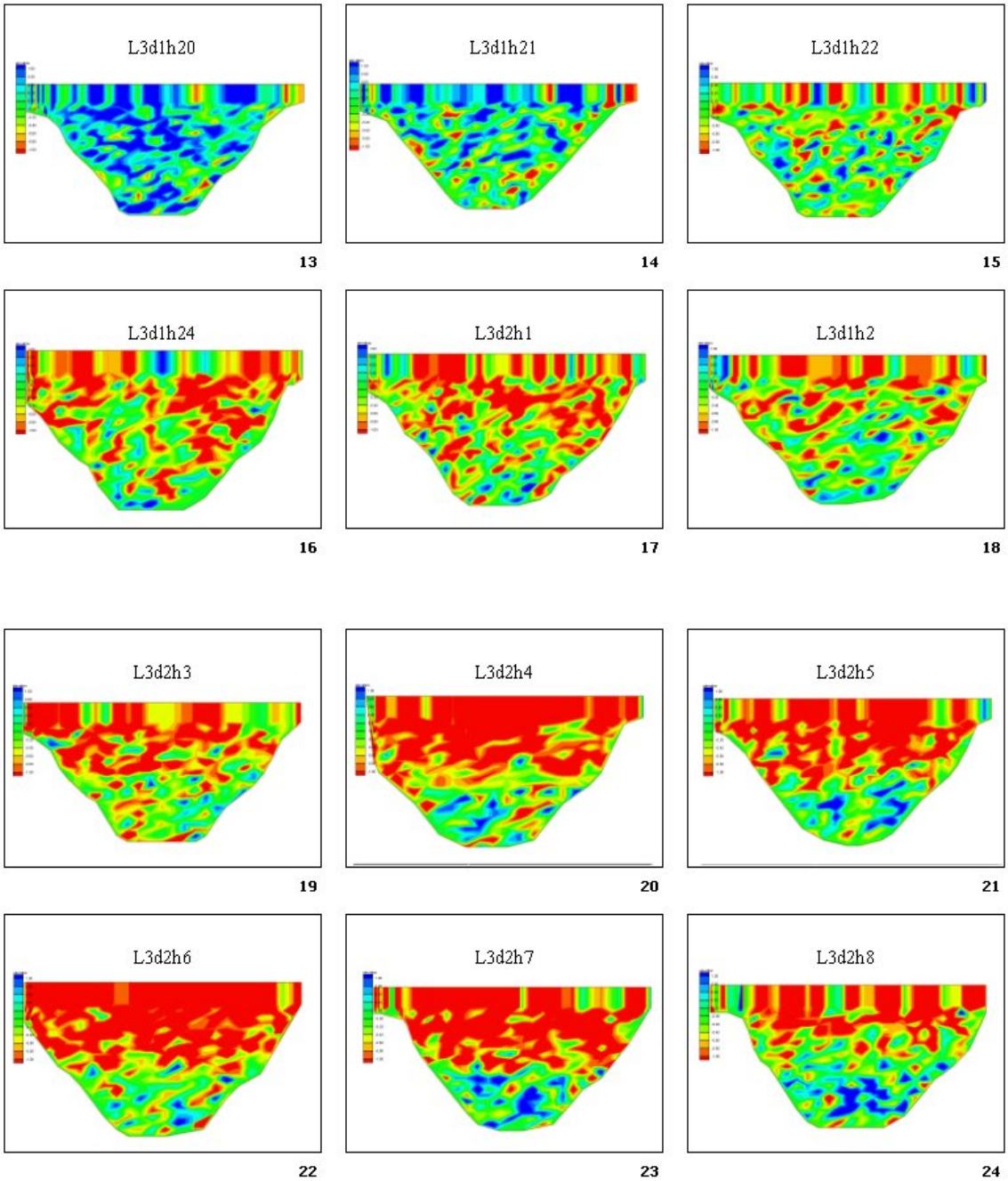


Figure 4.5.11: Velocity distribution in field at Transect 3, Plots 13-24

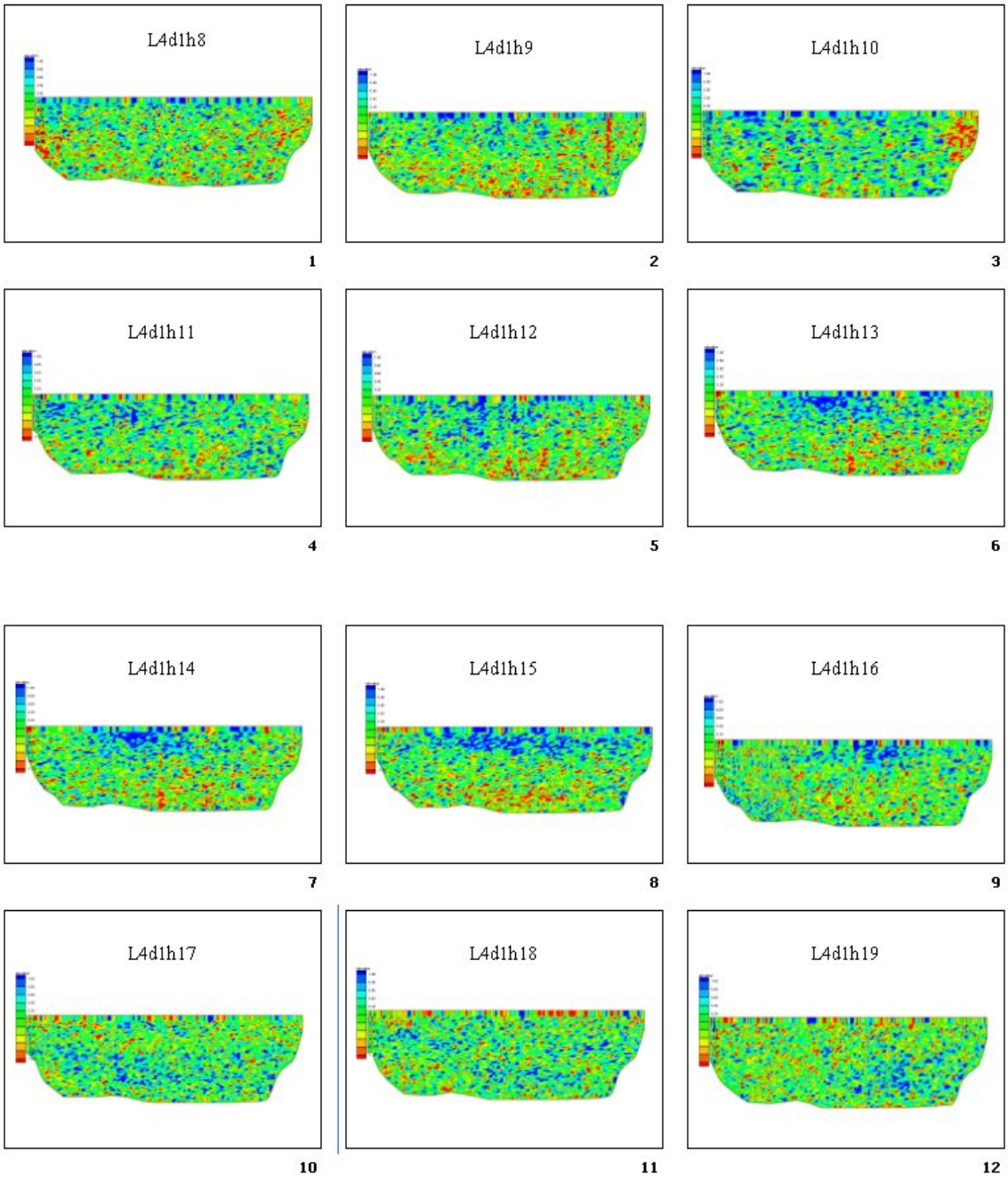


Figure 4.5.12: Velocity distribution in field at Transect4, Plots 1-12

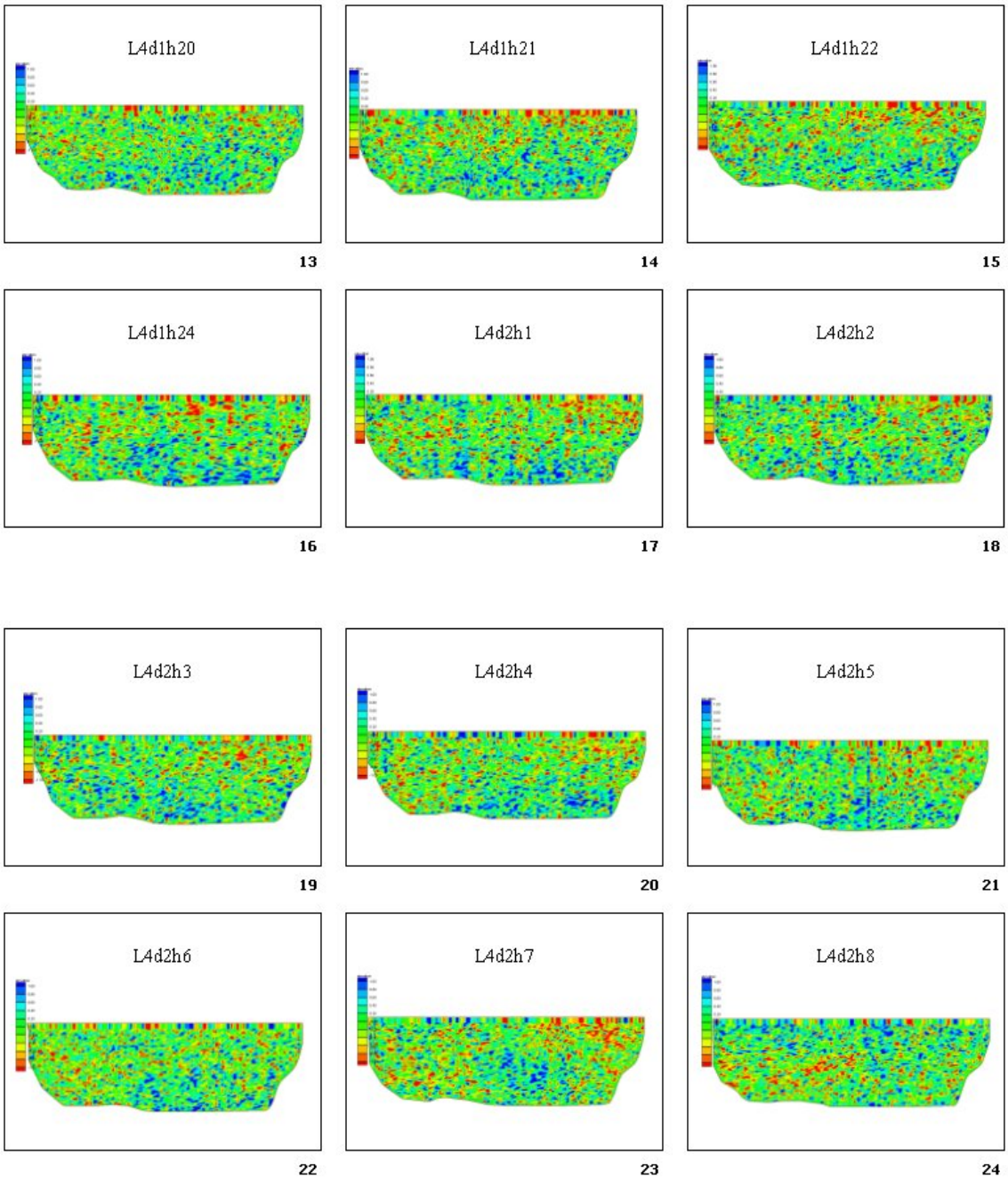


Figure 4.5.13: Velocity distribution in field at Transect4, Plots 13-24

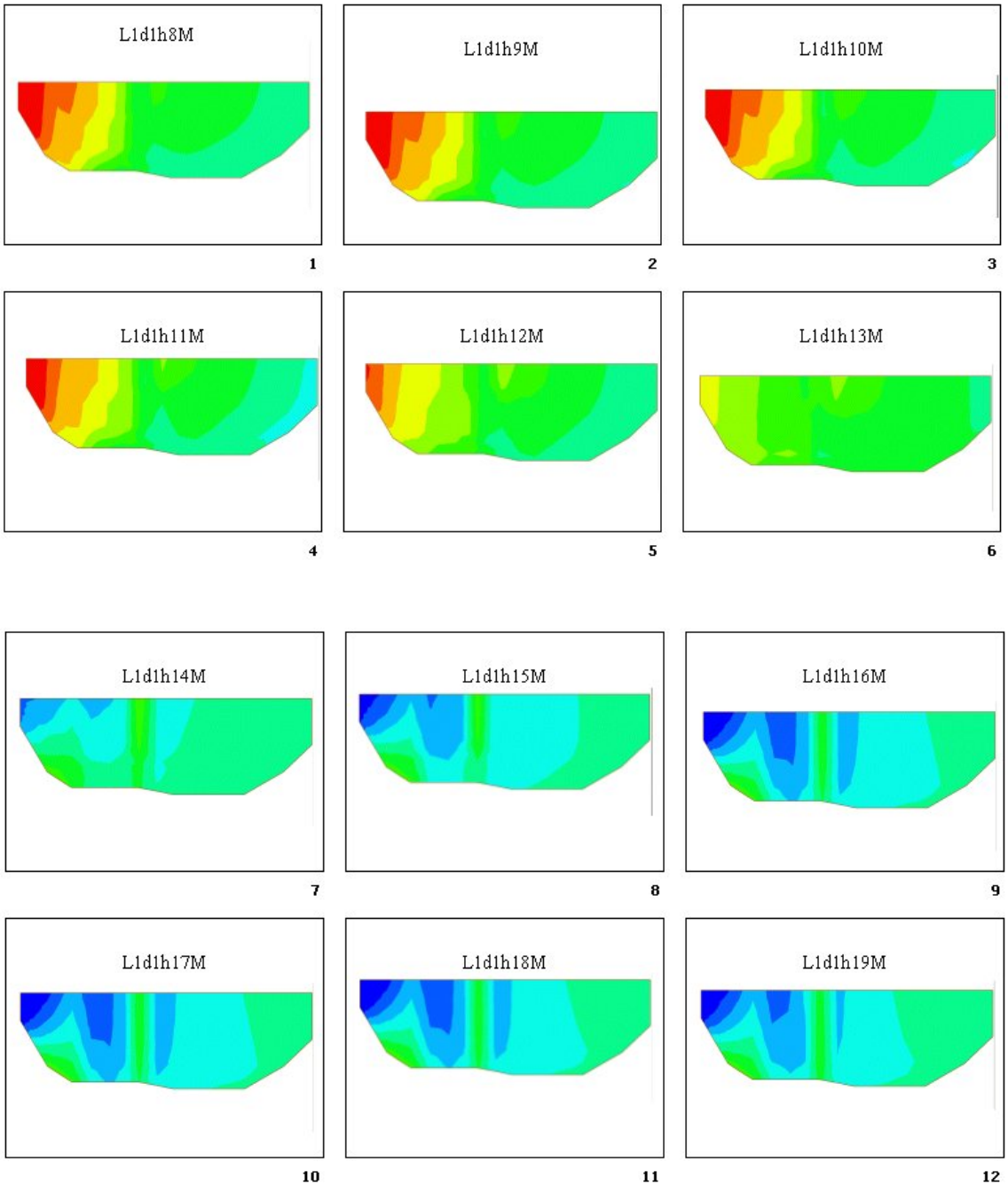


Figure 4.5.14: Velocity distribution in model at Transect 1, Plots 1-12

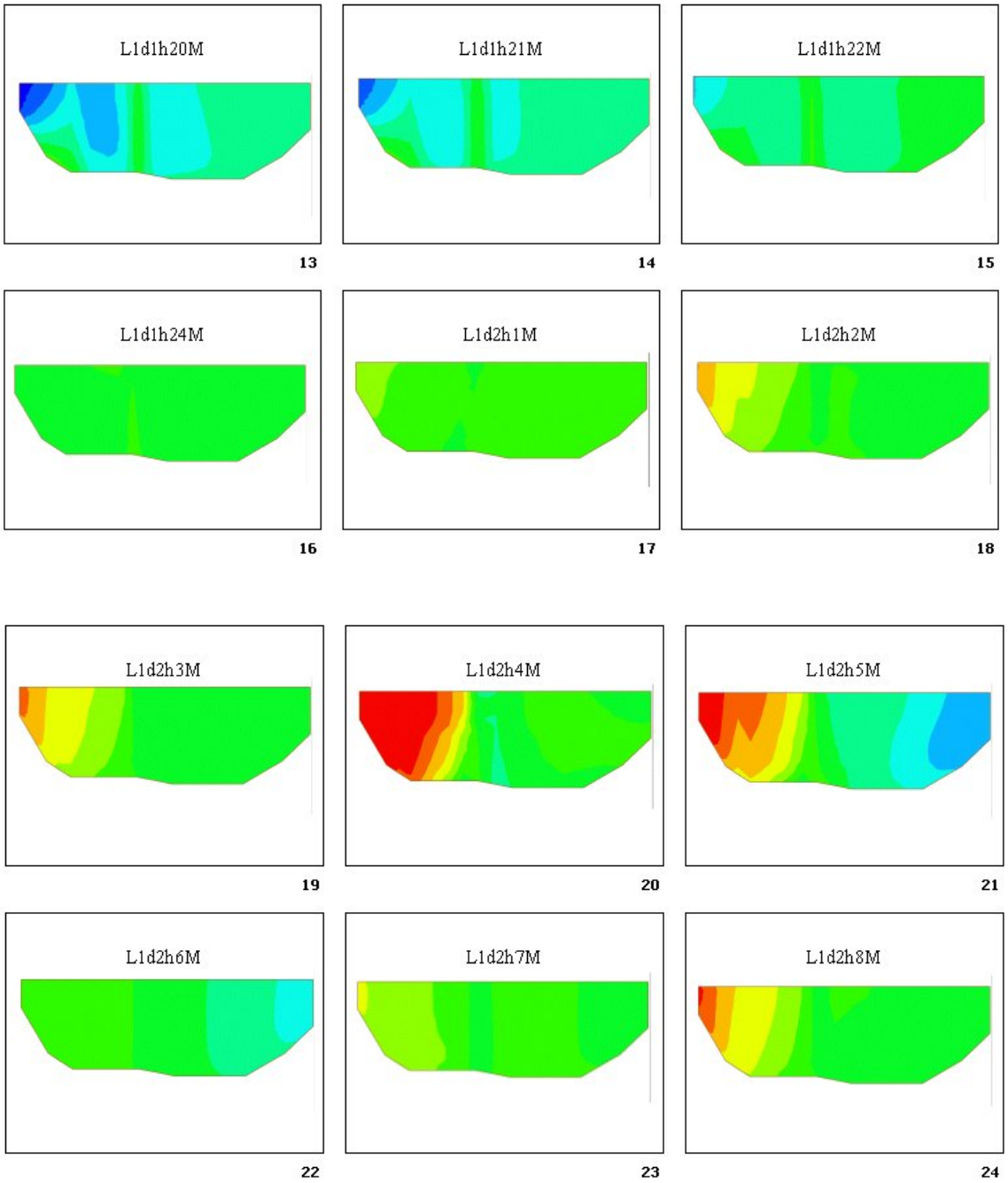


Figure 4.5.15: Velocity distribution in model at Transect 1, Plots 13-24

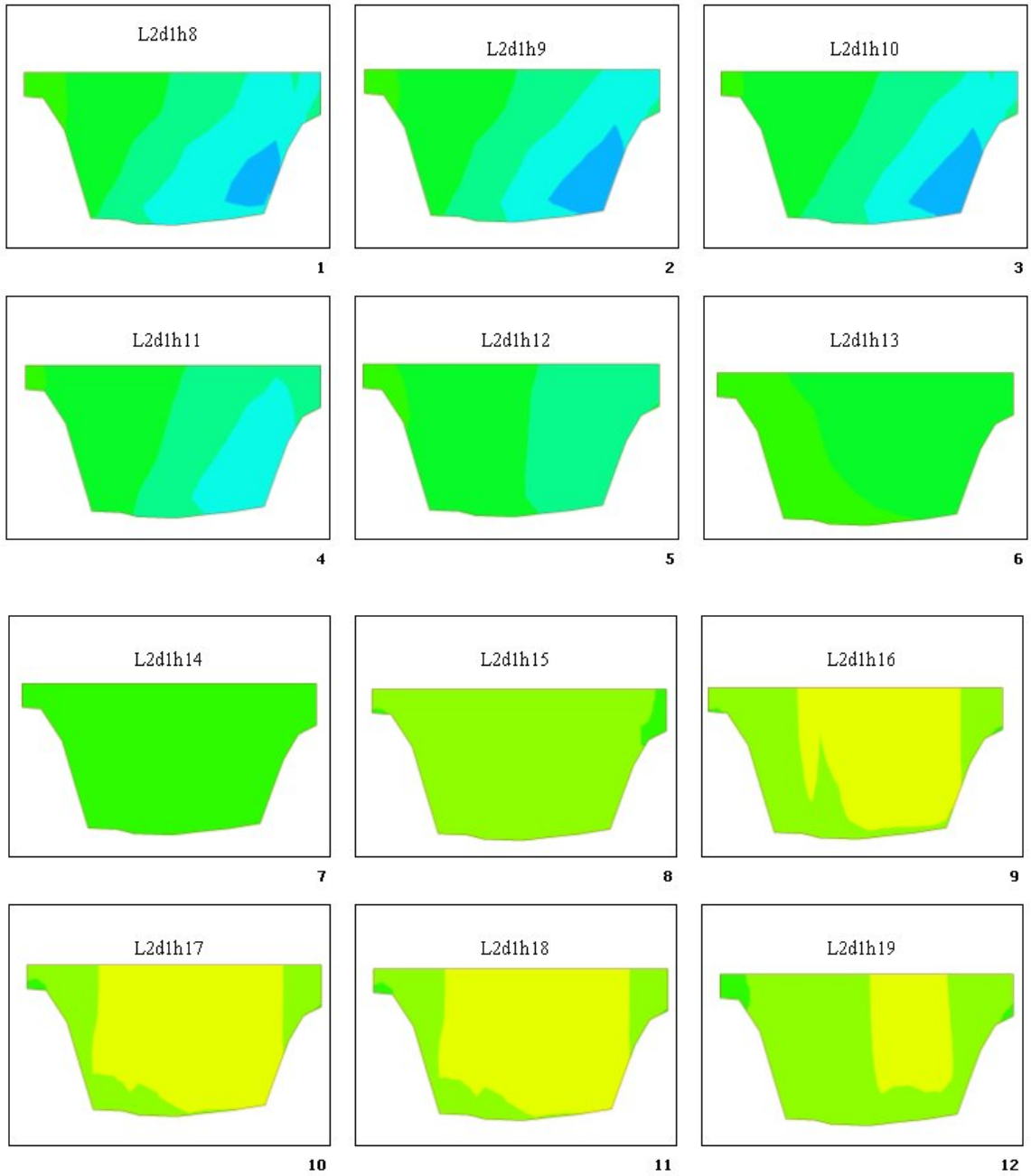


Figure 4.5.16: Velocity distribution in model at Transect 2, Plots 1-12

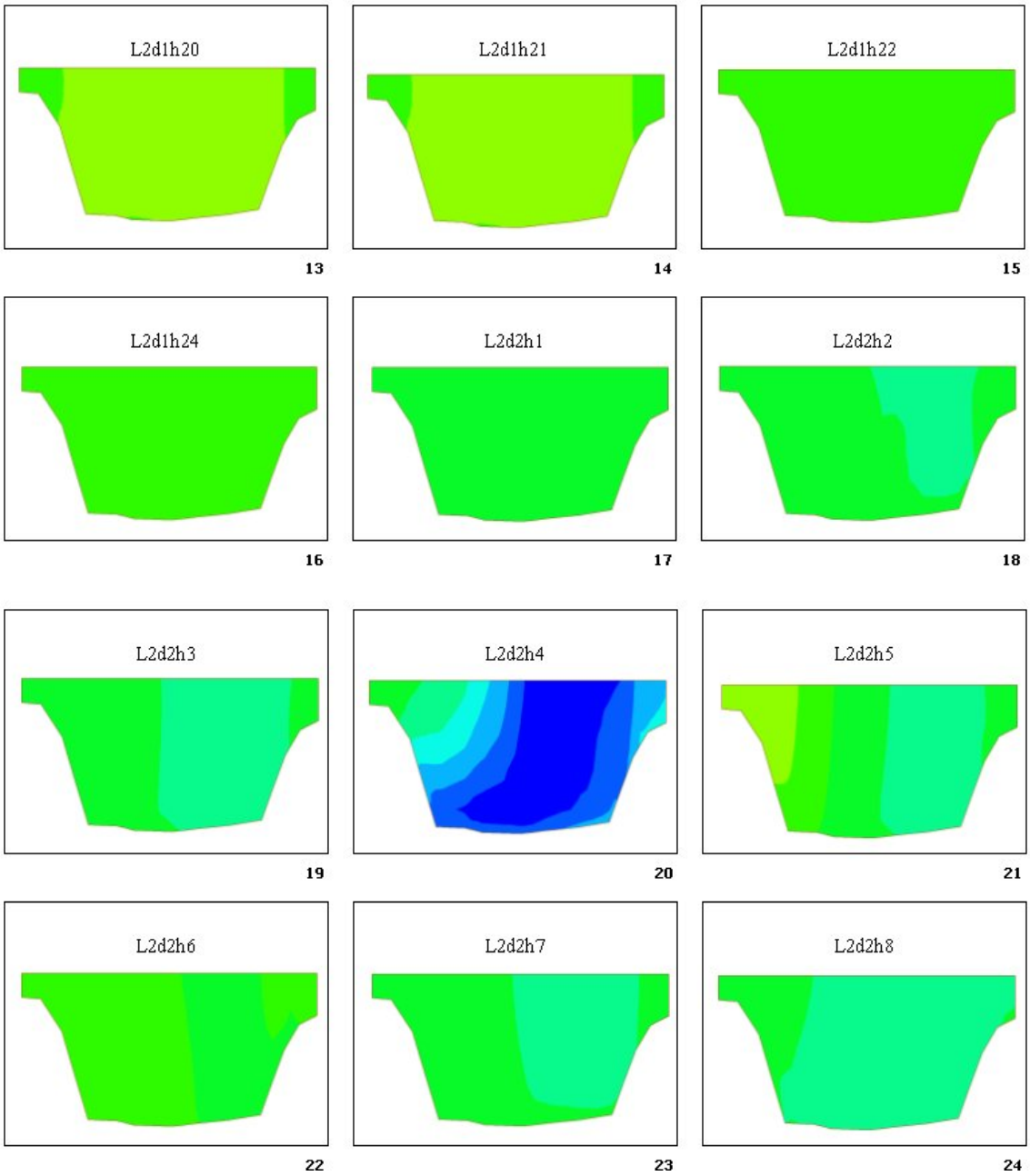


Figure 4.5.17: Velocity distribution in model at Transect2, Plots 13-24

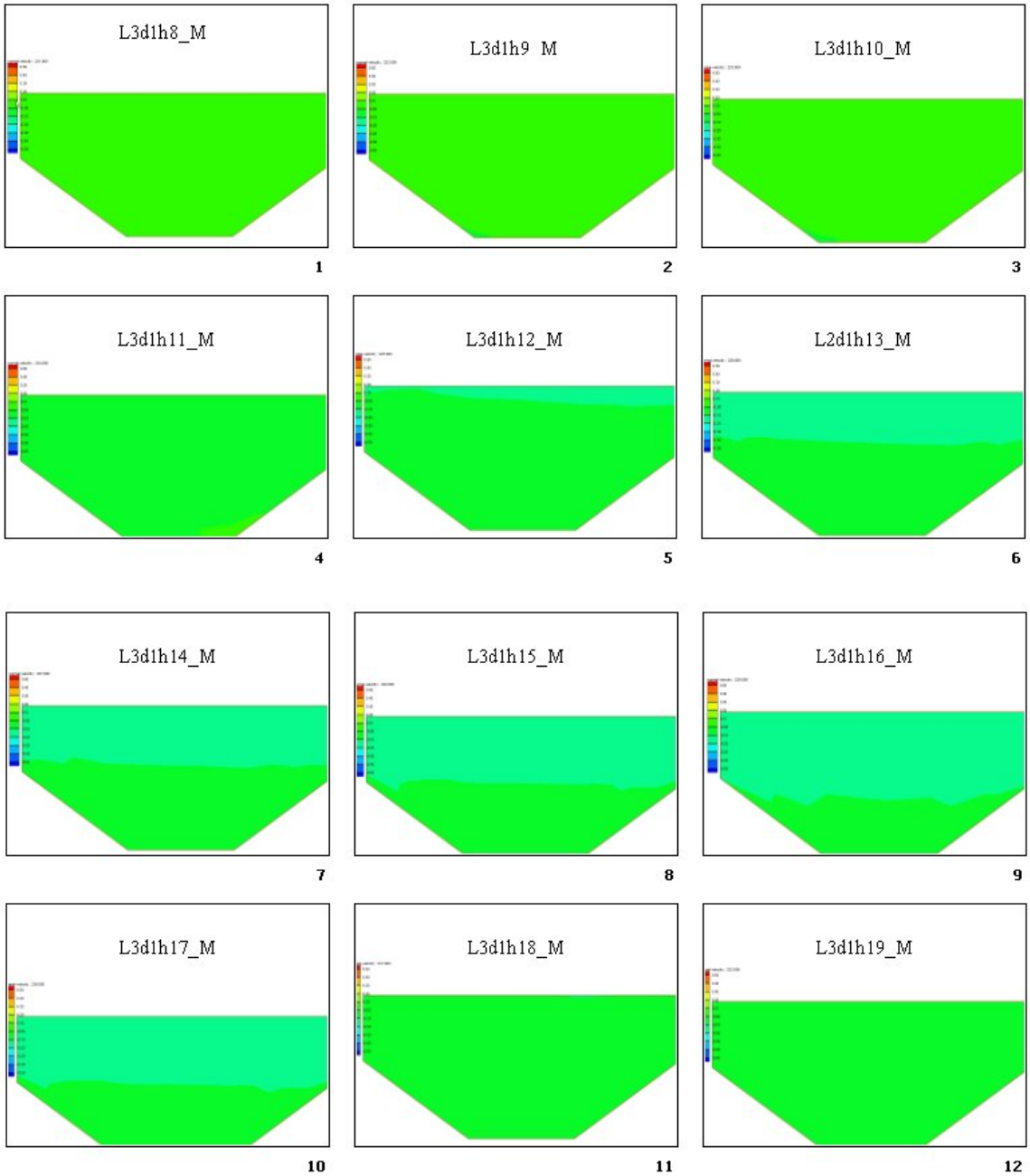


Figure 4.5.18: Velocity distribution in model at Transect 3, Plots 1-12

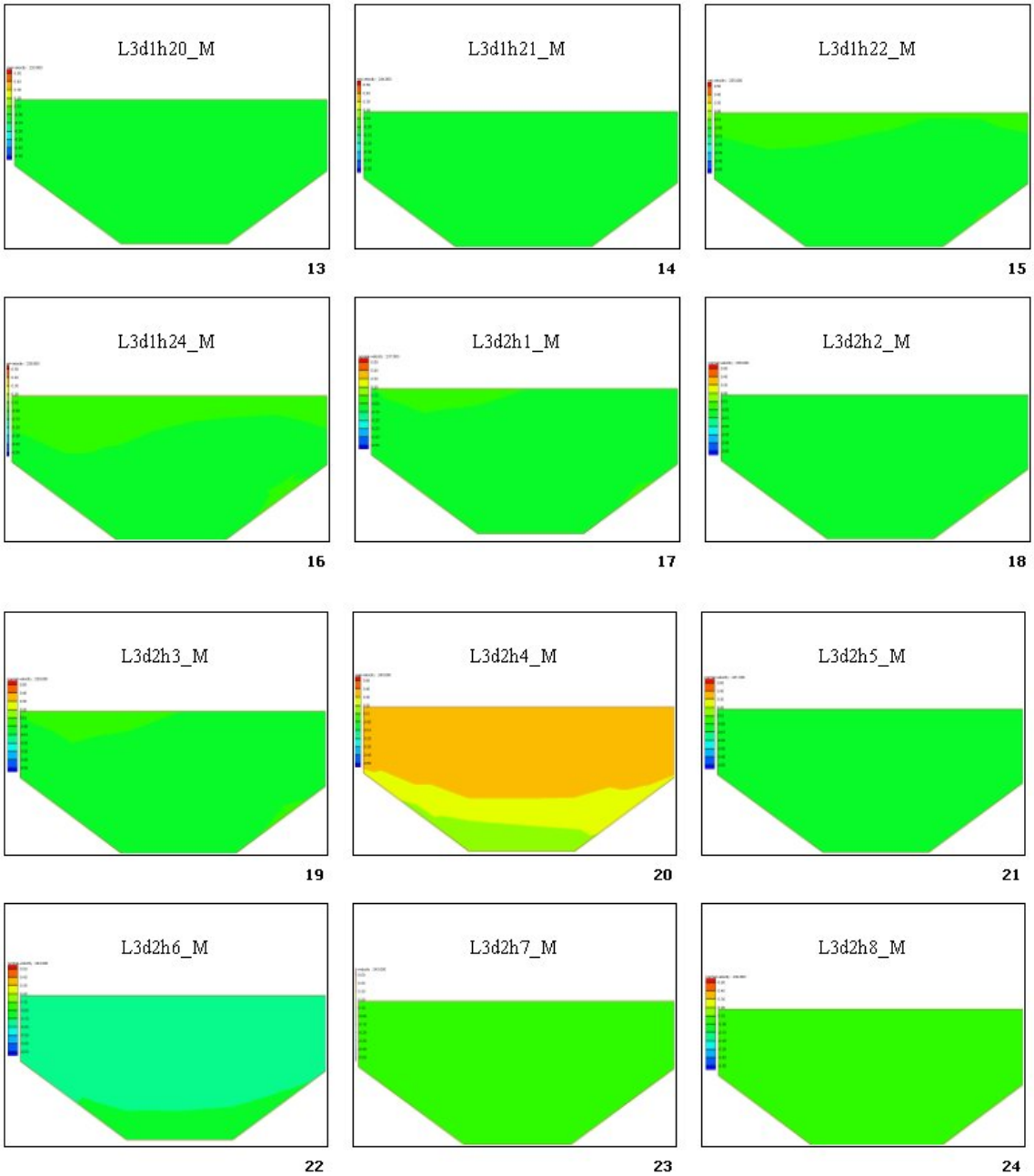


Figure 4.5.19: Velocity distribution in model at Transect 3, Plots 13-24

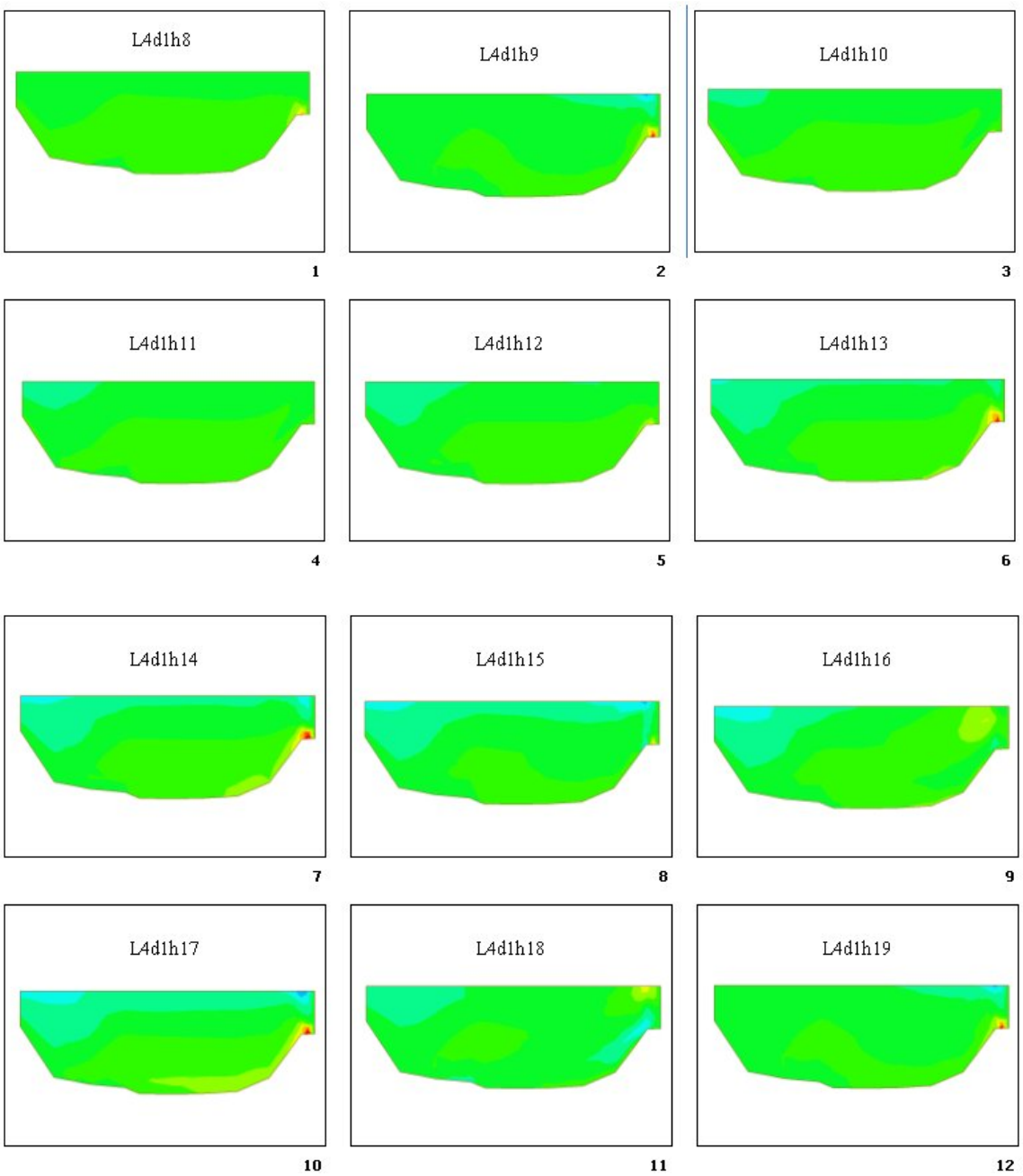


Figure 4.5.20: Velocity distribution in model at Transect 4, Plots 1-12

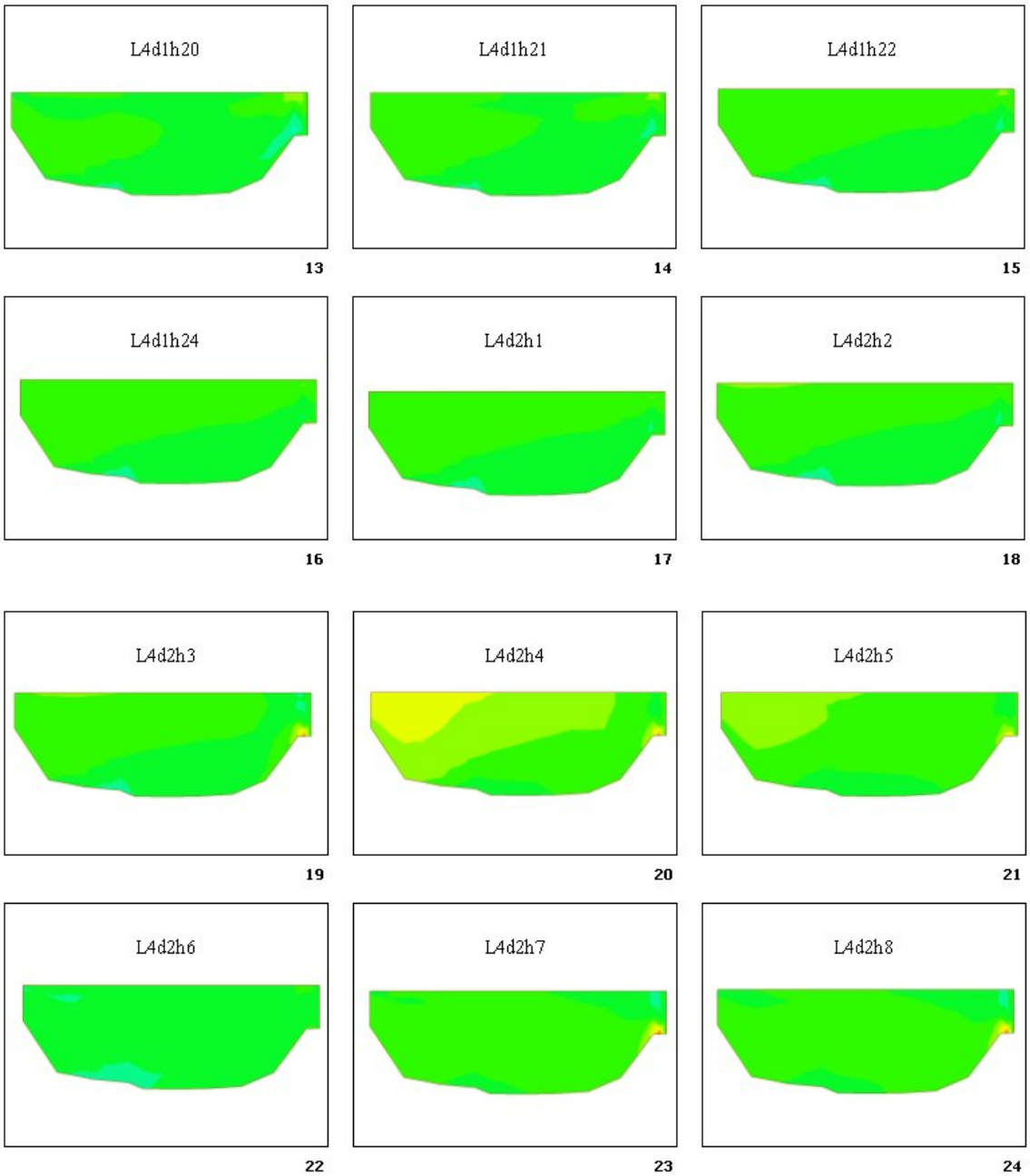


Figure 4.5.21: Velocity distribution in model at Transect 4, Plots 13-24

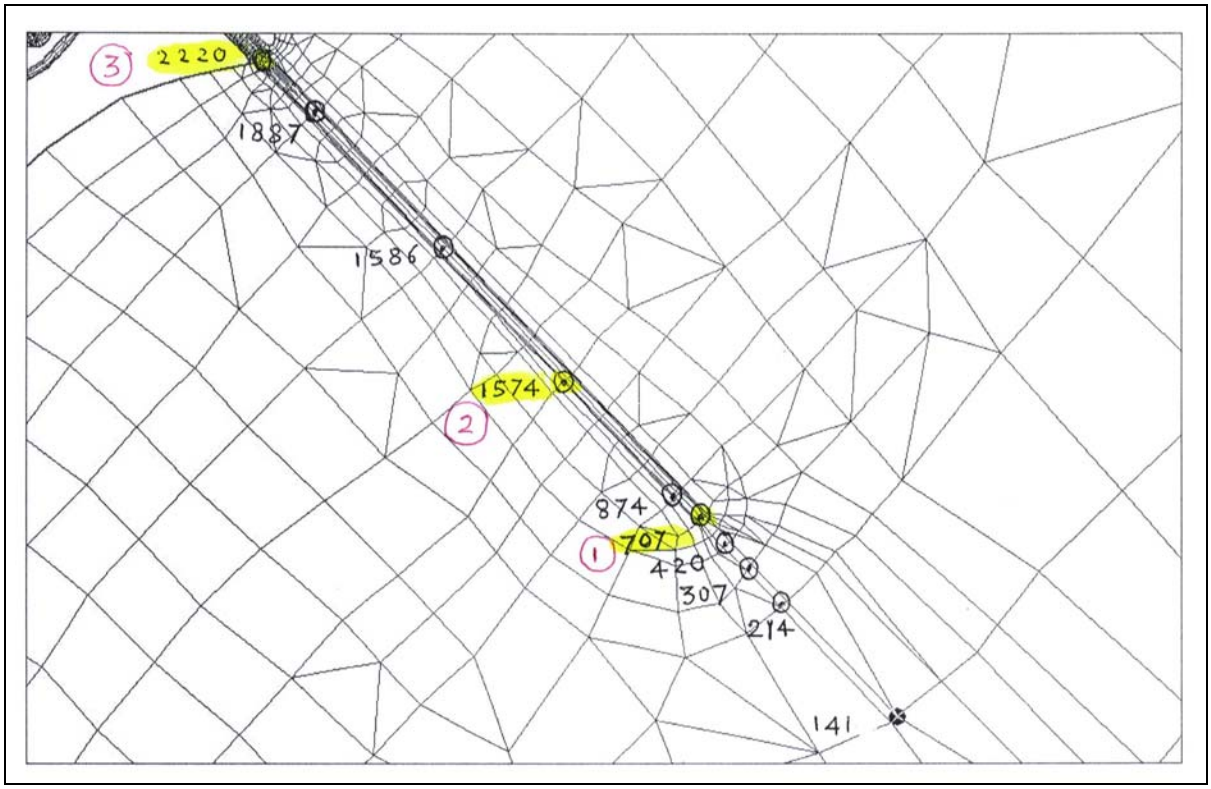


Figure 4.6.1: Nodes selected in outer navigation channel, Map 1

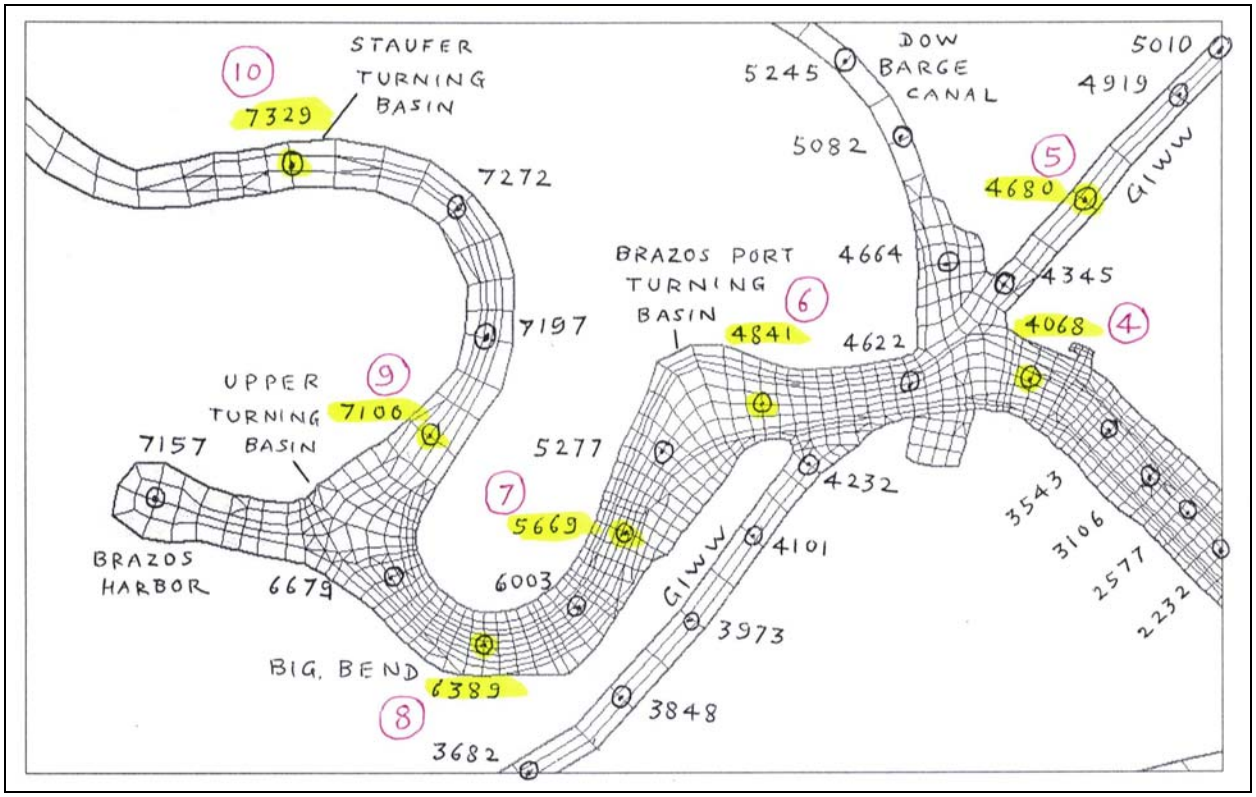


Figure 4.6.2: Nodes selected in inner navigation channel, Map 2

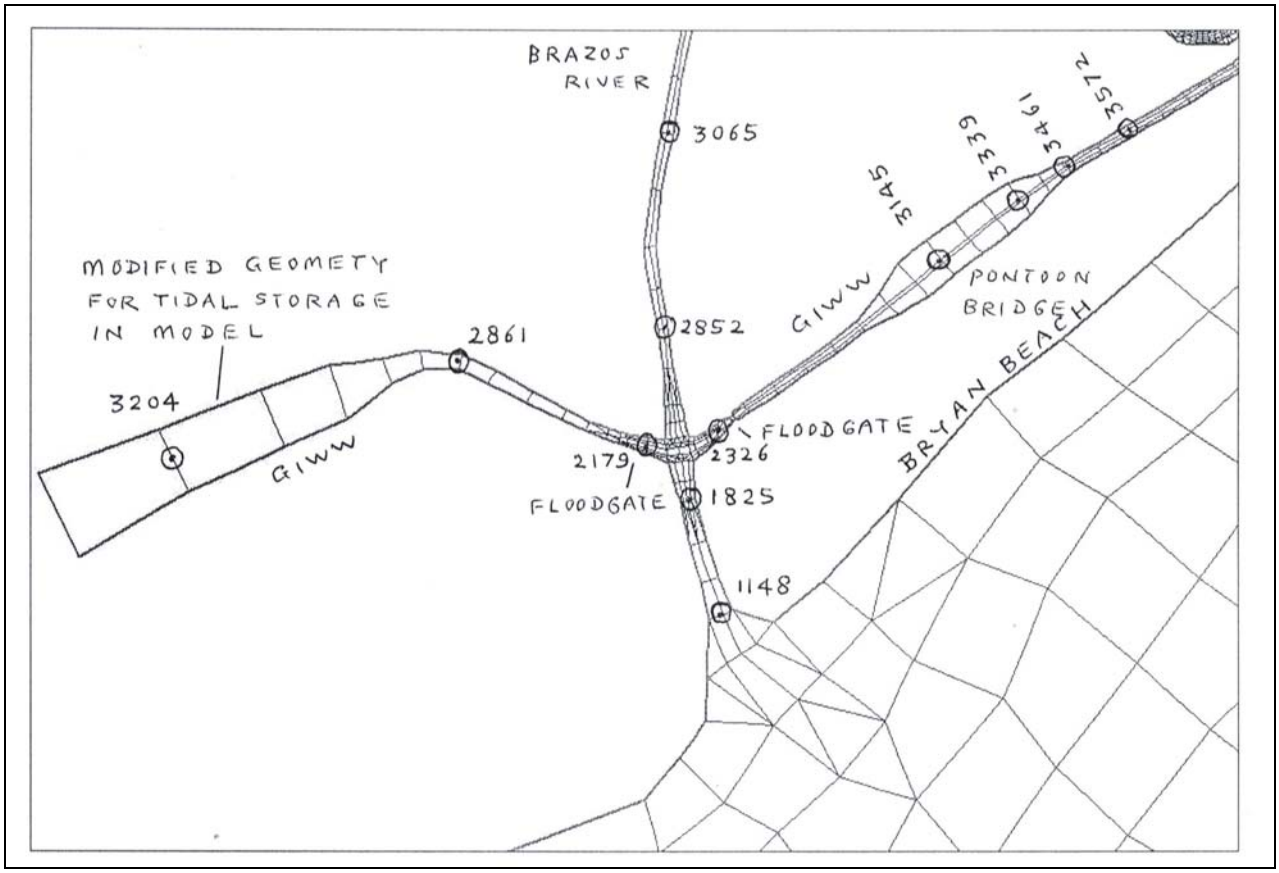


Figure 4.6.3: Nodes selected in GIWW west and Brazos River, Map 3

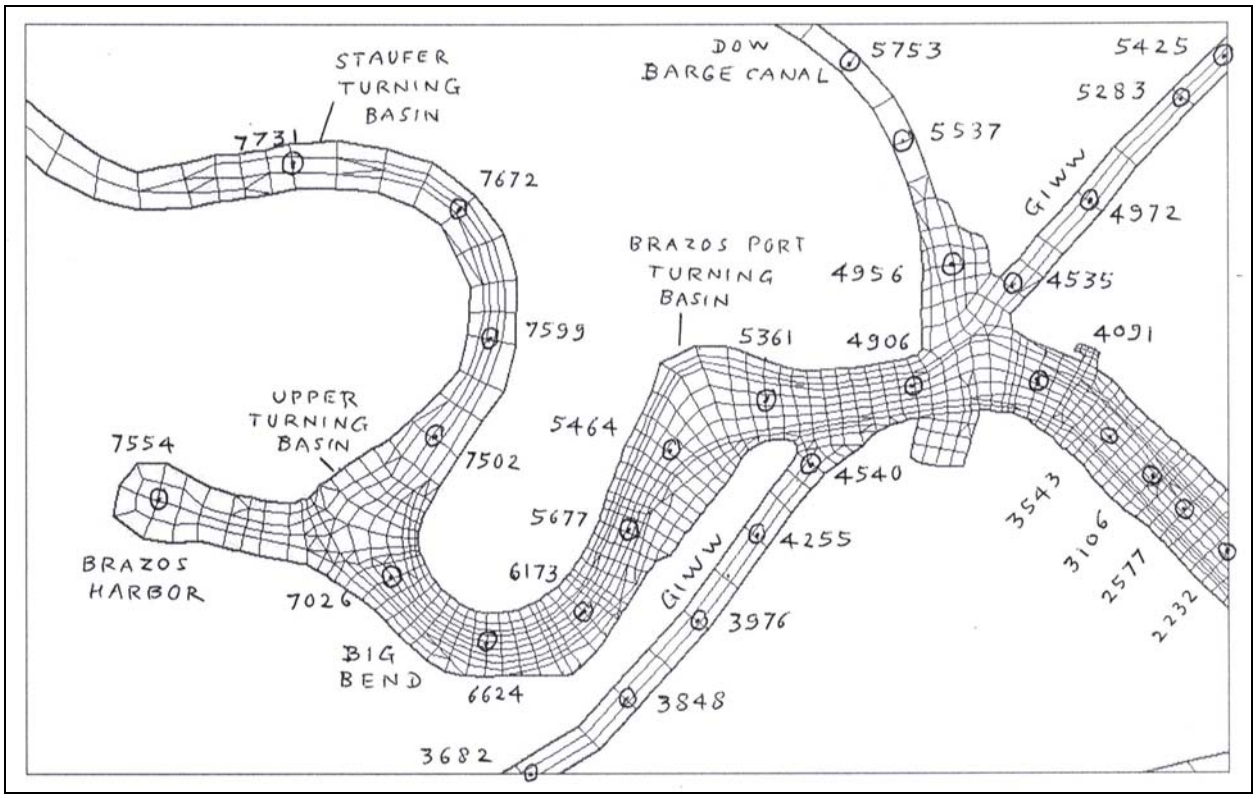


Figure 4.6.4: Nodes selected in inner navigation channel for Plan condition, Map 4

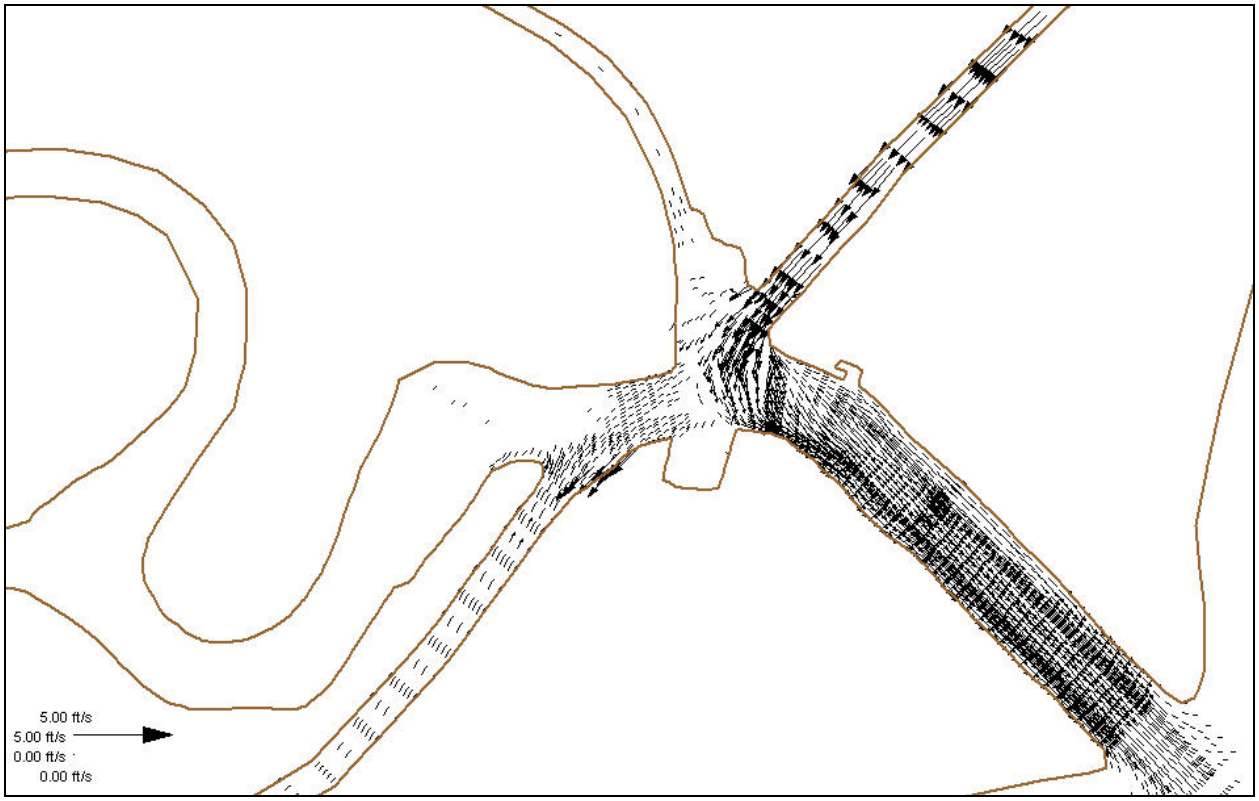


Figure 4.8.1: Flow pattern during Base condition ebb

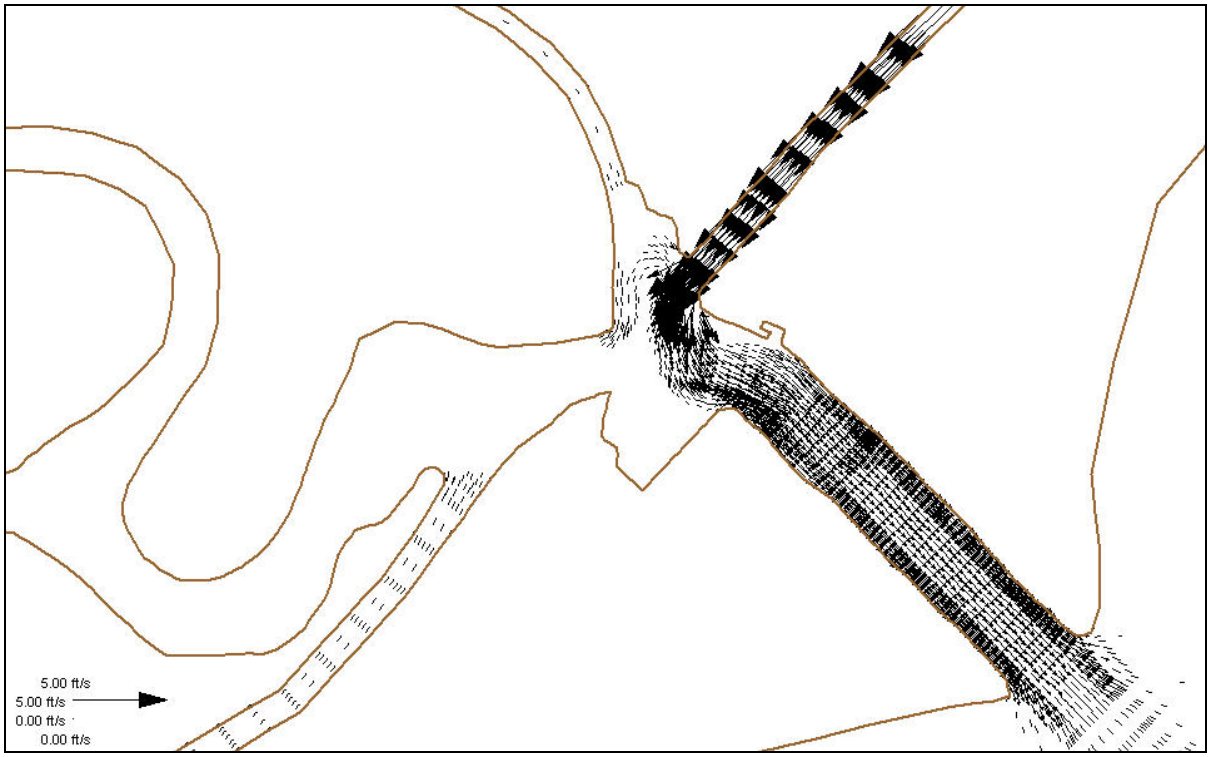


Figure 4.8.2: Flow pattern during Plan 4 condition ebb

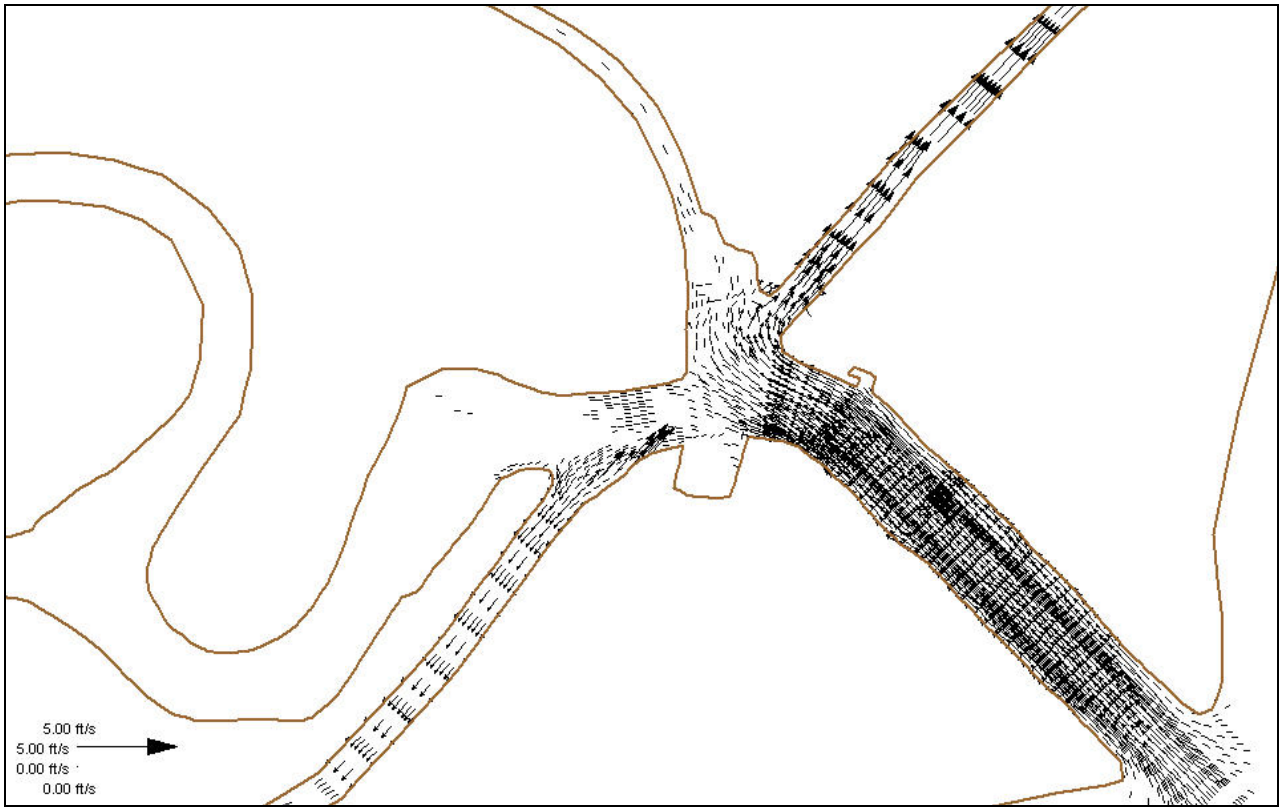


Figure 4.8.3: Flow pattern during Base condition flood

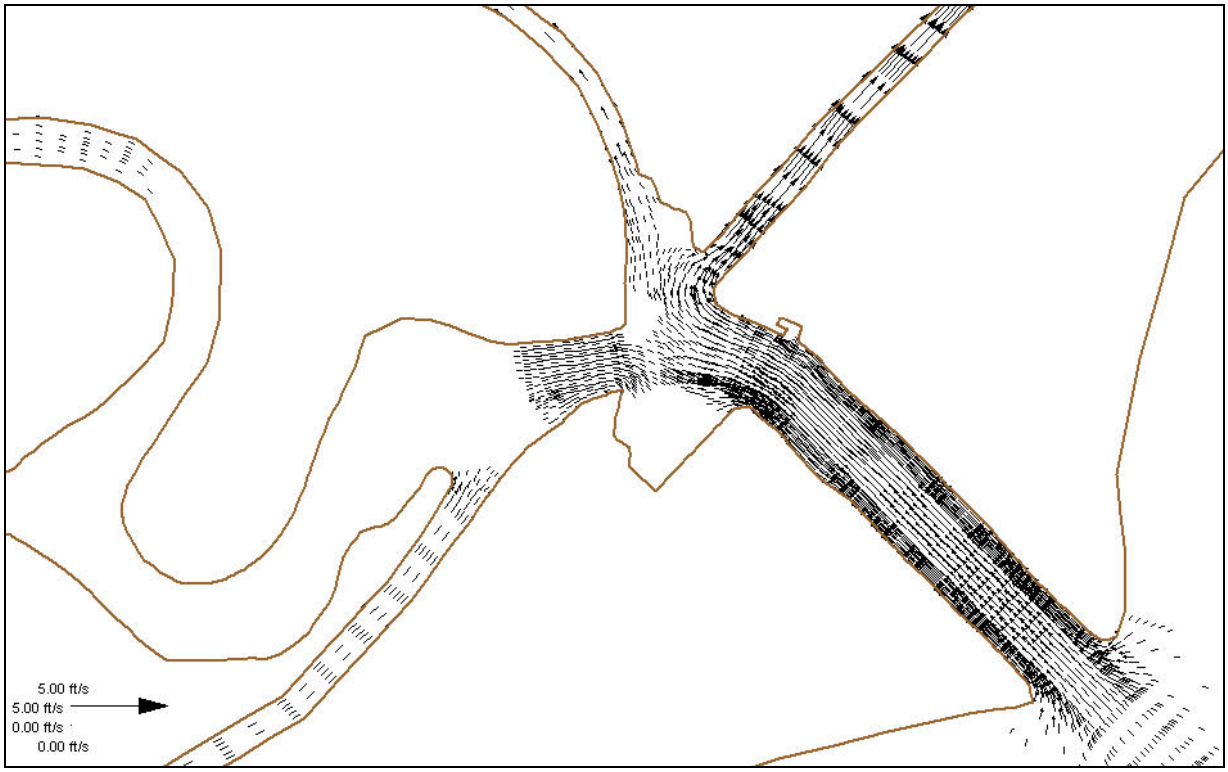


Figure 4.8.4: Flow pattern during Plan 4 condition flood

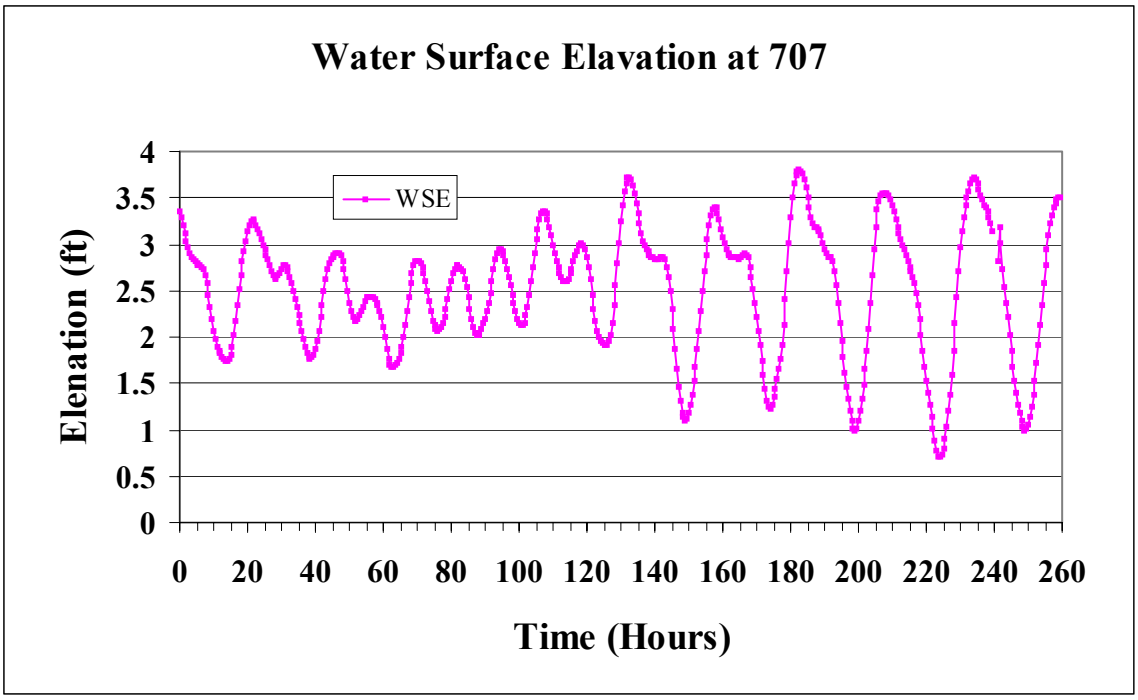


Figure 4.9.1: Tidal elevation at end of channel (0 to 260 hours)

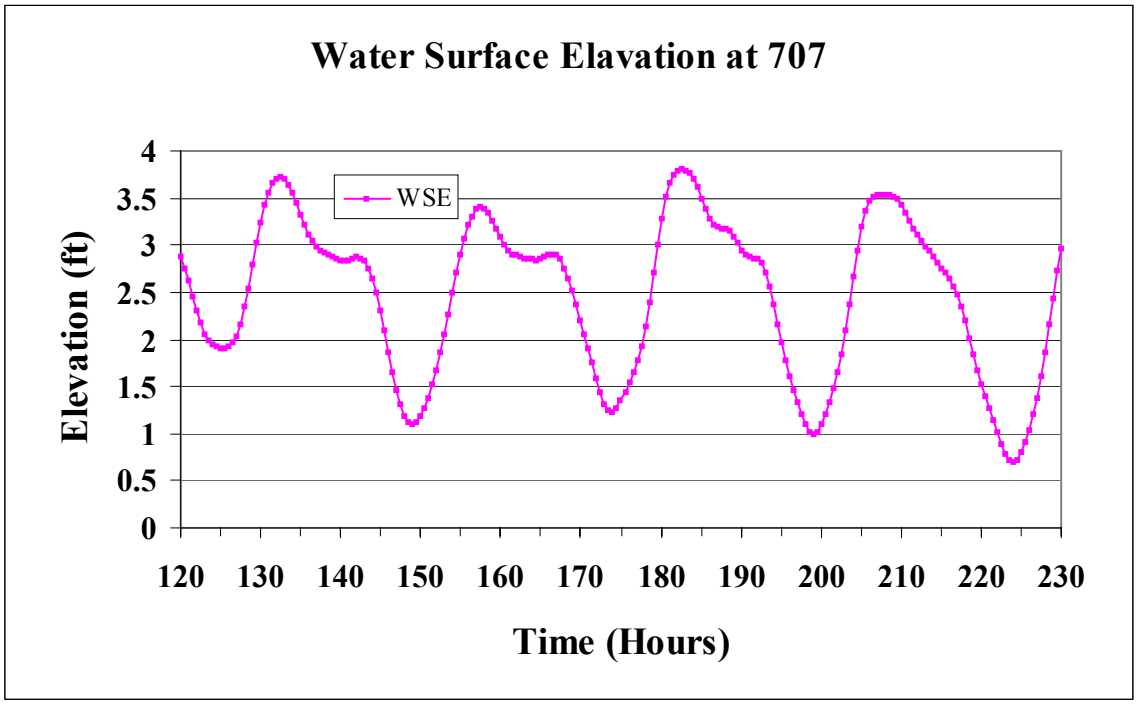


Figure 4.9.2: Tidal elevation at end of channel (120 to 230 hours)

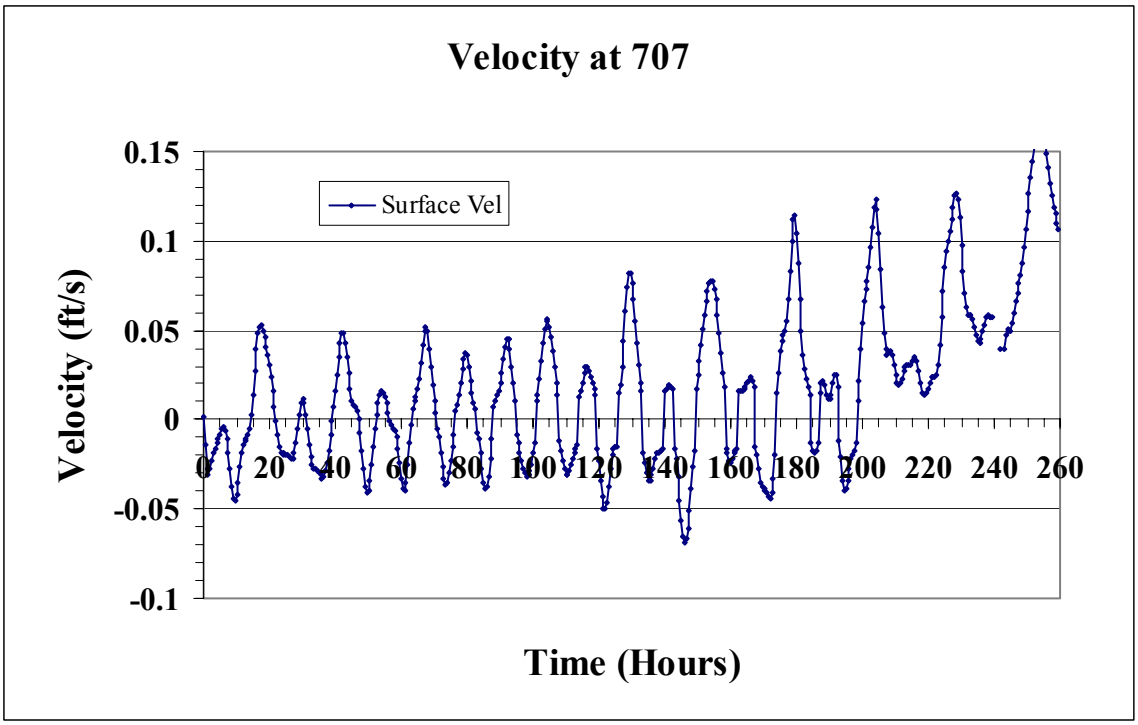


Figure 4.9.3: Velocity at end of channel (0 to 260 hours)

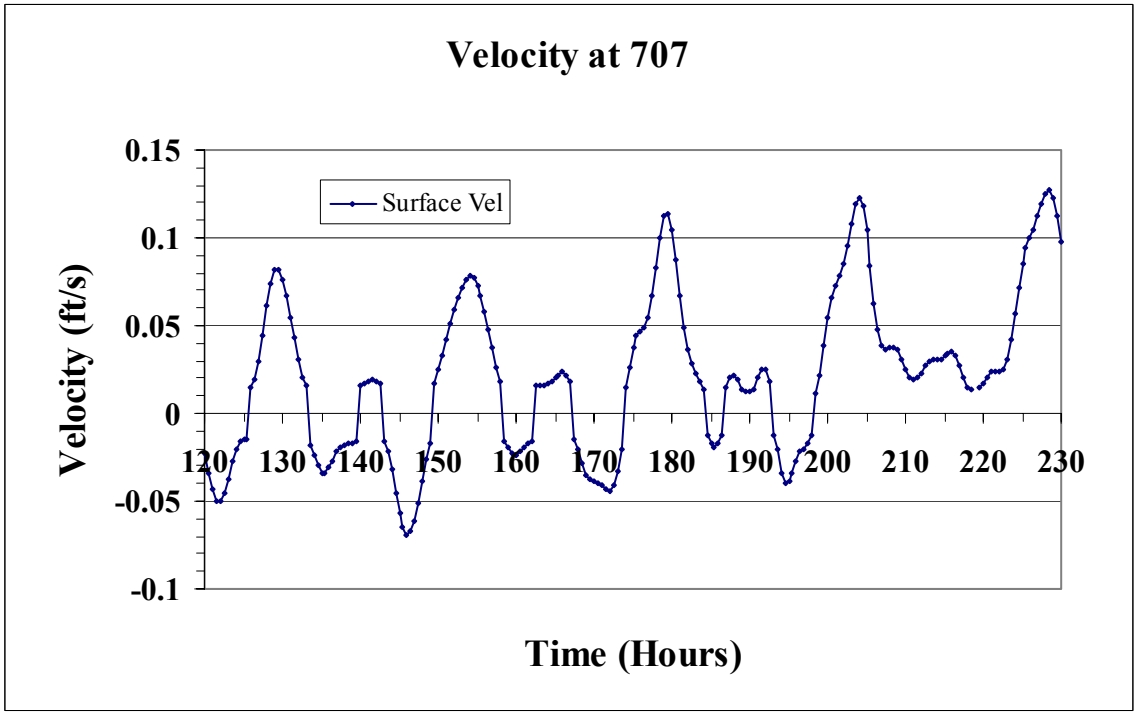


Figure 4.9.4: Velocity at end of channel (120 to 230 hours)

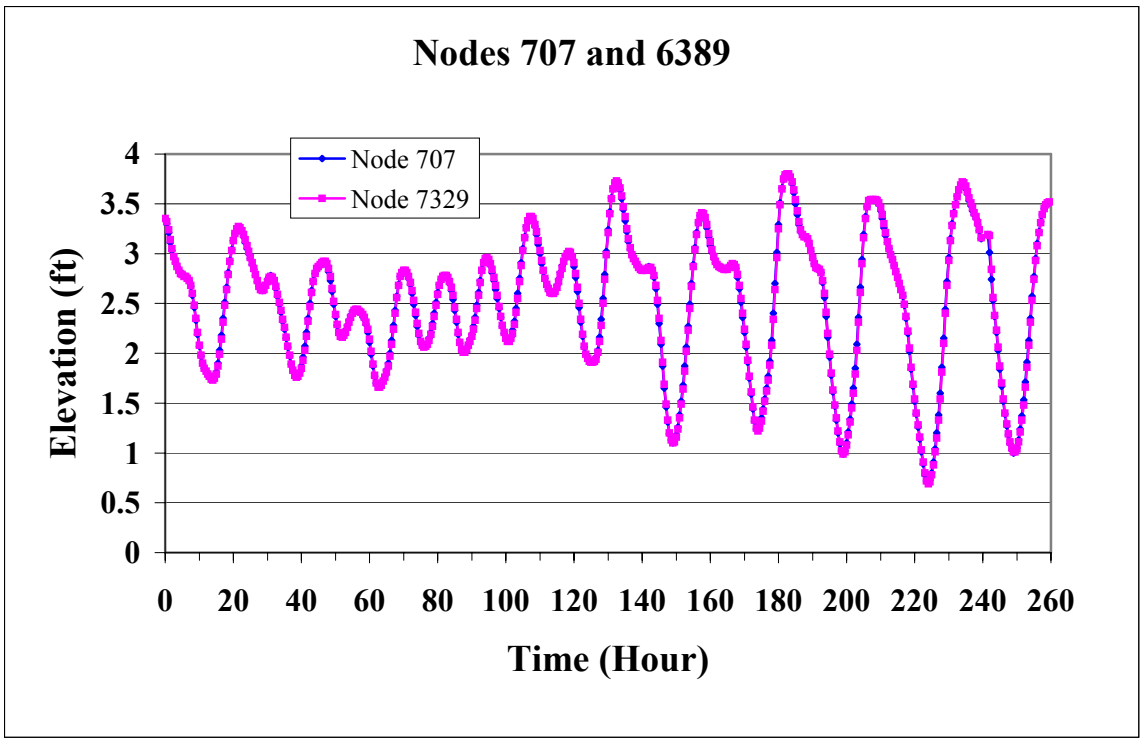


Figure 4.9.5: Superposed tidal elevations at end of channel and at Big Bend (0 to 260 hours)

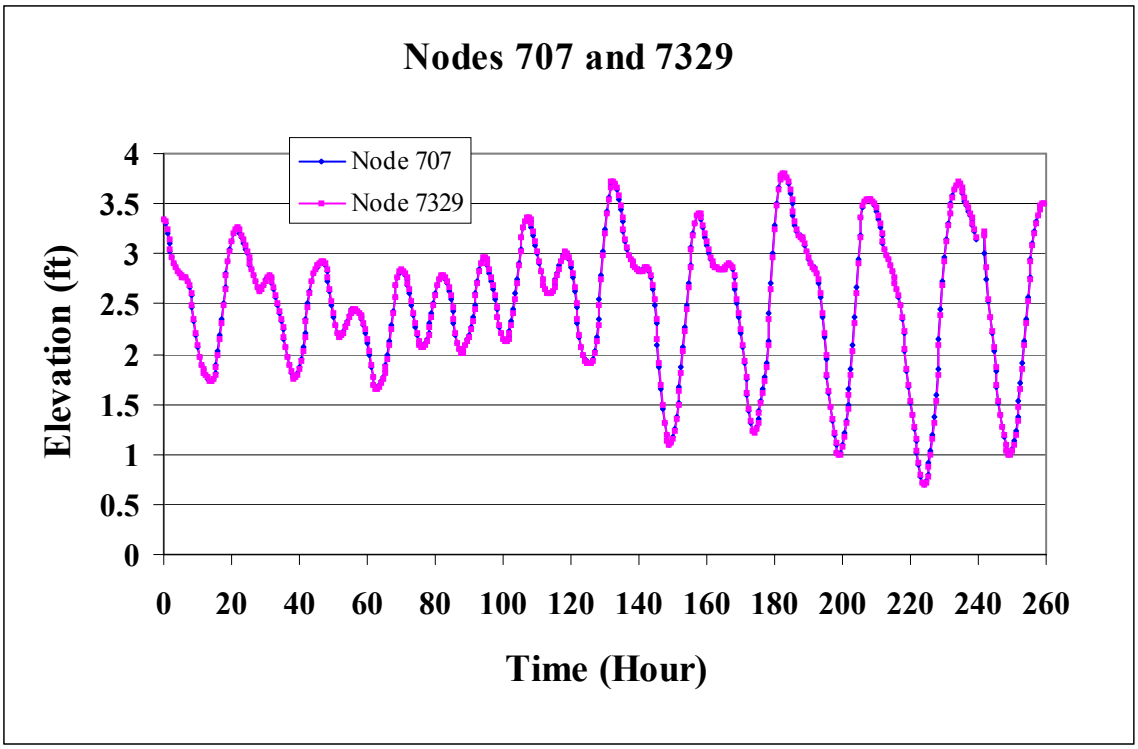


Figure 4.9.6: Superposed tidal elevations at end of channel and at end of channel (0 to 260 hours)

5 Shoaling Prediction

5.1 Shoaling Parameters

The following parameters influence quantities of shoaling in navigation channels. The sequence given below is not necessarily in the order of the importance of the parameter in influencing shoaling.

1. Relative change in length, depth and width

An increase in channel length and width increases its plan area. Since the dredged navigation channels are below the surrounding bed, they act as sediment traps. Hence, an increase in plan area (length and width) increases the quantity of sediment deposition quantity. A change in channel depth almost invariably results in increased sediment deposition, because a deeper channel acts as a more efficient sediment trap. If the channel is very shallow compared to the surrounding area, the trapping efficiency is small and considerable quantity of sediment may bypass over the channel. Sediment in suspension requires a certain amount of time to fall through the water column to reach the natural or dredged bed elevation. During this process, it is also being carried in the direction of flow. Hence, a sediment particle at water surface takes a trajectory path during its travel from surface to bed. If the channel is wide enough, the particle crossing the channel will deposit within the channel, otherwise it will bypass.

Deepening a navigation channel results in an increase in local cross-sectional area. Hence for the same amounts of fresh water discharge and tidal influx, the current velocity decreases. As a result, greater sediment deposition may be induced. However, other effects of channel deepening include a change in density current pattern and a change in the volume of tidal influx. Increased tidal volume increases velocity and reduces deposition. The combined effect can be evaluated only through a numerical model.

2. Properties of bed material

Current velocity and magnitude continuously change in an estuarine situation. Erosion of bed and banks occurs when the currents are sufficiently high, and sediment deposition occurs when the current velocity decreases. Thus, substantial shoaling occurs at high and low water slack times. Sediments are also transported over large distances by the tidal currents. While sediment remains in suspension due to turbulence, sediment deposition of larger particles and heavier flocs also occurs under flow. This is known as flow-deposition of sediment. The processes of erosion, transport and deposition take

place in a cyclic manner in an estuarine situation. Since a substantial quantity of bed sediment participates in these processes, knowledge of their characteristics is essential.

Non-cohesive and cohesive sediments have widely varying properties governing their erosion, transport, and deposition. Hence, the equations and methods used for determining these characteristics are also different. Mixtures of these two types of sediment prevail at most sites. Appropriate selection of approach needs to be made depending upon the sediment present at site.

3. Geometry of navigation channel

Alignment of a channel relative to currents is important. Currents crossing the channel width cause more sediment deposition than the currents flowing along a channel. The sedimentation pattern is also different for the protected channels versus channels with natural or man-made protection.

4. Suspended sediment

Non-cohesive sediment such as sand has a larger particle size (on the order of millimeters) and higher weight. When these particles are suspended they tend to deposit quickly as soon as the fluid-induced force that keeps them in suspension drops down below the critical value for deposition. This time may be on the order of a few minutes to hours. On the other hand, fine sediments have a small particle size (on the order of microns), which keeps them in suspension for a much longer time, on the order of weeks or months. Organic substances in suspension have low specific weight and an open floc structure. Hence, they remain in suspension for longer duration, on the order of several days, unless they flocculate with other inorganic substances.

Total suspended matter in a natural water column contains inorganic component (sediment of varying particle sizes) and organic component (detritus, diatoms, algae etc). Fine sediments prevailing in the bed are most commonly represented in the suspended sediments.

The non-cohesive sediment particles settle independently through the water column. Their fall velocity is a function of parameters such as shape factor, density, and size of particle. The fine sediment particles flocculate and settle as flocs. The fall velocity of flocs is a complex function of suspended sediment concentration, which varies over water depth.

5. Magnitude and direction of current

Currents have profound influence on erosion, deposition and transport of sediments. Strong current carries sediment in suspension without permitting any significant deposition. Synoptic situation of currents shown in the form of vector flow diagram can be significantly important. Such presentation of current pattern reveals areas of strong and weak currents, presence or absence of eddies and predominant direction of flow. Modification to channel geometry or channel dimensions may result in change in the magnitude and direction of currents and hence in the quantity of shoaling.

6. Wind and wave climate at site

Wind and waves induce shear stress on the water surface, which may extend through the water column all the way to the bed and influence sediment transport or resuspension. Breaking waves approaching shoreline at an angle other than 90 degrees induce littoral current, which results in littoral transport of sediment. This may be both bed load as well as suspended load. Ocean waves have sufficient energy to bring the bed sediment in suspension. Tidal currents carry this suspended sediment to the inner channel through the inlet. When the tidal current strength is reduced, the suspended sediment deposits.

7. Nature and location of sediment source

Local bed may be a source for sediment transport or the sediment may be reaching the area of interest from an external source. An assessment of sediment source helps in shoaling predictions.

8. Salinity

In estuarine situation, fine-sediment-laden fresh water from a river comes in contact with salt water from the sea. Salt water has dramatic effect in flocculating fine sediment particles resulting in their rapid deposition. A common effect of channel deepening is greater penetration of salinity towards upstream reaches. This changes the magnitudes and zones of siltation.

5.2 Shoaling Estimate: Analytical Methods

A general approach for an analytical method consists of using carefully selected formulas for calculating the quantities of erosion and deposition. The criteria for selection of formulas are based upon their applicability at the given site and the problem. The formulas may contain several fluid-related and sediment-related parameters. The value of each parameter may be determined by means of field or laboratory studies or

from literature and provided as input in the formulas for getting the answer. Several sediment formulas and methods are available for computing erosion, transport and deposition for a variety of parameters such as a) cohesive and non-cohesive sediments, b) bed load, suspended load, and total load, c) currents and waves, d) bank erosion, bed erosion and cliff erosion, e) incipient motion and turbulent convection and so on. They are available from simple formula given by DuBoys (1879) to the complex Bed Load Function given by Einstein (1950). The relationship between flow velocity and sediment discharge may be quite complex. The sediment discharge rate may be proportional to the flow velocity to the power of anywhere from 2 to 6. Hence the answer will vary by several orders of magnitude depending upon the power used. If selected carefully and applied properly, these methods sometimes provide an order of magnitude estimates of sediment erosion / deposition / transport.

Such formulas or methods that may be universally applicable are not available in books or published literature for estimating change in siltation rates in navigation channels as a result of extension, widening or deepening.

5.3 Shoaling Estimate: Empirical Methods

Empirical methods are not based upon any established theory. Laboratory or field data are collected on certain pre-selected parameters and empirical relationships are established using statistical / curve-fitting techniques. These methods are often too simplistic and less reliable and are not always approved by the technical communities. However, they sometimes serve the site-specific purpose very well. An example of such methods in the field of sediment transport is the century-old regime theory formulas developed for design of irrigation canals, some of which are still applicable. Such empirical methods are not available for application to sediment problems of navigation channels.

5.4 **Shoaling Estimates: Dredging Data Method**

An increase in length, width or depth of a navigation channel often results in an increased quantity of siltation and hence an increased cost and frequency of dredging. Data on dredging quantities before and after deepening and / or widening are very useful in prediction of future quantities. For instance, if a navigation channel was deepened from 35 feet to 40 feet and dredging records are available for the pre-deepening and post-deepening conditions, they could be analyzed and used for predicting the effect of further deepening from 40 feet to say 45 feet.

5.5 Shoaling Estimate: Desktop Study

A desktop study is done when application of none of the methods described above is possible for one reason or another. An accepted practice consists of applying a multiplication factor, greater than 1.0 to the dredging quantities for the pre-deepening and pre-widening conditions. Several parameters are taken into account while selecting this factor, which is very much site-specific and may vary for different locations of the same project. Such desktop study has severe limitations for want of adequate data, tools or methods available for making prediction of anticipated future dredging quantities. The estimates are based upon experience, field data, and understanding of site conditions. The study provides an order of magnitude estimates, which may be used for budgeting purposes, for determining feasibility of a project, or for working out an approximate benefit to cost ratio, etc.

5.6 Shoaling Parameter Values at Freeport

The parameters to be considered in study of navigation channel shoaling are explained in Section 5.1 above. Extensive data analysis was conducted for obtaining quantitative input against each parameter as applicable at Freeport. The Freeport site conditions are described below in the same sequence as they appear in Section 5.1.

1. Relative change in length, depth and width

Proposed channel modifications include changes in length, bottom width and depth in all the three reaches of Freeport navigation channel. Dimensions of existing channel and Plan 4 channel are given in Table 5.1. Cross-sections of the Base and Plan 4 channel are shown in Figure 5.1.

2. Properties of bed material

Laboratory analysis of bed sediment gave the following results:

a. The average composition of sediment in the Outer Channel is as follows.
   Sand: 26.14 %, Silt plus clay: 73.86 %
b. The average composition of sediment in the Inner Channel is as follows.
   Sand: 17.15 %, Silt plus clay: 82.85 %
c. The entire navigation channel consists of a very high quantity of silt plus clay (average of about 78 %).
d. The bulk density of sediment samples varied from 1.2 to 1.6 g/cm^3, with the average value of about 1.32 g/cm^3.
e. The average total organic contents in bed sediment in the outer and inner navigation channel are 5.86 % and 7.25 % respectively.

3. Geometry of navigation channel

The Freeport navigation channel has a complex geometry with turns and alignment changes on its course. Natural widths and depths near banks also vary to a great extent. Every curvature and depth change result in non-uniform flow in the channel. The Freeport tidal channel has a dead end, which imposes a severe restriction on the tidal propagation along the channel length. Intersection of GIWW with the navigation channel creates complex situation for fresh water discharge and tidal propagation.

4. Suspended sediment

Spatial variation in suspended sediment concentration is not very significant and does not indicate any specific trend. The values ranged mostly from 10 to 80 mg/l. Median diameter of sediment in suspension varied between 46 and 92 micron-size.

5. Magnitude and direction of current

Velocities at selected locations along the Freeport navigation channel were obtained for the base and plan conditions from the numerical model. It is necessary to compare plan velocities against base velocities in order to evaluate the impact of channel modification on current velocities. Appendix 5 shows superposed velocity plots for base and plan for surface, mid-depth and bottom. Summary of model velocities for base and plan is given in Table 4.7.6 under Chapter 4.

6. Wind and wave climate at site

Both wind and wave forces are significant at the Freeport Project, particularly for the Outer Channel.

7. Nature and location of sediment source

The following are the likely sources of sediment supply for shoaling of the navigation channel at Freeport: Overland inflows, Tidal influx from ocean, Open water dredged material disposal areas located close to the navigation channel, Bank and bed erosion, Local recirculation, and GIWW. Data on the sediment inflow from any of these sources are not available.

8. Salinity

There is significant variation in salinity values, ranging mostly from 31.5 to 20 along the navigation channel from south to north. Salinity values of 31.5 ppt were observed in the seaward part of navigation channel. From there it decreased along the navigation

channel to 26 ppt in the vicinity of junction area. Salinity decreased to 24 ppt in the Big Bend area. From the Big Bend to the end of channel it decreased to about 20 ppt. Some local deviations in this predominant trend were present.

The northern end of Freeport channel is not connected to the Brazos River and there is no freshwater input at this location. The channel does not have its own well-defined catchment area. Hence local groundwater runoff during rains is the most likely source of freshwater input along the Freeport navigation channel. Salinity in the east GIWW was 18.55 ppt, which indicates substantial input of fresh water in the GIWW. Salinity in the west GIWW was 4.87 ppt. The western location was about twice as far as the eastern location from the junction. Hence the salinity there was much lower. The GIWW appears to be a significant source of fresh water input to the Freeport navigation channel.

The Development Plan 4 has been accepted for implementation. The Plan 4 channels will have a constant width of 600 feet. It will be a 62 ft MLT Entrance Channel (east of the jetties) and 60 ft MLT from the western end of the jetties to the Upper Turning Basin. The channel widening for the entrance channel will be offset, 150-ft on the north side and 50-ft on the south side. Plan 4 will have a 1350-ft diameter turning basin at Brazos Point. The area northwest of the turning basin will be dredged to 60 feet to allow more area for the turning maneuver. This additional dredged area is proposed in order to accommodate additional turning radius needed by the VLCC and 165K LNG Tankers. The width of navigable area varies locally to accommodate turning basins. Ignoring local widening, a uniform channel width has been used for purposes of the present sediment study.

5.8 Shoaling Quantity Estimation

Dredging data analysis is given in Chapter 3.6. Average quantity of annual dredging was determined from the analysis of past dredging records. These quantities of dredging for each of the three reaches of navigation channel are given in Table 5.1. The Outer Bar Channel and the Harbor Channel are about 5 miles and 4 miles in lengths respectively. Shoaling over such long lengths is not expected to be uniform. Certain parts of these channels probably shoal more than others within the same reach. This is because the factors that cause shoaling are different over different parts of navigation channel. In the absence of detailed breakup of dredged quantities over small parts of the three reaches mentioned above, it is assumed that the shoaling rate is uniform over each reach.

Increase in shoaling quantities resulting from channel deepening may be attributed to five major factors listed below. A factor greater than 1.0 is applied under each of the four types and the existing quantity of dredging is multiplied by the combined factor to get the estimated quantity of dredging.

1. Increase in channel plan area due to increased bottom width (Area Factor).
A trapezoidal cross-section of the navigation channel is assumed with side slope of 1 vertical to 2 horizontal for all reaches. While the navigable depth is given below the water level, the channel is dredged below the natural bed level. The difference between the natural bed level and the channel bottom is the depth of cut. The plan area of channel at the natural bed elevation is an important parameter related to the volume of shoaling. Widening and deepening a channel increases this area, which results in trapping more sediment and hence in higher shoaling. Increase in plan area at the natural bed level was determined for each reach. The ratio of new area to the existing area gives the Area Factor for shoaling computations.

2. Increase in channel depth resulting in collection of more sediment (Trap Factor).
The change in channel depth is from 47 feet to 60 feet, a 28 percent increase. A deeper channel makes a more efficient trap for sediment.

3. Decrease in flow velocity due to increased cross-section under Plan (Velocity Factor).
Velocities obtained from numerical model for Plan were compared with the corresponding velocities for Base. The following observations are made.
    a. Outer Channel: Peak Plan flood velocities are smaller than peak Base flood velocities by 0.05 ft/s. Peak Plan ebb velocities are greater than peak Base ebb velocities by 0.07 ft/s. Since Plan ebb is slightly stronger than Base ebb, this should slightly improve flushing of sediment out to the sea.
    b. Jetty Channel: Same as above.
    c. Bolivar Roads Area: Both flood and ebb Plan velocities are smaller than Base velocities by 0.03 ft/s. This would increase sediment deposition.
    d. Big Bend: Both flood and ebb Plan velocities are smaller than Base velocities by 0.02 ft/s. This would increase sediment deposition.
    e. All other areas: Either no difference or the Plan velocities are smaller than Base by about 0.01 ft/s. Hence, deposition will be slightly higher.

The Base peak velocities have a small magnitude, which is on the order of 0.1 ft/s. Although the absolute change in velocities is small, between 0.01 and 0.05 ft/s, the relative change with reference to the present conditions is significant.

4. Modified salinity regime due to greater salt-water penetration (Salinity Factor).
Salinity along the Freeport channel has a substantial variation and the magnitudes change quickly with fresh water inflow at uneven time intervals. Since the bed sediment at Freeport has a large percentage of fine sediment, its deposition in navigation channel is influenced by salinity. Numerical model study was conducted with only a cursory validation for salinity. Increase in salinity between base and plan conditions was found to be small.

Settling of fine sediment is significantly impacted when salinity changes from 0 ppt up to about 5 ppt. Such impact decreases with increase in salinity from 5 to 10 ppt. When the salinity is already higher than 10 ppt, any further increase has very little impact in changing the flocculation and settling properties of fine sediment particles. Since salinity everywhere within the Freeport channel is higher than 10 ppt, any change in salinity will have no impact on shoaling rate.

5. Other factors. These include increased vessel traffic resulting in greater bank and bed erosion due to vessel-induced waves, channel bank failure, bank sloughing, sediment brought down by rivers, increased trap efficiency resulting from greater size and depth, and wave effect in case of the outer channel. Several unknown parameters related to the outer channel in the sea include direction and magnitudes of ocean currents and waves, varying wave climate, and bed sediment properties in the area where channel is extended beyond the end of the existing navigation channel. No data on the sediment characteristics for this part of the proposed channel are available.

After the channel is extended to the area where no channel existed before, sloughing of side slopes and other adjustments to the dredged part will result in higher shoaling during the early years, however a relatively stable regime will be established after initial settlements.

Table 5.2 gives the estimates based on this approach. It is concluded that the quantity of maintenance dredging in the Freeport navigation channel will increase from the present average of 2.10 million cubic yards per year to 5.05 million cubic yards per year as a result of widening the channel from 400 feet to 600 feet and deepening it from 47 feet to 60 feet.

5.9 Limitations of Study

The desktop study presented in this report has some limitations. A desktop study is done when application of rigorous analytical methods is not possible for one reason or another. Such a study includes study of available data on sediment, past dredging records, prevailing site conditions and experience gained at other projects. The results are based jointly on analysis of field data, results of numerical hydrodynamic model and to some extent on subjective judgment. Complex fine sediment phenomena such as fluid mud and impact of salinity on flocculation are not taken into account. It is assumed that unlimited supply of sediment is available in the system at site. The study provides order of magnitude estimates, which may be used for preliminary budgeting purposes, for determining feasibility of a project, or for working out an approximate benefit to cost ratio, etc.

Table 5.1: Details of Freeport navigation channel, present and Plan 4

Reach #	Name	From	To	Length (feet)	Length (Miles)	Width (feet)	Depth (feet)	Dredging Cu. Yd./ Year
Present Condition								
1 A	Outer Bar Channel	0+00	- 260+00	26,000	4.92	400	47	1,211,070
2	Jetty Channel	0+00	+ 50+00	5,000	0.95	400	47	377,775
3	Harbor Channel	+ 50+00	+ 257+86	20,186	3.82	400	47	519,030
			Total	51,186	9.69			2,107,875
Plan 4 Conditions								
1 A	Outer Bar Channel Present	0+00	- 260+00	26,000	4.92	600	62	
1 B	Outer Bar Channel Proposed Extension	- 260+00	- 430+00	17,000	3.22	600	62	
2	Jetty Channel	0+00	+ 50+00	5,000	0.95	600	60	
3	Harbor Channel	+ 50+00	+ 257+86	20,186	3.82	600	60	
			Total	68,186	12.91			
	New Outer Channel	0+00	- 430+00	43,000	8.14			

Table 5.2: Estimated average annual shoaling quantities after channel modifications

Reach	Area	Present Dredging (Cu. yd)	Area Factor	Trap Factor	Velocity Factor	Salinity Factor	Other Factors	Combined Factor	Estimated Dredging (Cu yd)
1 A	Outer Bar Channel	1,211,070	1.55	1.15	1.00	1.00	1.10	1.80	2,180,000
2	Jetty Channel	377,775	1.50	1.10	1.00	1.00	1.05	1.65	623,330
3	Harbor Channel	519,030	1.50	1.20	1.20	1.00	1.05	1.95	1,012,100
	Total	**2,107,875**							
1 B	Outer Bar Channel Extension	(792,610)*	1.36	1.10	1.00	1.00	1.10	1.56	1,236,470
									5,051,900

* It is assumed that if the extended channel existed, it would have dredging quantity proportional to the length of extension relative to the present Outer Channel.

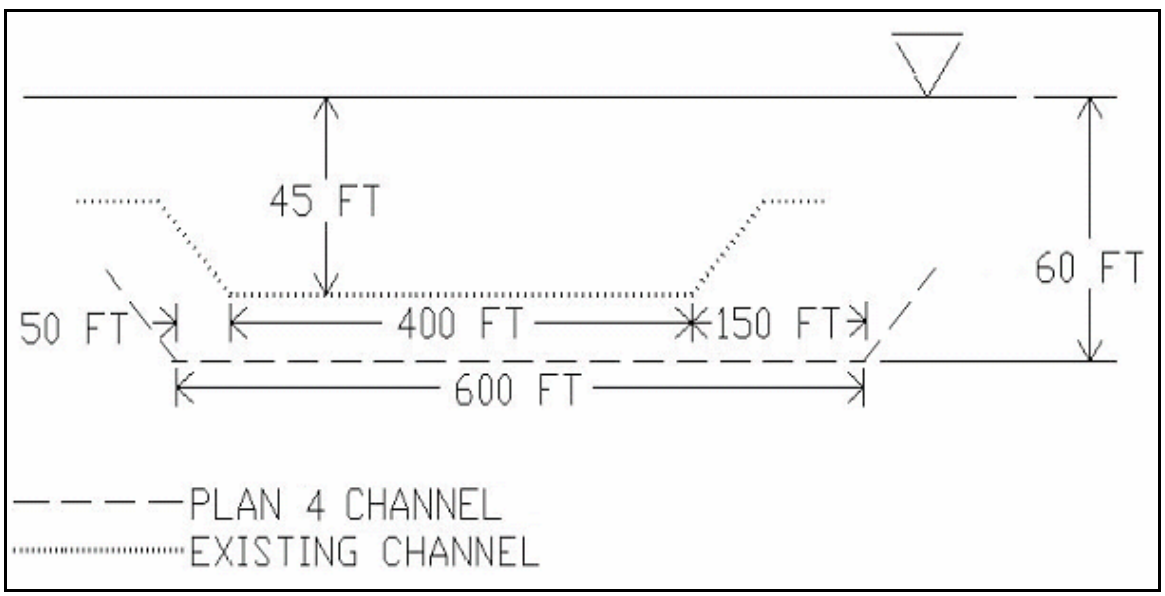


Figure 5.1: Cross section of existing channel and proposed channel under Plan 4

6 Conclusions

Field data on various parameters were collected specially for use of the desktop study. The sediment and water samples were analyzed in ERDC laboratory for determining their important properties. Field data on other parameters such as tides and currents were extensively analyzed and results were plotted for ease of interpretation. The main conclusions of field data analysis are given in this chapter.

Numerical model studies were conducted for determining the effect of implementing navigation channel modifications. The results of numerical model study were also extensively analyzed and presented in this report in the form of Tables and plots. Important conclusions of these are given in this chapter.

Finally, estimated quantity of shoaling in the modified navigation channel is given.

Tides

Tidal characteristics at the three field stations do not differ significantly from each other. The tides are predominantly diurnal, with tidal period varying between 22 and 28 hours. Neap tidal range varies from 0.8 ft to 1.5 ft and spring tidal range varies from 2.5 to 3 ft. A large variation between the elevations of high waters and low waters is noticed. The high waters vary between 2.5 and 4.3 ft. The low water elevations vary between 0.4 and 2.7 ft.

Field Currents

ADCP is a sensitive device for measuring field currents at a large number of locations across the width and depth of transect selected for measurements.
The voluminous data can be analyzed only with the help of software developed for this purpose. The sign assigned to magnitudes indicates current direction. Plus sign indicates flood tide and minus sign indicates ebb.

The data provide instantaneous values of velocities. Since the total time required to complete measurement along one transect is small relative to the duration of tidal cycle period, the data are considered synoptic.

Depth-averaged values along transect result in values that fluctuate around the zero current. Small magnitudes in the range of +0.2 ft/s to –0.2 ft/s may be ignored because these could be a result of local turbulence.

Although hourly depth-averaged values showed large variation between +2 ft/s and –2 ft/s, the predominant variation was between +1 ft/s and –1 ft/s for flood and ebb respectively.

Higher velocity magnitudes noticed in some cases is an indication of non-uniform velocity distribution across a section.

Bed Sediment

1. The average composition of sediment in the outer channel is as follows. Sand: 26.14 %, Silt plus clay: 73.86 %
2. The average composition of sediment in the inner channel is as follows. Sand: 17.15 %, Silt plus clay: 82.85 %
3. The entire navigation channel consists of a very high quantity (about 78 %) of silt plus clay.
4. The bulk density of sediment samples varied from 1.2 to 1.6 g/cm^3, with the average value of about 1.32 g/cm^3.
5. The average total organic contents in bed sediment in the outer and inner navigation channel are 5.86 % and 7.25 % respectively.

Suspended Sediment

1. Spatial variation in suspended sediment concentration is not very significant and does not indicate any specific trend. The values ranged mostly from 10 to 80 mg/l.
2. Higher concentrations varying between 50 and 150 mg/l were measured at Station 3, which is located in the western GIWW. This may be due to sediment load brought by the Brazos River.
3. Mid-depth and near-surface suspension concentrations were about the same at stations 1, 2, and 4. The magnitudes varied between 40 and 8 mg/l.
4. Near-bed suspension concentration values showed greater fluctuations. This may be due to bed sediment entering water sample during collection or due to instantaneous high resuspension caused by local disturbance.
5. Median diameter of sediment in suspension varied between 46 and 92 micron-size.

Field Salinity

Data Set 1: The following conclusions are drawn from the results of analysis.

9. There is significant variation in salinity values, ranging mostly from 31.5 to 20 along the navigation channel from south to north.

10. Salinity values of 31.5 ppt were observed in the seaward part of navigation channel. From there it decreased along the navigation channel to 26 ppt in the vicinity of junction area.
11. Salinity decreased to 24 ppt in the Big Bend area.
12. From the Big Bend to the end of channel it decreased to about 20 ppt. Some local deviations in this predominant trend were present.
13. The northern end of Freeport channel is not connected to the Brazos River and there is no freshwater input at this location. The channel does not have its own well-defined catchment area. Hence local groundwater runoff during rains is the most likely source of freshwater input along the Freeport navigation channel.
14. Salinity in the east GIWW was 18.55 ppt.
15. Salinity in the west GIWW was 4.87 ppt. The western location was about twice as far as the eastern location from the junction. Hence the salinity there was much lower.
16. The GIWW appears to be a significant source of fresh water input to the Freeport navigation channel.

Data Set 2: The following conclusions are drawn on the measured salinity.

7. As would be expected, salinity near surface was lower than salinity near bed because water with higher salt content is heavier due to higher specific gravity.
8. Greater variation in salinity magnitudes near bed is most likely to be a result of local fresh water input from rain, surface runoff or river discharge.
9. Station 1 is closer to ocean. Salinity at this station varied from 31 / 32 ppt near bed to 27 / 28 ppt near surface.
10. Station 2 in the east GIWW is not very far from the junction and showed a trend similar to that at Station 1. Salinity at this station varied from 31 / 32 ppt near bed to 28 / 29 ppt near surface.
11. Station 3 is closer to the Brazos River and hence susceptible to impact of fresh water from the river. Salinity at this location varied from 29 / 30 ppt near bed to 28 / 29 ppt near surface.
12. Station 4 located at Big Bend showed a variation in near bed salinity between 26 and 30 ppt.

Data Set 3: The following conclusions are drawn.

6. Salinity at 3 feet above bed at Station 0 varied between 15 and 30 ppt.
7. Salinity at 3 feet and 7.5 feet above bed at Station 2 did not show significant difference. The magnitude varied between 20 and 32 ppt.
8. At Station 3, salinity varied from 5 ppt to 24 ppt at 3 feet above bed.
9. At Station 4, salinity at 3 feet above bed varied from 16 to 30 ppt.
10. At Station 5, salinity at 3 feet above bed, salinity varied from 21 to 31 ppt and at 7 feet above bed it varied from 20 to 26 ppt.

Model Currents

1. Current velocity in the GIWW East was high. It varied from 3 ft/s at bottom to 5 ft/s at surface for flood and from3.5 ft/s at surface to 2.1 ft/s at bottom for ebb.
2. Current velocities in the navigation channel at the throat section at the shoreline and in the Bolivar Roads area was also high. The variation in surface velocity was 0.7 ft/s to 0.9 ft/s.
3. At all the other locations within the navigation channel, the magnitude of surface current velocity during flood and ebb mostly varied from 0.05 to 0.17 ft/s.
4. Superposition of velocities at surface, mid-depth and bottom showed no significant variation over water depth in the outer channel in the sea as well as in the inner channel upstream of the Big Bend area.
5. In the area between the Big Bend and the Bolivar Roads simultaneous surface and bottom velocity were seen in opposite directions. This is the result of salinity-induced and fresh-water-induced density flows.

Comparison of Base and Plan Results

Velocities obtained from numerical model for Plan were compared with the corresponding velocities for Base. The following observations are made:

a. Outer Channel: Peak Plan flood velocities are smaller than peak Base flood velocities by 0.05 ft/s. Peak Plan ebb velocities are greater than peak Base ebb velocities by 0.07 ft/s. Since Plan ebb is slightly stronger than Base ebb, this should slightly improve flushing of sediment out to the sea.
b. Jetty Channel: Same as above.
c. Bolivar Roads Area: Both flood and ebb Plan velocities are smaller than Base velocities by 0.03 ft/s. This would increase sediment deposition.
d. Big Bend: Both flood and ebb Plan velocities are smaller than Base velocities by 0.02 ft/s. This would increase sediment deposition.
e. All other areas: Either no difference or the Plan velocities are smaller than Base by about 0.01 ft/s. Hence, deposition will be slightly higher.

The Base peak velocities have a small magnitude, which is on the order of 0.1 ft/s. Although the absolute change in velocities is small, between 0.01 and 0.05 ft/s, the relative change with reference to the present conditions is significant.

Schematic flow pattern diagrams showed no significant difference in the flow pattern for Plan in comparison with the Base condition.

Shoaling Estimate

It is concluded that the quantity of maintenance dredging in the Freeport navigation channel will increase from the present average of 2.10 million cubic yards per year to 5.05 million cubic yards per year as a result of widening the channel from 400 feet to 600 feet and deepening it from 47 feet to 60 feet.

6 References

Letter J.V., W.L. Boyt, B. Brown, C.T. Goodin, and D.M. McVan, 2005, Freeport harbor ship simulator hydrodynamic study, Draft report submitted to US Army Engineer District Galveston.

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Parchure T.M., S. Sarruff, and B. Brown, 2002, Desktop study for La Quinta Project: Shoaling prediction in La Quinta navigation channel and effect of a barrier on siltation in extended La Quinta channel, US Army Engineer ERDC, Technical Report TR-02-19.

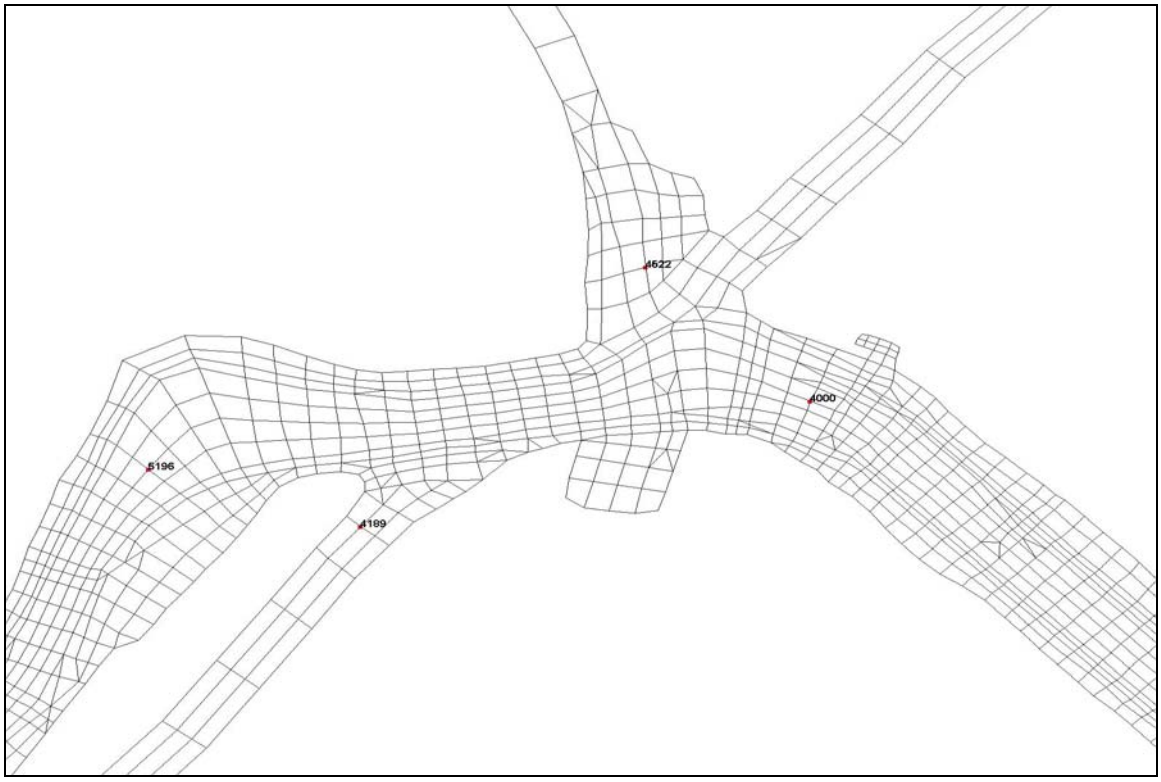
Parchure T.M., and S. Sarruff, 2005, Desktop study for sediment-related problems at Sabine Neches project, Texas, US Army Engineer ERDC, Technical Report submitted to the US Army Engineer District Galveston.

Shelton T. (2005), Navigation study for Port Freeport, US Army Engineer ERDC, Technical Report submitted to the US Army Engineer District Galveston.

Appendix 1:
Particle Size Distribution of Finer Fraction of Sediment Samples Collected at Freeport

Appendix 2
Illustrative Plots of ADCP Field Current Data Collected at Freeport

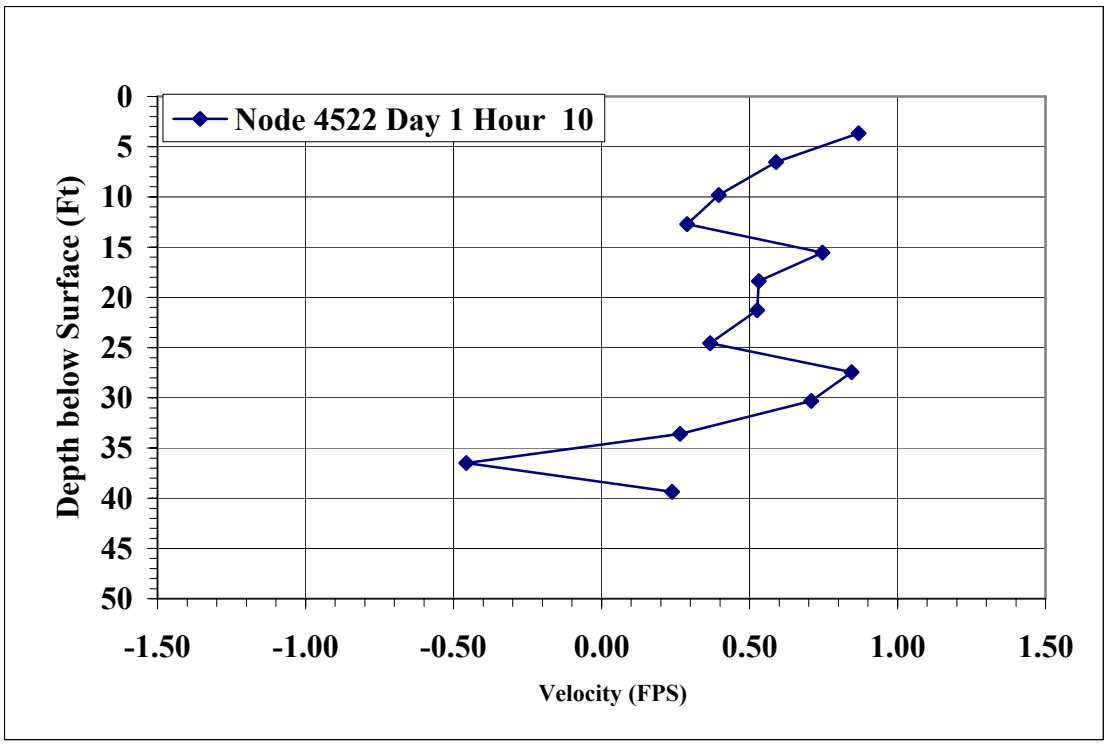
Part 1: Depth-Variation of Currents at Node 4522 Transect 1
Part 2: Depth-Variation of Currents at Node 4000 Transect 2
Part 3: Depth-Variation of Currents at Node 4189 Transect 3
Part 4: Depth-Variation of Currents at Node 5196 Transect 4



Locations of nodes on each transect for presenting observed ADCP velocity data

Depth-Variation of Currents Observed at Freeport Harbor Node 4522 Transect 1

Flood: Positive, Ebb: Negative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15
20
25
30
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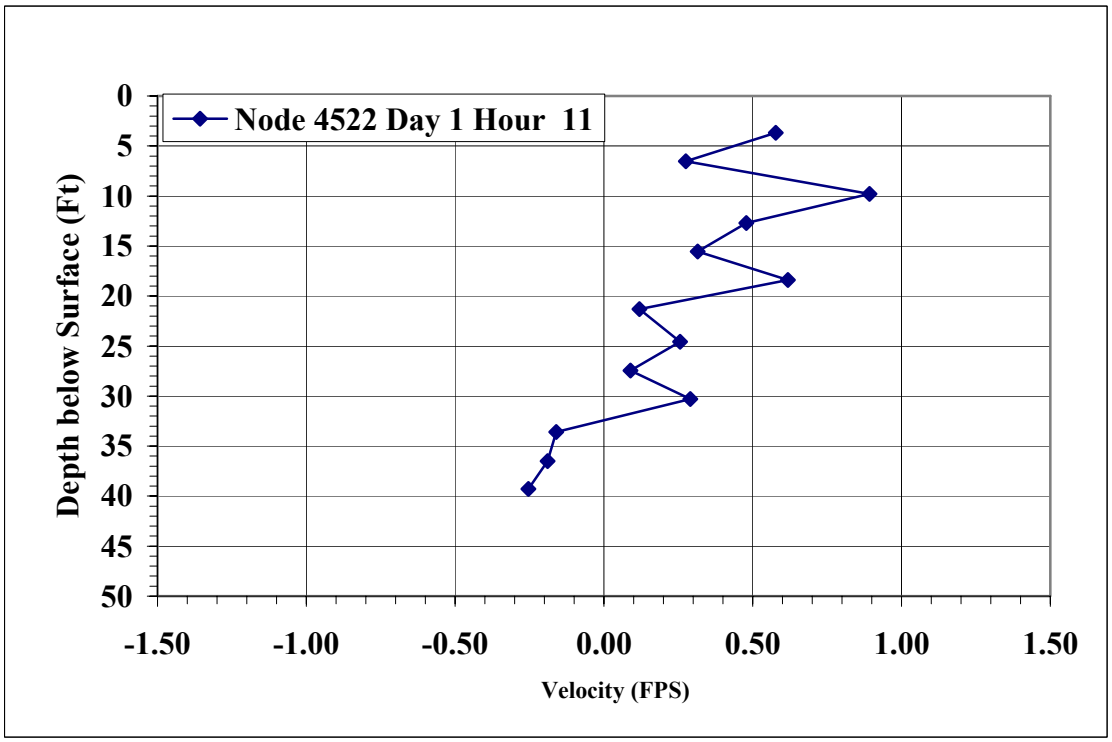
0.50
1.00
1.50
Velocity (FPS)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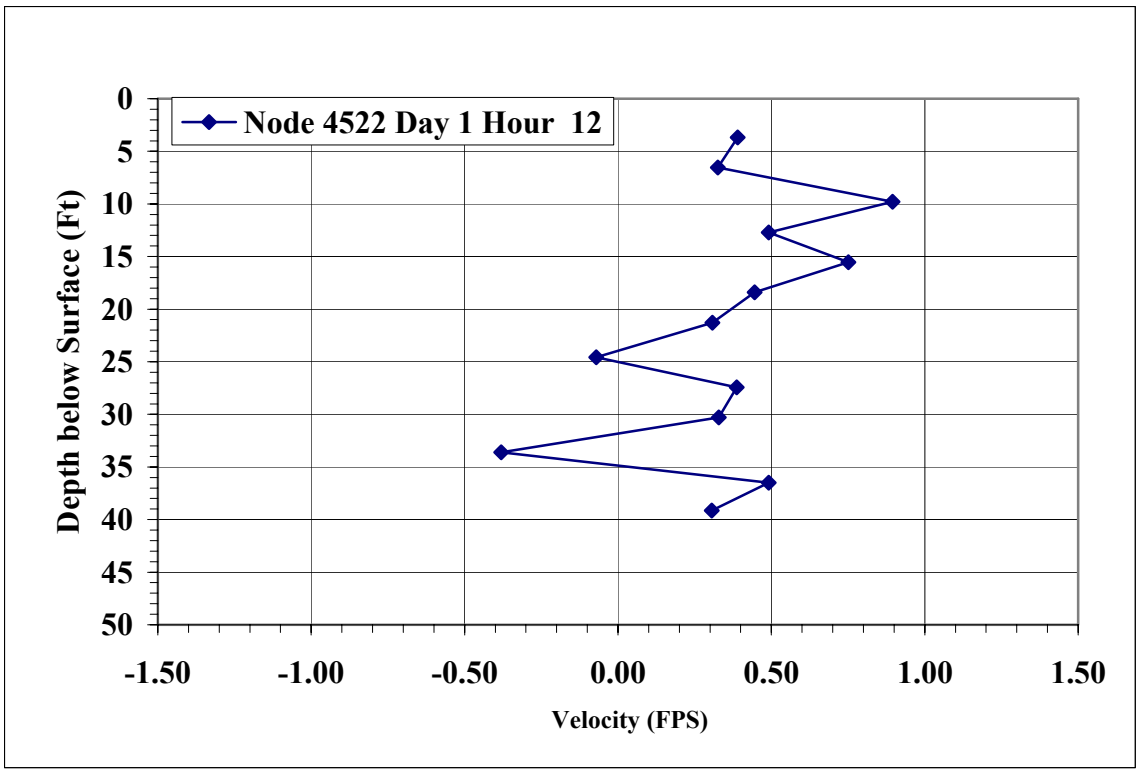
1.50
Velocity (FPS)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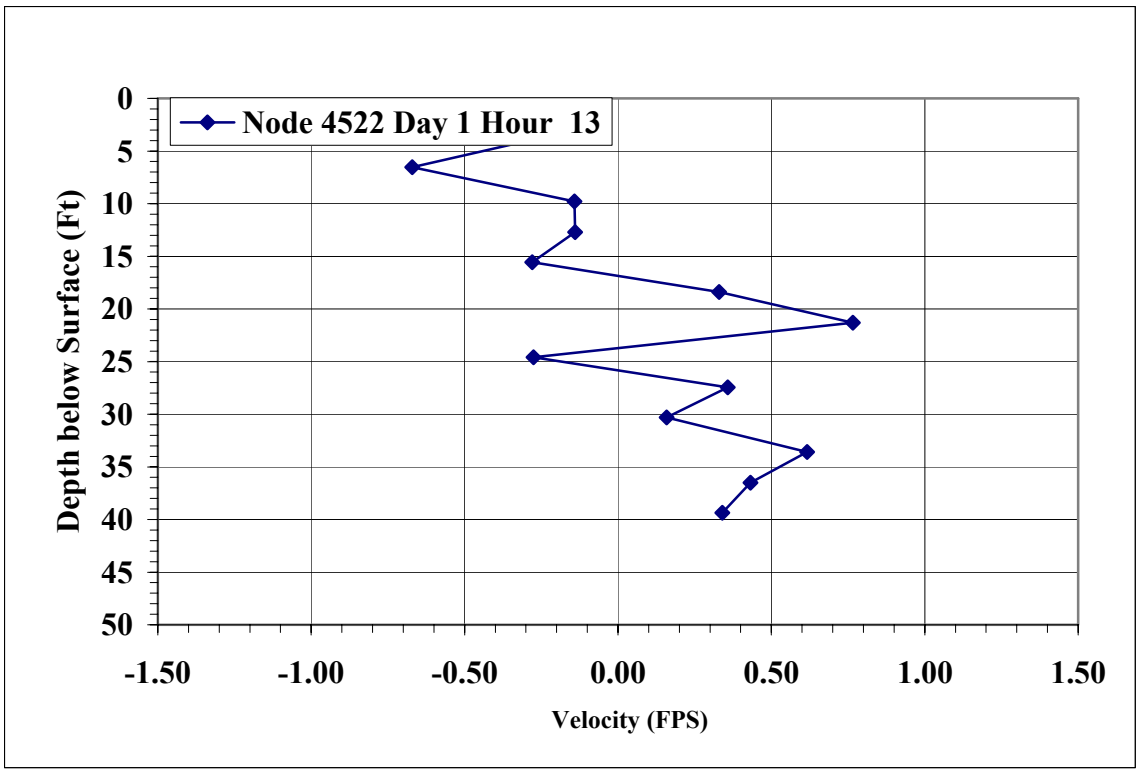
Velocity (FPS)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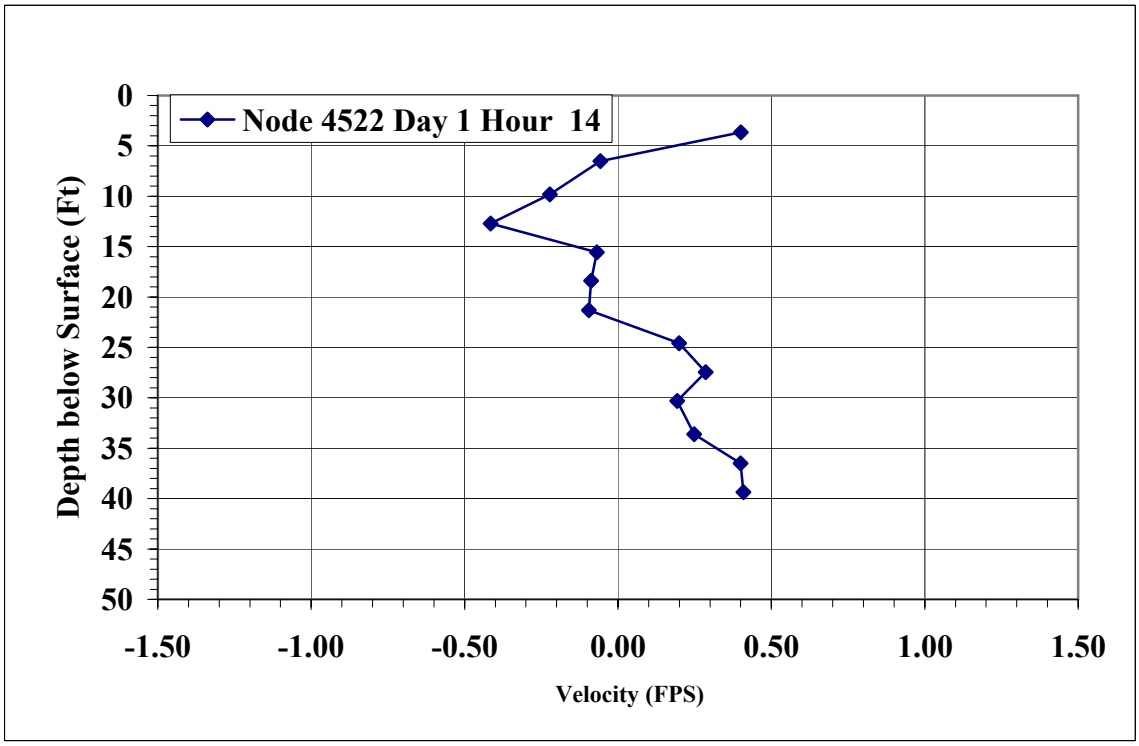
Velocity (FPS)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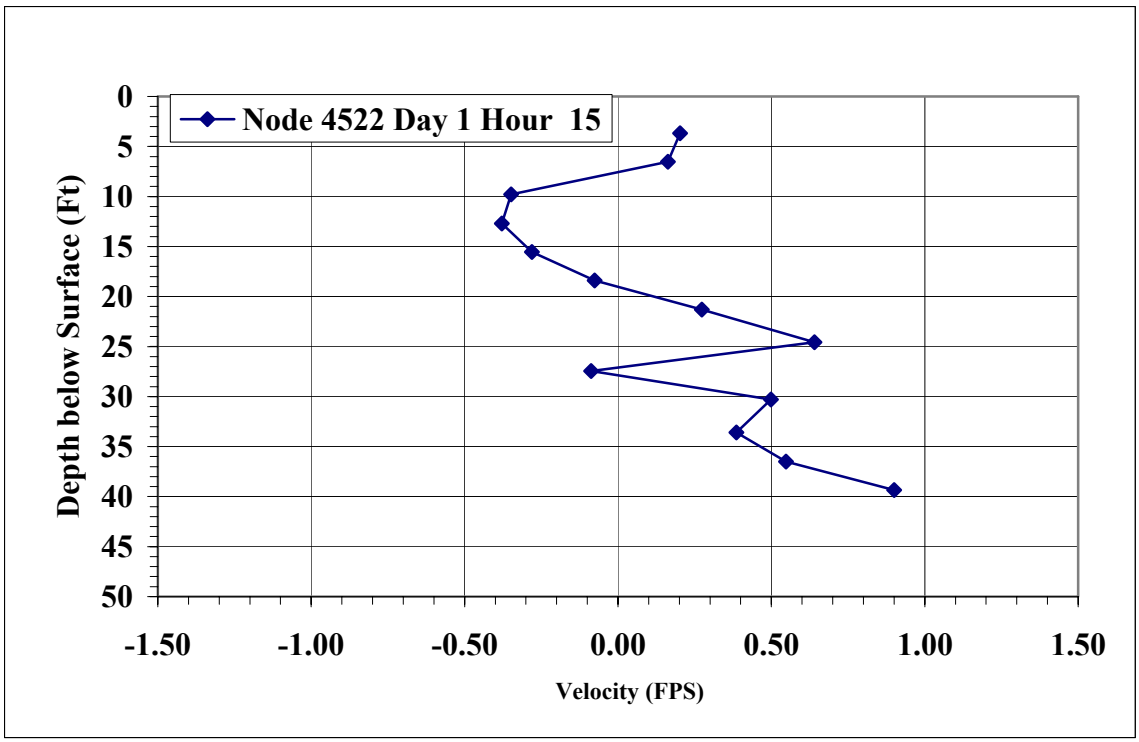
Velocity (FPS)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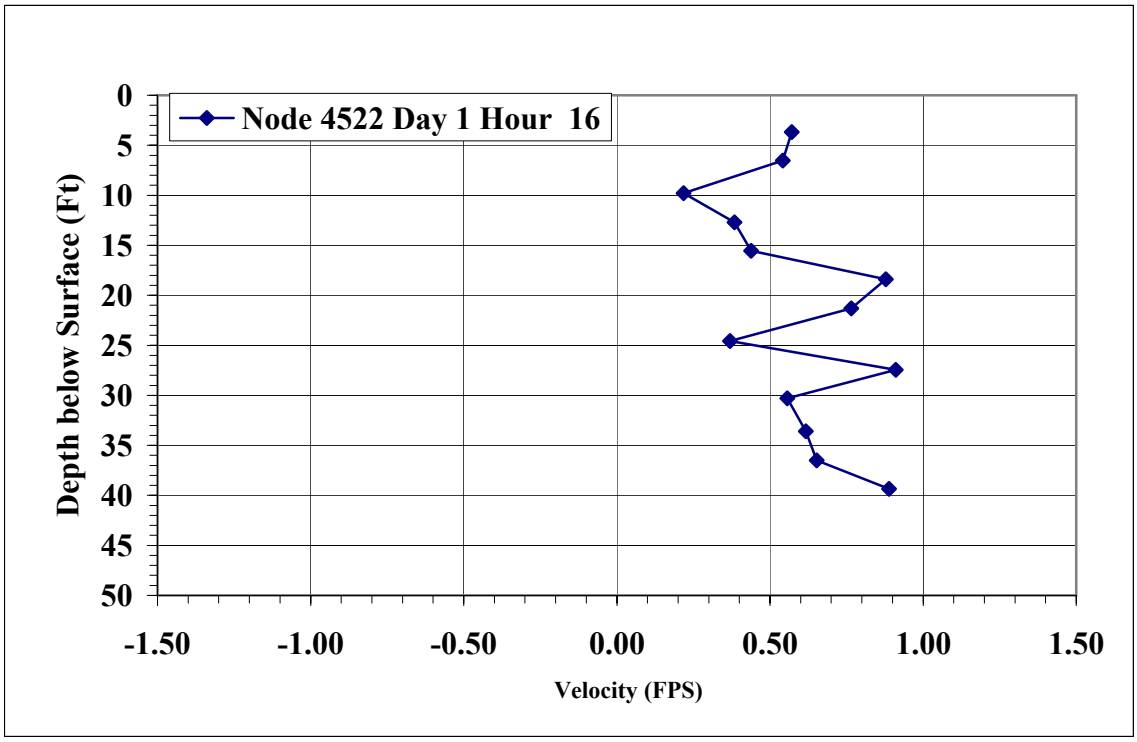
Velocity (FPS)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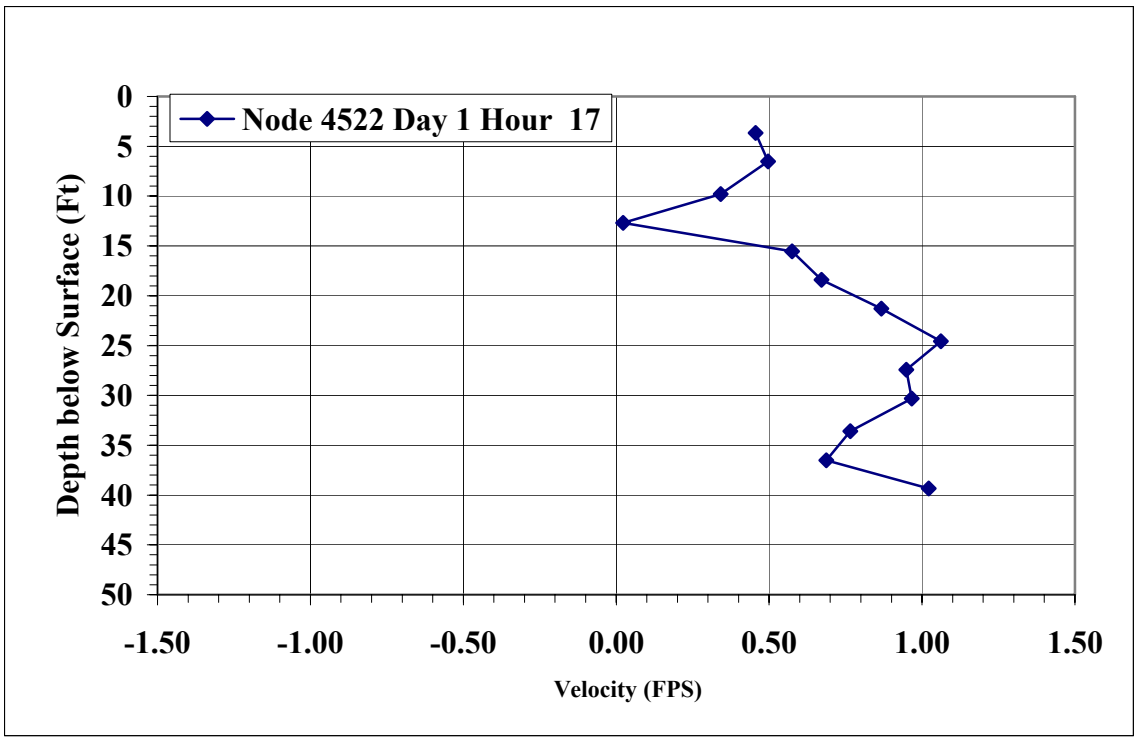
Velocity (FPS)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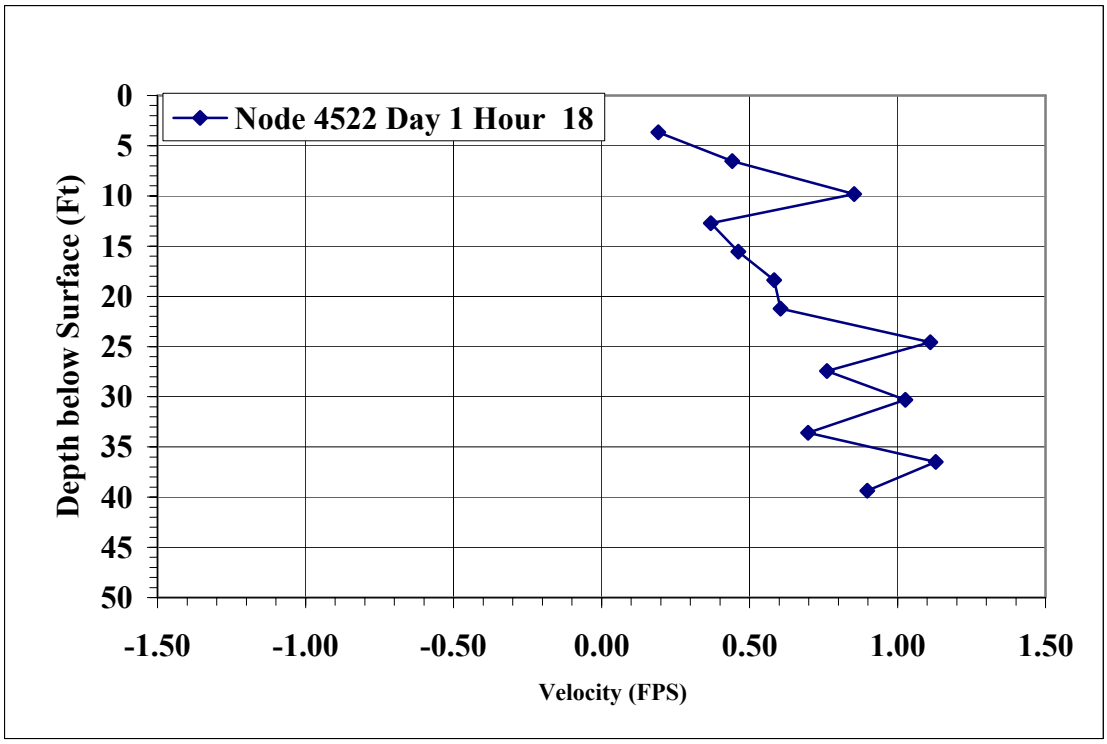
Velocity (FPS)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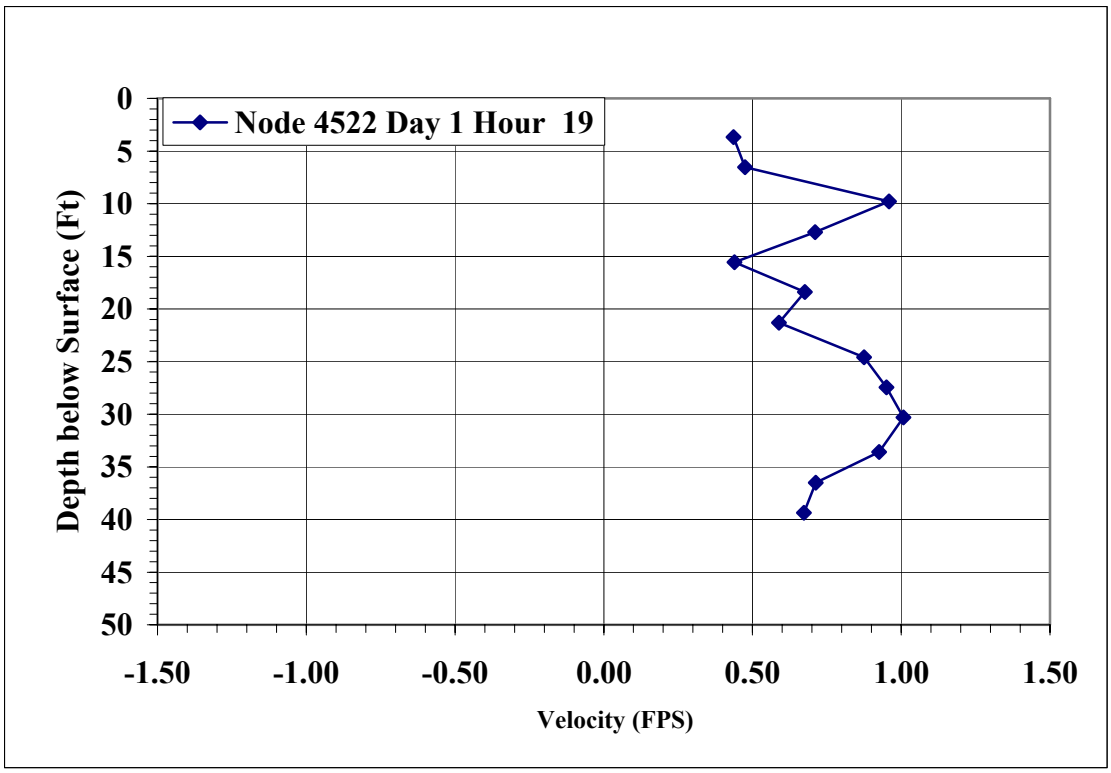
1.50
Velocity (FPS)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0.50
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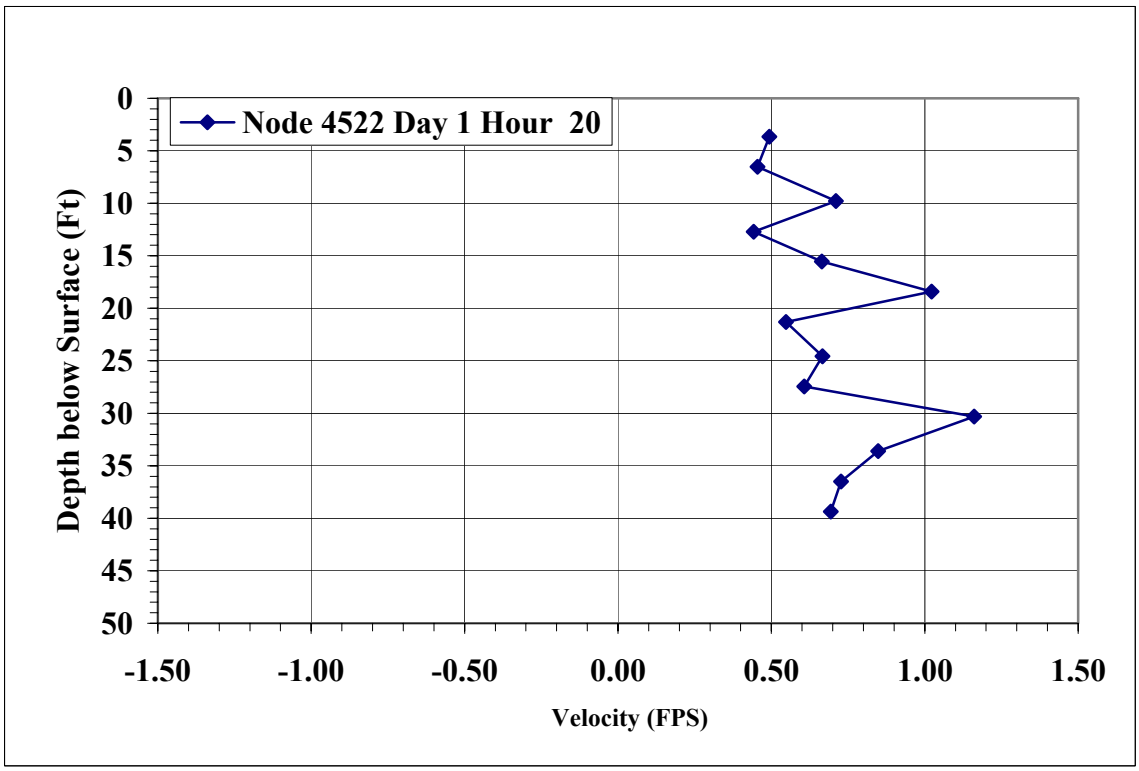
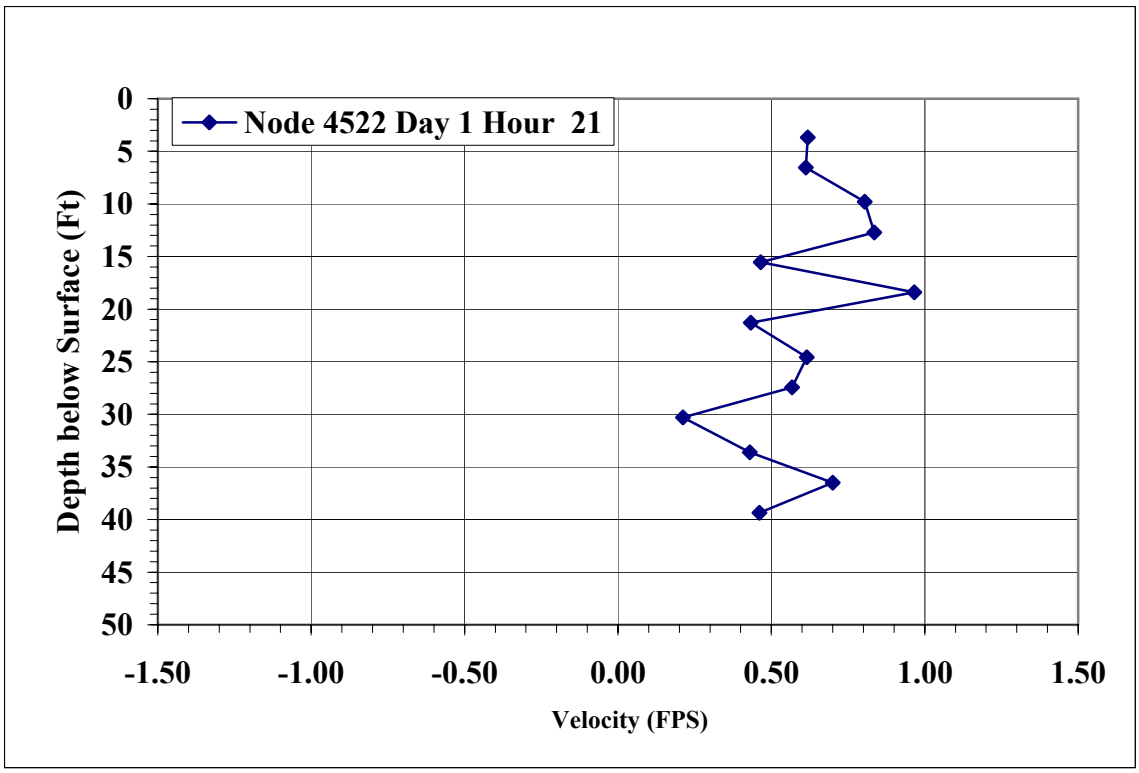
1.50
Velocity (FPS)


Node 4522 Day 1 Hour 20
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 1 Hour 21
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
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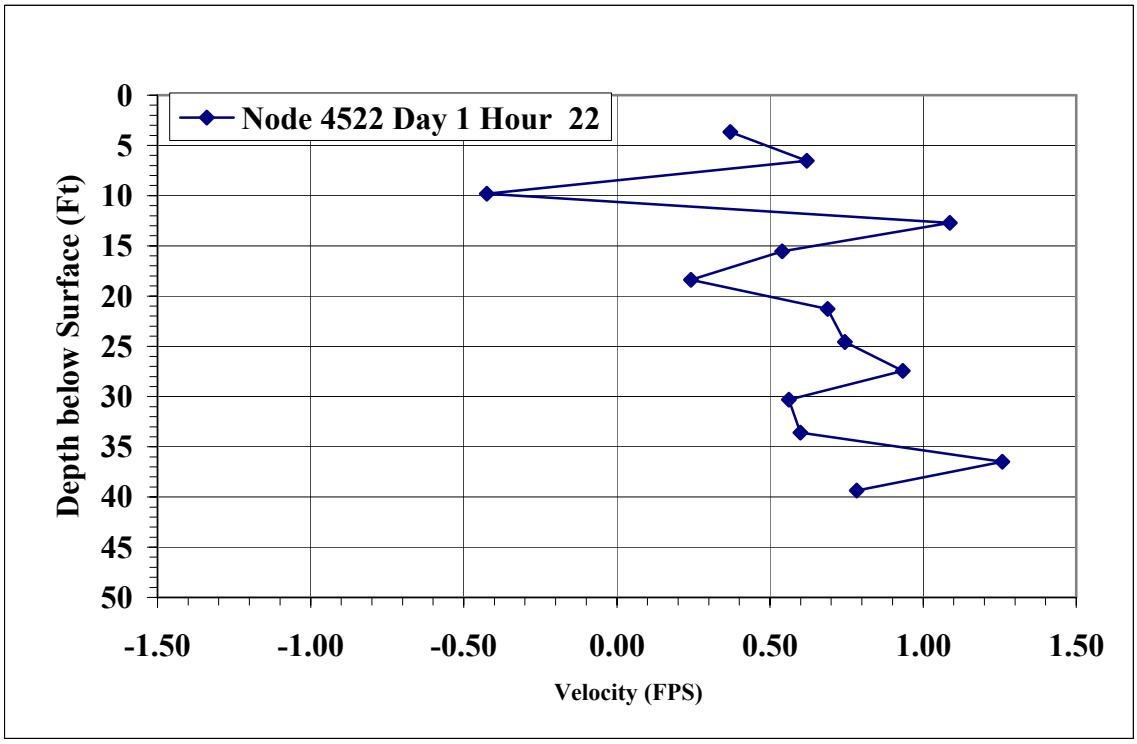
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 1 Hour 22
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
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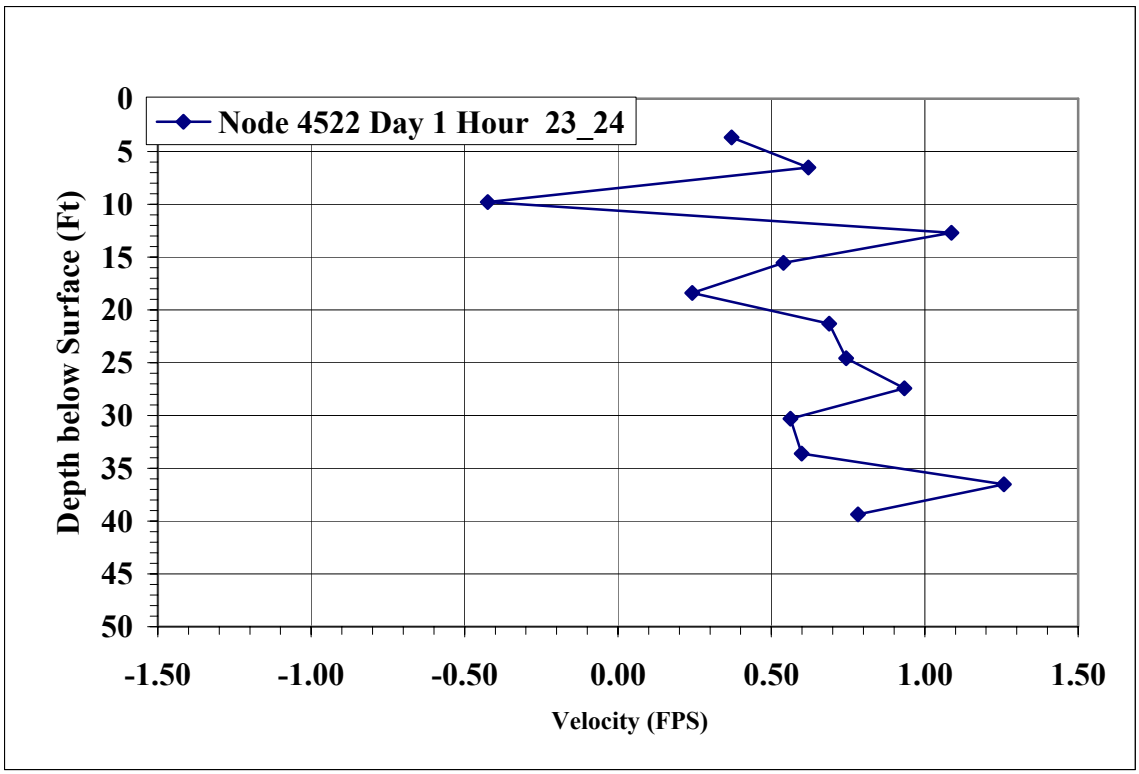
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 1 Hour 23_24
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
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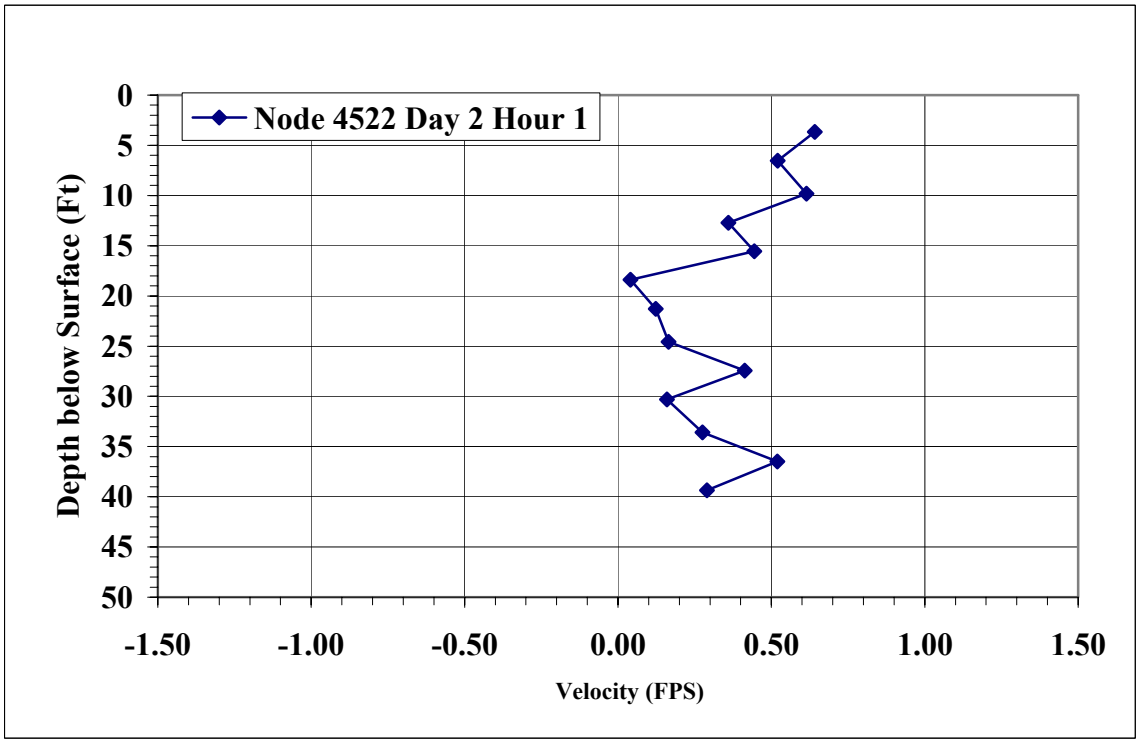
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 1
Depth below Surface (Ft)
0
5
10
15
20
25
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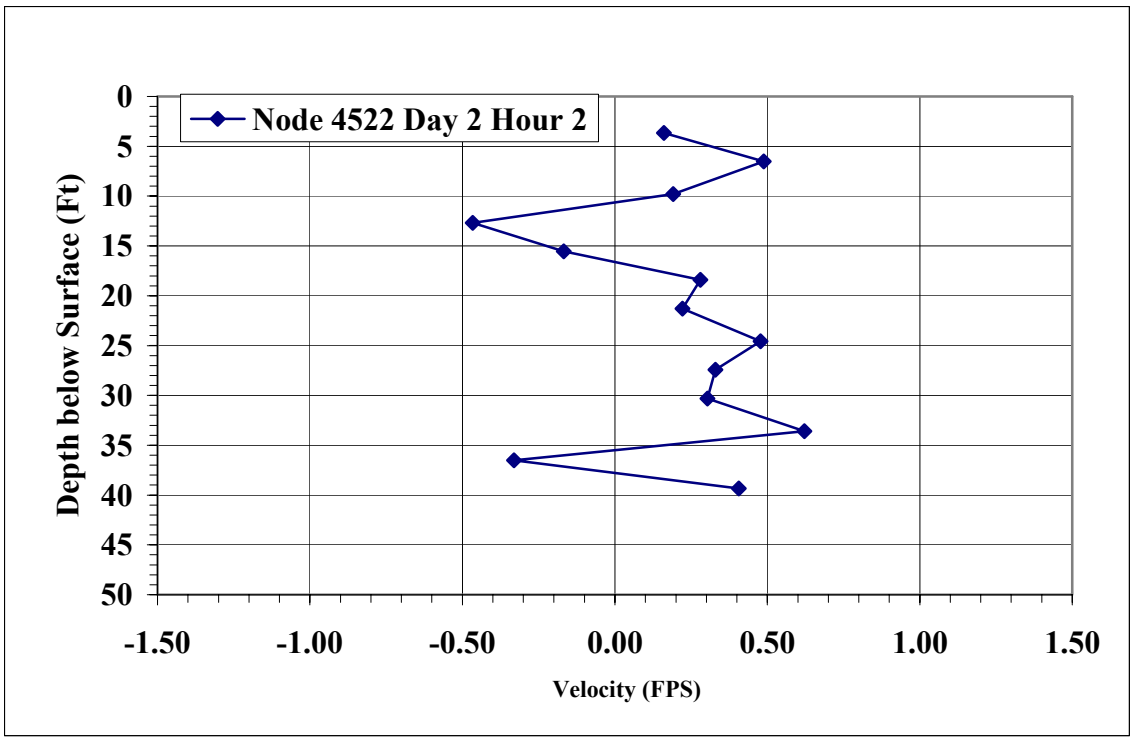
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 2
Depth below Surface (Ft)
0
5
10
15
20
25
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-1.50
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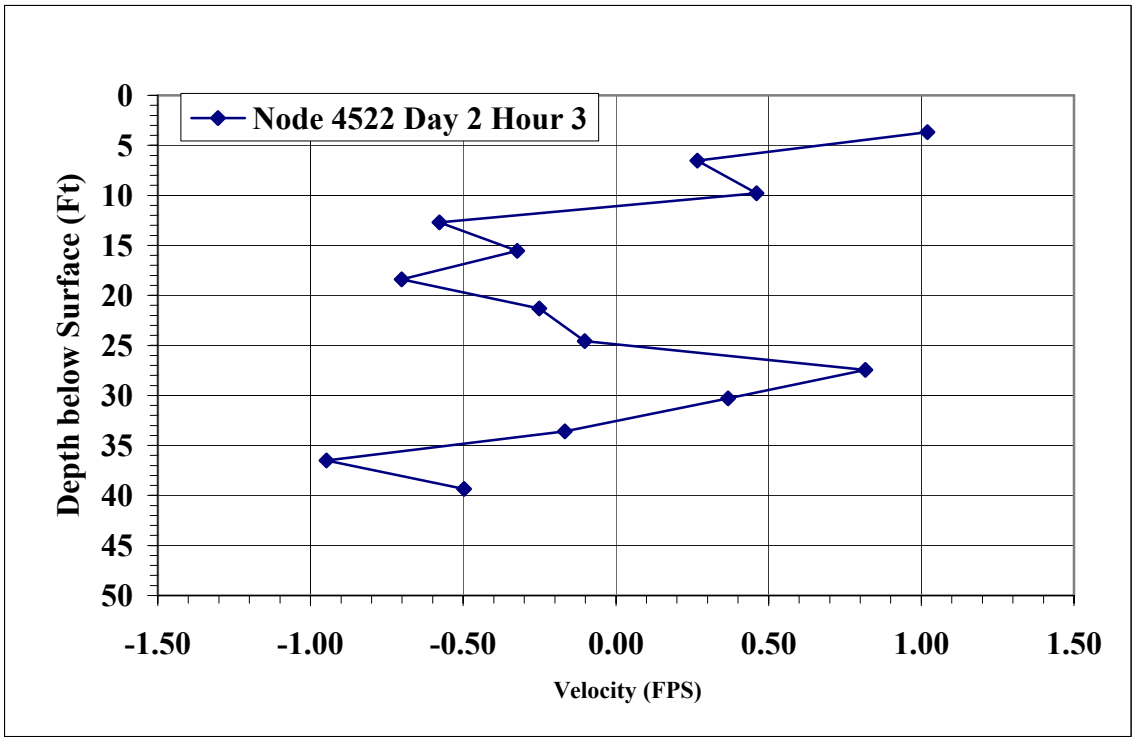
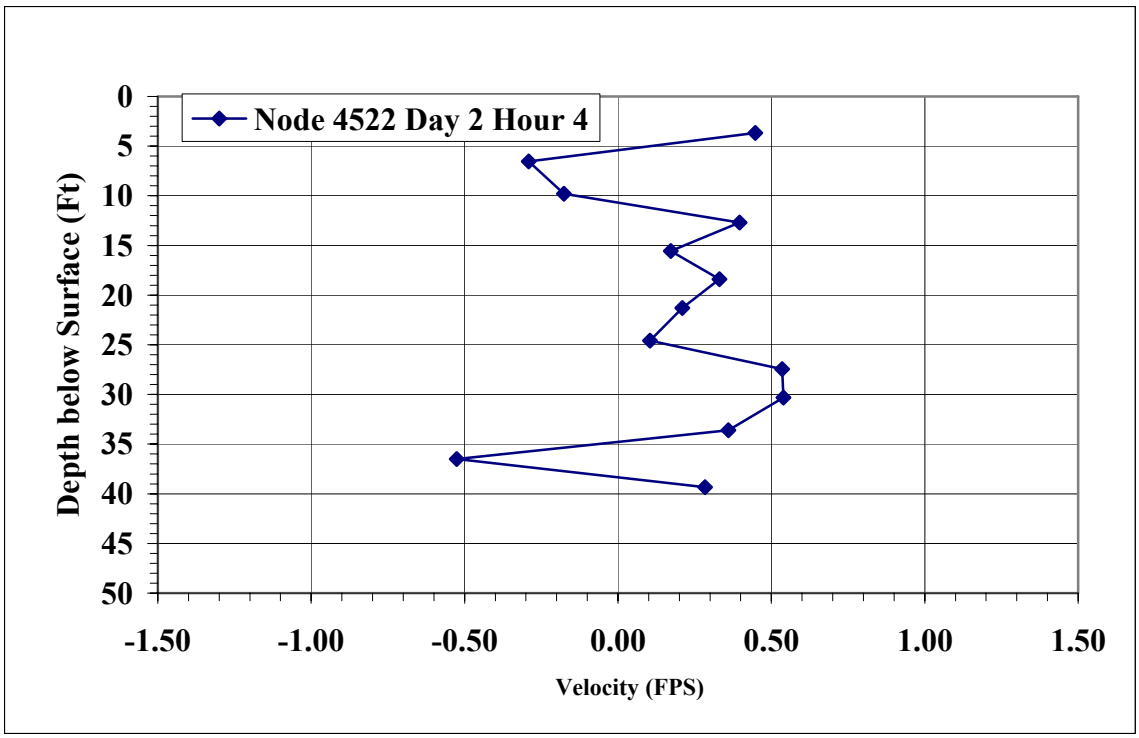
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 3
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 4
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
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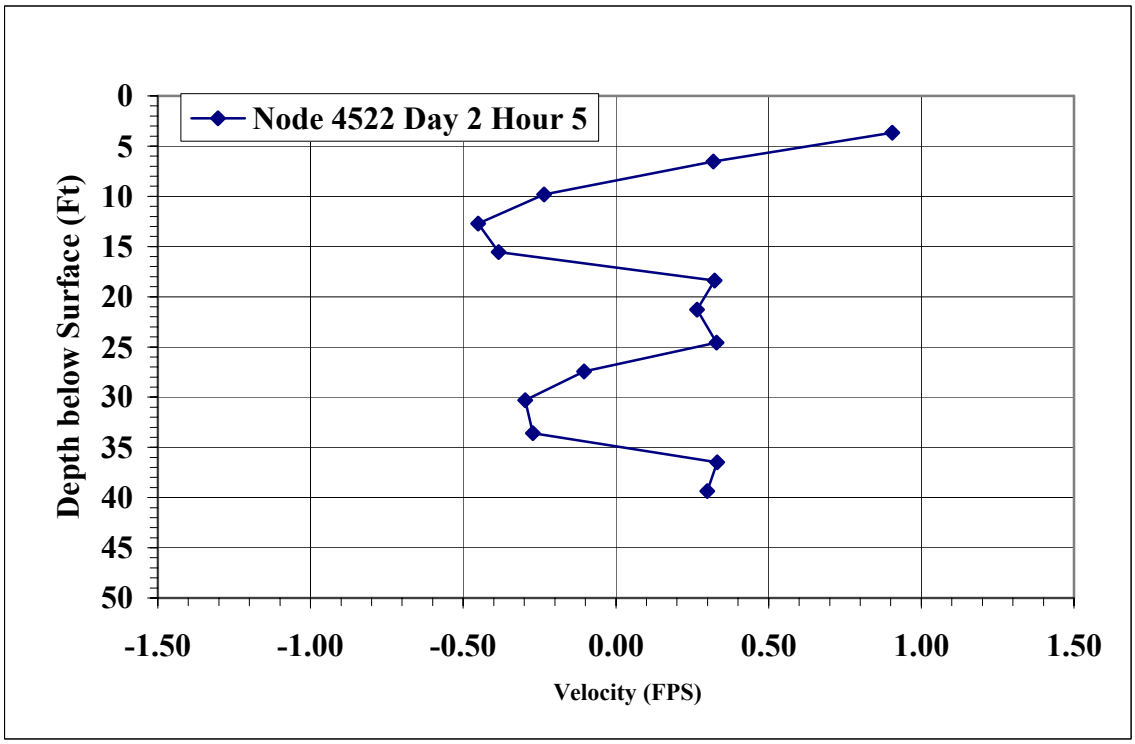
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 5
Depth below Surface (Ft)
0
5
10
15
20
25
30
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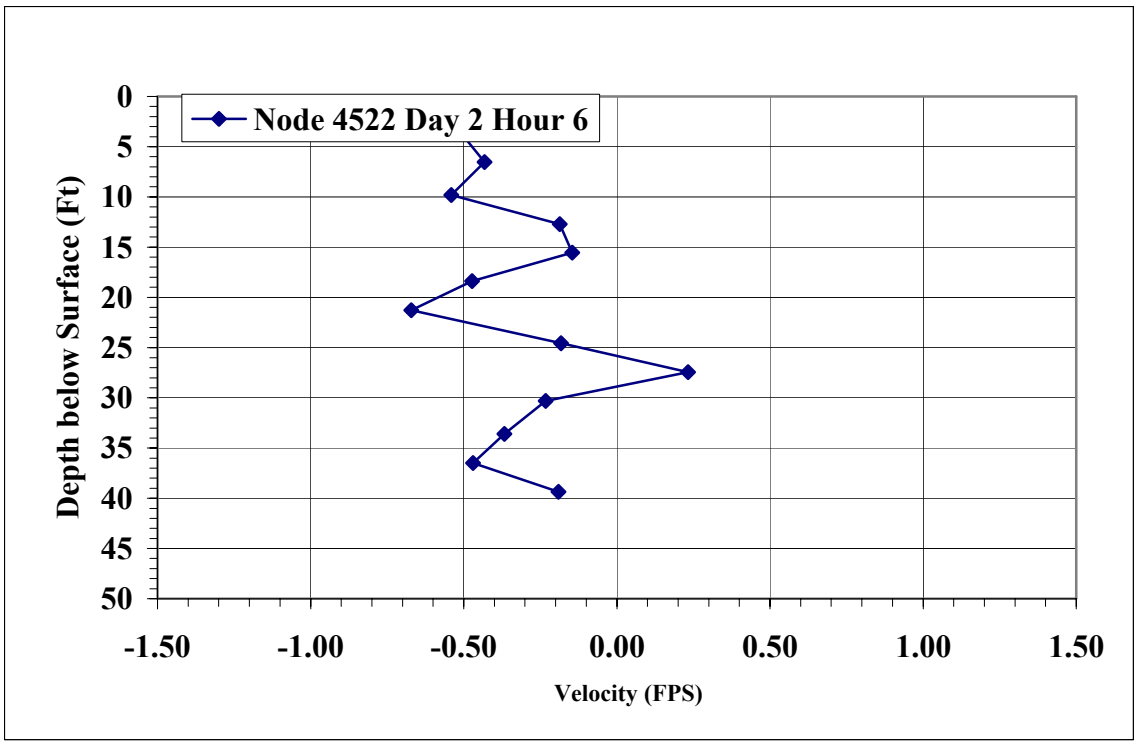
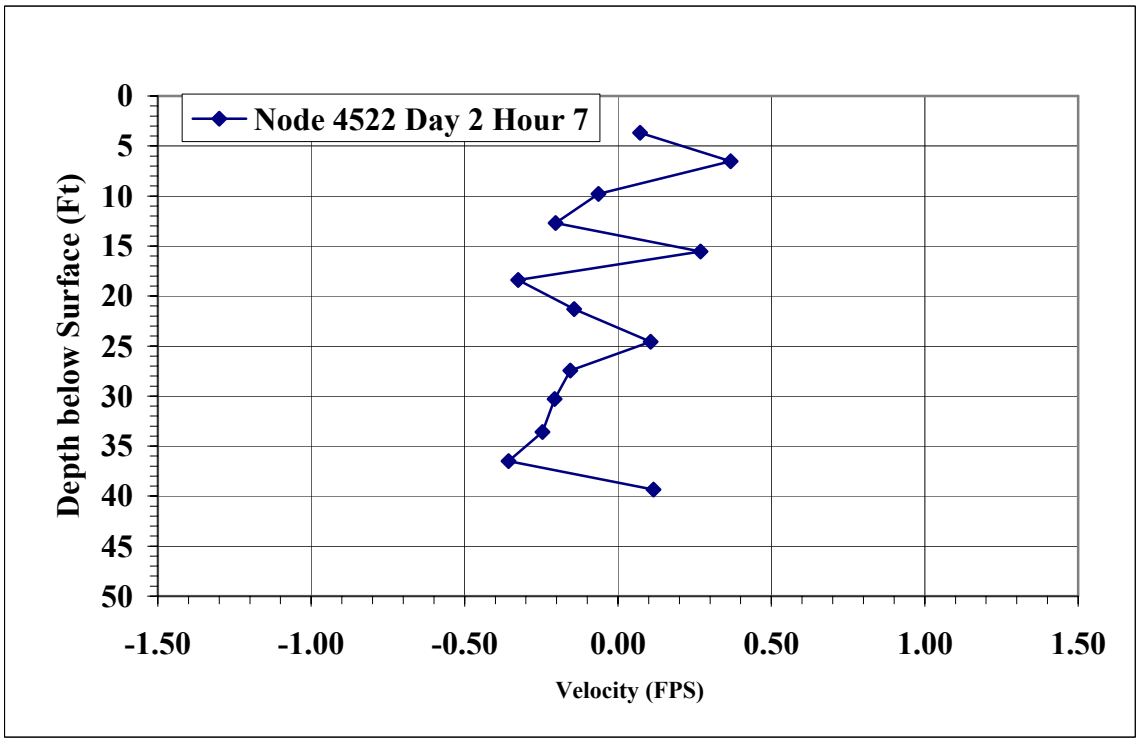
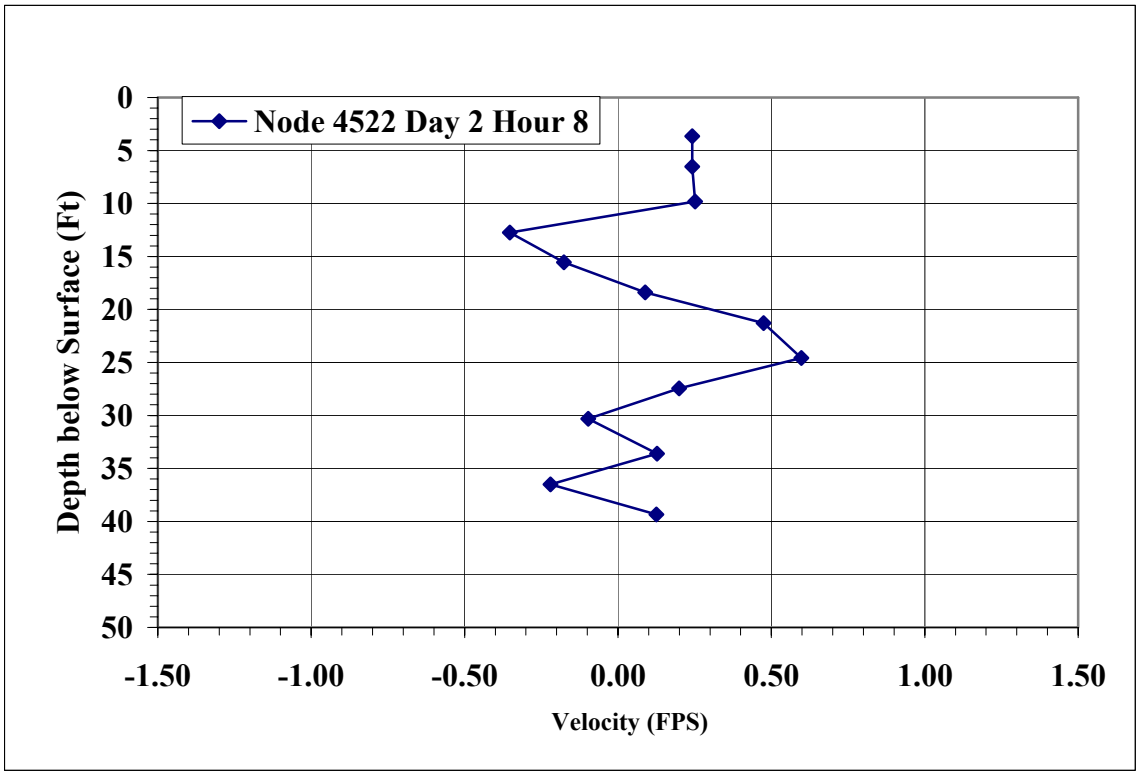
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 6
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 7
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 8
Depth below Surface (Ft)
0
5
10
15
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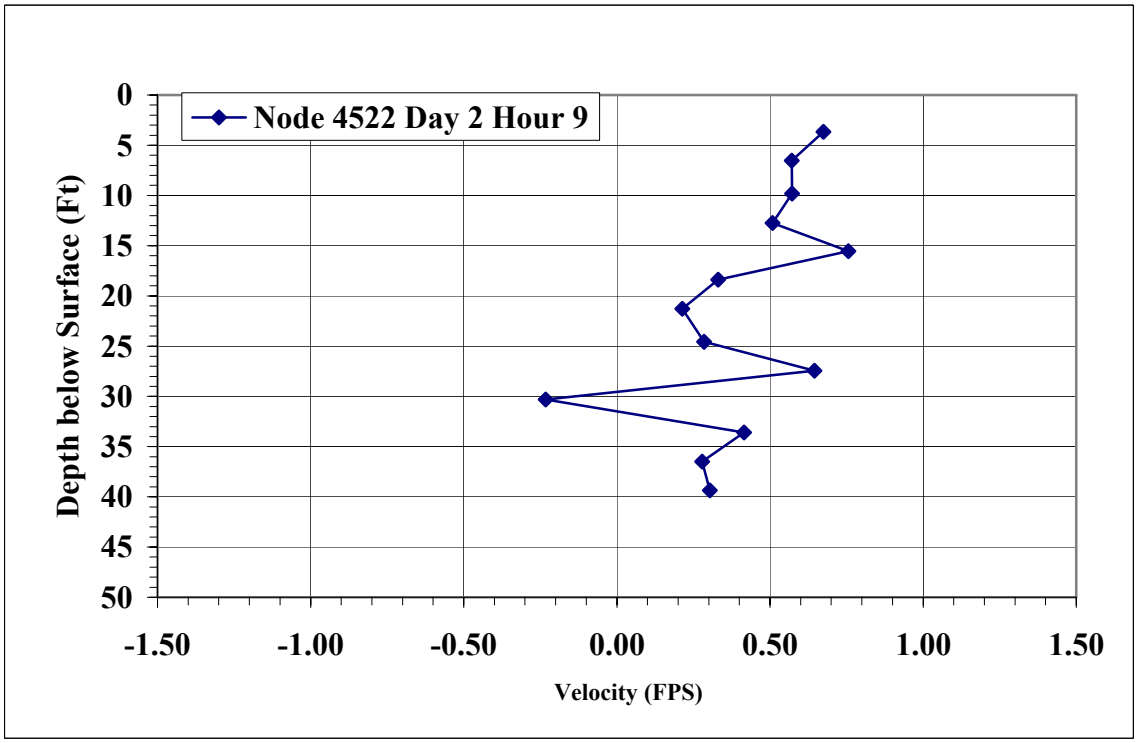
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4522 Day 2 Hour 9
Depth below Surface (Ft)
0
5
10
15
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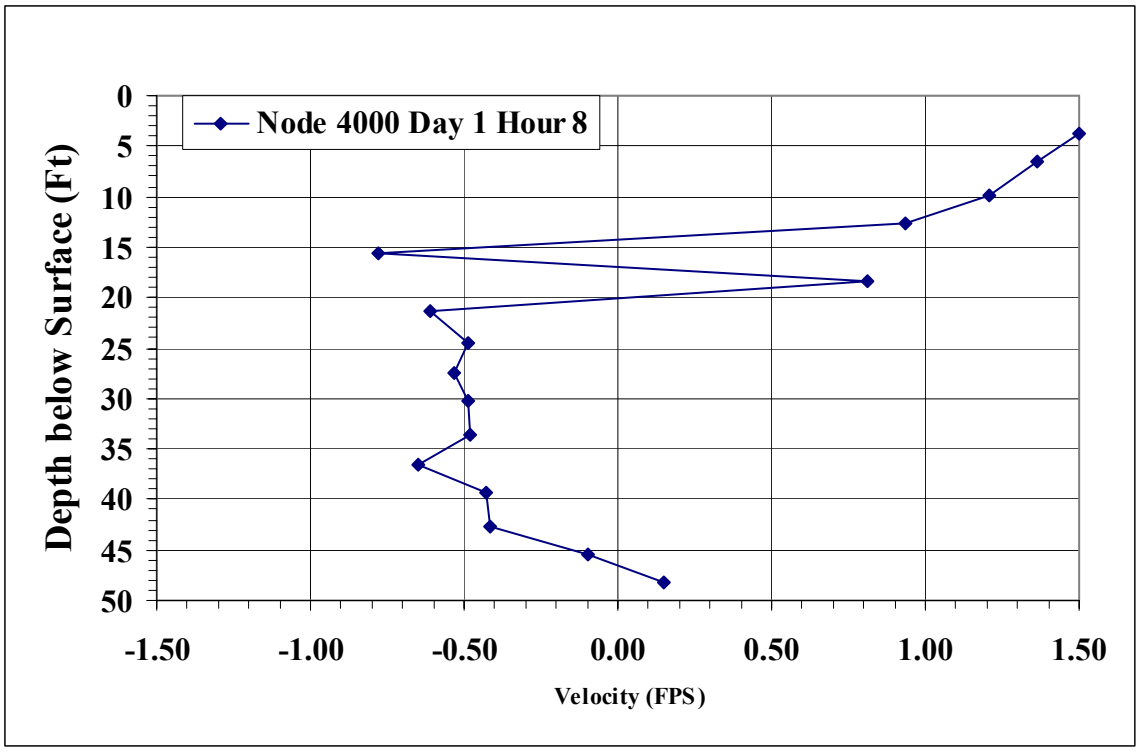
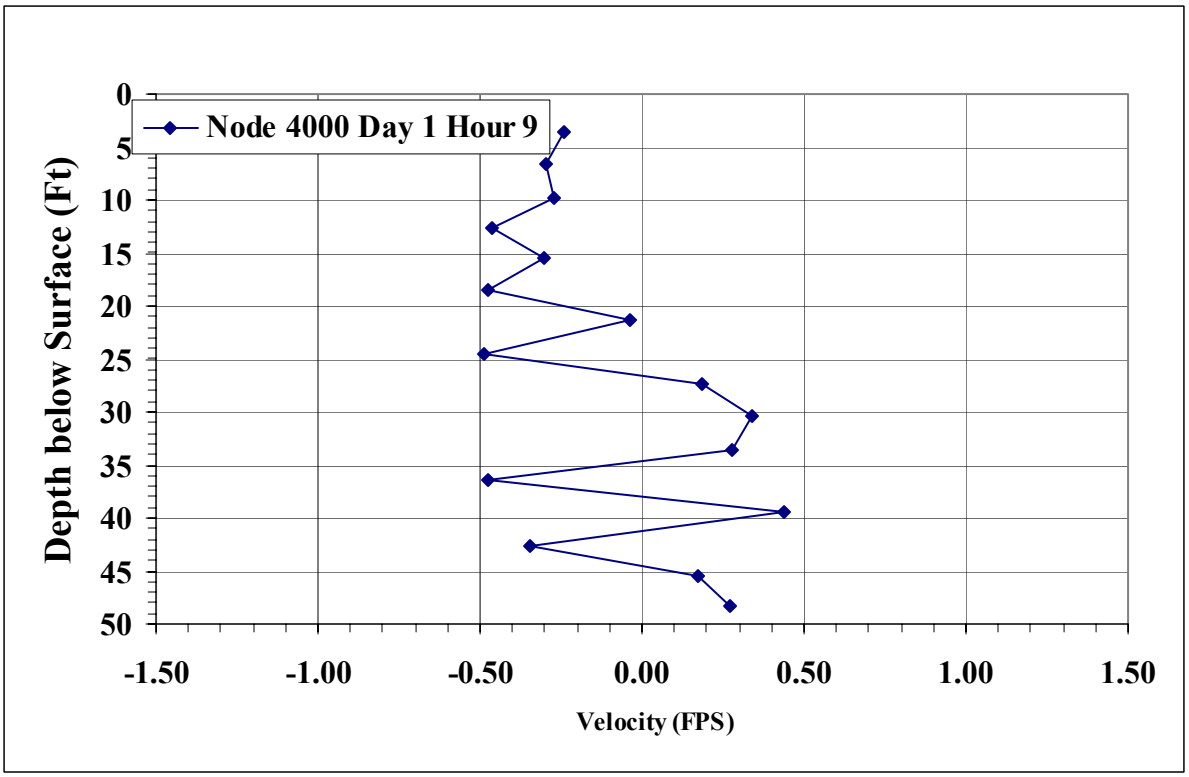
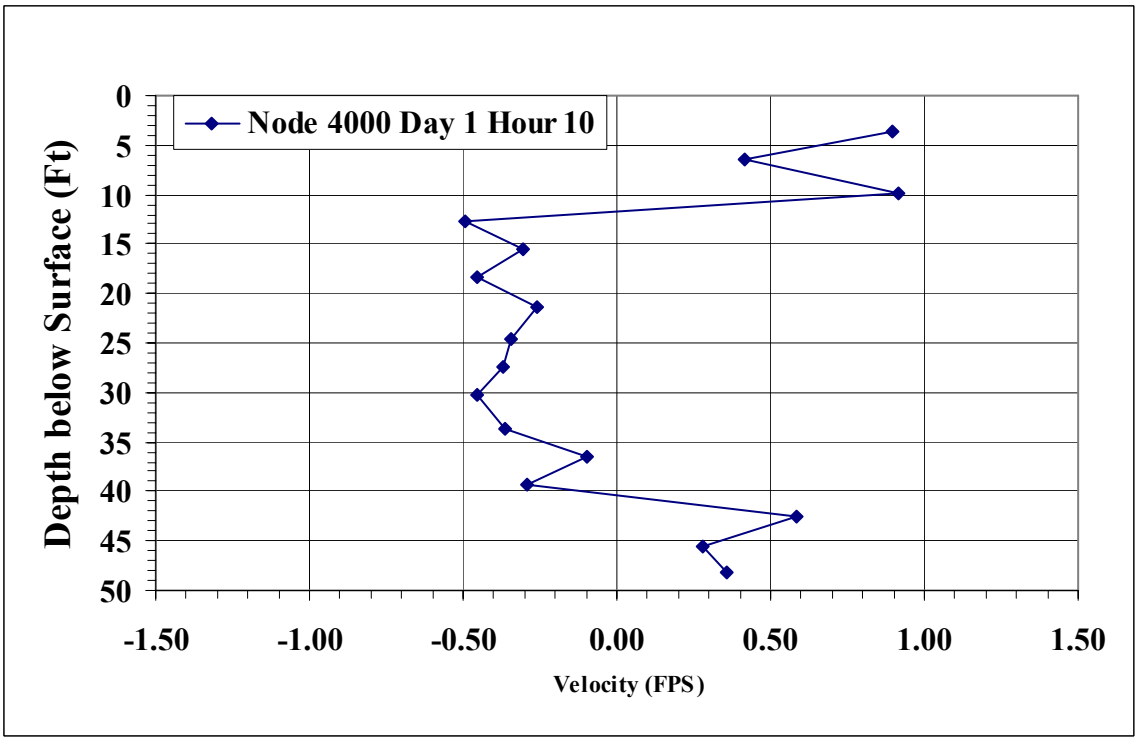
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

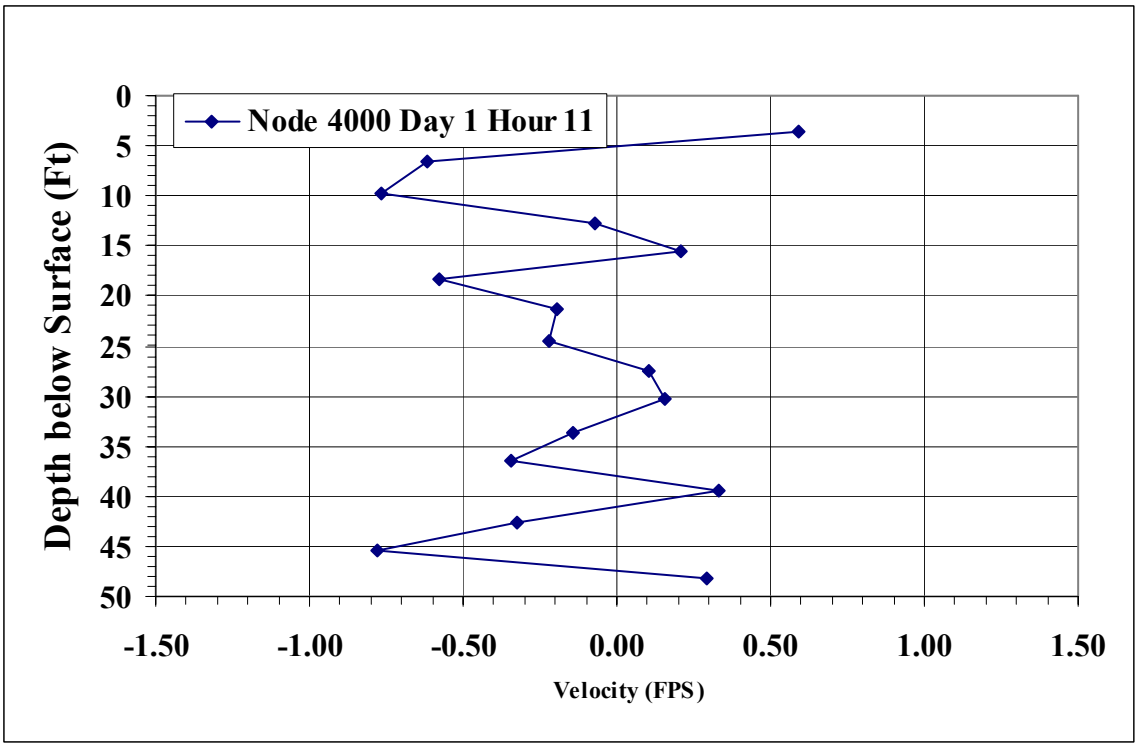
Depth-Variation of Currents Observed at Freeport Harbor Node 4000 Transect 2

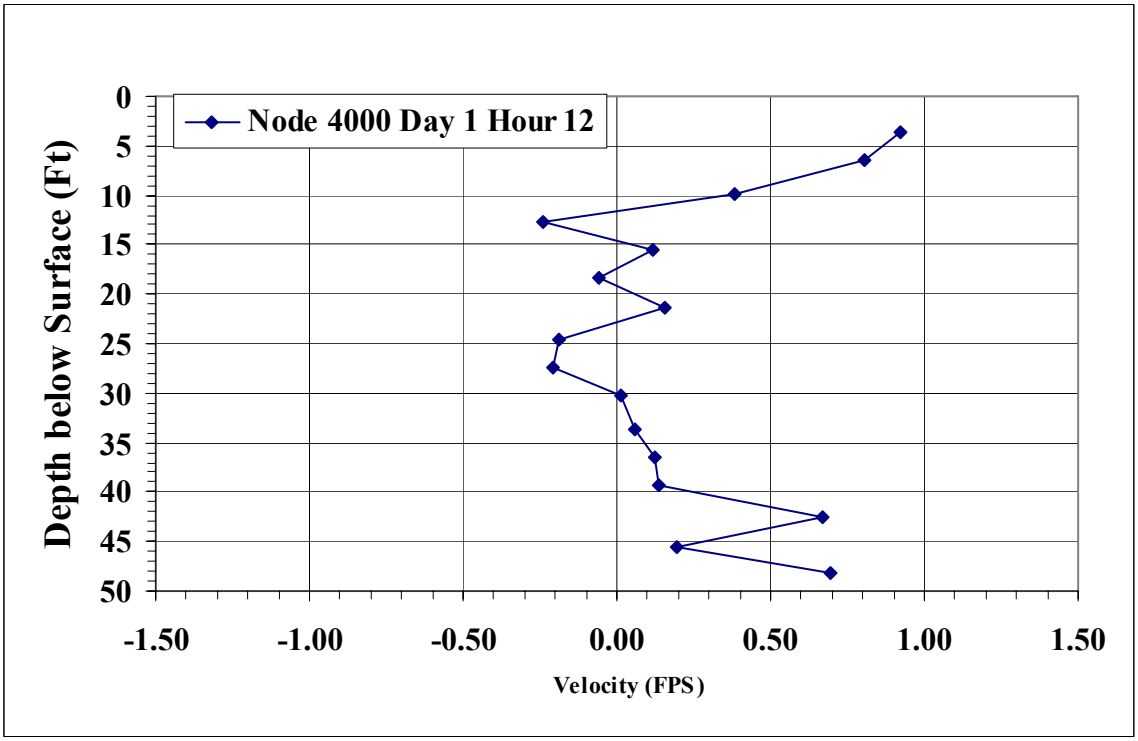
Flood: Positive, Ebb: Negative

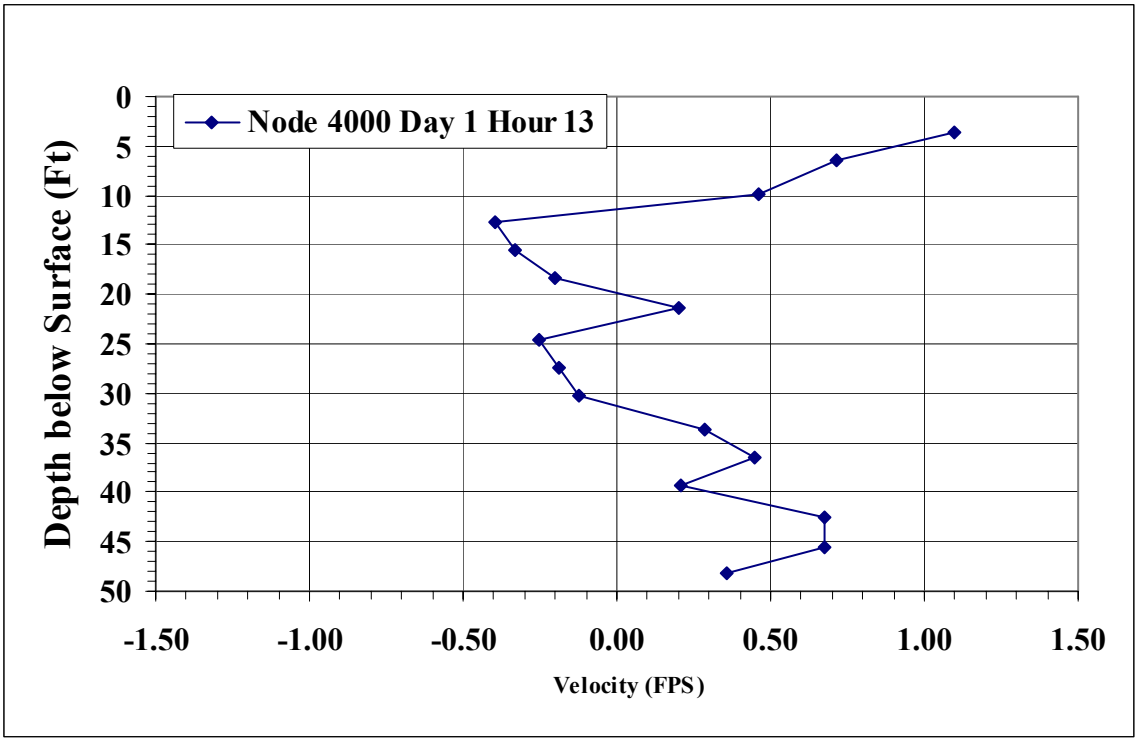

Node 4000 Day 1 Hour 8
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 9
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 10
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 11
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 12
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 13
Depth below Surface (Ft)
0
5
10
15
20
25
30
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40
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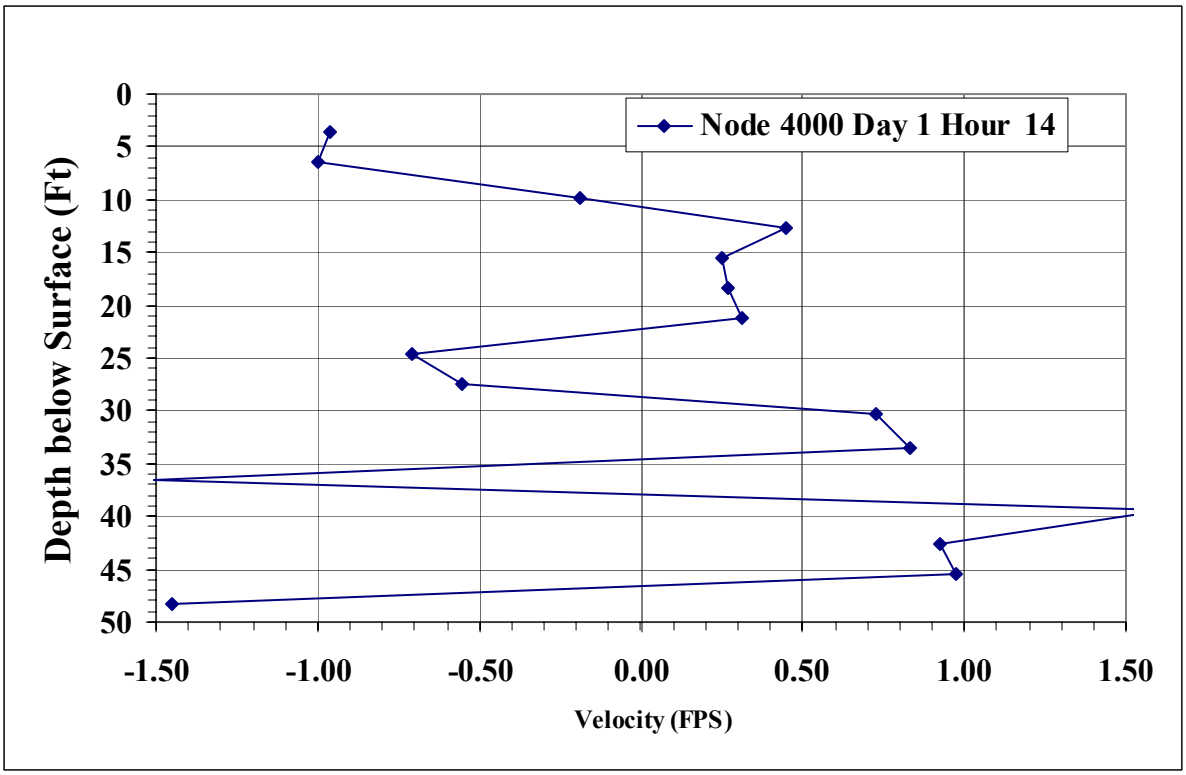
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 14
Depth below Surface (Ft)
0
5
10
15
20
25
30
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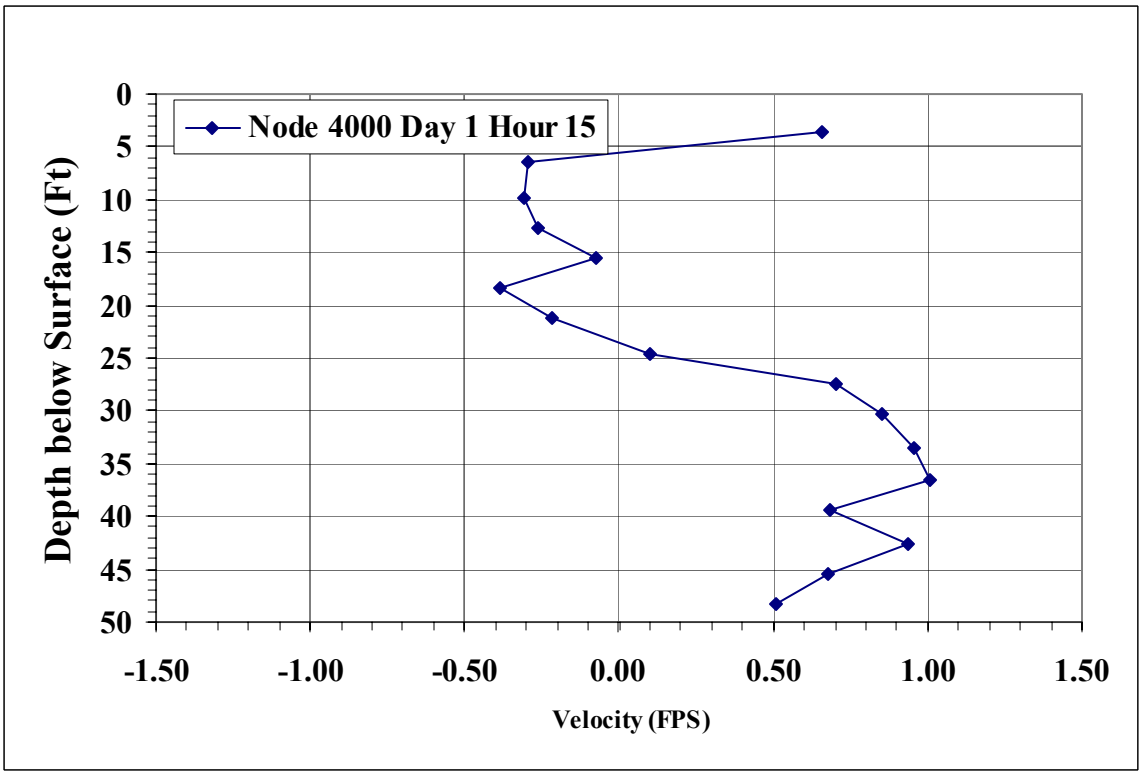
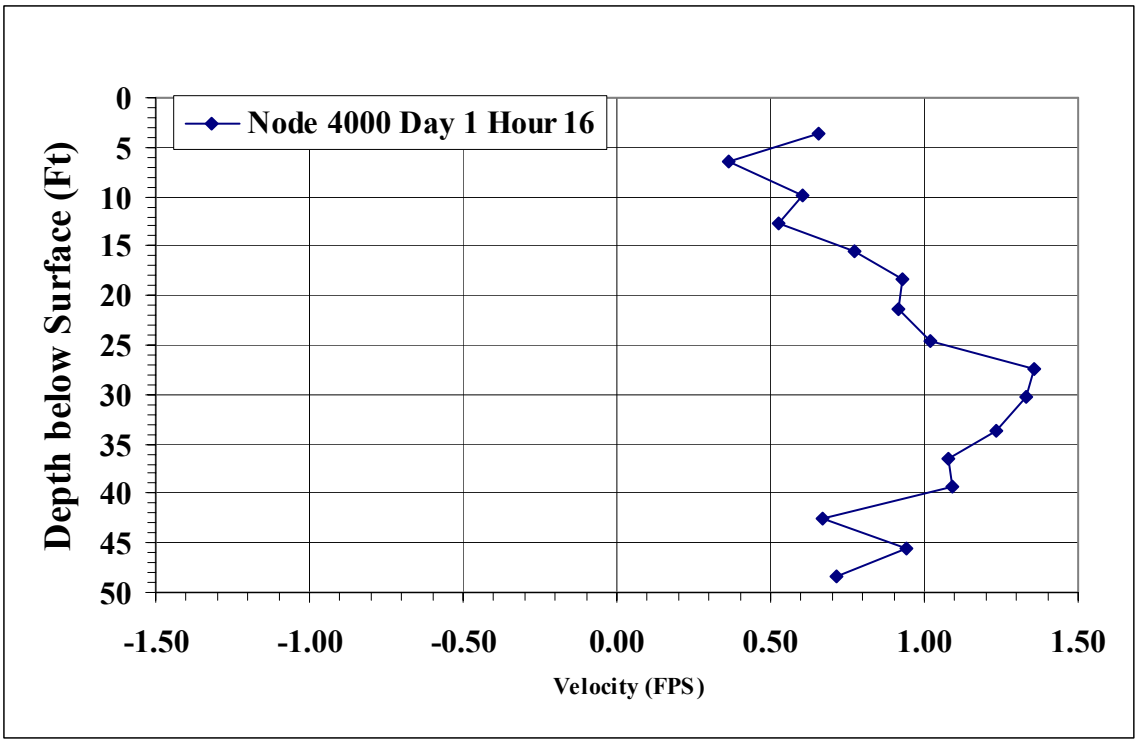
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 15
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 16
Depth below Surface (Ft)
0
5
10
15
20
25
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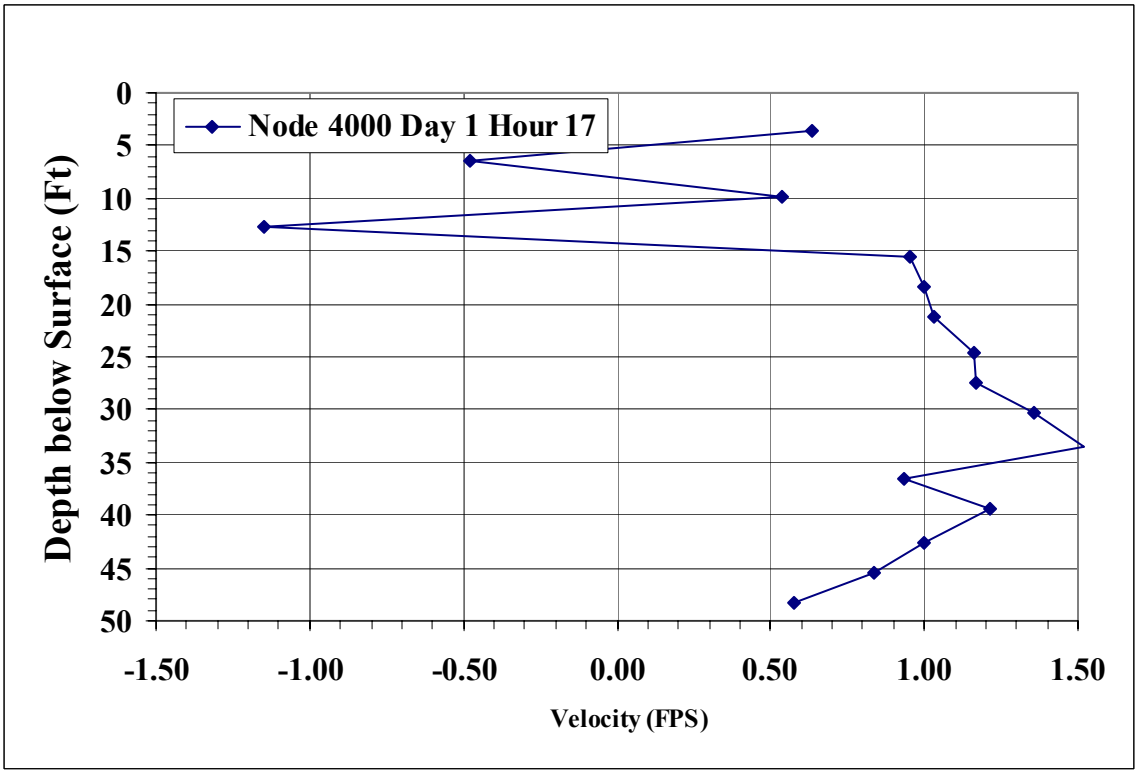
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 17
Depth below Surface (Ft)
0
5
10
15
20
25
30
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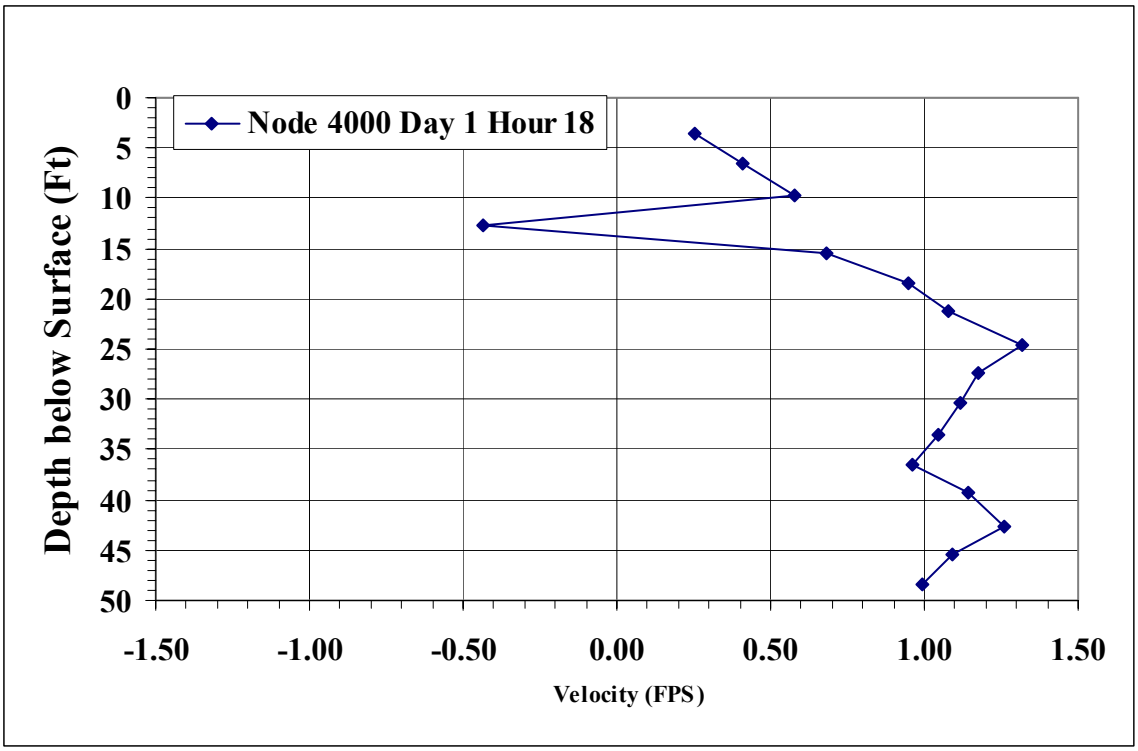
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 18
Depth below Surface (Ft)
0
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10
15
20
25
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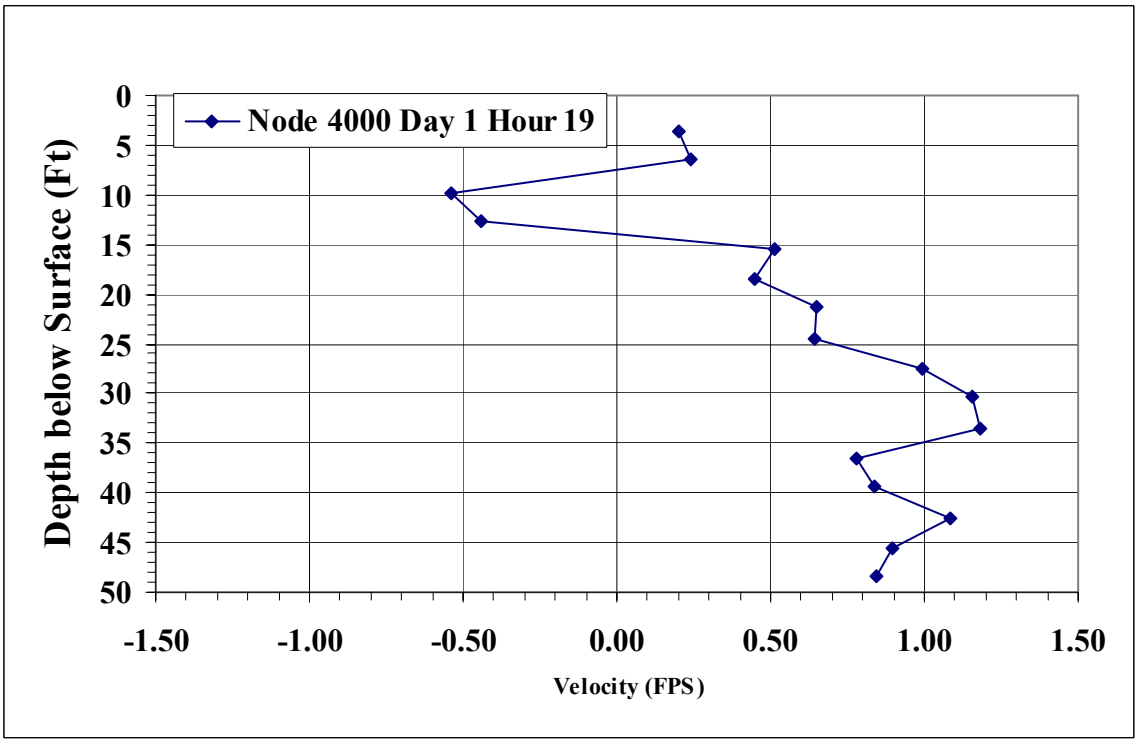
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 19
Depth below Surface (Ft)
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10
15
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-1.50
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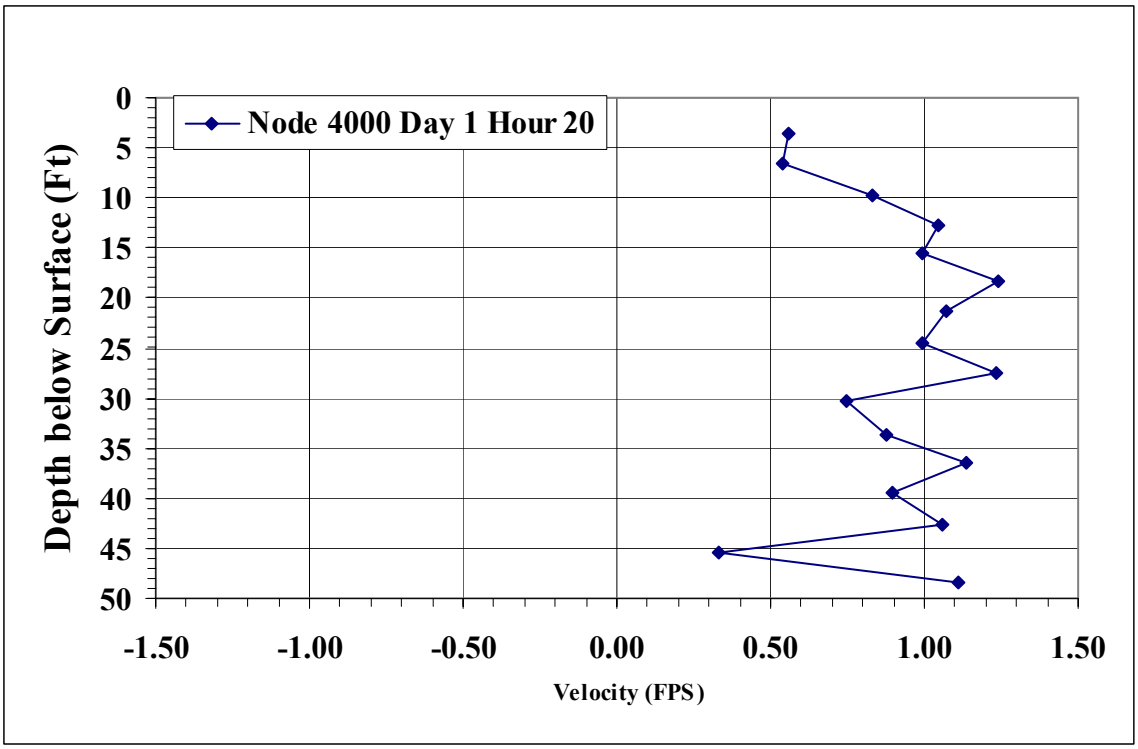
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 20
Depth below Surface (Ft)
0
5
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25
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50
-1.50
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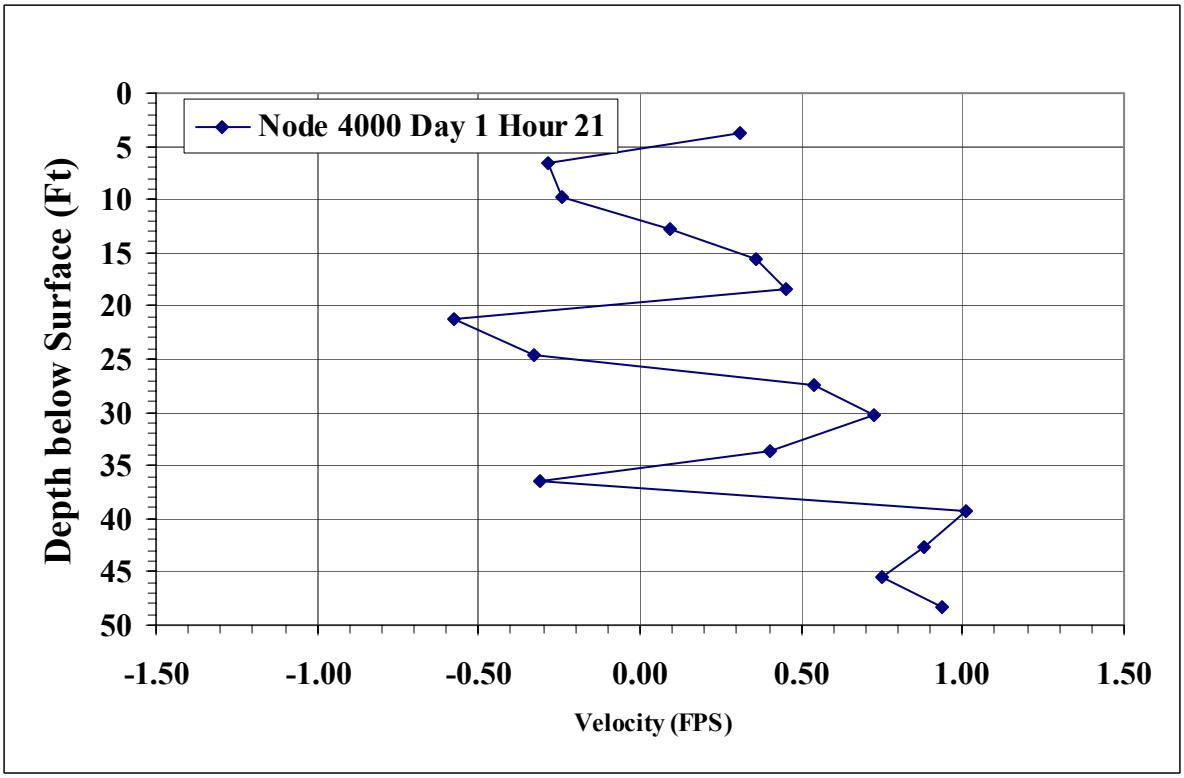
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 21
Depth below Surface (Ft)
0
5
10
15
20
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30
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40
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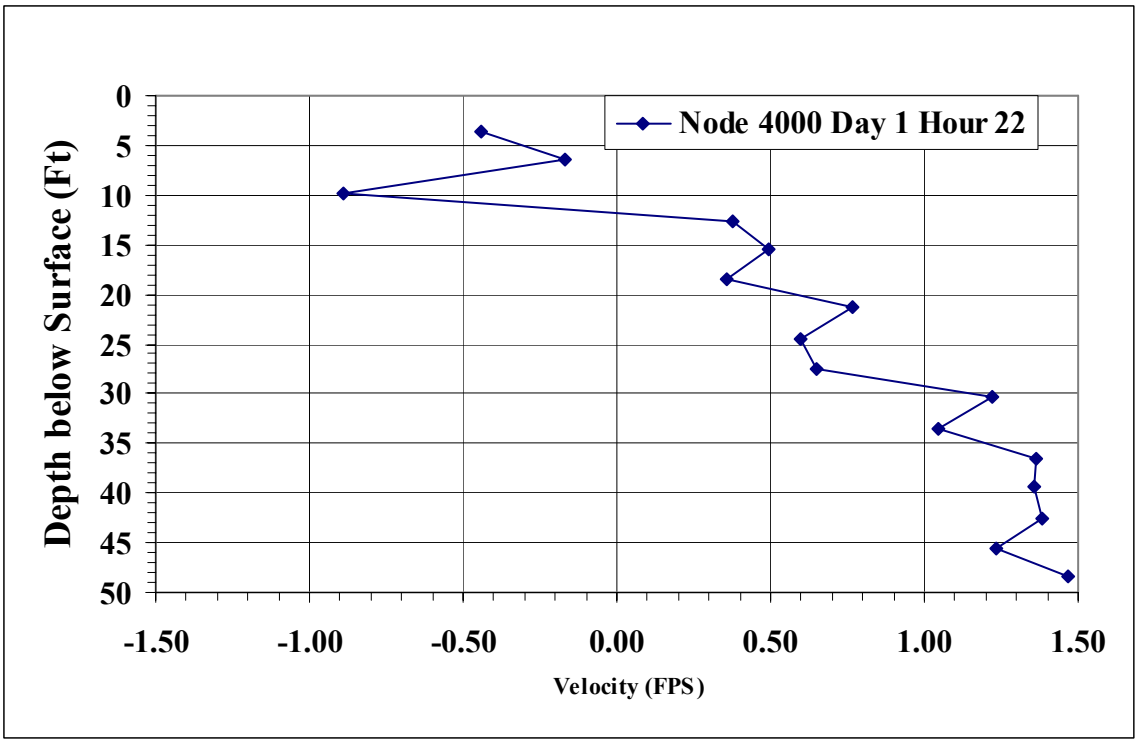
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 22
Depth below Surface (Ft)
0
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10
15
20
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-1.50
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-0.50
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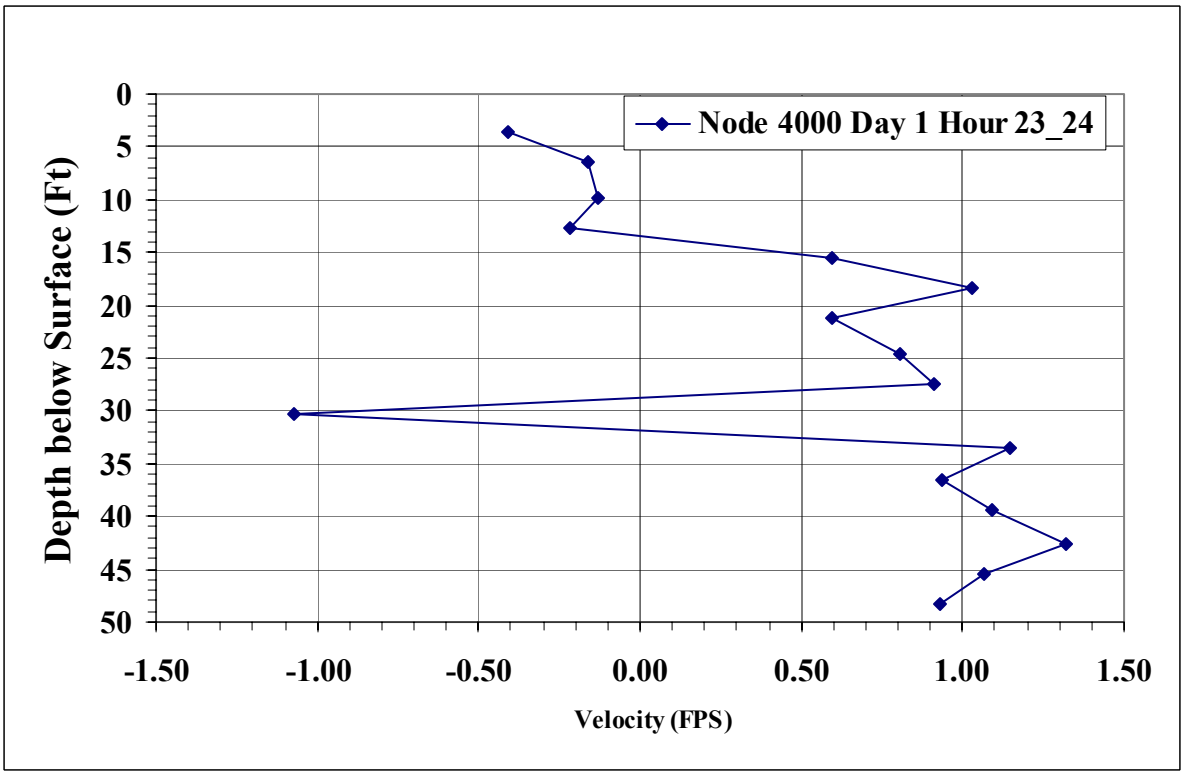
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 1 Hour 23_24
Depth below Surface (Ft)
0
5
10
15
20
25
30
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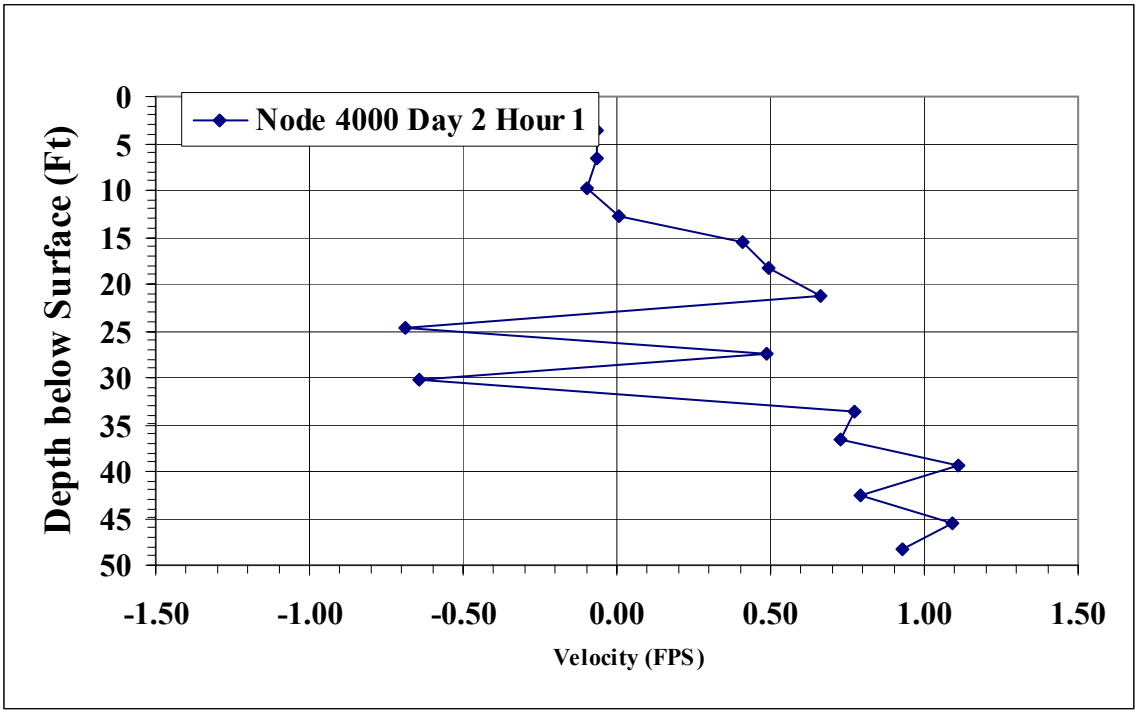
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 2 Hour 1
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
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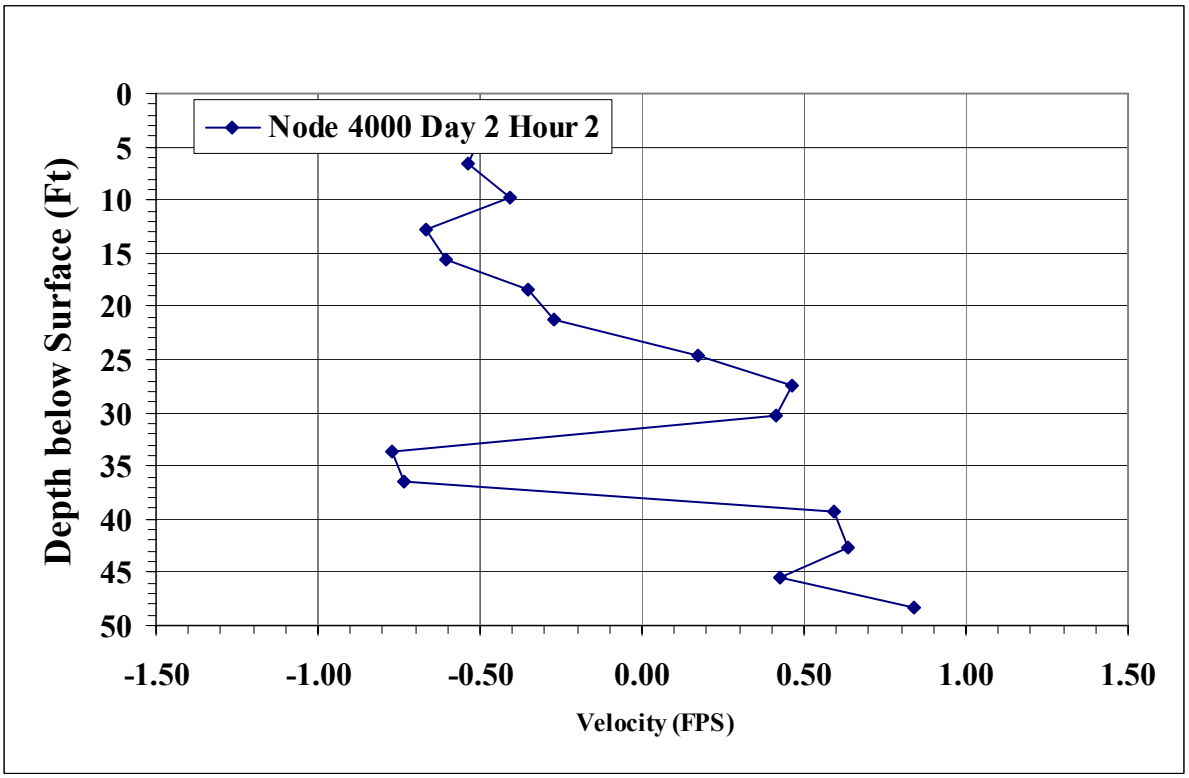
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 2 Hour 2
Depth below Surface (Ft)
0
5
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15
20
25
30
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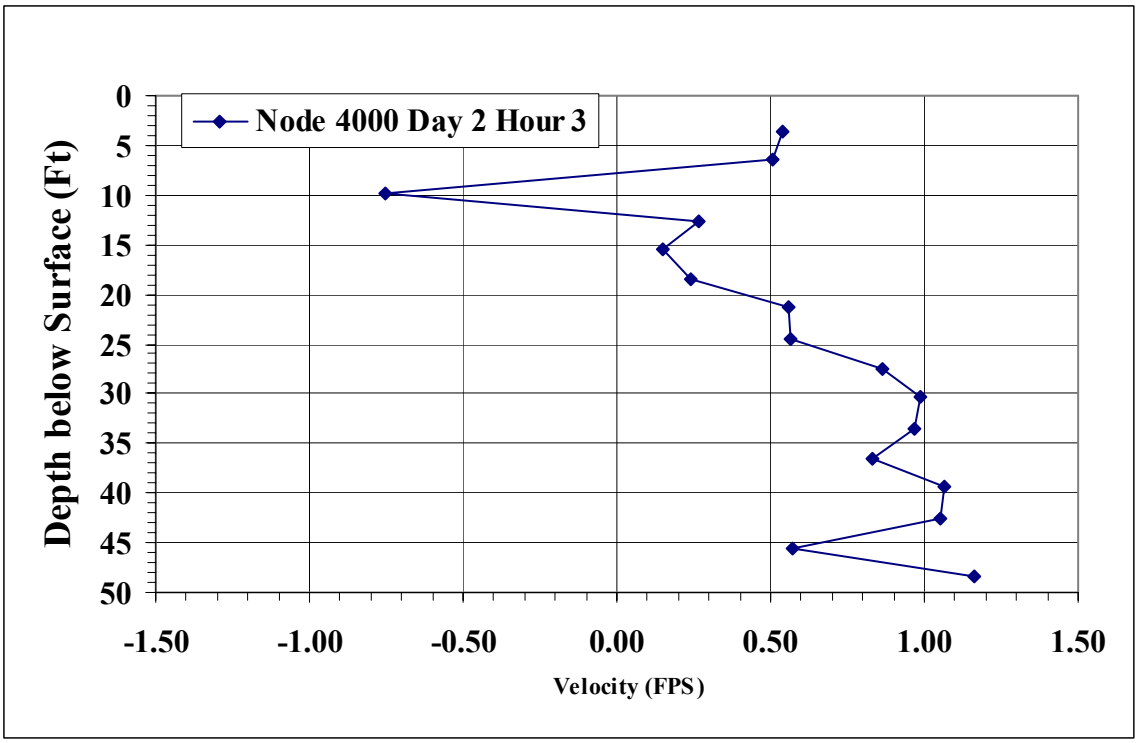
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 2 Hour 3
Depth below Surface (Ft)
0
5
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20
25
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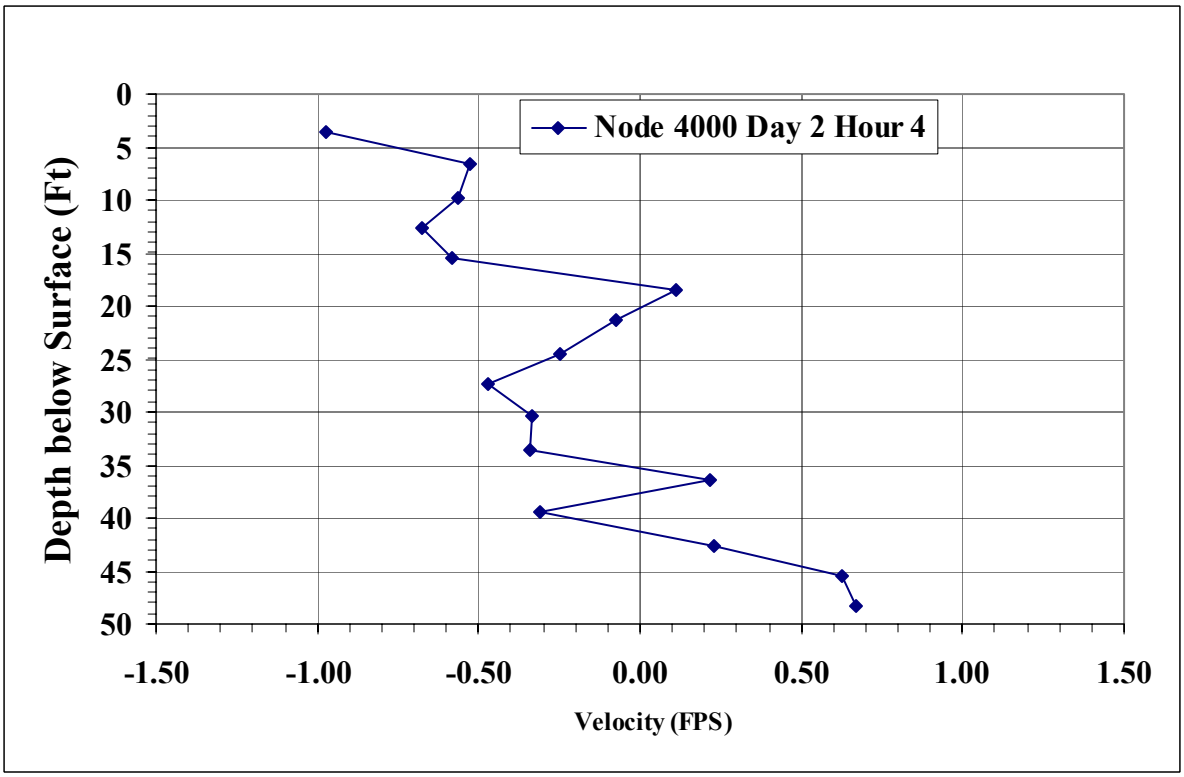
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 2 Hour 4
Depth below Surface (Ft)
0
5
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15
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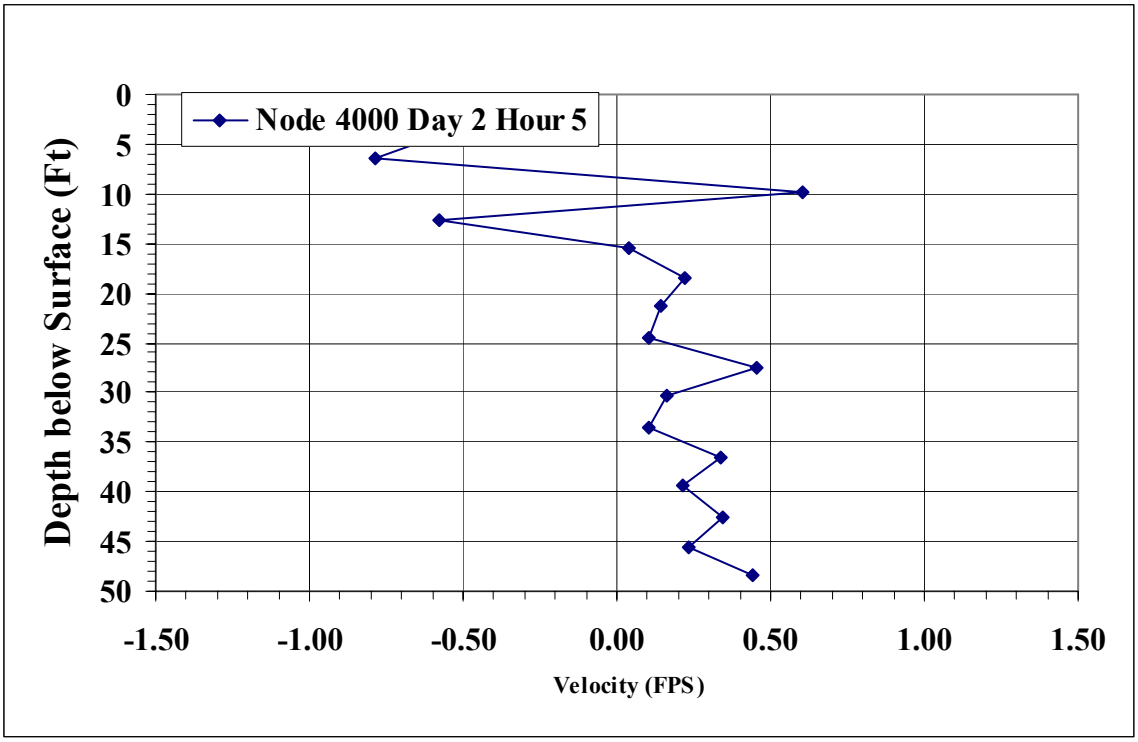
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 2 Hour 5
Depth below Surface (Ft)
0
5
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40
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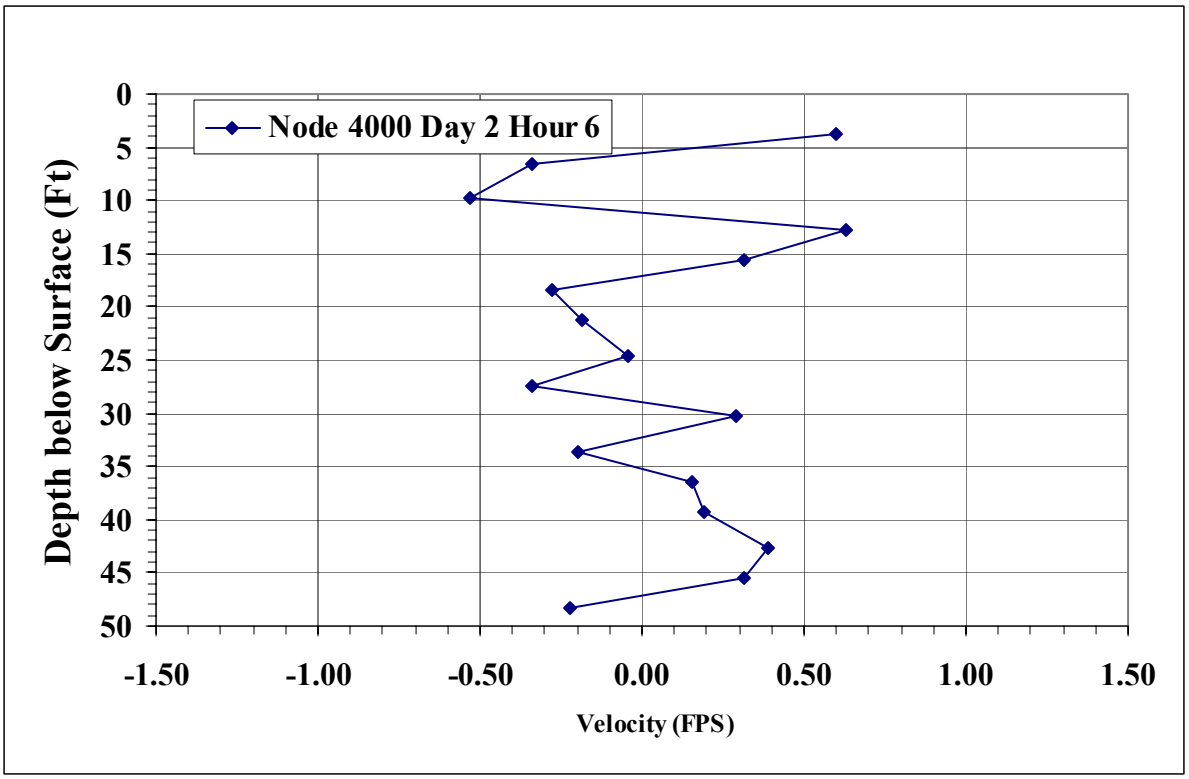
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 2 Hour 6
Depth below Surface (Ft)
0
5
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40
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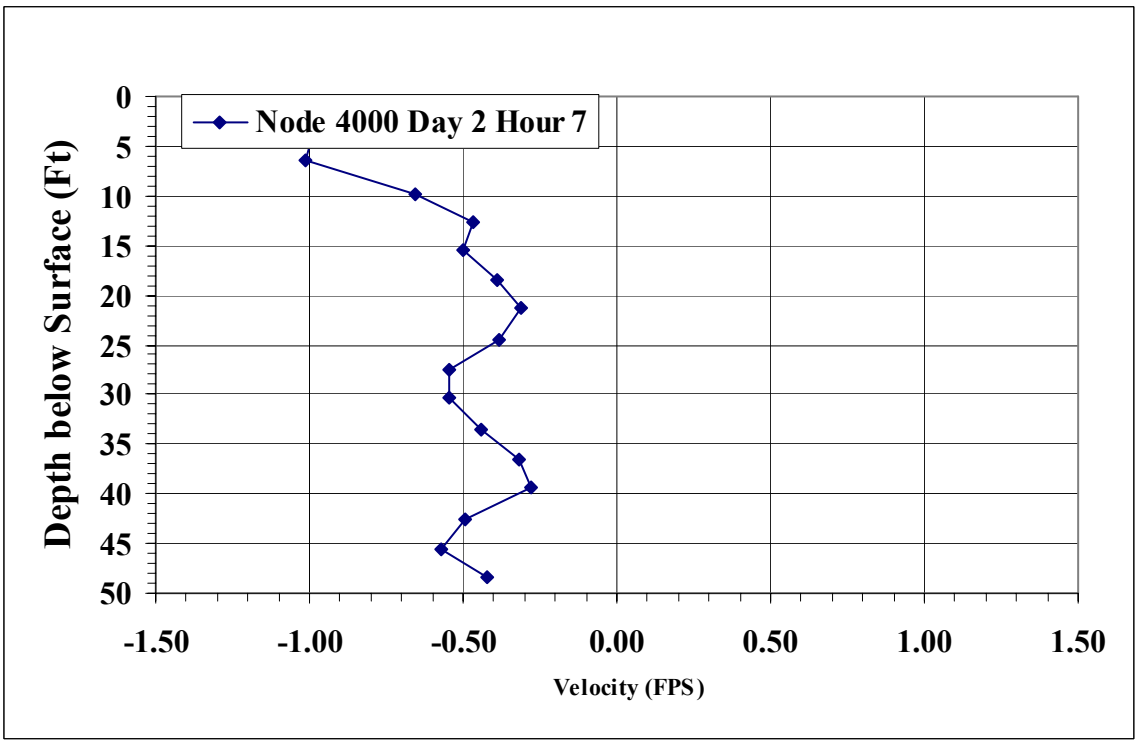
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4000 Day 2 Hour 7
Depth below Surface (Ft)
0
5
10
15
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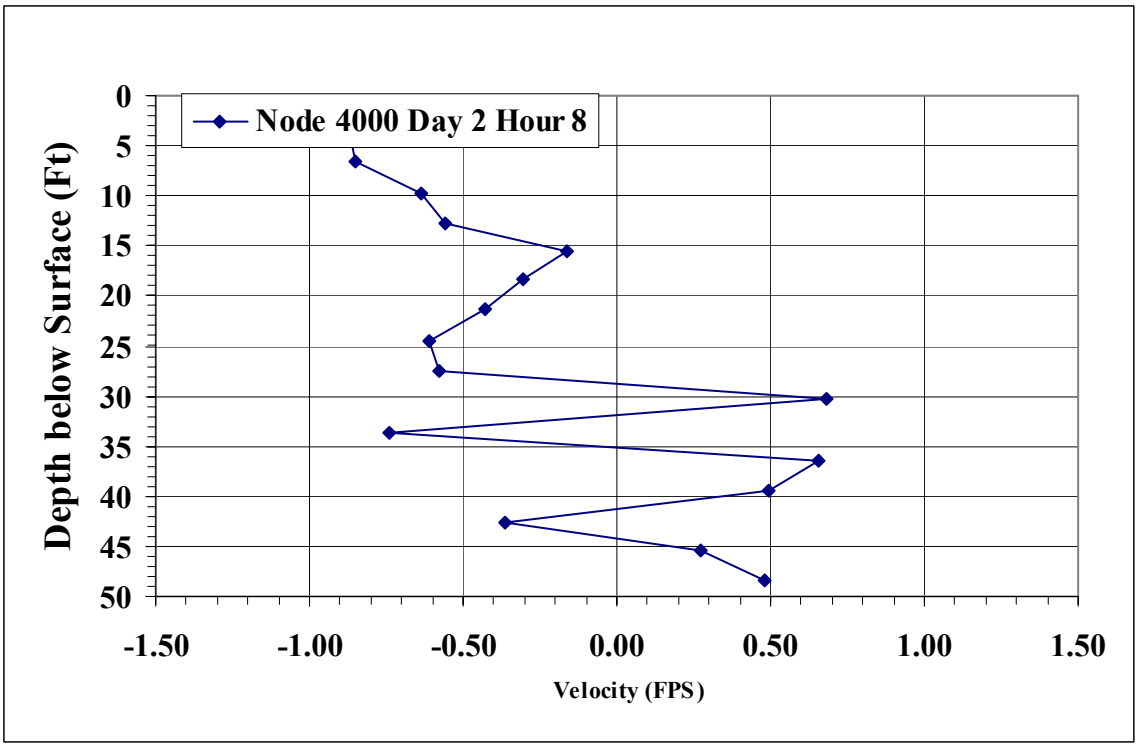
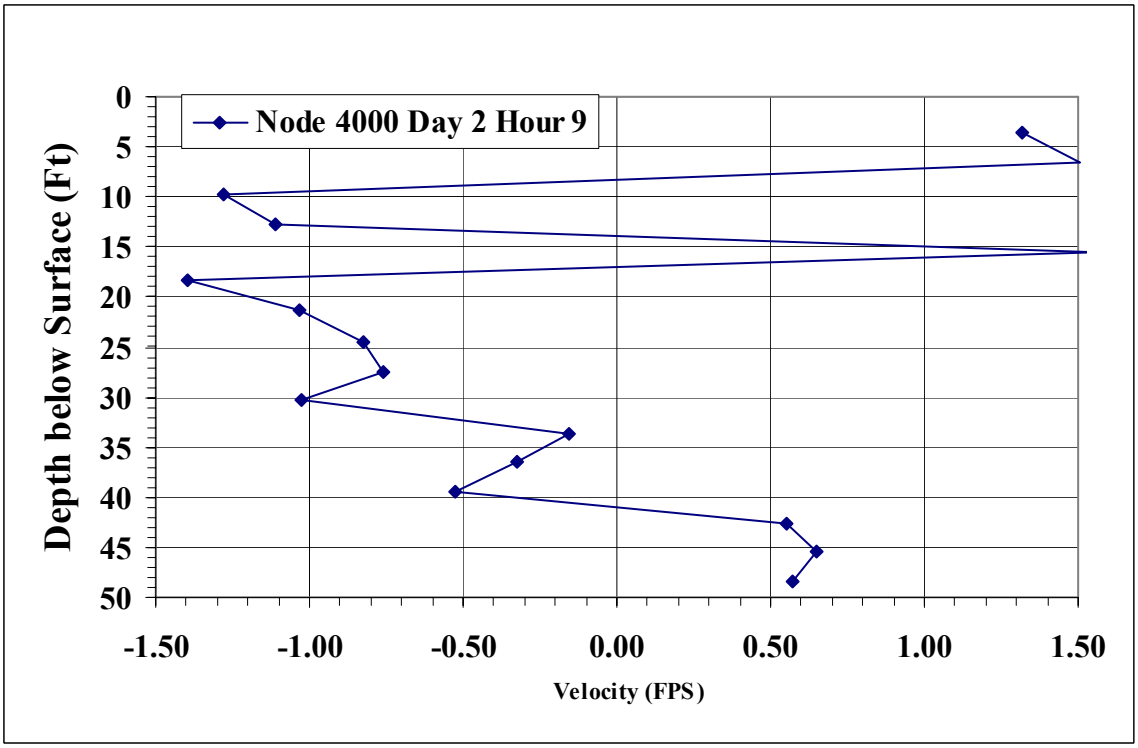
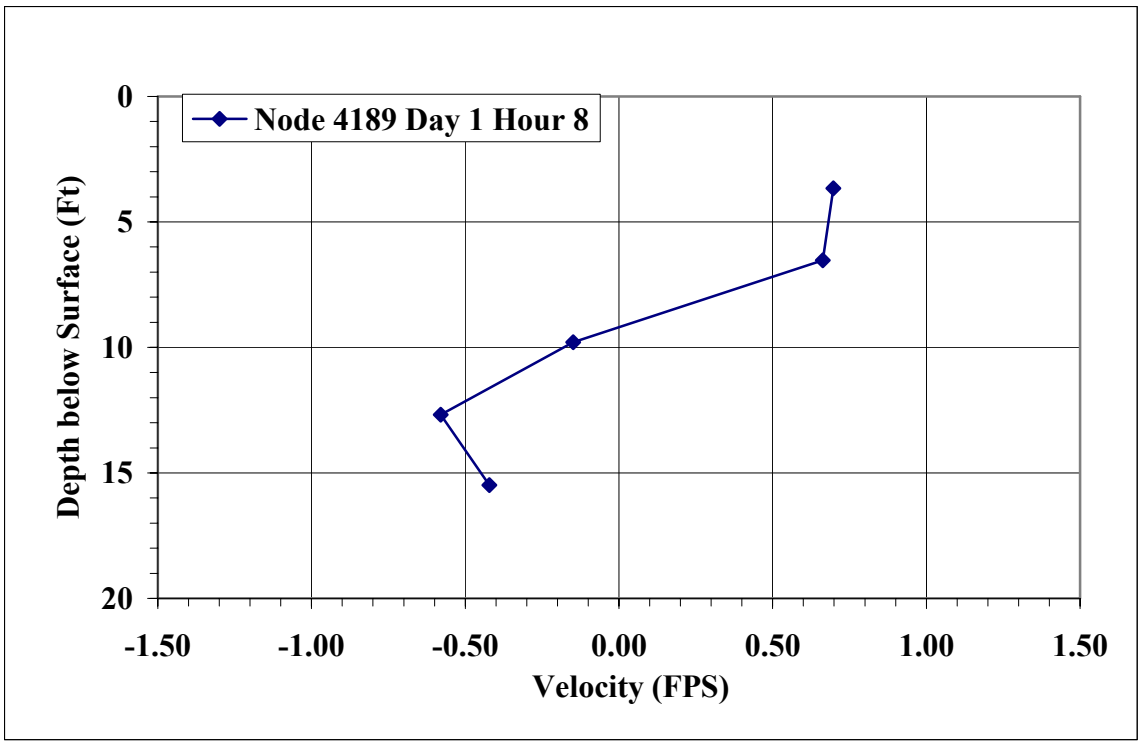
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

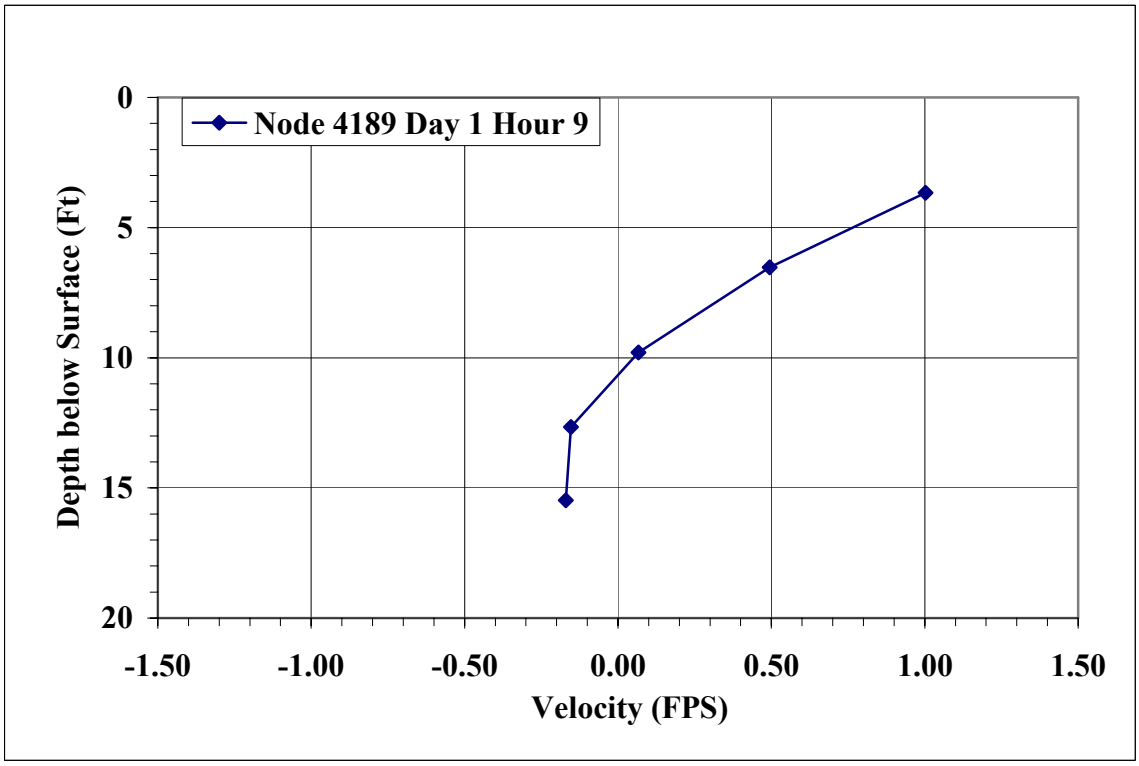

Node 4000 Day 2 Hour 8
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

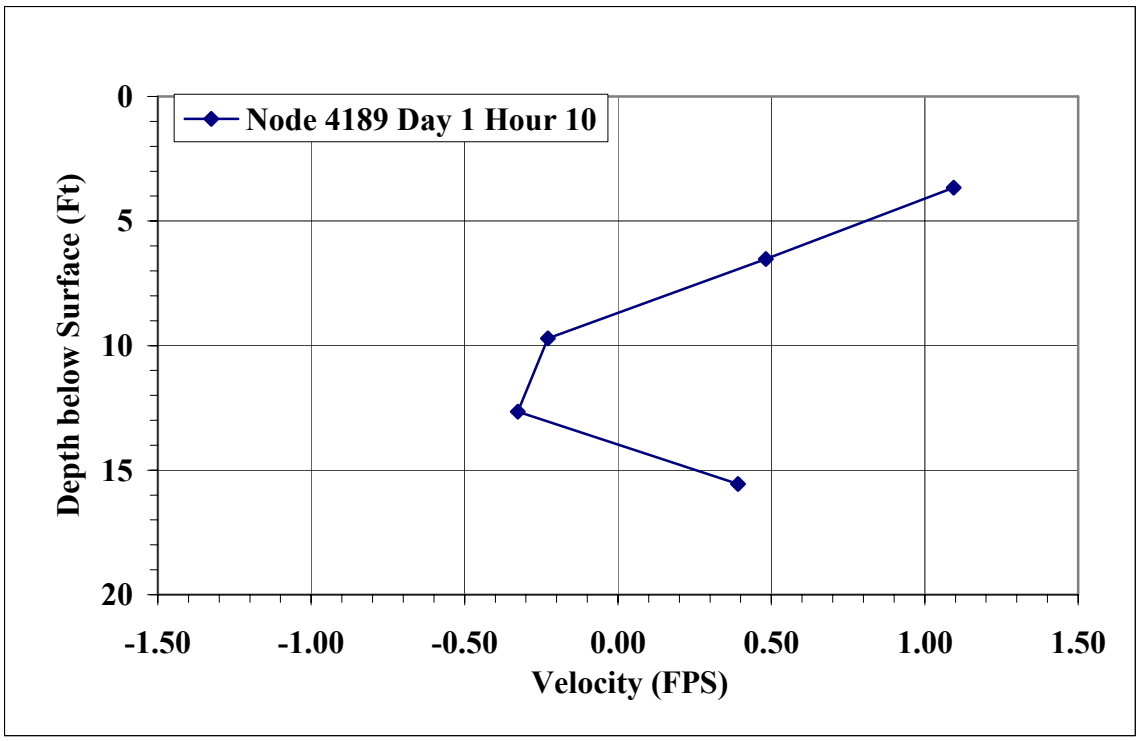

Node 4000 Day 2 Hour 9
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

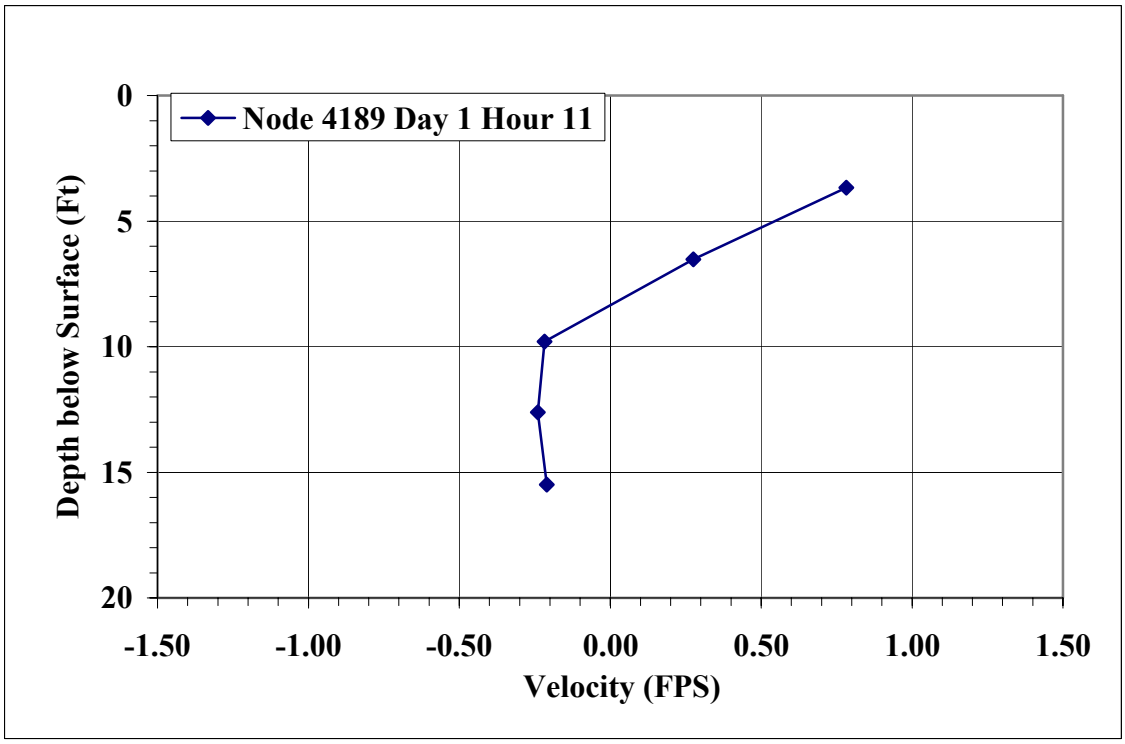
Depth-Variation of Currents Observed at Freeport Harbor Node 4189 Transect 3

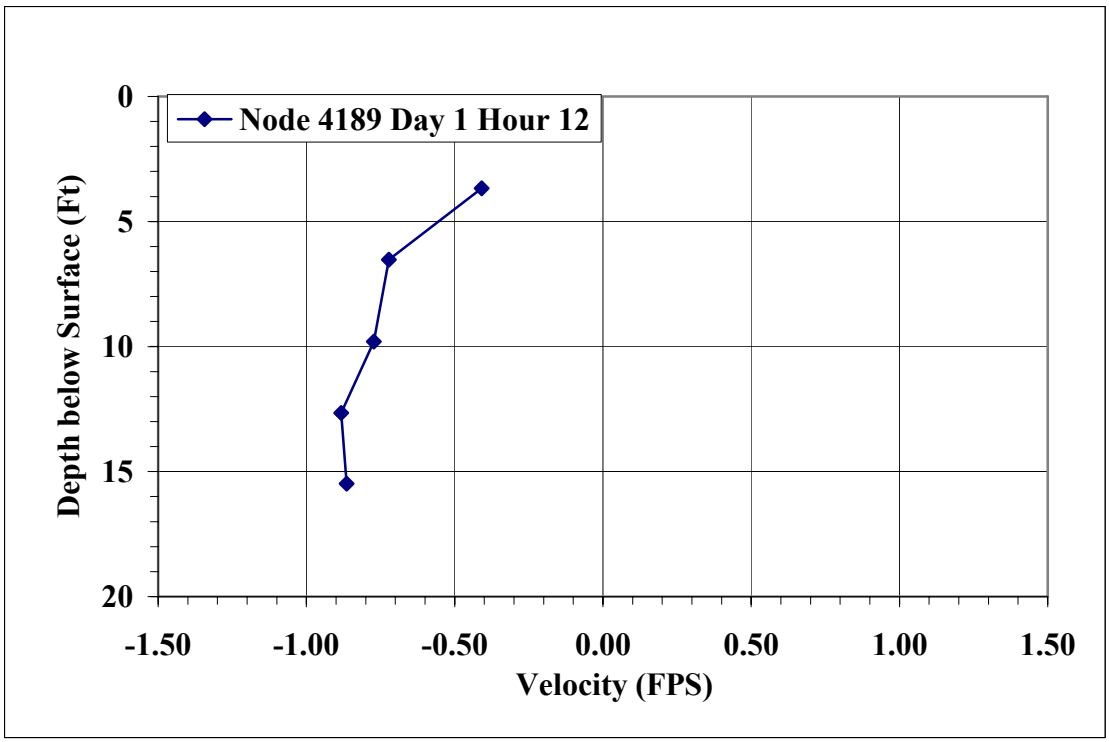
Flood: Positive, Ebb: Negative

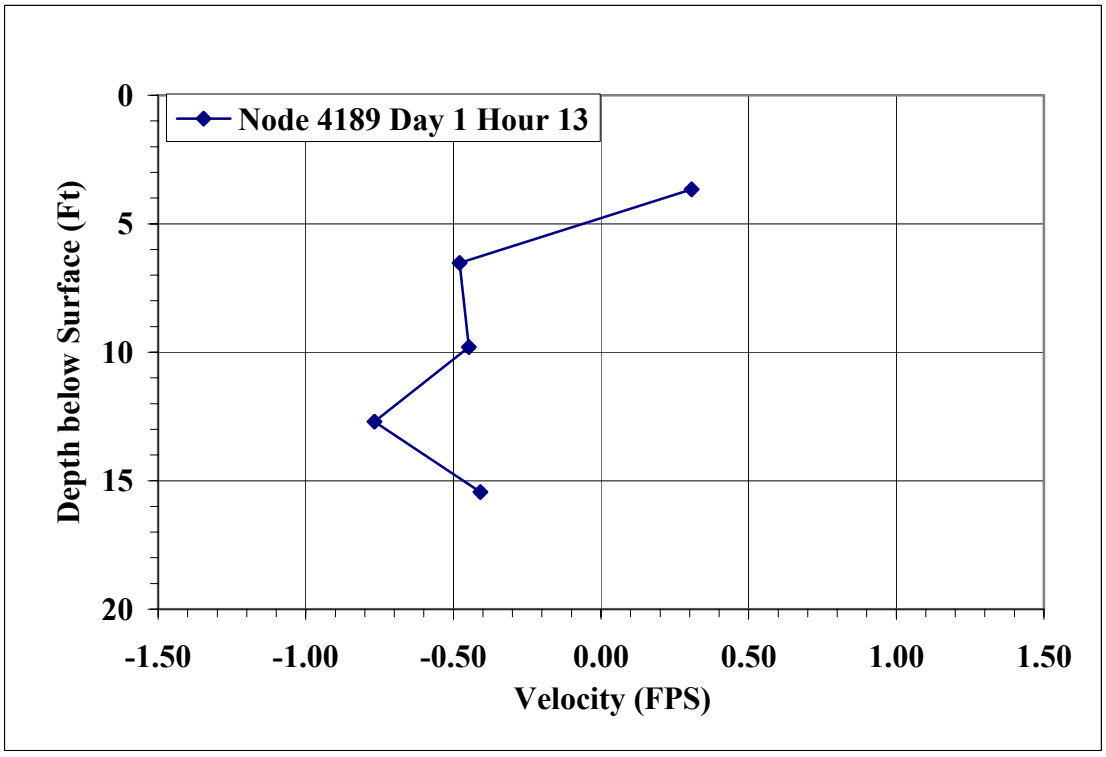

Node 4189 Day 1 Hour 8
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

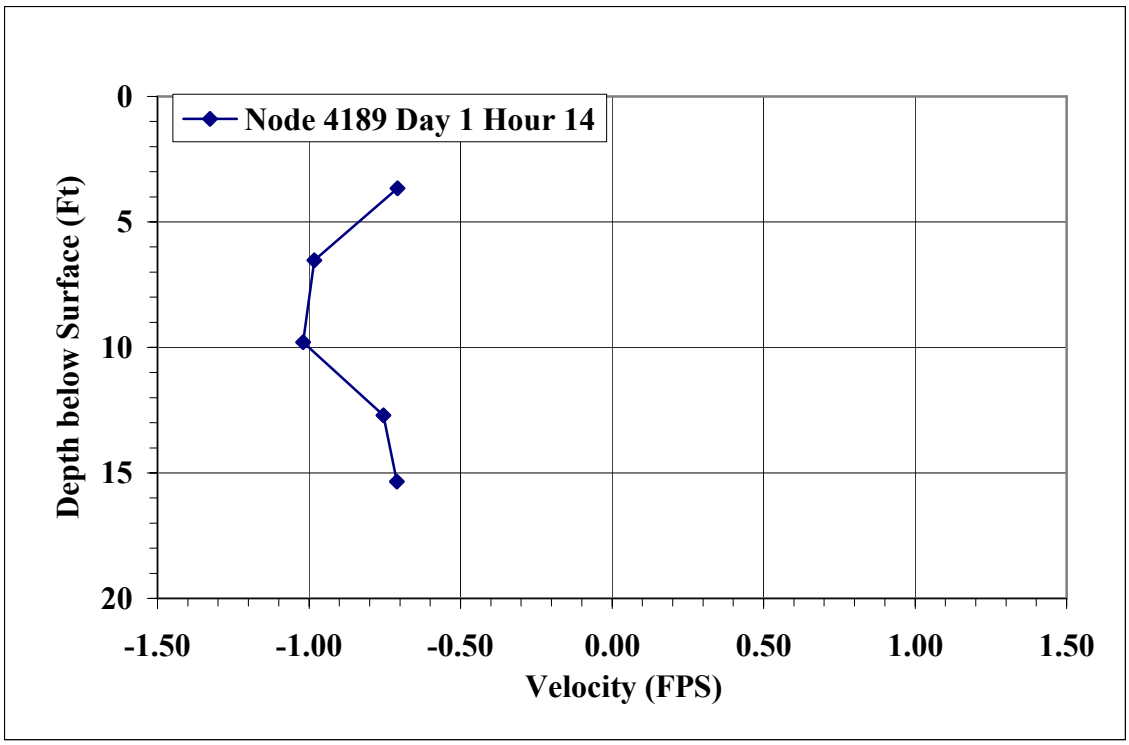

Node 4189 Day 1 Hour 9
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

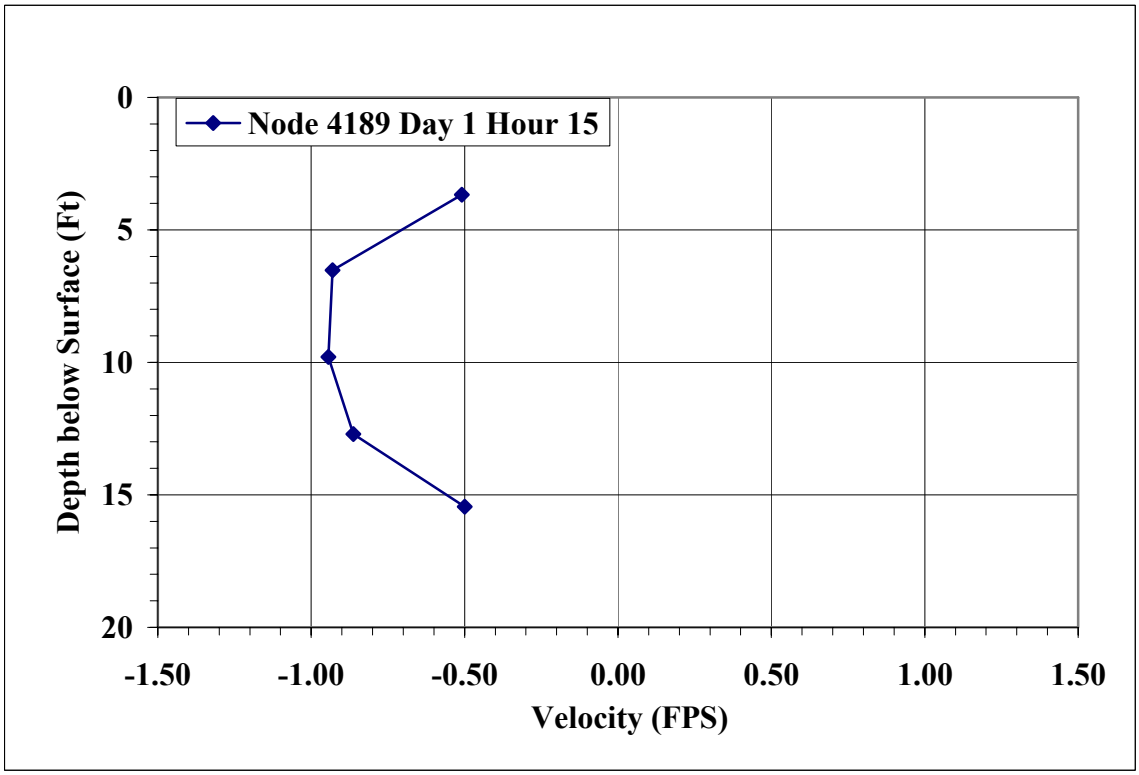

Node 4189 Day 1 Hour 10
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

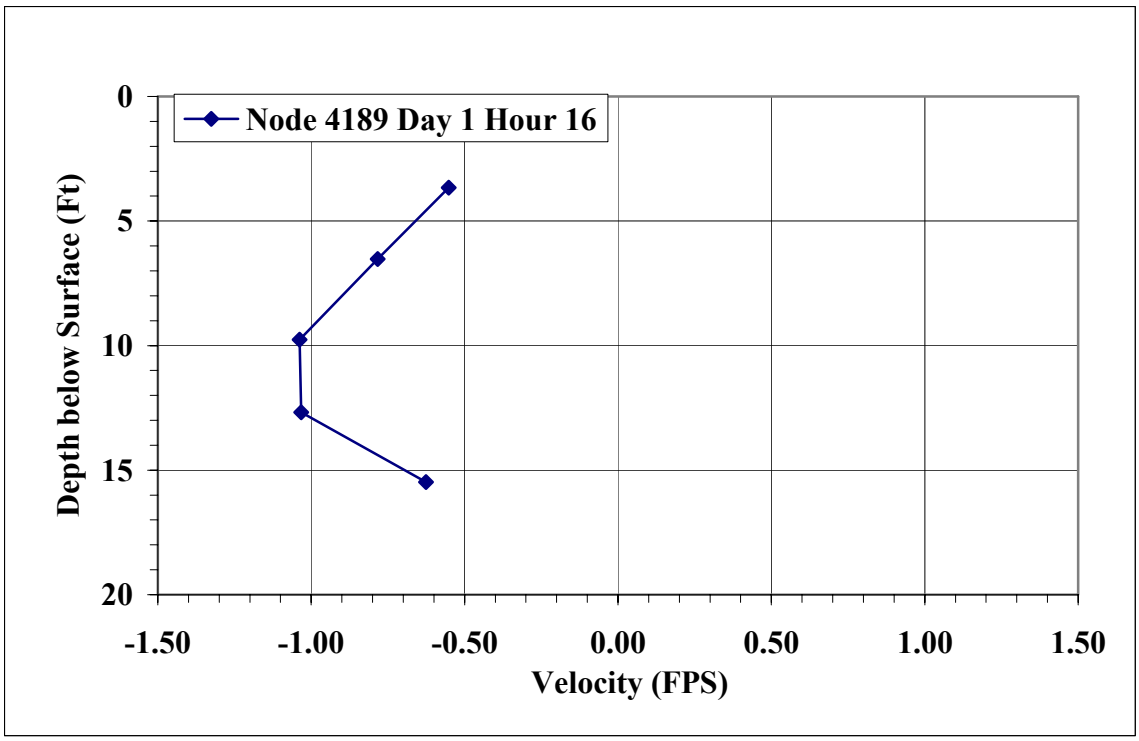

Node 4189 Day 1 Hour 11
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

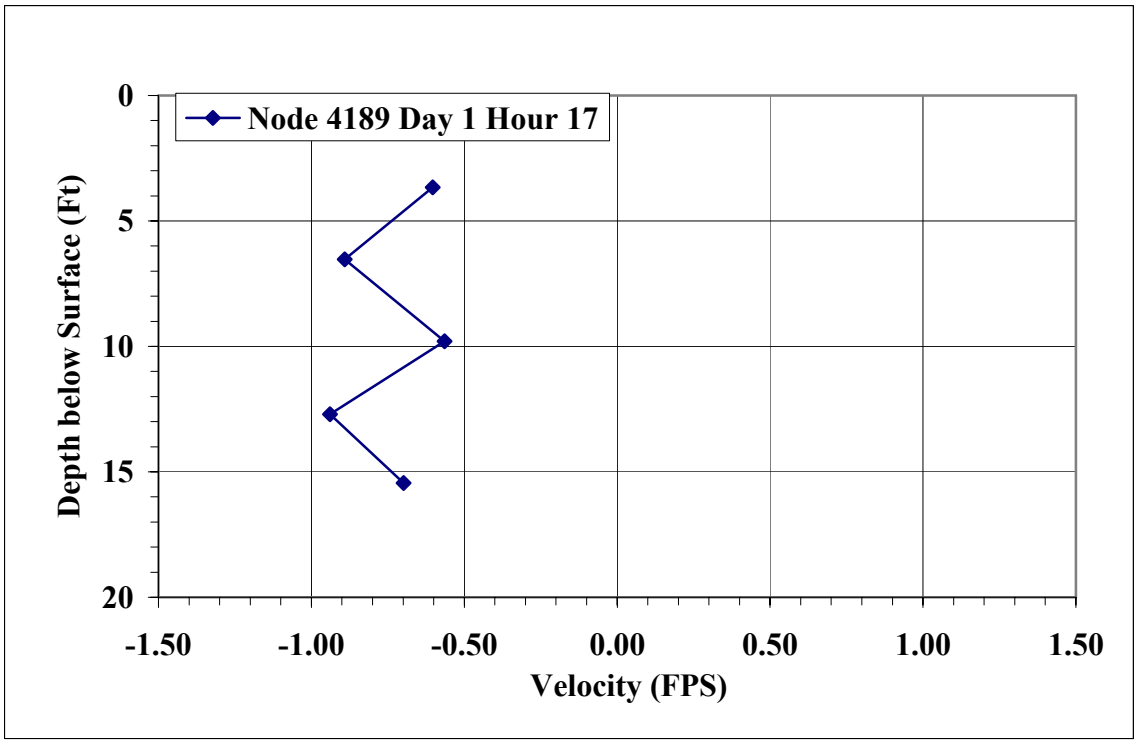

Node 4189 Day 1 Hour 12
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

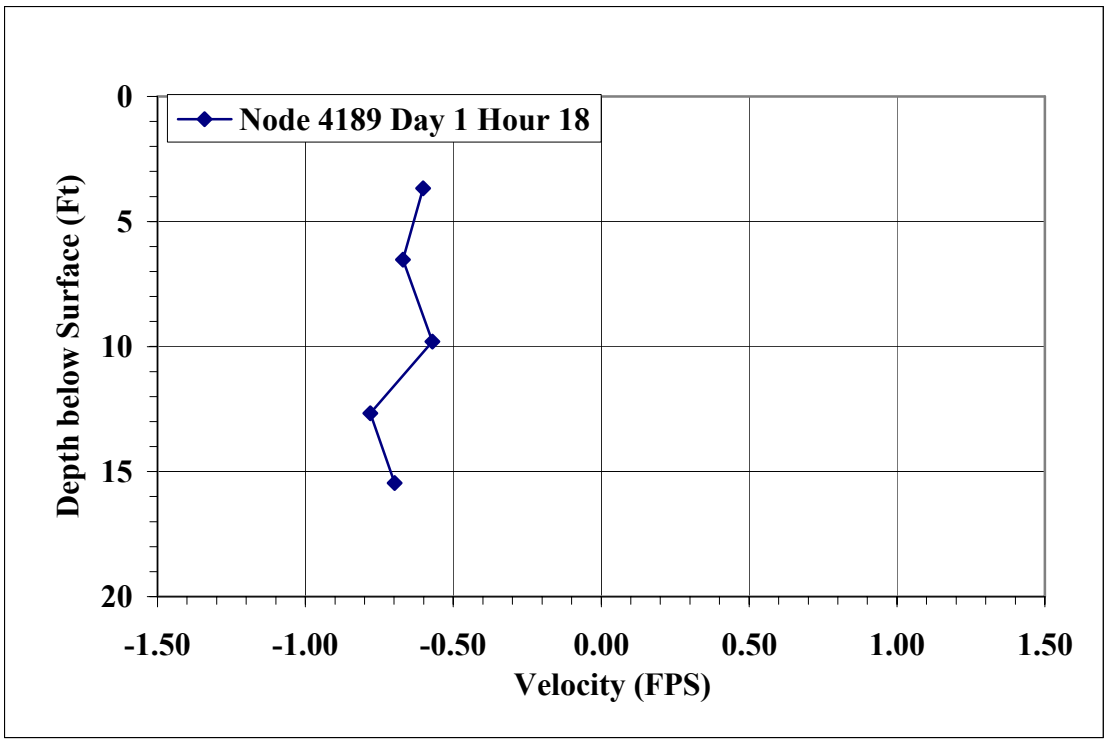

Node 4189 Day 1 Hour 13
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

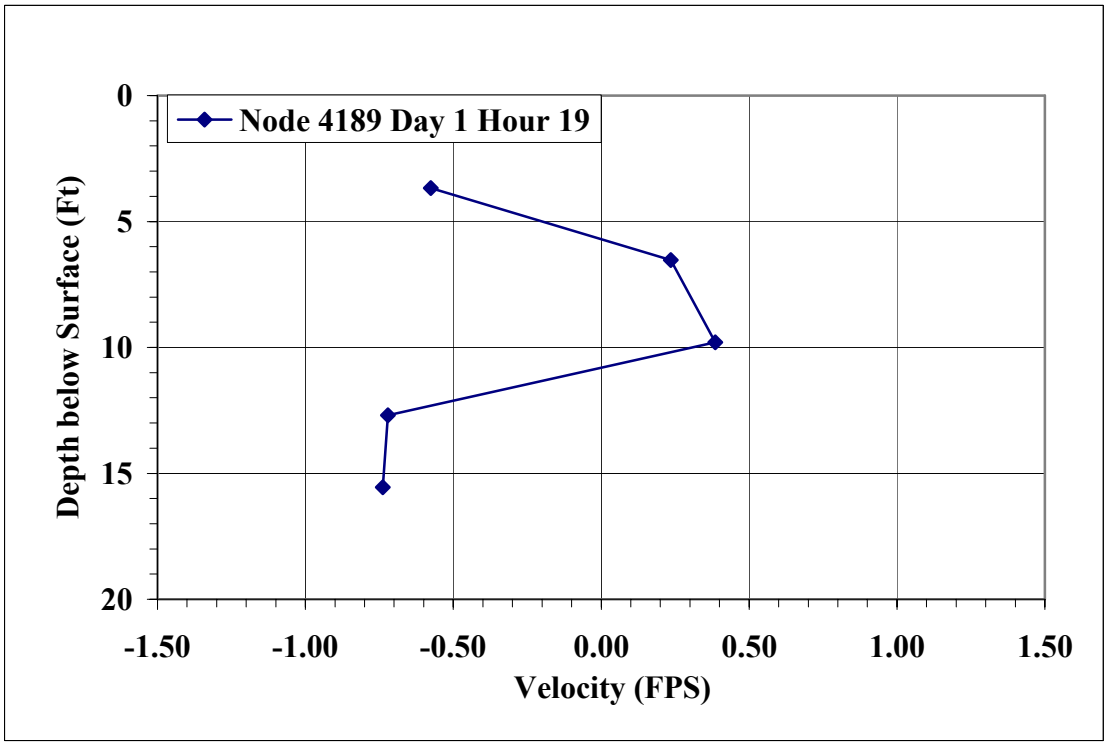

Node 4189 Day 1 Hour 14
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

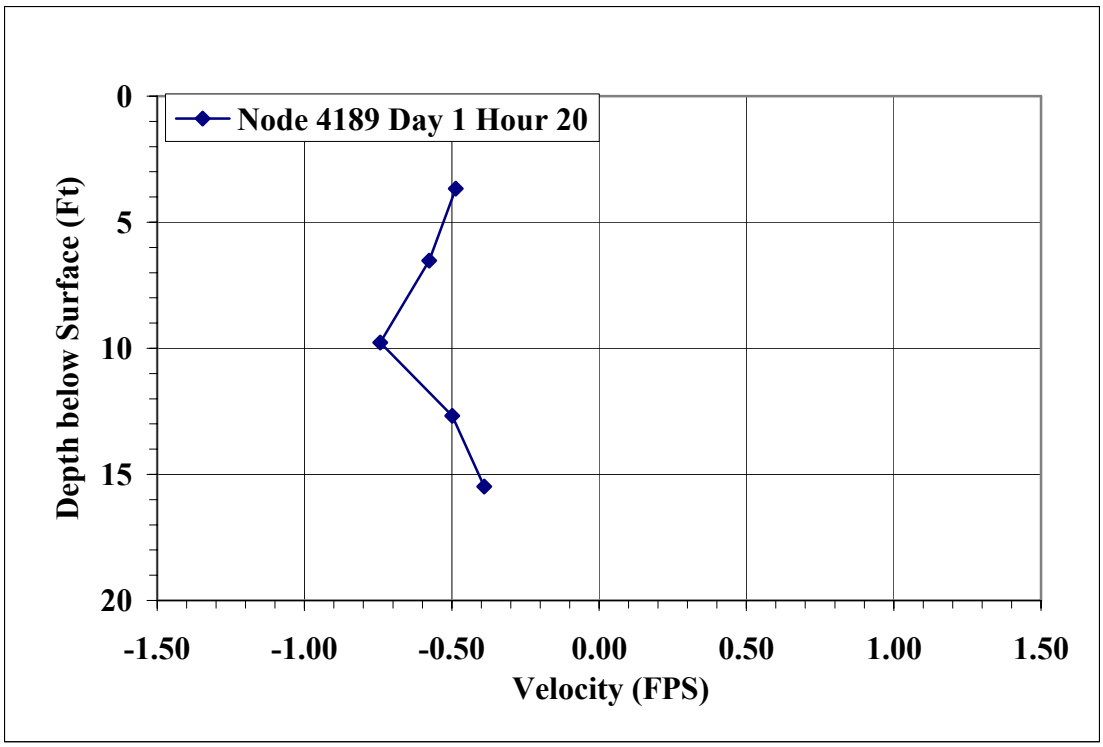

Node 4189 Day 1 Hour 15
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

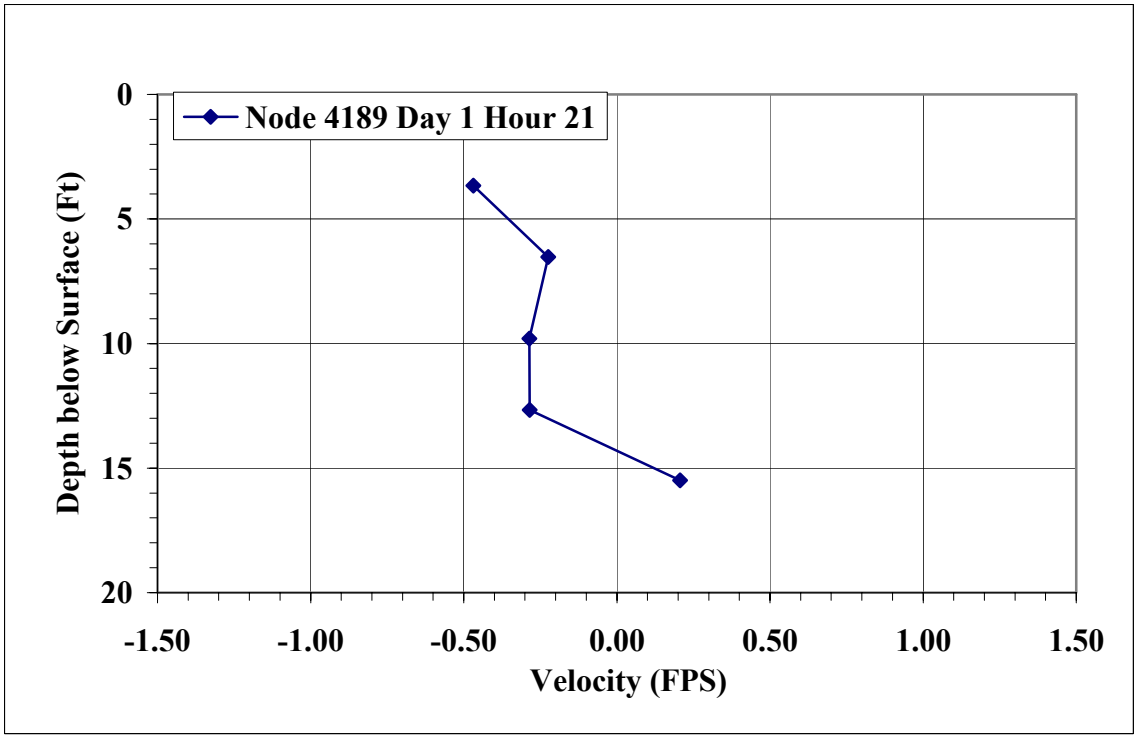

Node 4189 Day 1 Hour 16
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

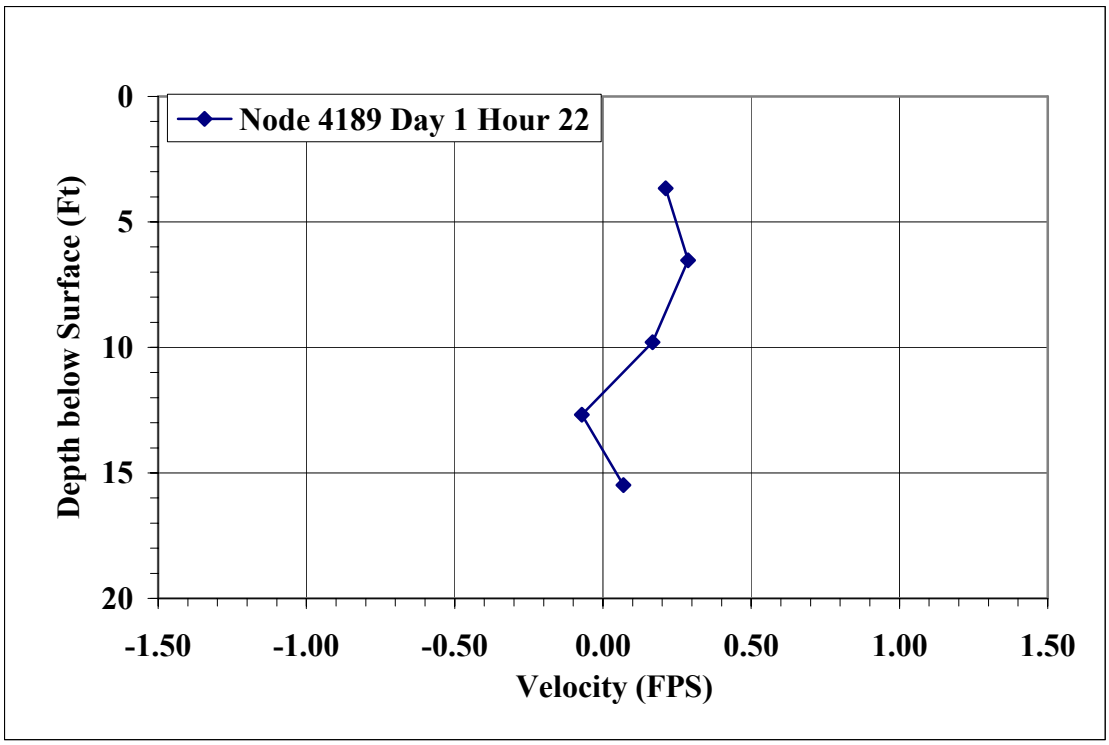

Node 4189 Day 1 Hour 17
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

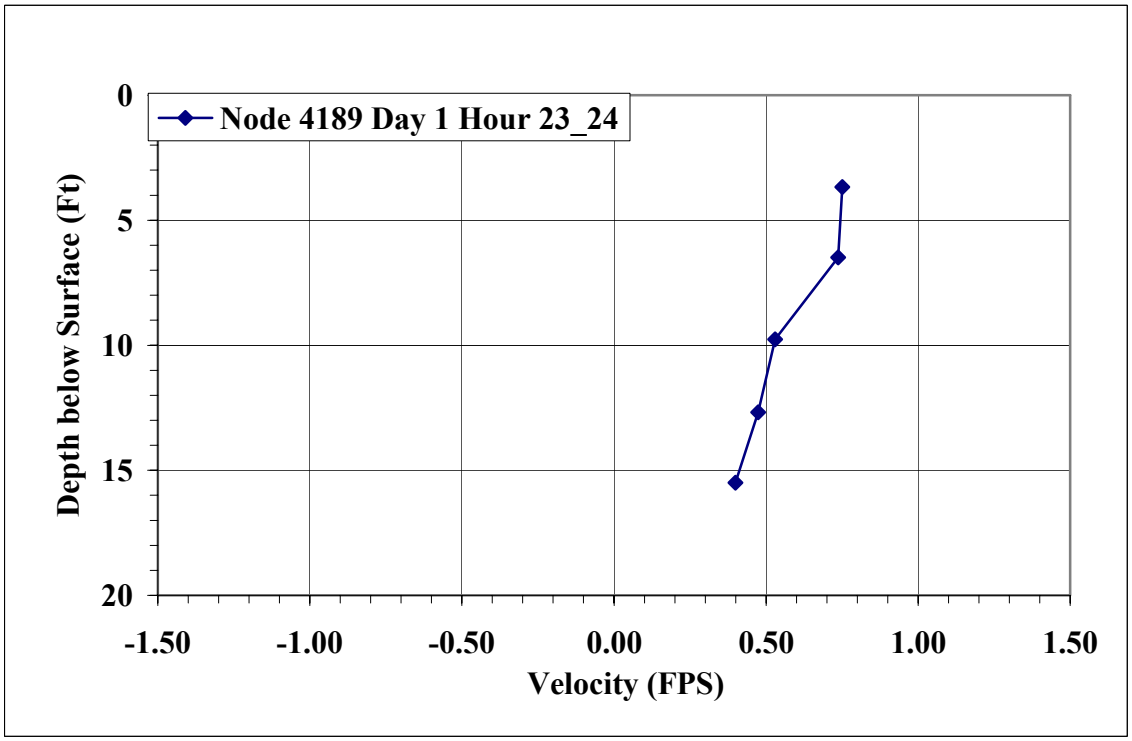

Node 4189 Day 1 Hour 18
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

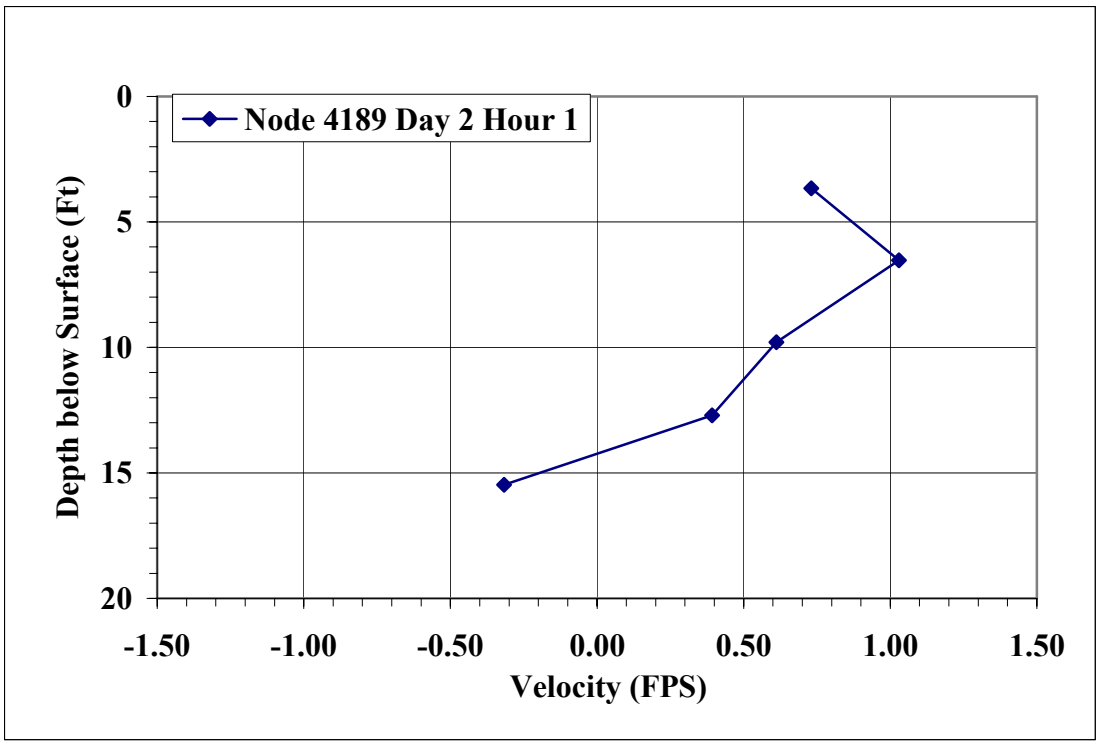

Node 4189 Day 1 Hour 19
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

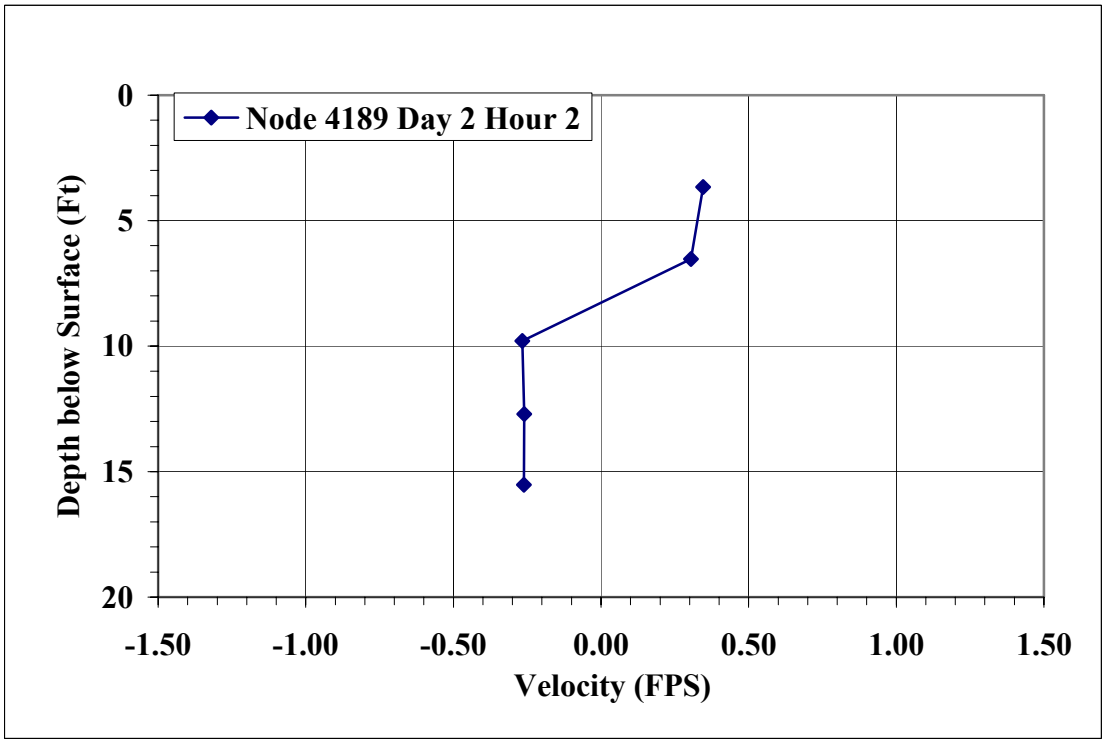

Node 4189 Day 1 Hour 20
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

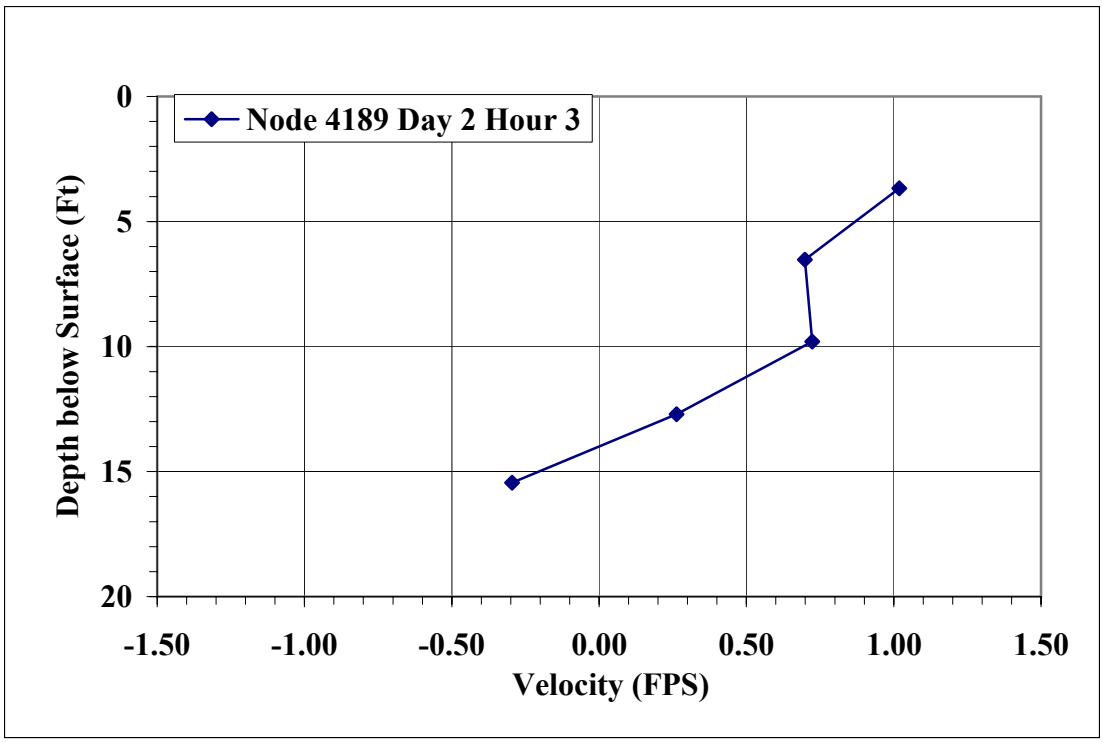

Node 4189 Day 1 Hour 21
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

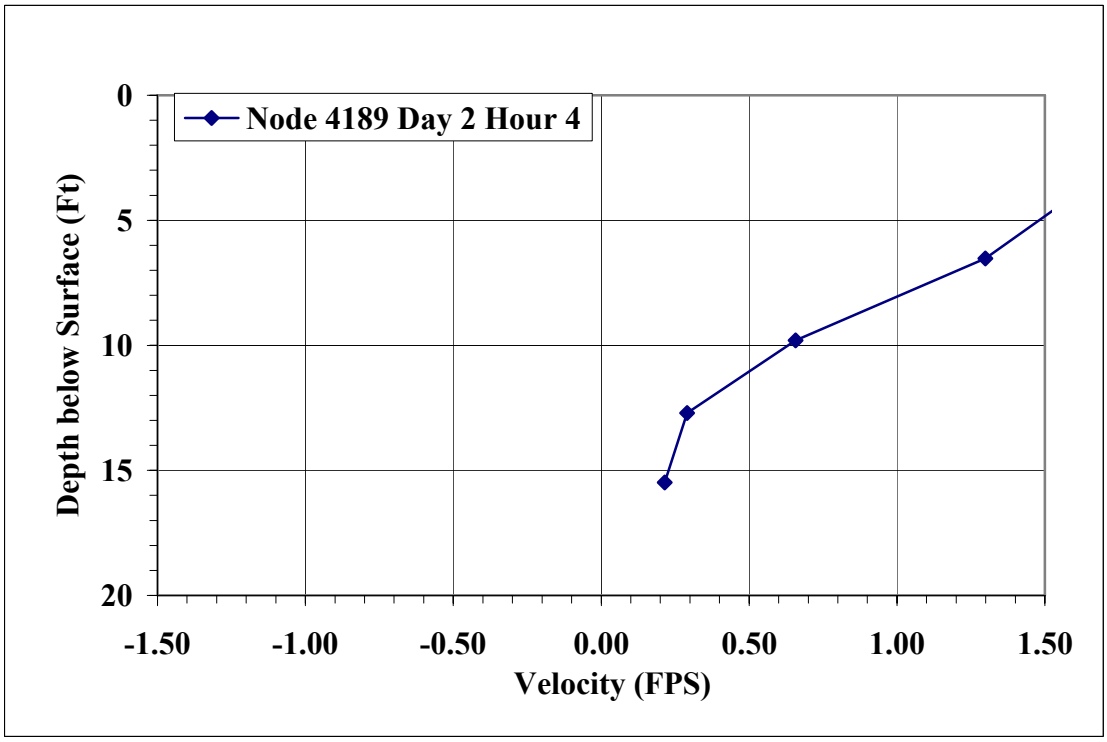

Node 4189 Day 1 Hour 22
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

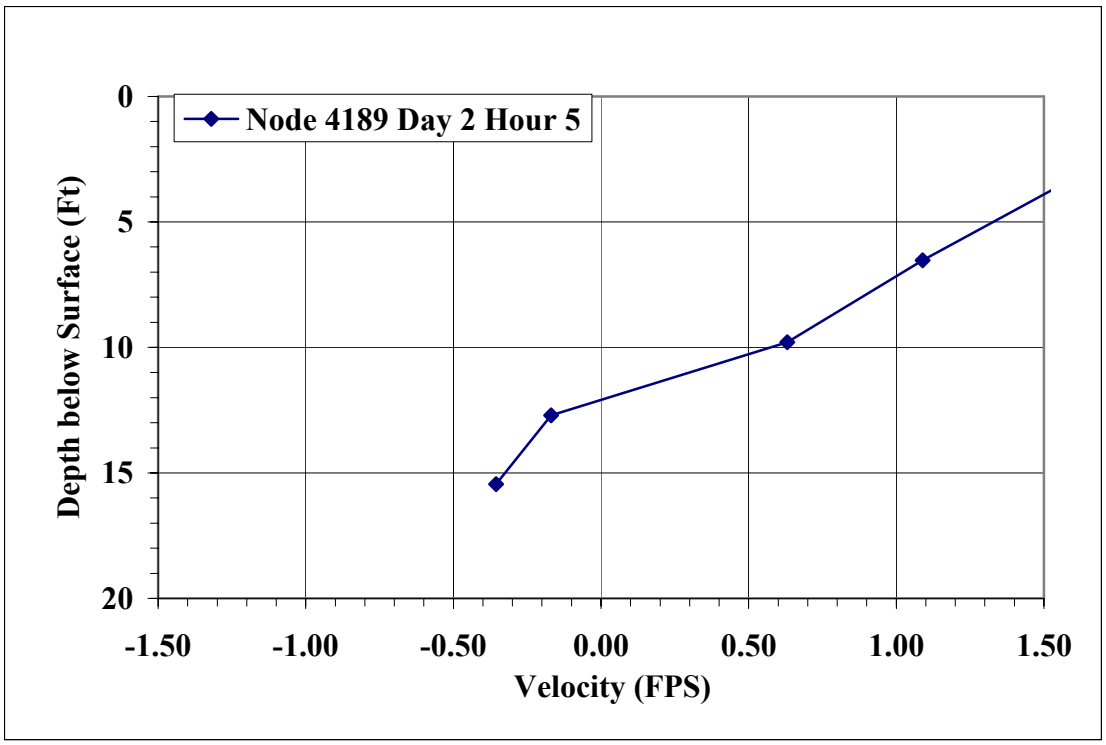

Node 4189 Day 1 Hour 23_24
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

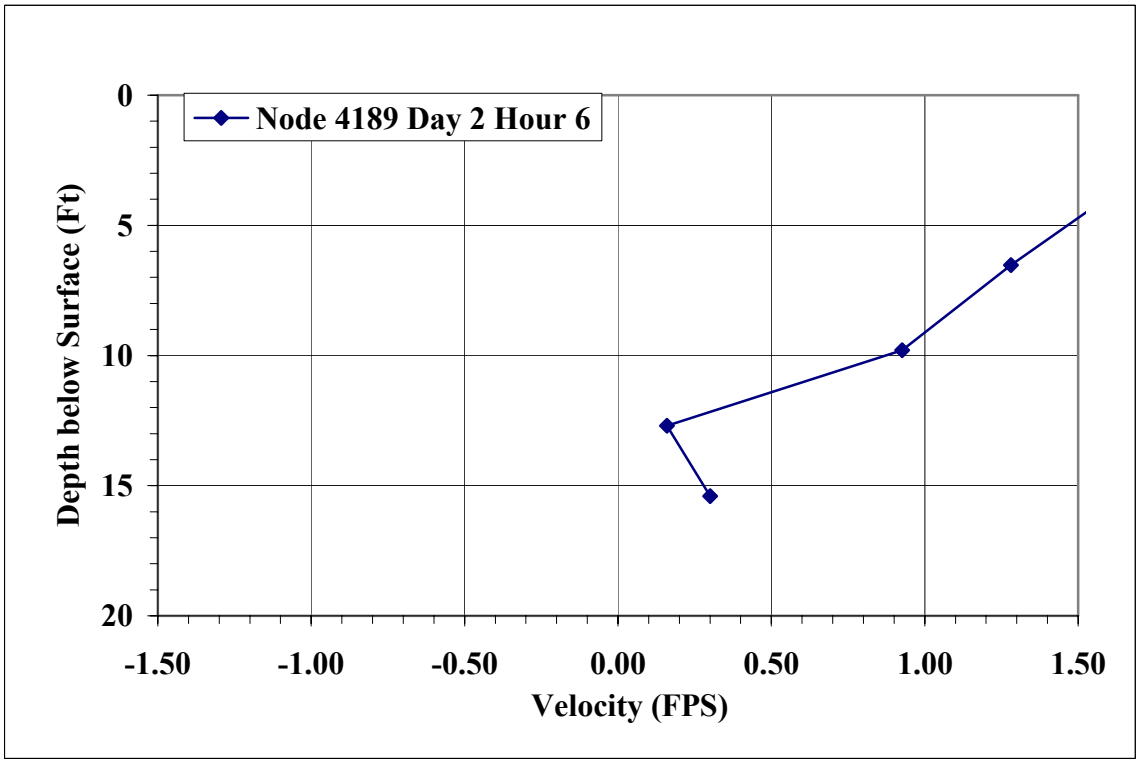

Node 4189 Day 2 Hour 1
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

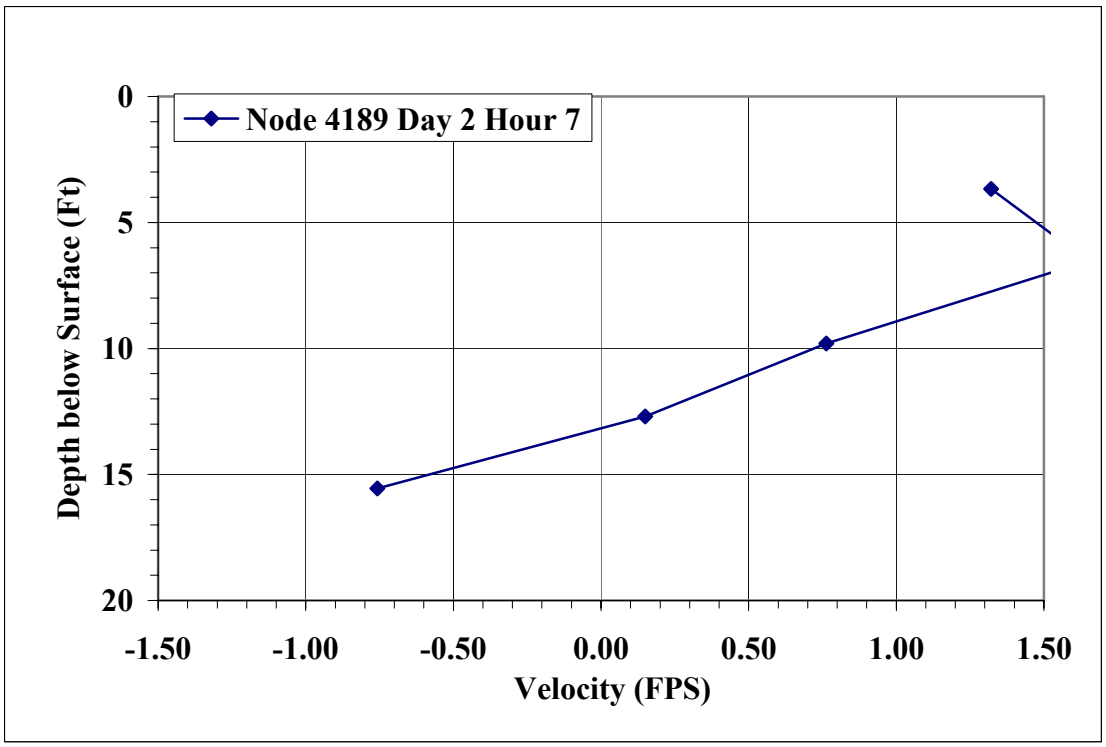

Node 4189 Day 2 Hour 2
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

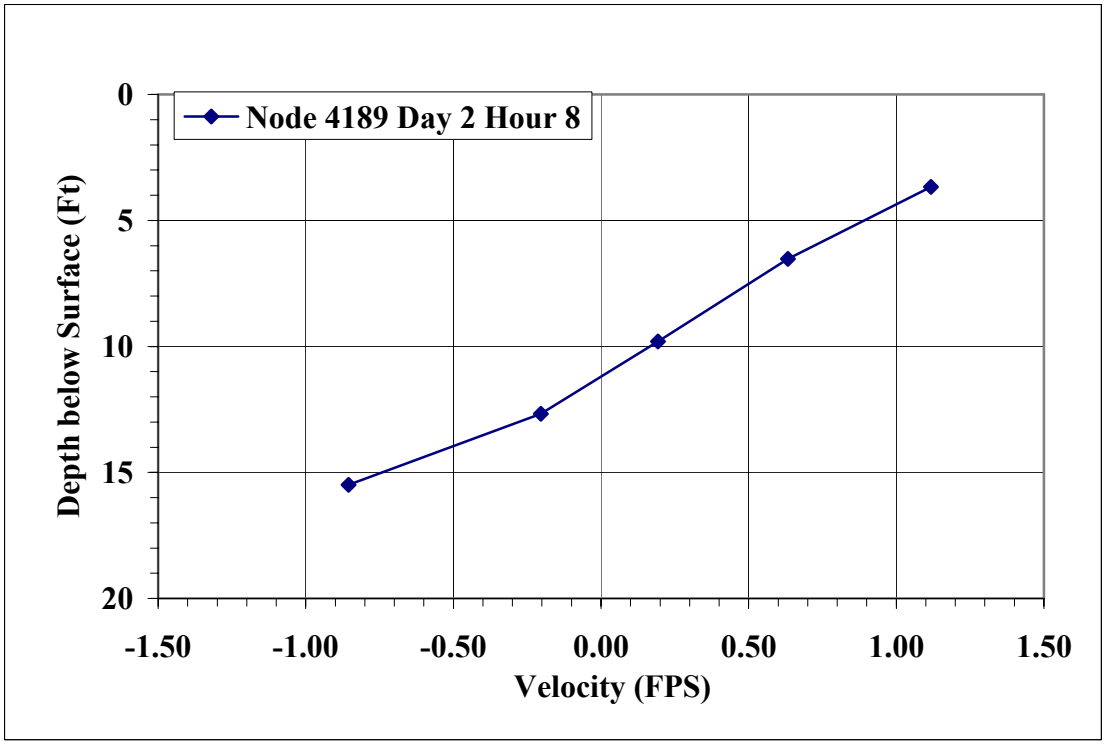

Node 4189 Day 2 Hour 3
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

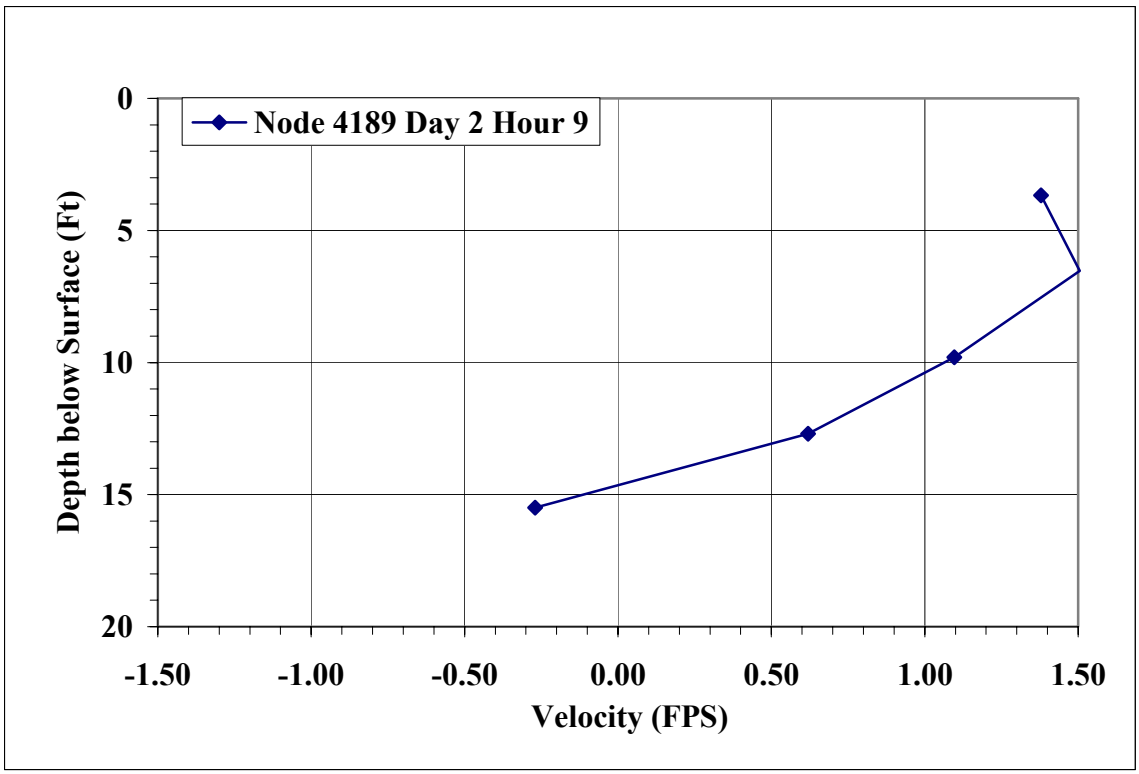

Node 4189 Day 2 Hour 4
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4189 Day 2 Hour 5
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 4189 Day 2 Hour 6
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

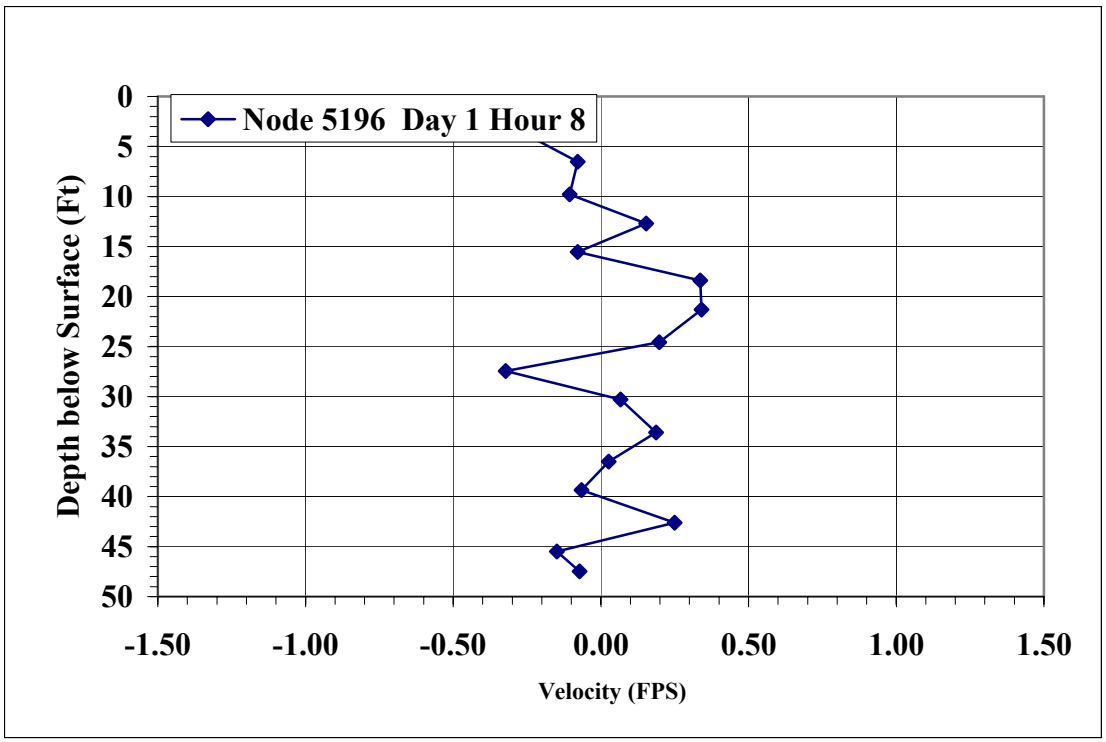

Node 4189 Day 2 Hour 7
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

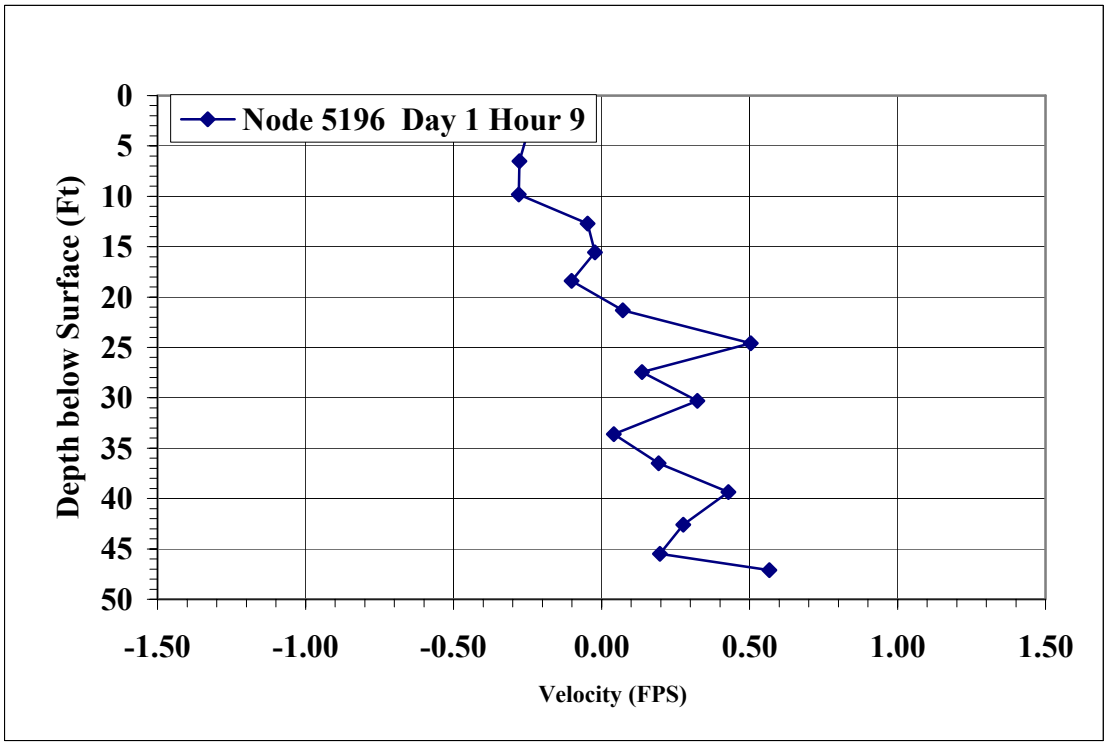

Node 4189 Day 2 Hour 8
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

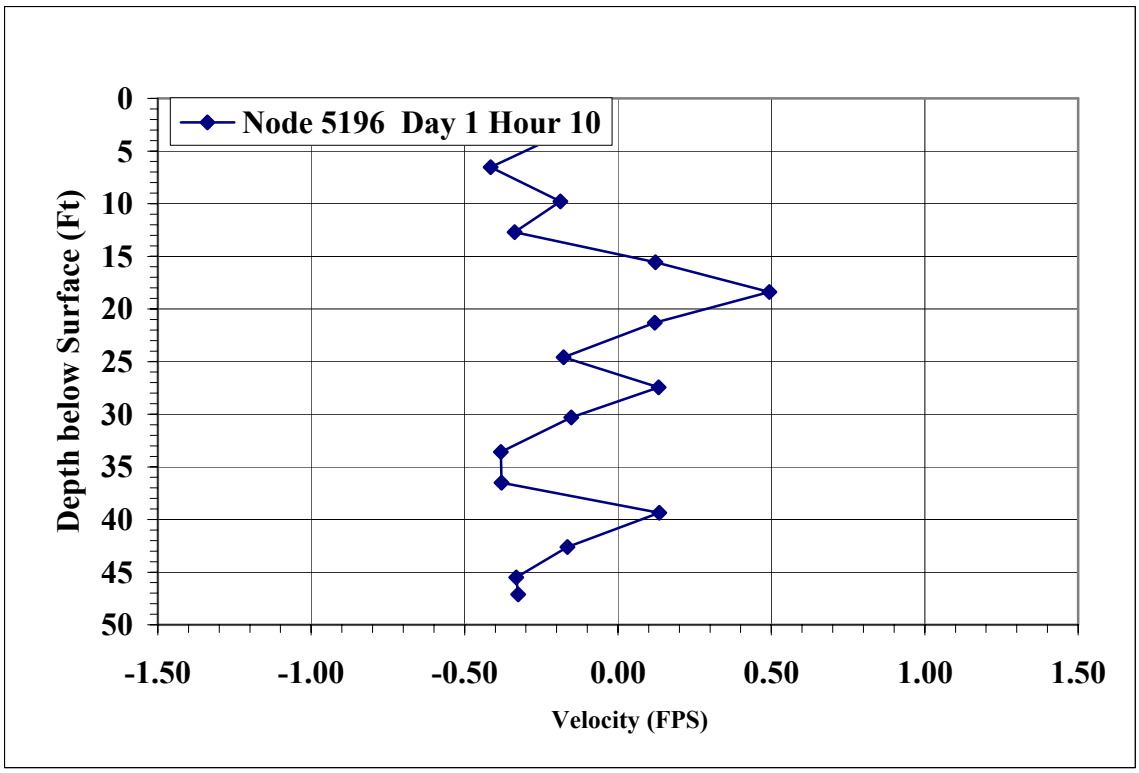

Node 4189 Day 2 Hour 9
Depth below Surface (Ft)
0
5
10
15
20
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

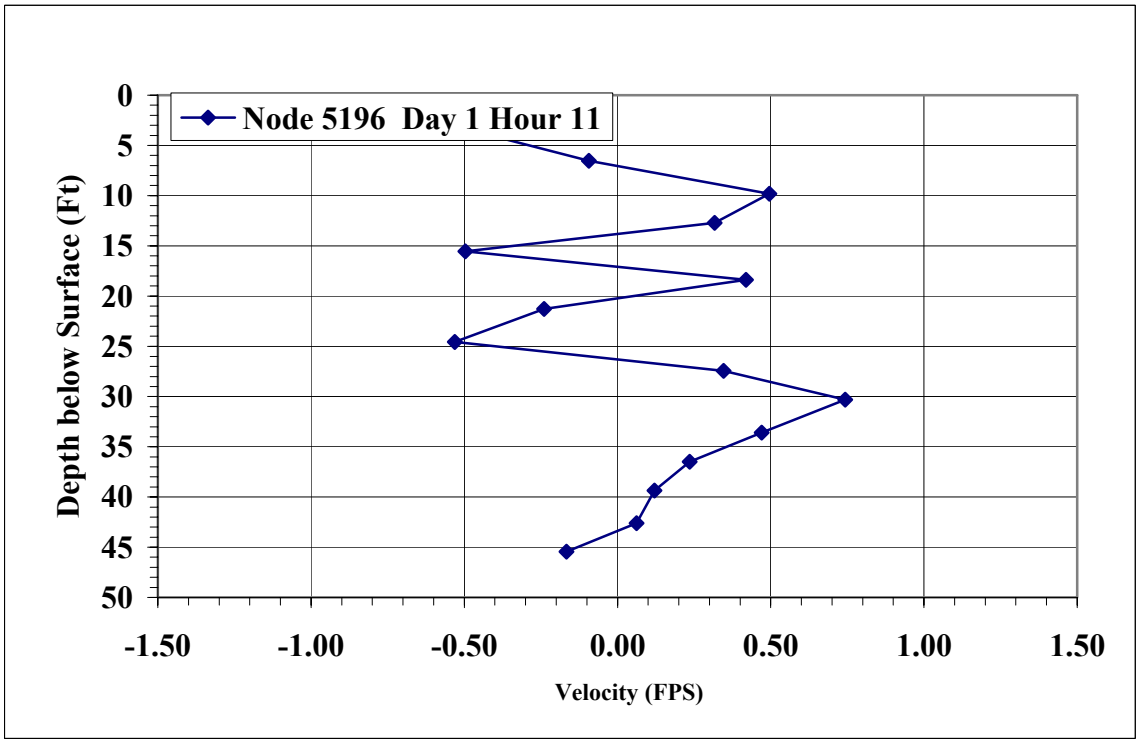
Depth-Variation of Currents Observed at Freeport Harbor Node 5196 Transect 4

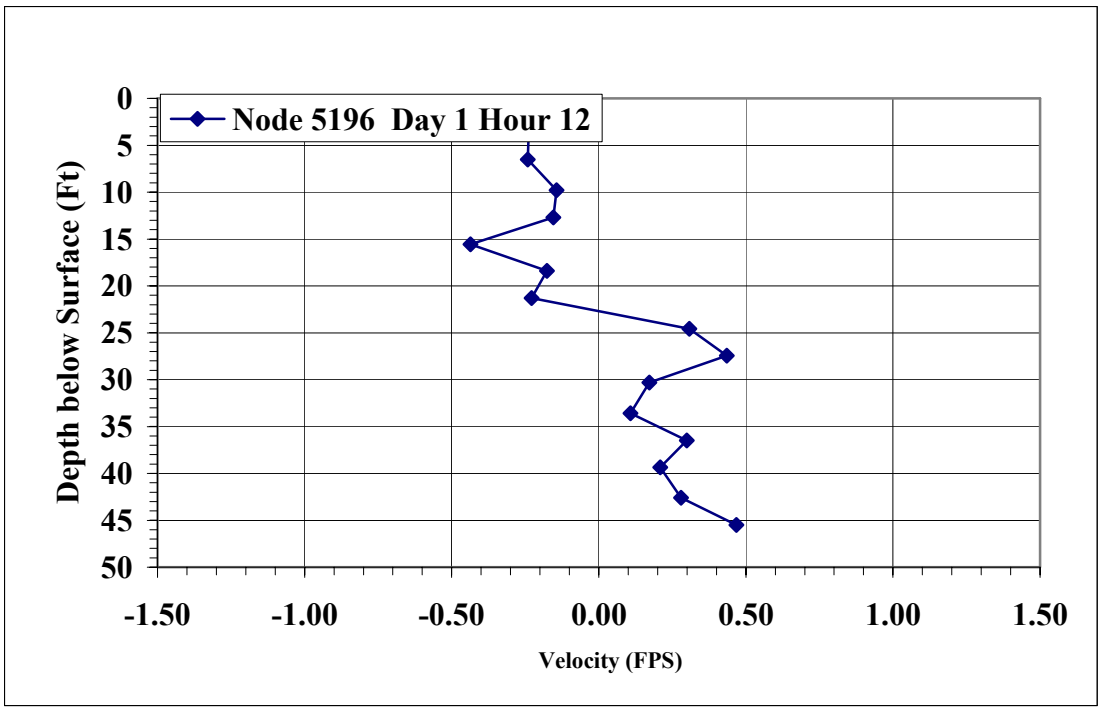
Flood: Positive, Ebb: Negative

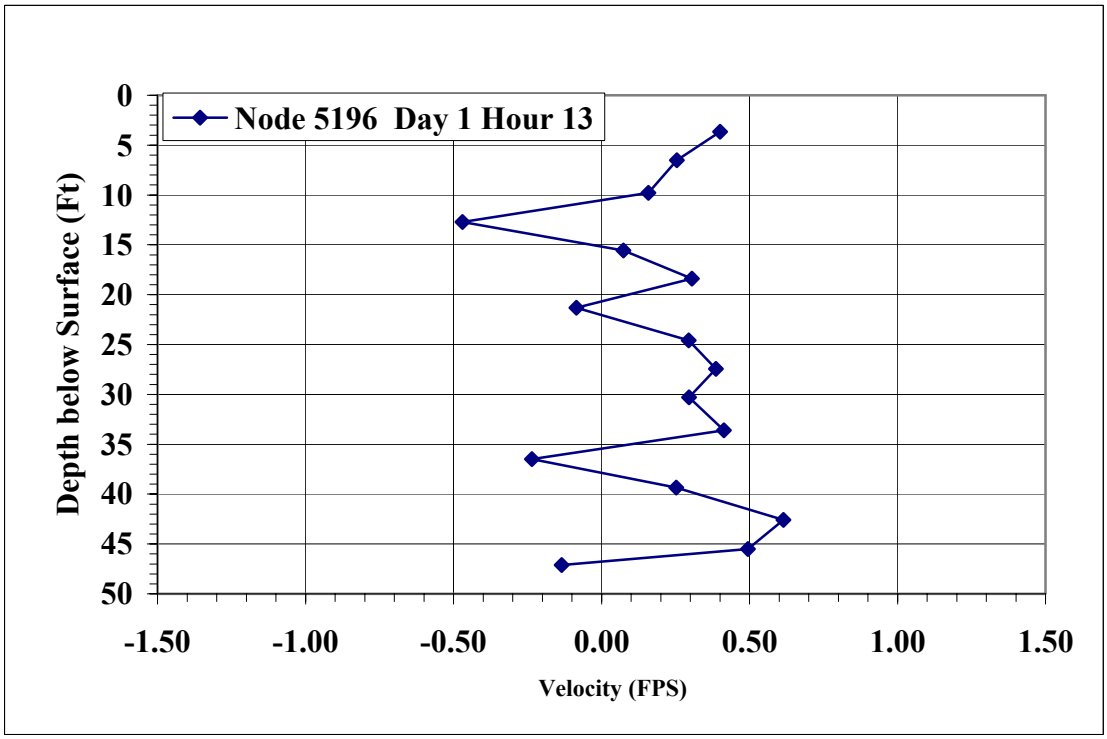

Node 5196 Day 1 Hour 8
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

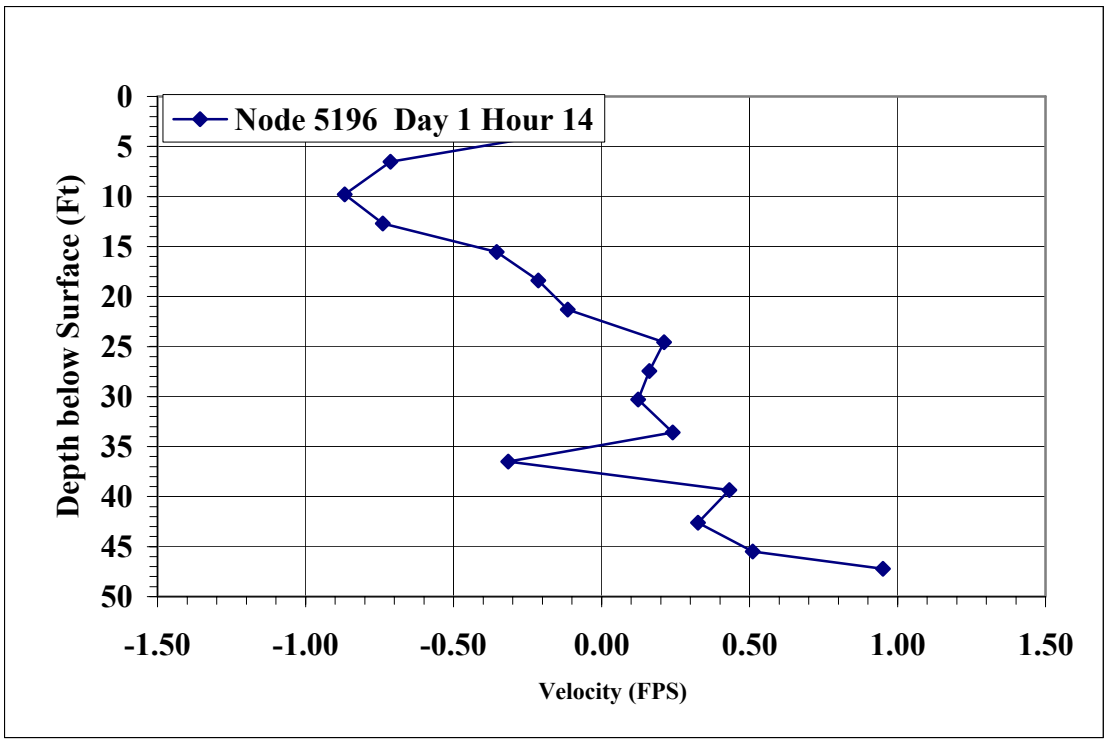

Node 5196 Day 1 Hour 9
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

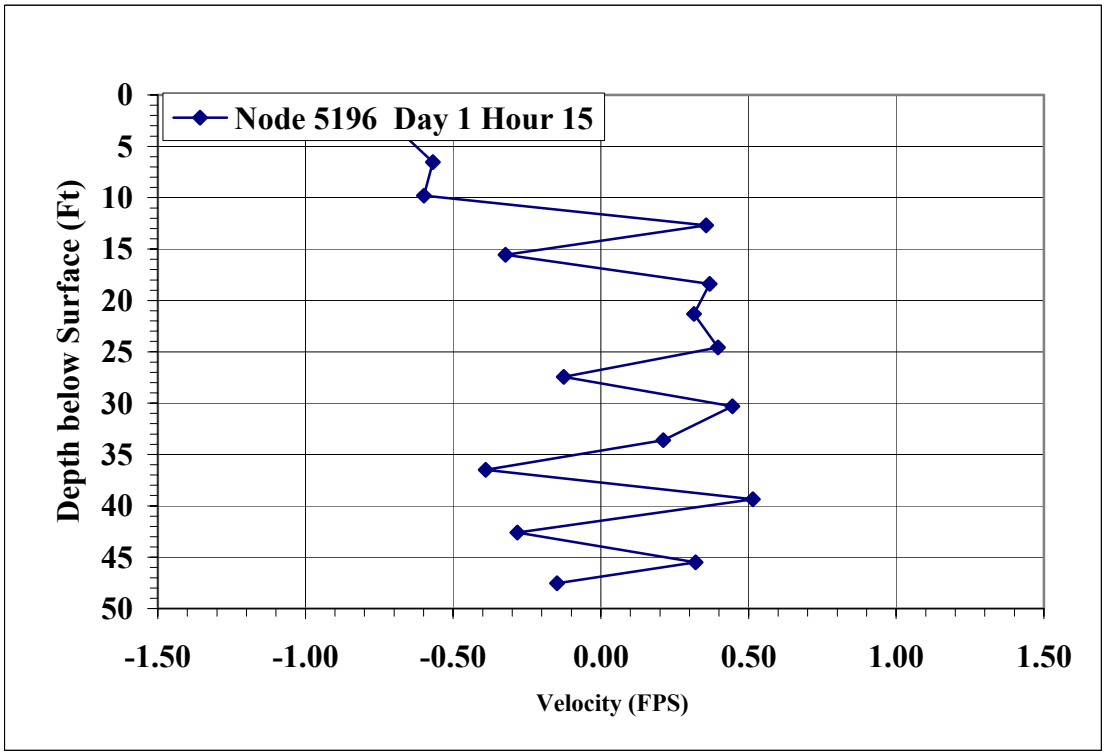

Node 5196 Day 1 Hour 10
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

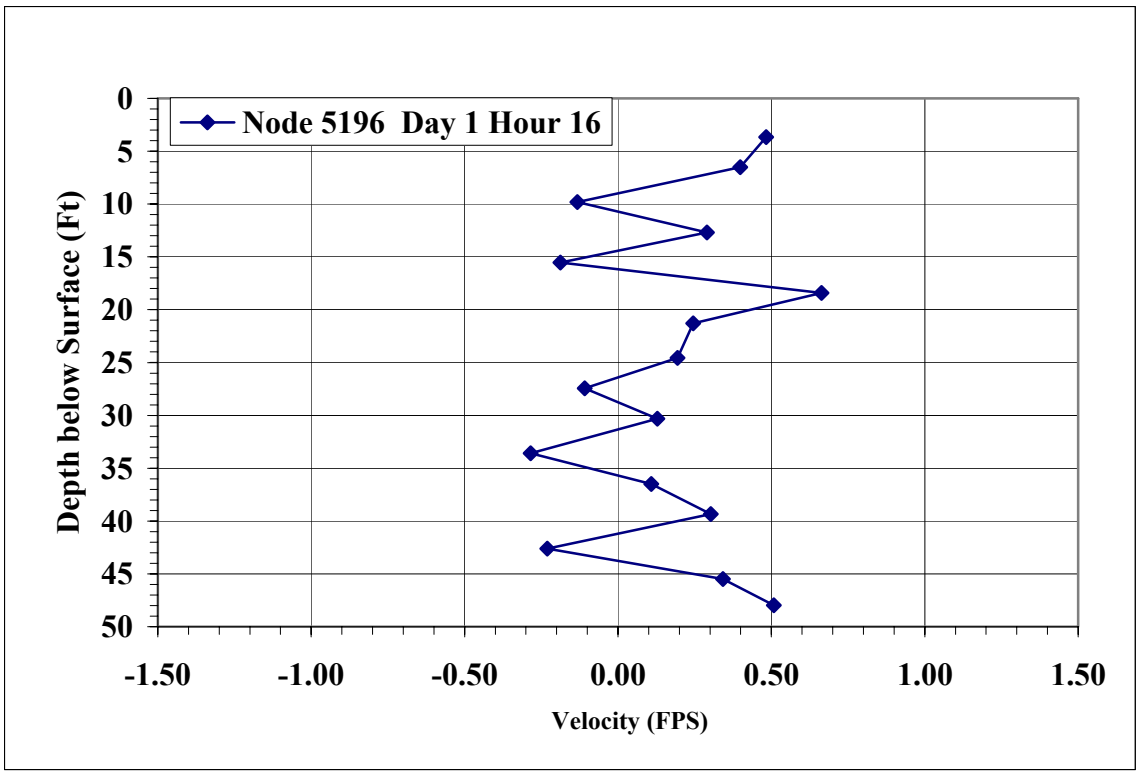

Node 5196 Day 1 Hour 11
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

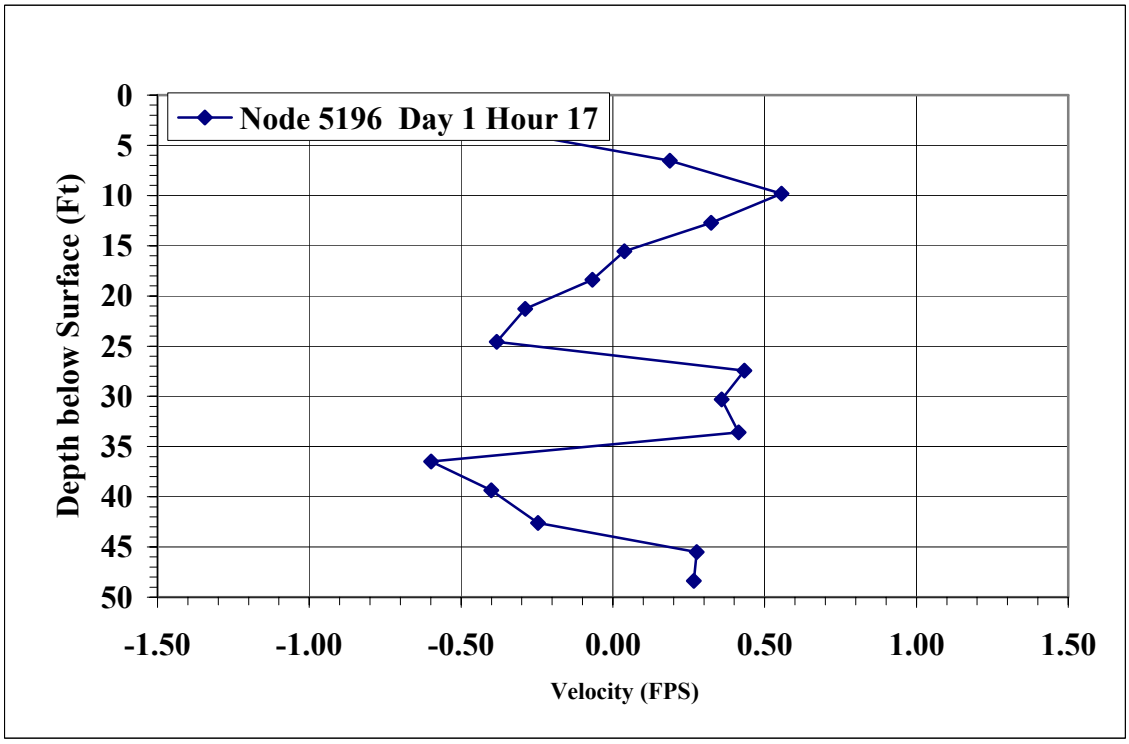

Node 5196 Day 1 Hour 12
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)

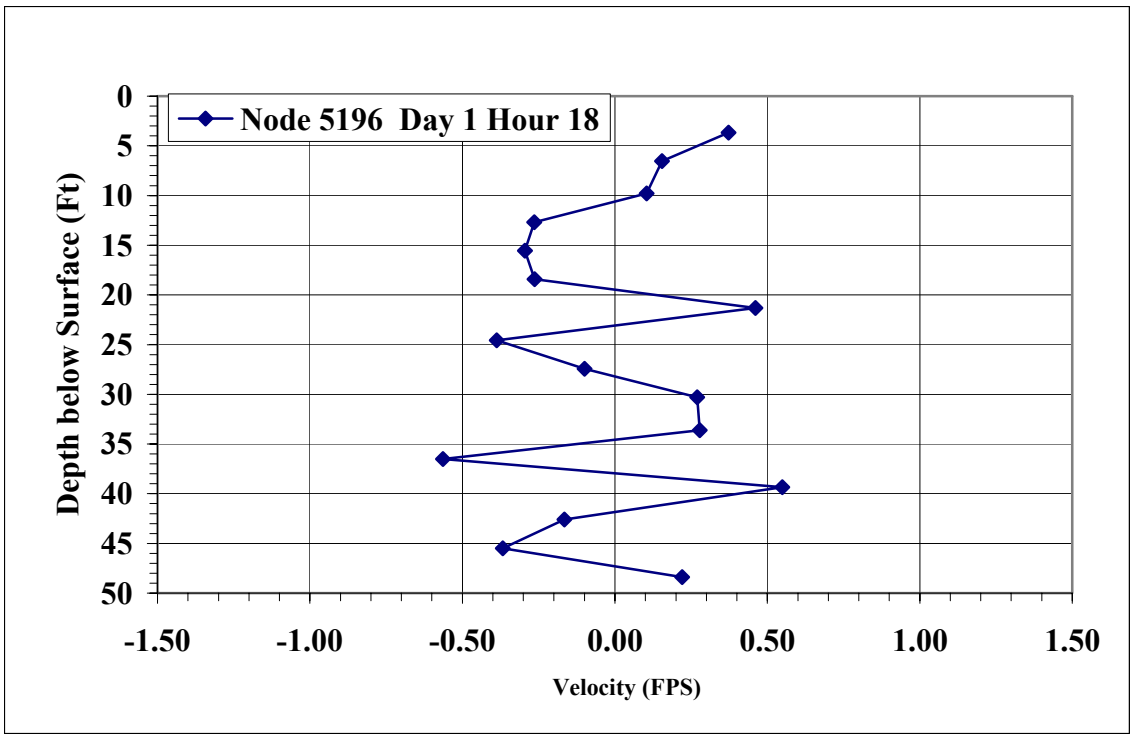

Node 5196 Day 1 Hour 13
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 5196 Day 1 Hour 14
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 5196 Day 1 Hour 15
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 5196 Day 1 Hour 16
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 5196 Day 1 Hour 17
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Velocity (FPS)


Node 5196 Day 1 Hour 18
Depth below Surface (Ft)
0
5
10
15
20
25
30
35
40
45
50
-1.50
-1.00
-0.50
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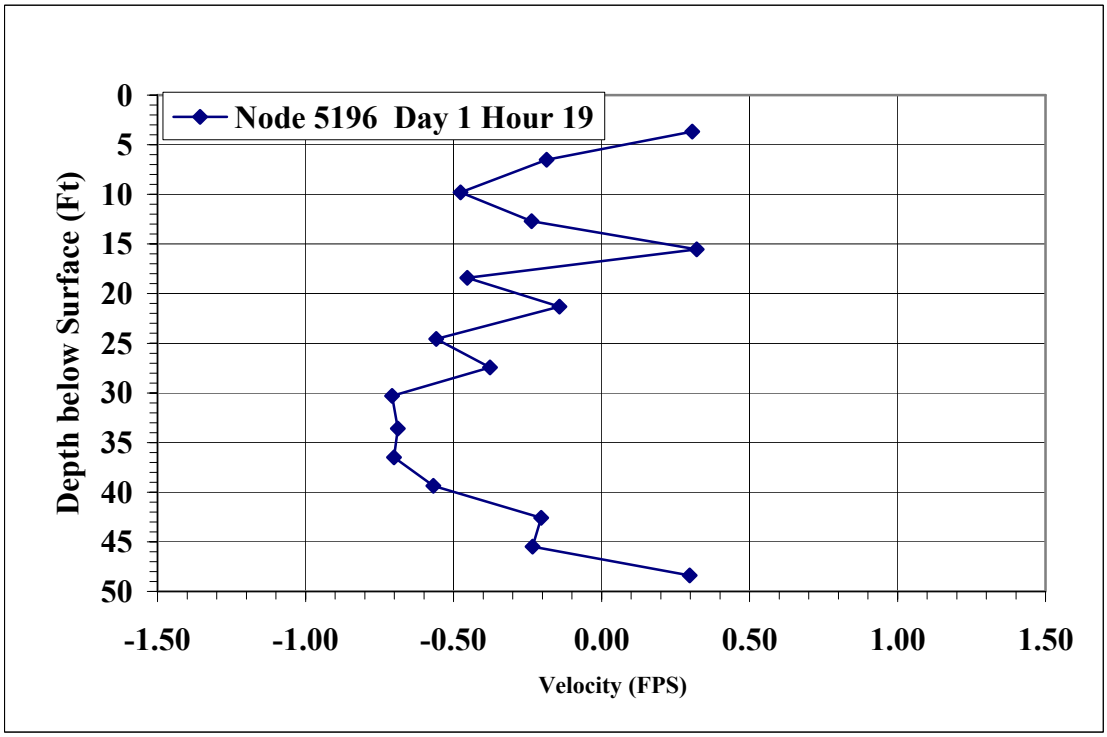
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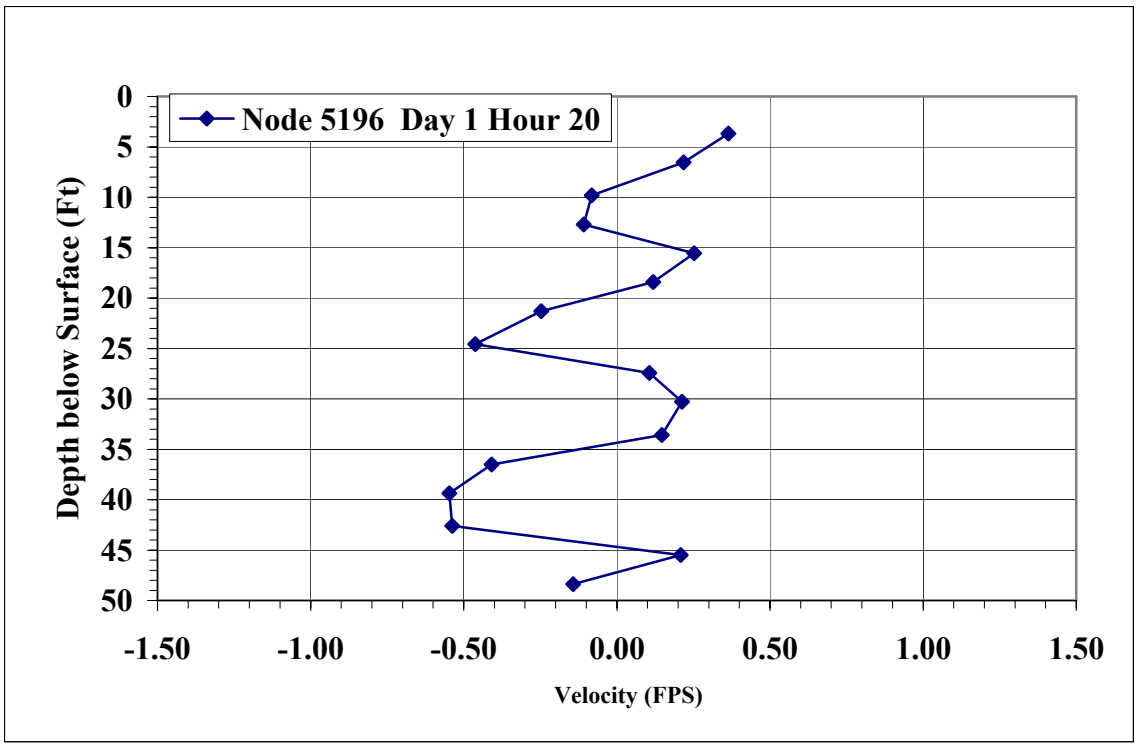
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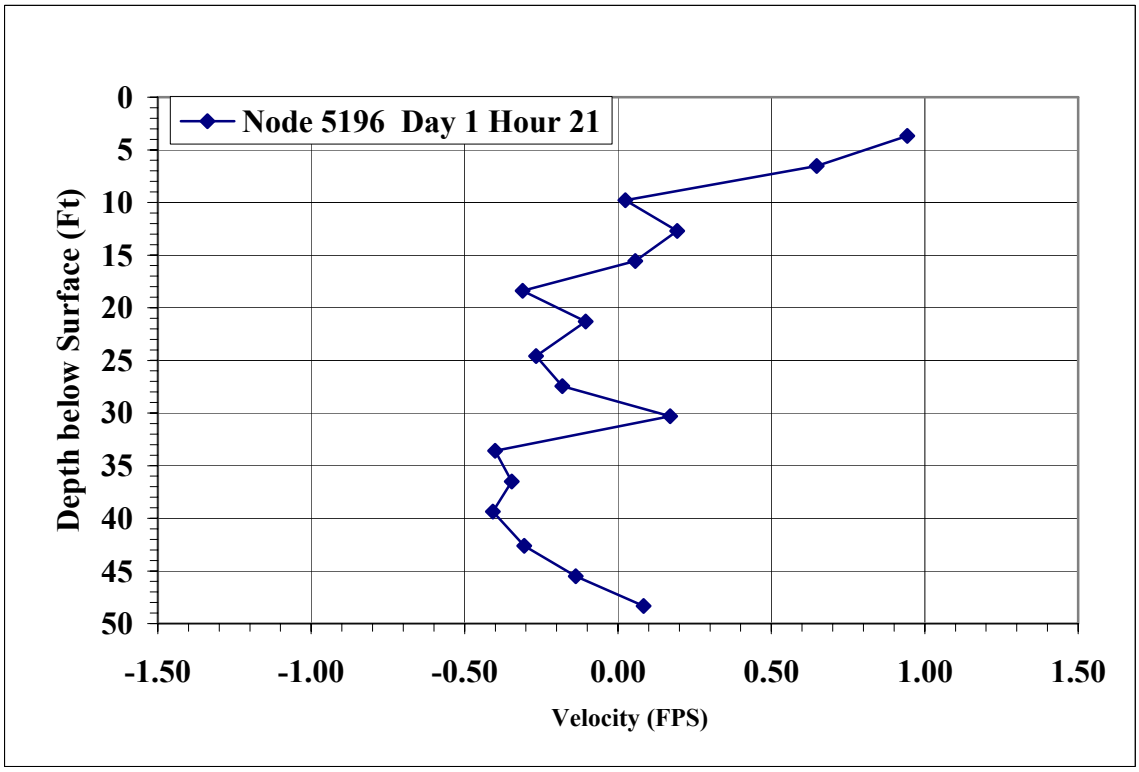
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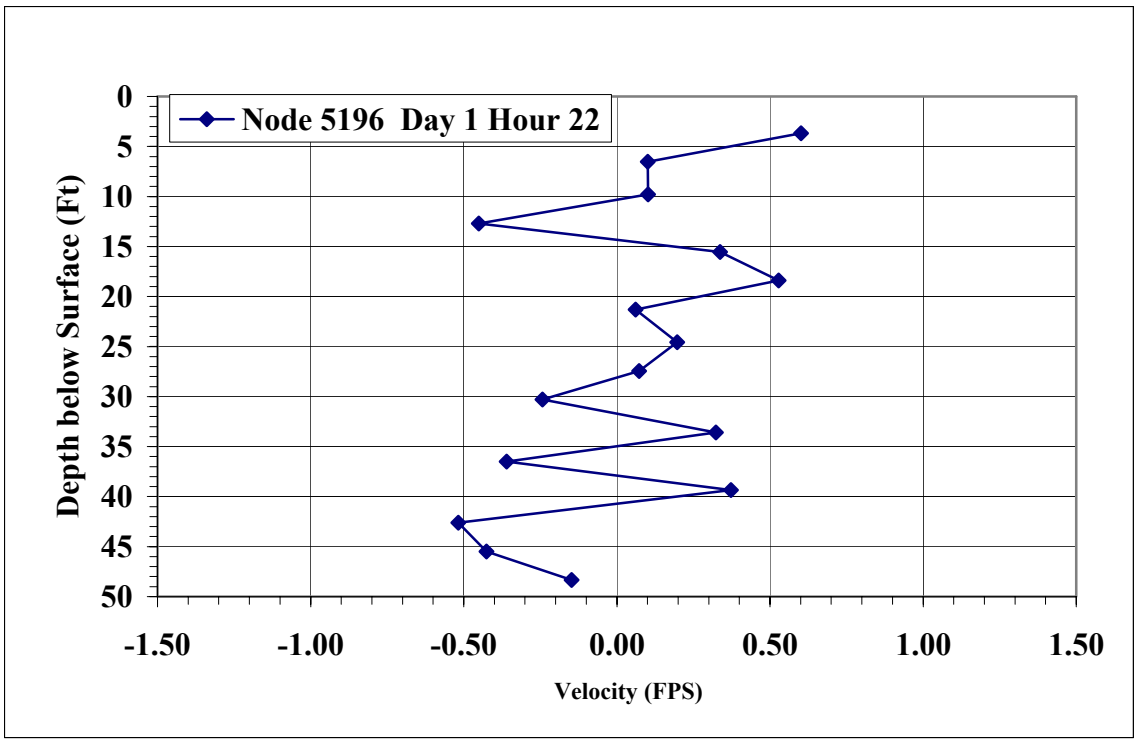
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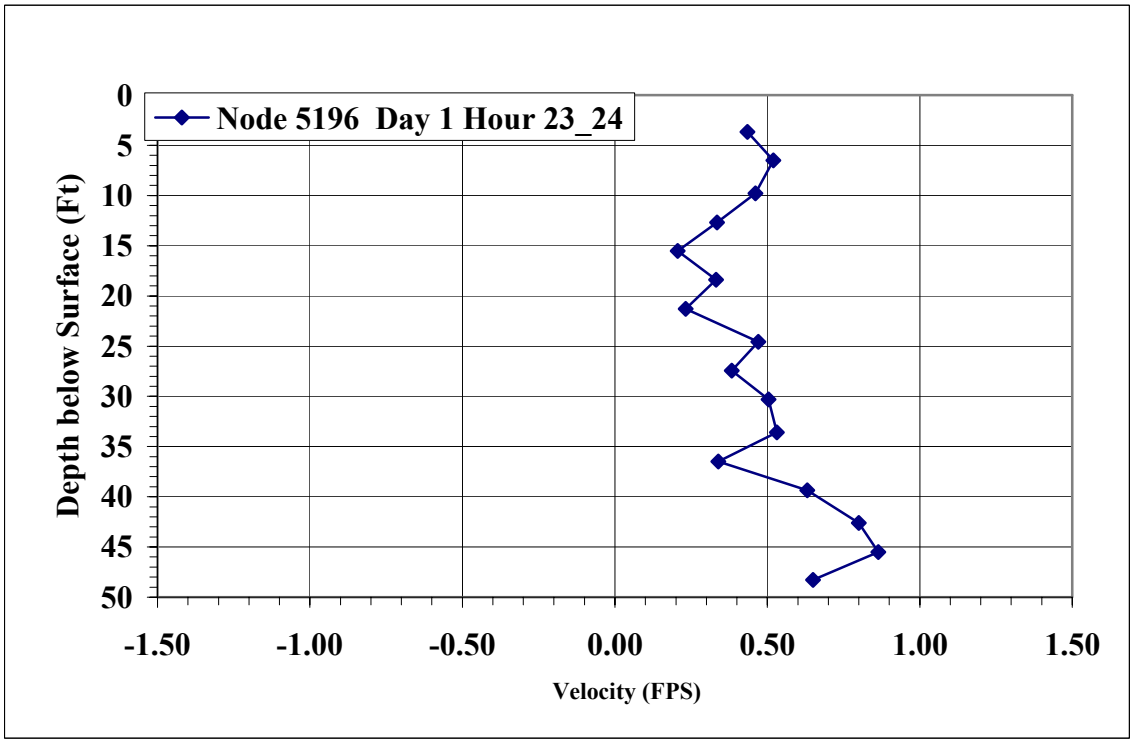
Velocity (FPS)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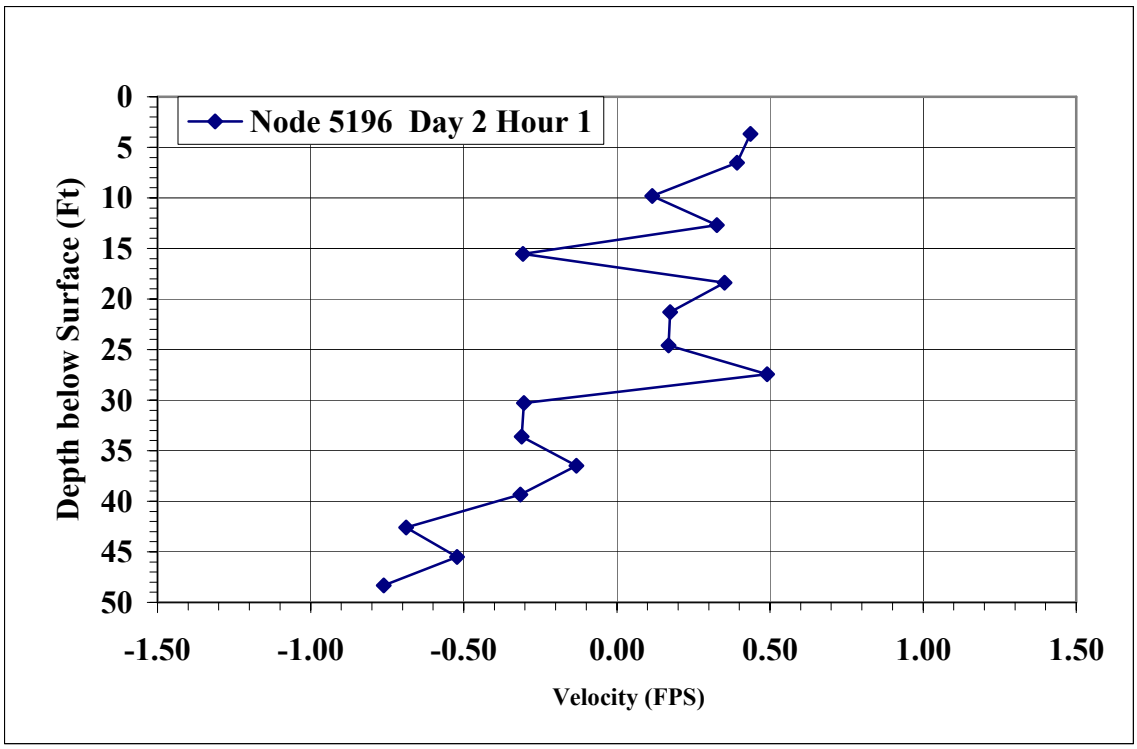
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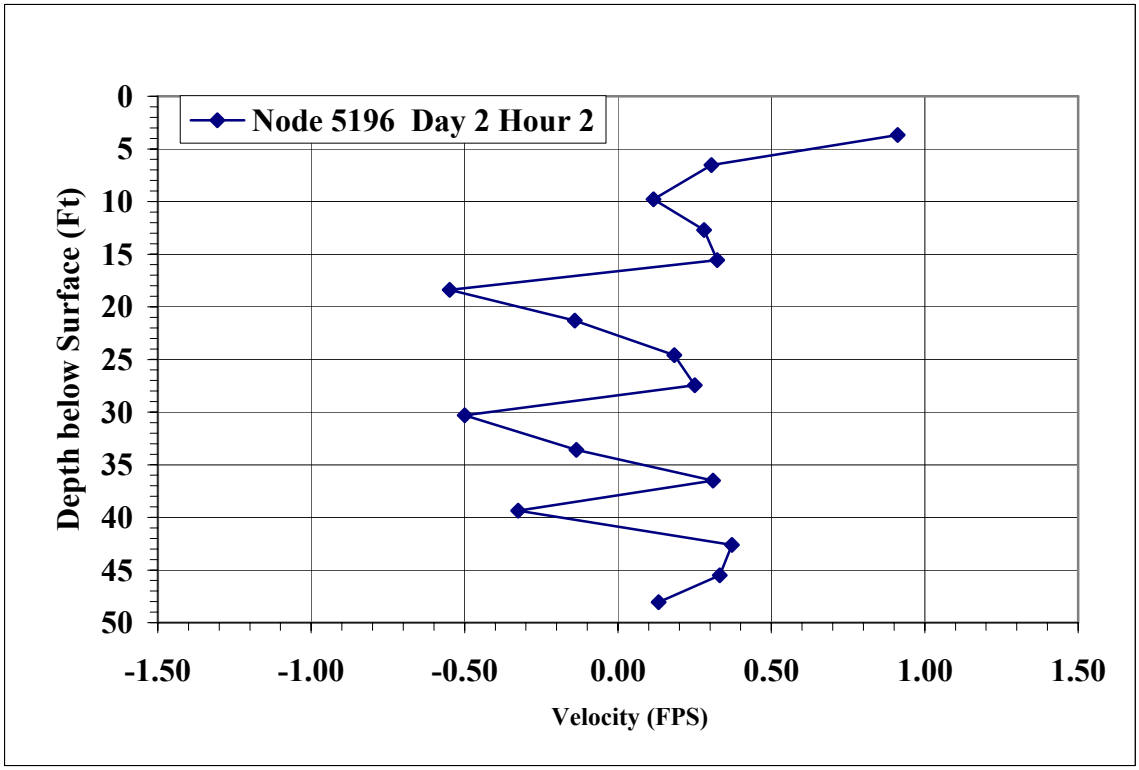
Velocity (FPS)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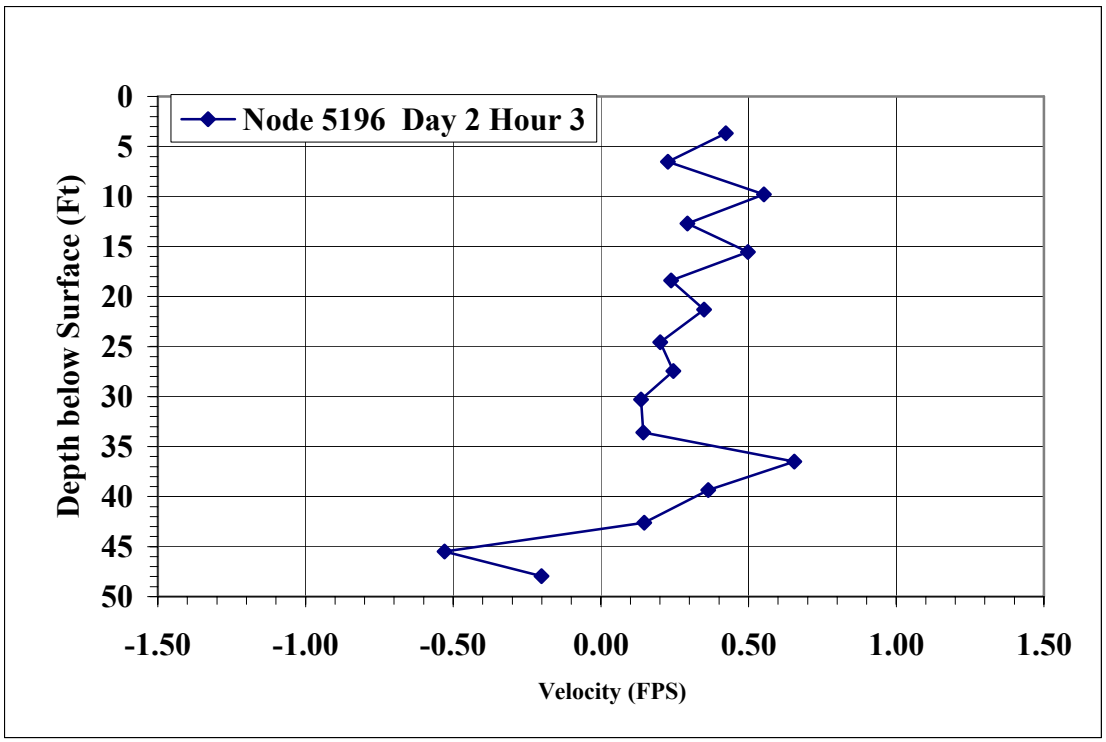
Velocity (FPS)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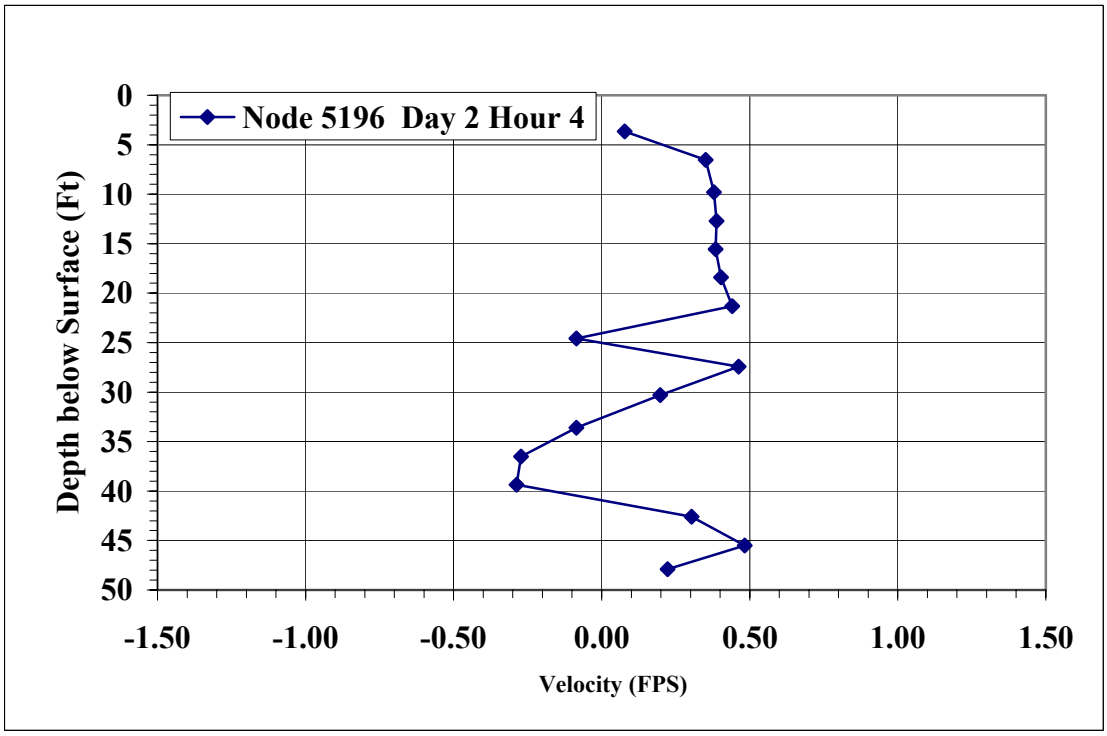
Velocity (FPS)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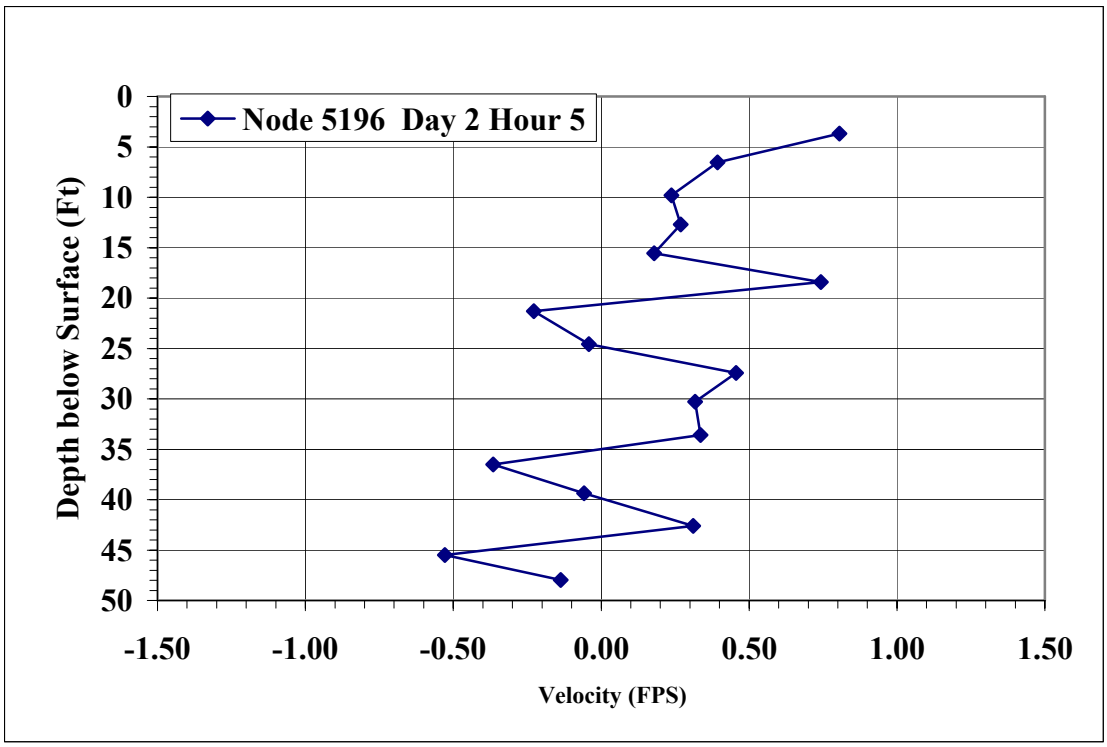
Velocity (FPS)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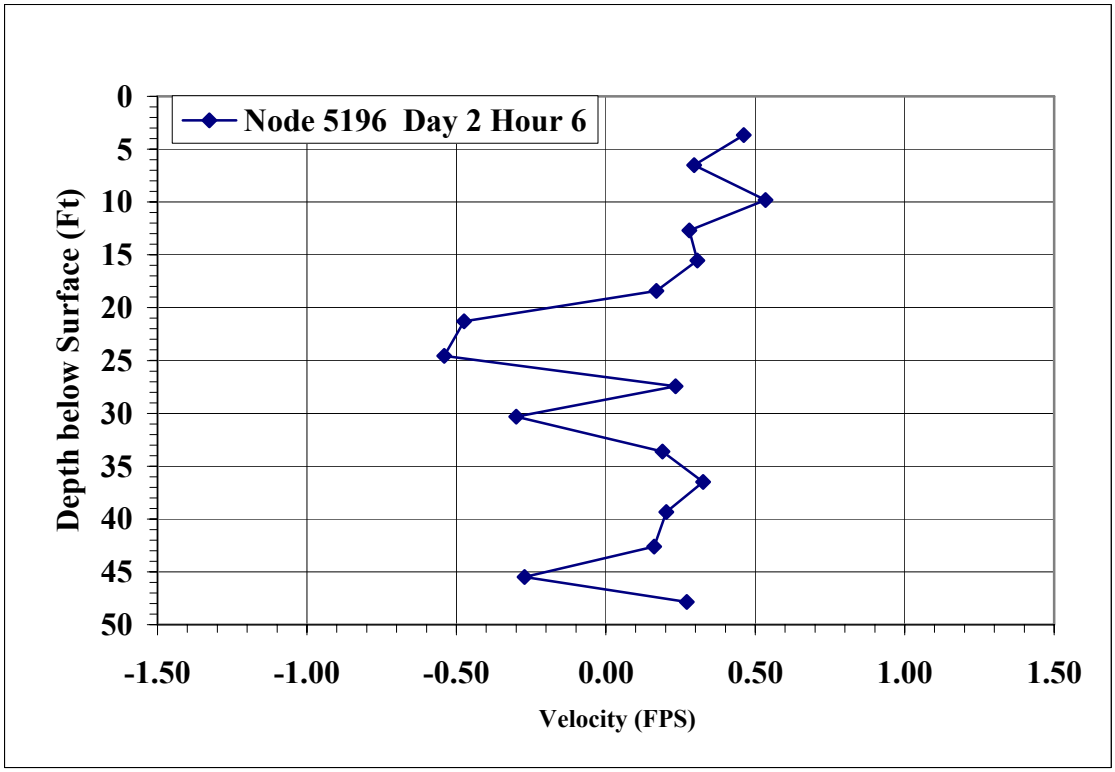
Velocity (FPS)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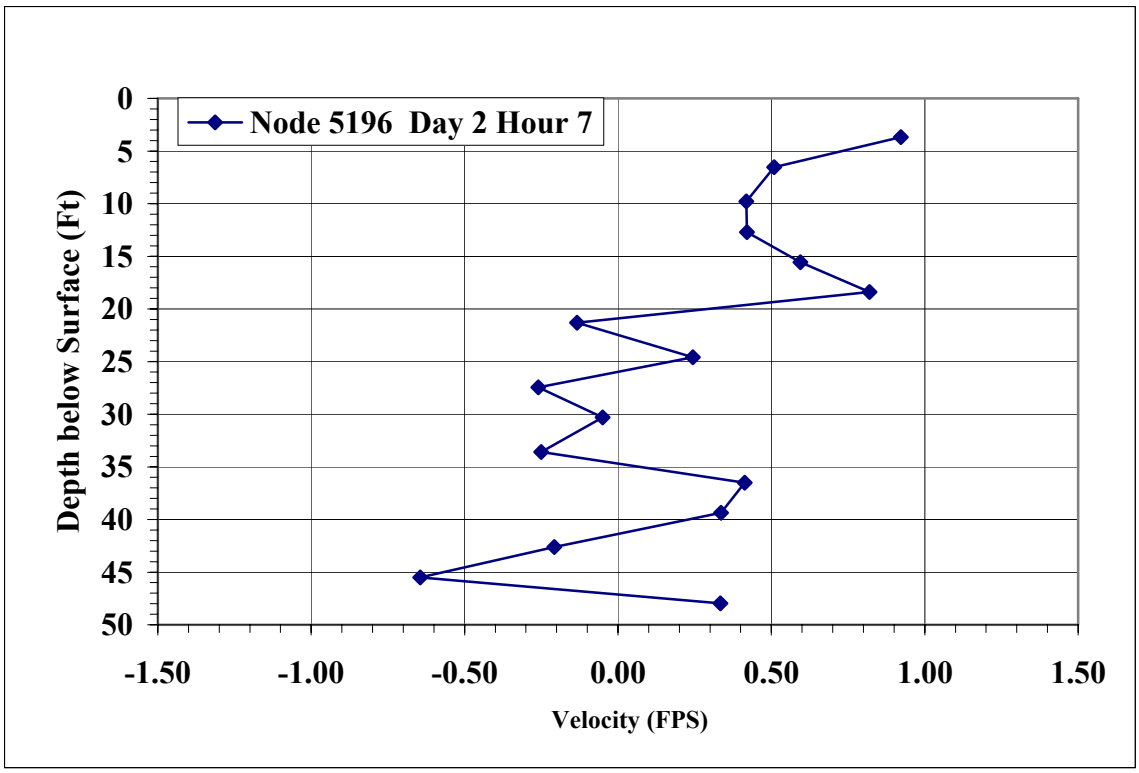
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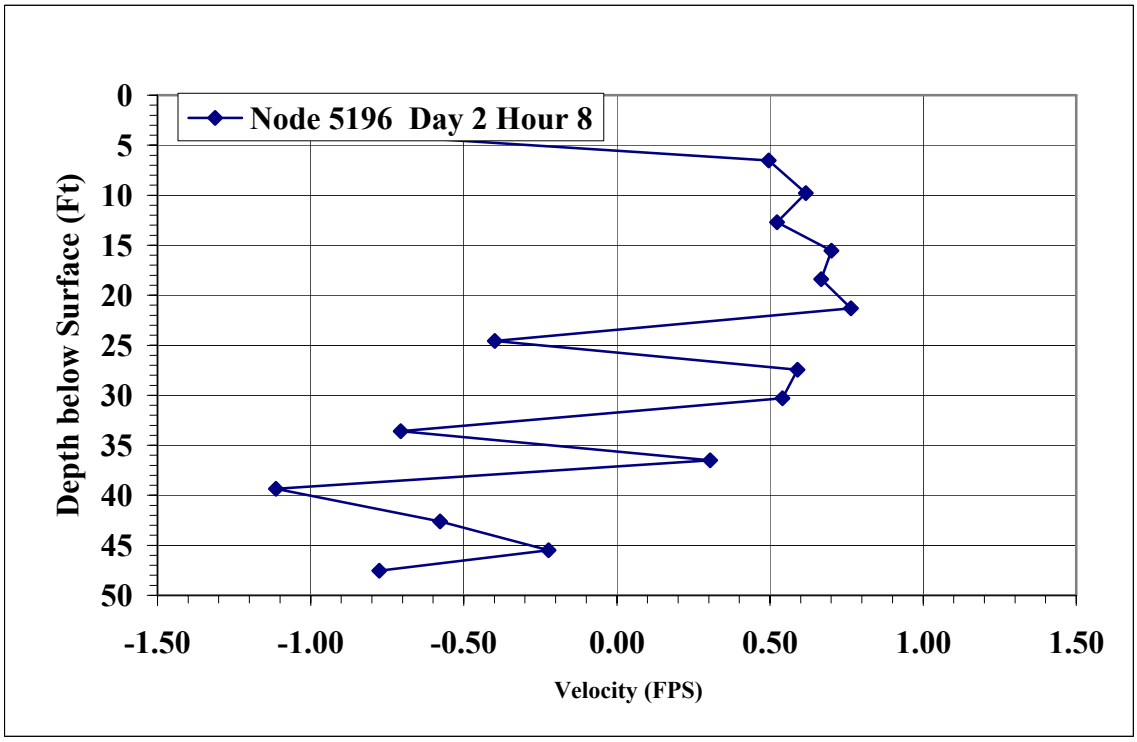
Velocity (FPS)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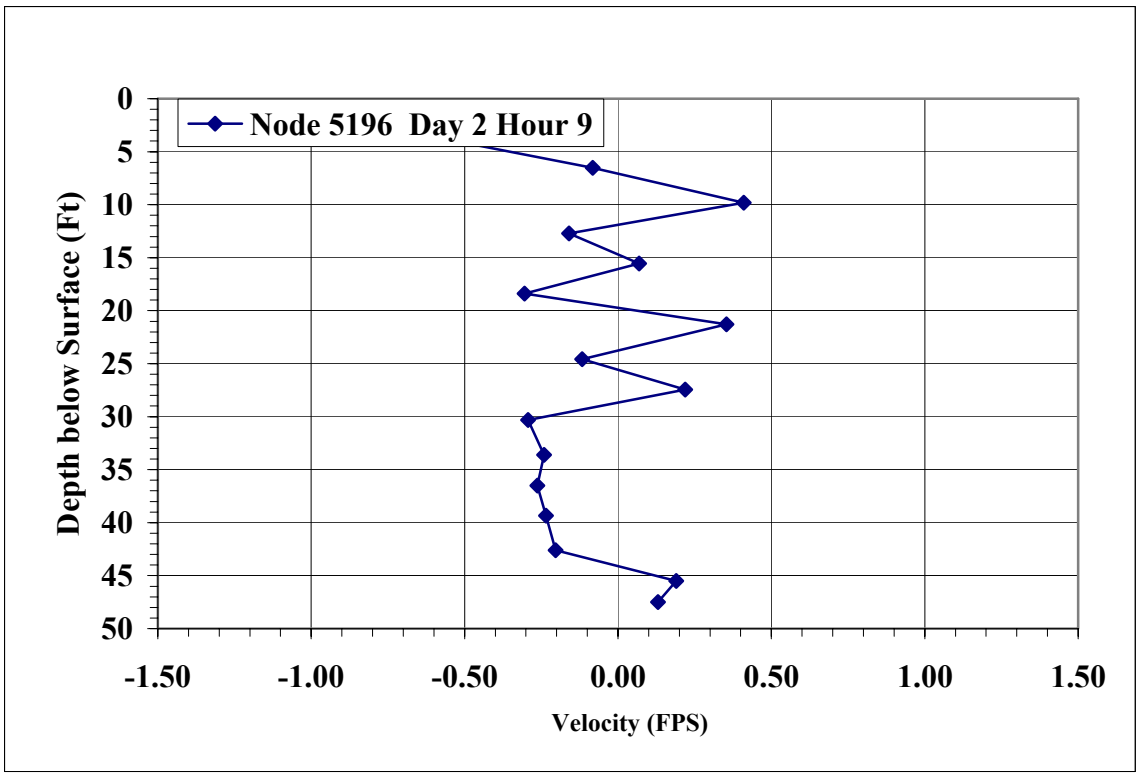
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Velocity (FPS)

Appendix 3
General Information on RMA 10 Code

Contents

1. TABS-MDS Introduction

2. 3-D Equations

3. Geometric transform

4. 2-D Vertically Averaged Equations

5. 2-D Laterally Averaged Equations

6. 1-D Equations

7. Finite Element Formulation

8. Time Derivative Solution Method

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10. Expressions for Applied Loads and Turbulent Mixing

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12. Vertical Turbulent Mixing and Diffusion

References

1. TABS-MDS Introduction

TABS-MDS (Multi-Dimensional, Sediment) is a finite element, hydrodynamic model. It is based on RMA10, a model written by Ian King of Resource Management Associates (King, 1993). It is capable of modeling turbulent, sub-critical flows using 1-D, 2-D, and/or 3-D elements. It is also capable of modeling constituent transport. This includes modeling salinity, temperature, and/or fine-grained sediment. The model is capable of coupling the spatial density variation induced by concentration gradients in the constituent field to the hydrodynamic calculations. This enables the model to simulate phenomena such as saline wedges in estuaries. The model has features that permit the simulation of intermittently wetted regions of the domain, such as coastal wetlands. Mathematical equations used in the TABS-MDS Theoretical Development are given below.

2. 3-D Equations

We have 6 unknowns (u,v,w,h,s,ρ). Therefore, we require 6 equations.
The Navier-Stokes Equations (i.e. conservation of fluid momentum)

$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}-\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial u}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{xy}\frac{\partial u}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_{xz}\frac{\partial u}{\partial z}\right)+\frac{\partial p}{\partial x}-\tau_x=0 \tag{1}$$

$$\rho\frac{\partial v}{\partial t}+\rho u\frac{\partial v}{\partial x}+\rho v\frac{\partial v}{\partial y}+\rho w\frac{\partial v}{\partial z}-\frac{\partial}{\partial x}\left(\varepsilon_{yx}\frac{\partial v}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{yy}\frac{\partial v}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_{yz}\frac{\partial v}{\partial z}\right)+\frac{\partial p}{\partial y}-\tau_y=0 \tag{2}$$

$$\rho\frac{\partial w}{\partial t}+\rho u\frac{\partial w}{\partial x}+\rho v\frac{\partial w}{\partial y}+\rho w\frac{\partial w}{\partial z}-\frac{\partial}{\partial x}\left(\varepsilon_{zx}\frac{\partial w}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{zy}\frac{\partial w}{\partial y}\right)-\frac{\partial}{\partial z}\left(\varepsilon_{zz}\frac{\partial w}{\partial z}\right)+\frac{\partial p}{\partial z}+\rho g-\tau_z=0 \tag{3}$$

The Volume Continuity Equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{4}$$

The Advection-Diffusion Equation

$$\frac{\partial s}{\partial t} + u\frac{\partial s}{\partial x} + v\frac{\partial s}{\partial y} + w\frac{\partial s}{\partial z} - \frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y\frac{\partial s}{\partial y}\right) - \frac{\partial}{\partial z}\left(D_z\frac{\partial s}{\partial z}\right) \tag{5}$$
$$-\theta_s = 0$$

The Equation of State

$$\rho = F(s,t) \tag{6}$$

where:

τ	=	applied forces (e.g. wind stress, bed shear stress, Coriolis force)
θ_s	=	salinity source/sink term

Now we reduce the number of unknowns requiring a simultaneous solution from 6 to 3. Assuming that the influence of vertical momentum on the system is small and may be neglected, equation 3 reduces to the following equation:

$$\frac{\partial p}{\partial z} + \rho g = 0 \tag{7}$$

Equation 7 is a statement that the vertical pressure distribution is hydrostatic. Equation 4 may then be integrated in the vertical direction to yield the following equation:

$$\int_a^{a+h}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)d\eta = -\int_a^{a+h}\frac{\partial w}{\partial z}d\eta = -w_s + w_b \tag{8}$$

where:

w_s	=	the vertical velocity at the water surface
w_b	=	the vertical velocity at the bed

The surface velocity can be expressed as follows:

$$w_s = u_s\frac{\partial(z_b + h)}{\partial x} + v_s\frac{\partial(z_b + h)}{\partial y} + \frac{\partial(z_b + h)}{\partial t} \tag{9}$$

Similarly, the bed velocity can be expressed as:

$$w_b = u_b \frac{\partial z_b}{\partial x} + v_b \frac{\partial z_b}{\partial y} + \frac{\partial z_b}{\partial t} \tag{10}$$

where:

u_s, v_s = the surface horizontal velocity components
u_b, v_b = the near bed horizontal velocity components
z_b = the bed elevation

Note that by replacing equations 3 and 4 with 6 and 8, we recast the equations such that w is present only in the horizontal momentum equations and the advection diffusion equation. It can now be solved in a separate decoupled calculation using the original form of the continuity equation (equation 4). This is done by taking the derivative of equation 4 with respect to z and solving for w, applying w_s and w_b as boundary conditions.

We can further eliminate ρ from the list of unknowns requiring a simultaneous solution by solving the equation of state (equation 6) in a decoupled step.

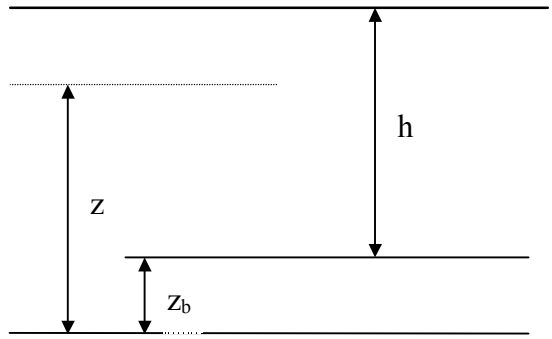
Thus, we are left with 4 equations (1,2,8 and 5) and 4 unknowns (u,v,h and s) to be solved simultaneously. In practice, however, the solution is broken up into 2 steps: First the velocities and depth are solved simultaneously, and then the constituent concentration is solved. This method improves solution efficiency dramatically over the simultaneous solution of all 4 equations and unknowns.

Hence, the solution of a system of 4 equations and 4 unknowns becomes the solution of a system of 3 equations (1,2, and 8) and 3 unknowns (u,v, and h), followed by the solution of 1 equation (5) and 1 unknown (s).

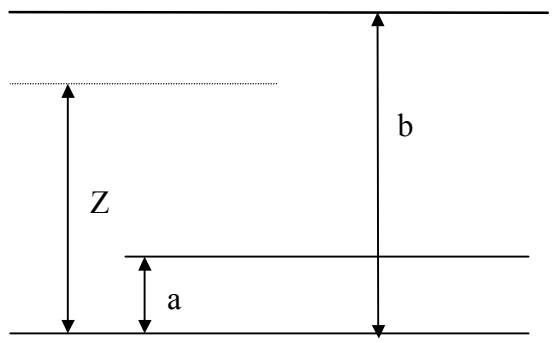
3. Geometric transform

In order to use a fixed geometry to model a system with a time varying vertical dimension (depth) it is convenient to use a geometric transformation to map the system to a fixed geometry.

Time varying system



Fixed grid system



The transformation is based on the following relation:

$$\frac{h}{(z - z_b)} = \frac{(b - a)}{(Z - a)} \tag{11}$$

$$z = \frac{(Z - a)}{(b - a)} h + z_b \tag{12}$$

Hence:

$$U(x, y, z) = u(X, Y, \left(\left(\frac{Z - a}{b - a}\right) h + z_b\right)) \tag{13}$$

After completing the transformation of the terms and simplifying, we arrive at the following transformed equations:

The Momentum Equations

$$\left\{\begin{array}{l}\rho\left[h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y}+\frac{\partial u}{\partial z}(b-a)\left(w-uT_x-vT_y-\frac{(z-a)}{(b-a)}\frac{\partial h}{\partial t}-\frac{\partial z_b}{\partial t}\right)\right]\\ -h\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial u}{\partial x}\right)-h\frac{\partial}{\partial y}\left(\varepsilon_{xy}\frac{\partial u}{\partial y}\right)-(b-a)\frac{\partial}{\partial z}\left(\varepsilon_{xz}\left(\frac{(b-a)}{h}\right)\frac{\partial u}{\partial z}\right)\\ +\rho gh\frac{\partial z_b}{\partial x}+\rho gh\frac{\partial h}{\partial x}+h\frac{\partial p}{\partial x}+\rho gh\frac{\partial h_D}{\partial x}-h\tau_x\end{array}\right\}\frac{1}{(b-a)}=0 \quad (14)$$

$$\left\{\begin{array}{l}\rho\left[h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y}+\frac{\partial v}{\partial z}(b-a)\left(w-uT_x-vT_y-\frac{(z-a)}{(b-a)}\frac{\partial h}{\partial t}-\frac{\partial z_b}{\partial t}\right)\right]\\ -h\frac{\partial}{\partial x}\left(\varepsilon_{yx}\frac{\partial v}{\partial x}\right)-h\frac{\partial}{\partial y}\left(\varepsilon_{yy}\frac{\partial v}{\partial y}\right)-(b-a)\frac{\partial}{\partial z}\left(\varepsilon_{yz}\left(\frac{(b-a)}{h}\right)\frac{\partial v}{\partial z}\right)\\ +\rho gh\frac{\partial z_b}{\partial y}+\rho gh\frac{\partial h}{\partial y}+h\frac{\partial p}{\partial y}+\rho gh\frac{\partial h_D}{\partial y}-h\tau_y\end{array}\right\}\frac{1}{(b-a)}=0 \quad (15)$$

Volume Continuity

$$\int_a^b\left[\frac{h}{(b-a)}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)-\frac{\partial u}{\partial z}T_x-\frac{\partial v}{\partial z}T_y\right]dz$$
$$+u_s\frac{\partial(z_b+h)}{\partial x}+v_s\frac{\partial(z_b+h)}{\partial y}+\frac{\partial(z_b+h)}{\partial t}-u_b\frac{\partial z_b}{\partial x}-v_b\frac{\partial z_b}{\partial y}-\frac{\partial z_b}{\partial t}=0 \quad (16)$$

Advection-Diffusion Equation

$$\left\{\begin{array}{l}h\frac{\partial s}{\partial t}+hu\frac{\partial s}{\partial x}+hv\frac{\partial s}{\partial y}+\frac{\partial s}{\partial z}(b-a)\left(w-uT_x-vT_y-\frac{(z-a)}{(b-a)}\frac{\partial h}{\partial t}-\frac{\partial z_b}{\partial t}\right)\\ -h\frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right)-h\frac{\partial}{\partial y}\left(D_y\frac{\partial s}{\partial y}\right)-(b-a)\frac{\partial}{\partial z}\left(D_z\left(\frac{(b-a)}{h}\right)\frac{\partial s}{\partial z}\right)-h\theta_s\end{array}\right\}\frac{1}{(b-a)}=0 \quad (17)$$

where:

$$T_x = \frac{\partial z_b}{\partial x} + \frac{(z-a)}{(b-a)}\frac{\partial h}{\partial x} - \frac{h}{(b-a)}\frac{\partial a}{\partial x} + \frac{(z-a)}{(b-a)^2}h\frac{\partial a}{\partial x} \tag{18}$$

$$T_y = \frac{\partial z_b}{\partial y} + \frac{(z-a)}{(b-a)}\frac{\partial h}{\partial y} - \frac{h}{(b-a)}\frac{\partial a}{\partial y} + \frac{(z-a)}{(b-a)^2}h\frac{\partial a}{\partial y} \tag{19}$$

$$h_D = -\frac{(b-z)}{(b-a)}h \tag{20}$$

4. 2-D Vertically Averaged Equations

If u,v,and s are assumed constant with respect to elevation (z), the 3-D equations can be integrated over depth to yield 2-D vertically averaged equations. For example, the X-momentum equation reduces to the following:

$$\left\{\begin{array}{l} \rho(b-a)\left[h\frac{\partial u}{\partial t} + hu\frac{\partial u}{\partial x} + hv\frac{\partial u}{\partial y}\right] \\ -h(b-a)\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial u}{\partial x}\right) - h(b-a)\frac{\partial}{\partial y}\left(\varepsilon_{xy}\frac{\partial u}{\partial y}\right) \\ +\rho gh(b-a)\left(\frac{\partial z_b}{\partial x} + \frac{\partial h}{\partial x}\right) + (b-a)\frac{gh^2}{2}\frac{\partial \rho}{\partial x} - h(b-a)\tau_x \end{array}\right\}\frac{1}{(b-a)} = 0 \tag{21}$$

Similarly, the continuity equation reduces to:

$$h\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} + \frac{\partial h}{\partial t} = 0 \tag{22}$$

And the advection-diffusion equation reduces to:

$$\left\{\begin{array}{l} h(b-a)\frac{\partial s}{\partial t} + h(b-a)u\frac{\partial s}{\partial x} + h(b-a)v\frac{\partial s}{\partial y} \\ -h(b-a)\frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right) - h(b-a)\frac{\partial}{\partial y}\left(D_y\frac{\partial s}{\partial y}\right) - h(b-a)\theta_s \end{array}\right\}\frac{1}{(b-a)} = 0 \tag{23}$$

5. 2-D Laterally Averaged Equations

Lateral averaging eliminates the momentum equation in the direction normal to the dominant flow direction. The equations are integrated across the width of the channel. This operation requires that the channel width c is specified. For the purposes of TABS-MDS, the channel width in laterally averaged elements is constrained such that it is constant with respect to depth, but can vary with respect to x and y (i.e. along the channel length). For example, the X-momentum equation reduces to the following.

$$\left\{\begin{array}{l} \rho\left[h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+\frac{\partial u}{\partial z}(b-a)\left(w-uT_x-\frac{(z-a)}{(b-a)}\frac{\partial h}{\partial t}-\frac{\partial z_b}{\partial t}\right)\right] \\ -h\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial u}{\partial x}\right)-(b-a)\frac{\partial}{\partial z}\left(\varepsilon_{xz}\left(\frac{(b-a)}{h}\right)\frac{\partial u}{\partial z}\right) \\ +\rho gh\frac{\partial z_b}{\partial x}+\rho gh\frac{\partial h}{\partial x}+h\frac{\partial p}{\partial x}+\rho gh\frac{\partial h_D}{\partial x}-h\tau_x \end{array}\right\}\frac{c}{(b-a)}=0 \tag{24}$$

Similarly, the continuity equation reduces to:

$$\begin{array}{l} \int_a^b\left[\frac{h}{(b-a)}\left(c\frac{\partial u}{\partial x}+u\frac{\partial c}{\partial x}\right)-c\frac{\partial u}{\partial z}T_x\right]dz \\ +cu_s\frac{\partial(z_b+h)}{\partial x}+\frac{\partial(z_b+h)}{\partial t}-cu_b\frac{\partial a}{\partial x}-\frac{\partial z_b}{\partial t}=0 \end{array} \tag{25}$$

And the advection-diffusion equation reduces to:

$$\left\{\begin{array}{l} h\frac{\partial s}{\partial t}+hu\frac{\partial s}{\partial x}+\frac{\partial s}{\partial z}(b-a)\left(w-uT_x-\frac{(z-a)}{(b-a)}\frac{\partial h}{\partial t}-\frac{\partial z_b}{\partial t}\right) \\ -h\frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right)-(b-a)\frac{\partial}{\partial z}\left(D_z\left(\frac{(b-a)}{h}\right)\frac{\partial s}{\partial z}\right)-h\theta_s \end{array}\right\}\frac{c}{(b-a)}=0 \tag{26}$$

6. 1-D Equations

Under this approximation both vertical and lateral integration are applied. Hence, the form of the cross-section must be defined. In TABS-MDS, the cross section is assumed trapezoidal, with allowance made for off-channel storage.

For example, the X-momentum equation reduces to the following:

$$\left\{\begin{array}{l} \rho\left[A\frac{\partial u}{\partial t}+Au\frac{\partial u}{\partial x}\right] \\ -A\frac{\partial}{\partial x}\left(\varepsilon_{xx}\frac{\partial u}{\partial x}\right) \\ +\rho gA\frac{\partial z_b}{\partial x}+\rho gA\frac{\partial h}{\partial x}+\frac{gAh}{2}\frac{\partial \rho}{\partial x}-A\tau_x \end{array}\right\}=0 \tag{27}$$

Similarly, the continuity equation reduces to:

$$A\left(\frac{\partial u}{\partial x}\right)+u\frac{\partial A}{\partial x}+\frac{\partial(A+A_{OC})}{\partial t}=0 \tag{28}$$

And the advection diffusion equation reduces to:

$$\left\{(A+A_{OC})\frac{\partial s}{\partial t}+A\frac{\partial s}{\partial x}-A\frac{\partial}{\partial x}\left(D_x\frac{\partial s}{\partial x}\right)-A\theta_s\right\}=0 \tag{29}$$

where:

A	=	The main channel cross-sectional area
A_{OC}	=	The off-channel storage cross-sectional area

7. Finite Element Formulation

In order to generate the finite element equations, we must integrate each of the equations over the element volume (for 3-D), area (for 2-D), or length (for 1-D), remembering to include the weight function in the integration (which, for the Galerkin method, is the same as the basis function).

In addition, we must recast the higher-order terms using integration by parts. This causes the boundary terms to drop out of the equations. For example,
Take the following pressure term, multiplied through by a weight function N.

$$N\frac{\rho gh}{(b-a)}\frac{\partial h}{\partial x} \tag{30}$$

This can be rewritten as:

$$N\frac{\rho g}{2(b-a)}\frac{\partial h^2}{\partial x} \tag{31}$$

Then , it can be integrated by parts:

$$\begin{aligned} N\frac{\rho g}{2(b-a)}\frac{\partial h^2}{\partial x} &= \frac{\partial}{\partial x}\left(N\frac{\rho g h^2}{2(b-a)}\right) - \frac{\partial N}{\partial x}\left(\frac{\rho g h^2}{2(b-a)}\right) \\ &- N\frac{g h^2}{2(b-a)}\frac{\partial \rho}{\partial x} - N\frac{\rho g h^2}{2(b-a)^2}\frac{\partial a}{\partial x} \end{aligned} \tag{32}$$

Note that the first term on the right hand side of the equation can be evaluated as an area integral via the Gauss Divergence Theorem. Hence, it becomes a boundary term.

8. Time Derivative Solution Method

The time derivative is approximated with a simple, fully-implicit finite difference formulation. I.e.,

$$\frac{\partial \beta_t}{\partial t} = \frac{(\beta_t - \beta_{t-\Delta t})}{\Delta t} \tag{33}$$

where:

β_t = any of the unknown variables at time t.

Δt = the time step

9. Newton-Rhapson Implementation

Once the finite element equations are built, they are solved using the Newton-Rhapson iterative method. In order to do this, partial derivatives with respect to each of the unknown variables must be derived for each system equation. These derivatives compose the stiffness matrix, and are used to drive the residual (i.e. the integral of each equation across an element) to 0.

$$\begin{bmatrix} X_u Y_u Z_u \\ X_v Y_v Z_v \\ X_h Y_h Z_h \end{bmatrix} \begin{bmatrix} u \\ v \\ h \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{34}$$

10. Expressions for Applied Loads and Turbulent Mixing

Bed Shear Stress

The bed shear stress is given by a modified form of Manning's Equation, as given by Christensen (1970). Any of 3 expressions can be used, depending on the instantaneous value of the depth/roughness height ratio ($\frac{d}{k}$). The expressions are as follows (given for the X-direction only):

$$\text{for } \frac{d}{k} < 4.32 \qquad \tau_x = \frac{\rho\, g}{L^2} \frac{|v| v_x}{d^{2/3}} \quad \text{where } L = \frac{6.46\sqrt{g}}{k^{1/3}} \tag{35}$$

$$\text{for } 4.32 < \frac{d}{k} < 276 \quad \tau_x = \frac{\rho\, g}{M^2} \frac{|v| v_x}{d^{1/3}} \quad \text{where } M = \frac{8.25\sqrt{g}}{k^{1/6}} \tag{36}$$

$$\text{for } \frac{d}{k} > 276 \qquad \tau_x = \frac{\rho\, g}{N^2} \frac{|v| v_x}{d^{1/6}} \quad \text{where } N = \frac{13.18\sqrt{g}}{k^{1/12}} \tag{37}$$

where:

τ_x	=	the bed shear in the X-direction
k	=	the roughness height
d	=	the local depth
v	=	the local velocity
g	=	the gravitational constant
ρ	=	the density of water

k is found as a function of Manning's n from the following expression:

$$k = \left(\frac{8.25\sqrt{g}\, n}{1.486} \right)^6 \tag{38}$$

The Wind Stress

The wind stress is given by the following expression (given for the X-direction only):

$$\tau_{wx} = \rho_a C_w V_w^2 \cos\theta_w \quad \textbf{(39)}$$

where:

τ_{wx} = the wind stress in the X-direction
ρ_a = the density of air
V_w = the wind velocity
θ_w = the direction from which the wind is blowing, measured counterclockwise from the positive X- axis.
C_w = the wind stress coefficient

For deep water, the wind stress coefficient is given by Wu (1980).

$$C_w = \frac{0.8 + 0.065 \times V_w}{1000} \quad \textbf{(40)}$$

For shallow water, the wind stress is given by Teeter et. al., (2001)

$$C_w = \left(\frac{0.4}{16.11 - 0.5\ln(d) - 2.48\ln(V_w)} \right)^2 \times \left(1 - \frac{1.118}{\sqrt{V_{w1}}} e^{-.6(d_1 - 2)} \right) \quad \textbf{(41)}$$

where:

d = the local water depth (in meters)
$_1$ = the maximum of the local water depth (in meters) and 2 meters
V_{w1} = the maximum of the wind velocity (in m/s) and 5.063 m/s

11. Horizontal Turbulent Mixing and Diffusion

Horizontal Turbulent mixing can be specified directly, or it can be controlled by the method of Smagorinsky (1963). A description of this method follows:

The Smagorinsky method of describing horizontal eddy viscosities and diffusion coefficients is a "tensorially invariant generalization of the mixing length type representation" (Speziale, 1998). The Smagorinsky description of the turbulent mixing terms in the Navier-Stokes Equations are given as follows. For the x-momentum equation

$$\rho h \frac{\partial}{\partial x}\left(2S\frac{\partial u}{\partial x}\right) + \rho h \frac{\partial}{\partial y}\left(S\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right) \tag{42}$$

For the y momentum equation

$$\rho h \frac{\partial}{\partial y}\left(2S\frac{\partial v}{\partial y}\right) + \rho h \frac{\partial}{\partial x}\left(S\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right) \tag{43}$$

where:

$$S = kA\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right]^{\frac{1}{2}} \tag{44}$$

k	=	Smagorinsky coefficient, usually given a value ranging from approximately 0.005 for rivers to 0.05 for estuaries and lakes (Speziale, 1998; Thomas et al, 1995)
A	=	the surface area of the element

The Smagorinsky description of the turbulent diffusion terms in the advection-diffusion equation is given as follows:

$$h \frac{\partial}{\partial x}\left(2S\frac{\partial C}{\partial x}\right) + h \frac{\partial}{\partial y}\left(2S\frac{\partial C}{\partial y}\right) \tag{45}$$

In order to promote numerical stability, TABS-MDS provides a means of establishing minimum values of turbulent mixing and turbulent diffusion. These values are used in place of the Smagorinsky term (S) when they are found to exceed the value of that term. The minimum turbulent mixing value is given by the following equation:

$$S_{Emin} = TBMINF \times \rho\alpha\sqrt{A} \tag{46}$$

The minimum turbulent diffusion value is given by the following equation:

$$S_{Dmin} = TBMINFS \times \alpha\sqrt{A} \tag{47}$$

where

TBMINF = minimum turbulent mixing factor (default = 1.0)

TBMINFS = minimum diffusion factor (default = 1.0)
α = a coefficient, given as 5.00×10^{-3} ft/sec or 1.52×10^{-3} m/s, depending on the unit system being used in the simulation. This value is an arbitrary estimate of the minimum turbulent mixing needed to ensure model stability. It equals the value of eddy viscosity/diffusion which corresponds to a Peclet number of 40 and a velocity magnitude of 0.2 ft/sec.

Also, if $|V| < \text{TBMINF} \times V_{min}$, S_{Emin} is applied, regardless of the turbulent mixing as given by the Smagorinsky calculation. This is done to inhibit numerical instability in areas with both extremely small velocities and high velocity gradients.

12. Vertical Turbulent Mixing and Diffusion

Vertical turbulent mixing and diffusion are given by the method of Mellor-Yamada (1982) with a modification according to Hendersen-Sellers (1984).
The Mellor-Yamada expressions for vertical eddy viscosity and diffusion are given as follows:

$$E_{xz} = E_{yz} = \rho S_m l_m q \qquad \textbf{(48)}$$

$$D_z = S_h l_m q \qquad \textbf{(49)}$$

where:

$$l_m = 0.4(z-a)\left|1-\frac{(z-a)}{h}\right|^{\frac{1}{2}} \qquad \textbf{(50)}$$

$$q = \left\{ b_1 l^2{}_m S_m \left[\left|\frac{\partial u}{\partial z}\right|^2 + \left|\frac{\partial v}{\partial z}\right|^2 \right] \right\}^{\frac{1}{2}}$$

(51)

S_m = 0.393
S_h = 0.494
b_1 = 16.6

The Henderson-Sellers adjustment is a factor that accounts for the dampening affect on turbulence induced by stable stratification. The factor is expressed in terms of the Richardson Number:

$$R_i = \frac{-g(\partial\rho/\partial z)}{\rho\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]} \tag{52}$$

For vertical diffusion of momentum (i.e. vertical eddy viscosity) the expression is given as follows:

$$E_z = \frac{E_{zo}}{\left(1 + 0.74R_i\right)} \tag{53}$$

Where E_z is the vertical eddy viscosity, and E_{zo} is the vertical eddy viscosity assuming no stratification influence on the turbulence (i.e. the value taken from Mellor-Yamada).

For vertical diffusion of salinity (i.e. vertical diffusion coefficient) the expression is given as follows:

$$D_z = \frac{D_{zo}}{\left(1 + 37R_i^2\right)} \tag{54}$$

Where D_z is the vertical diffusion coefficient, and D_{zo} is the vertical diffusion coefficient assuming no stratification influence on the turbulence (i.e. the value taken from Mellor-Yamada).

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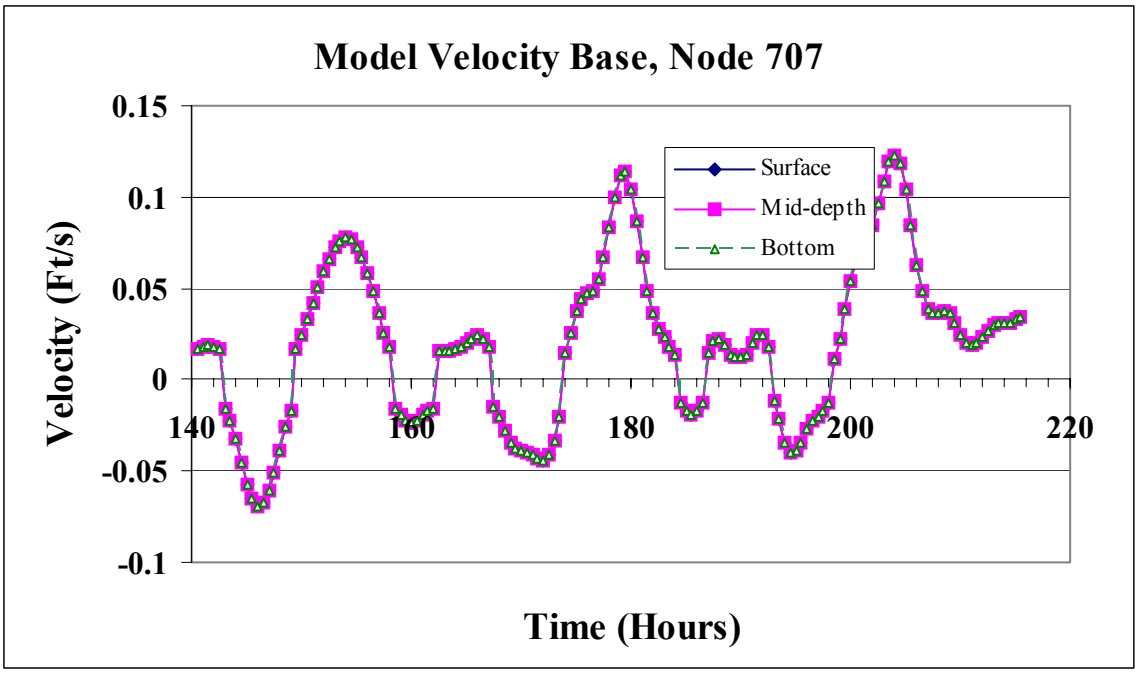
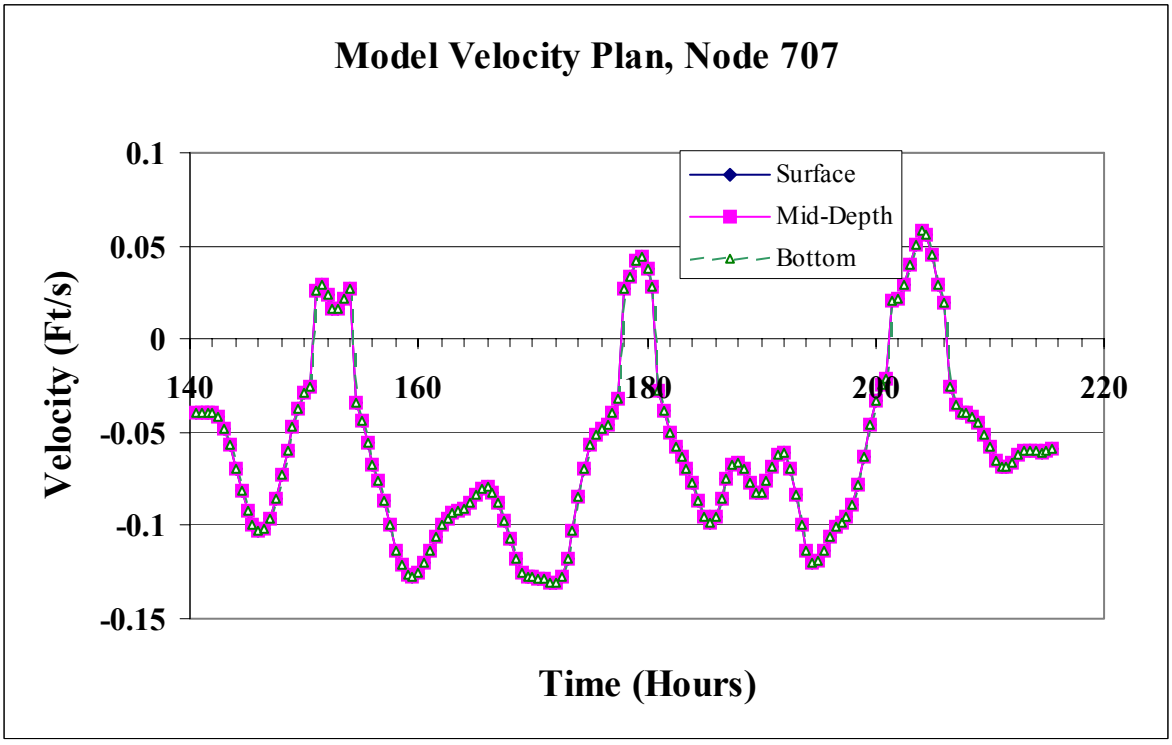
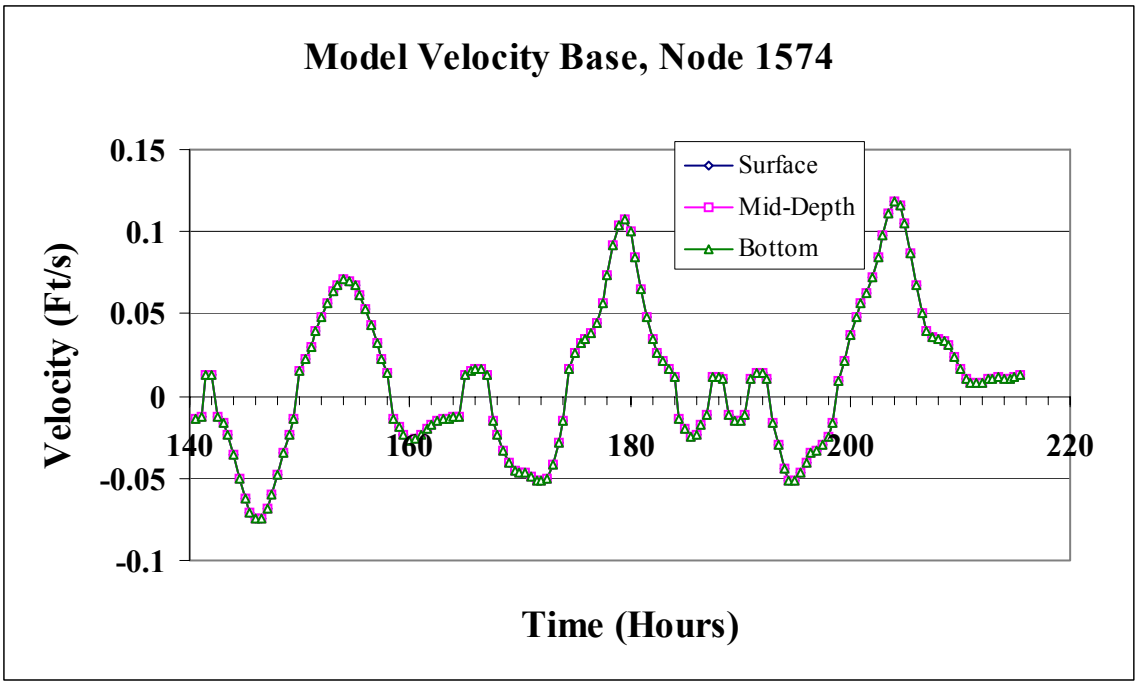
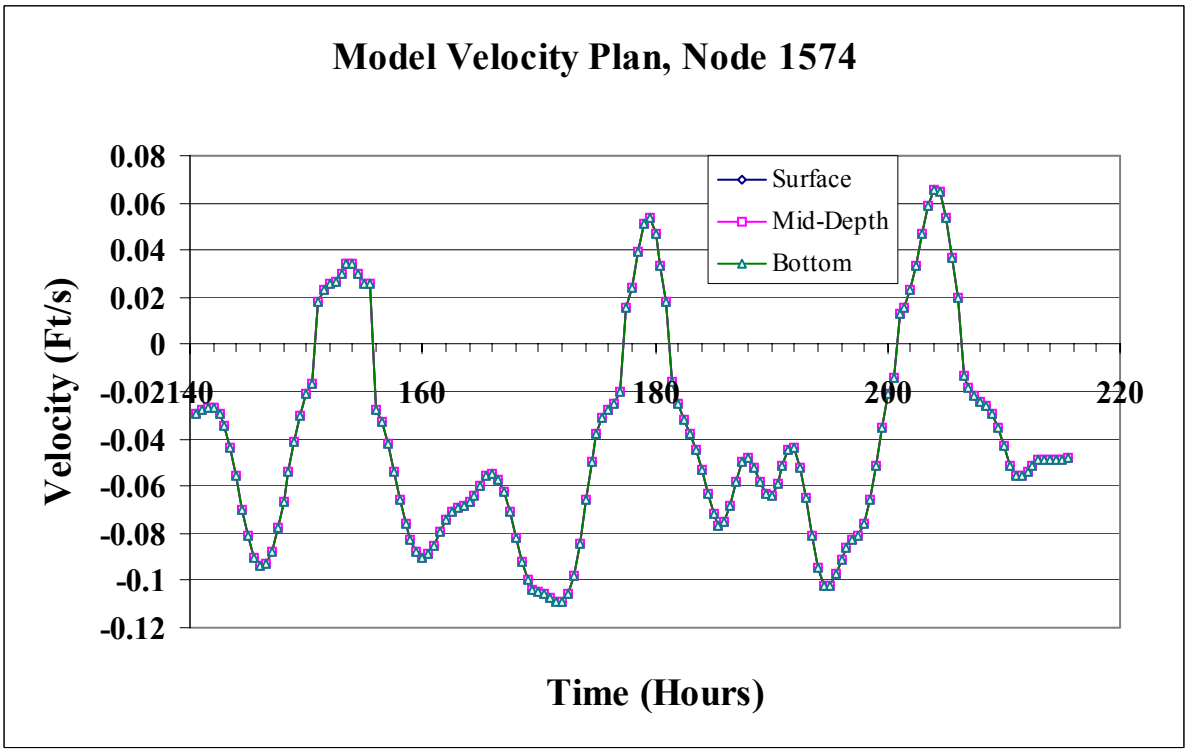
Appendix 4
Comparison of Velocities Over Vertical
<u>From 3D Numerical Model</u>

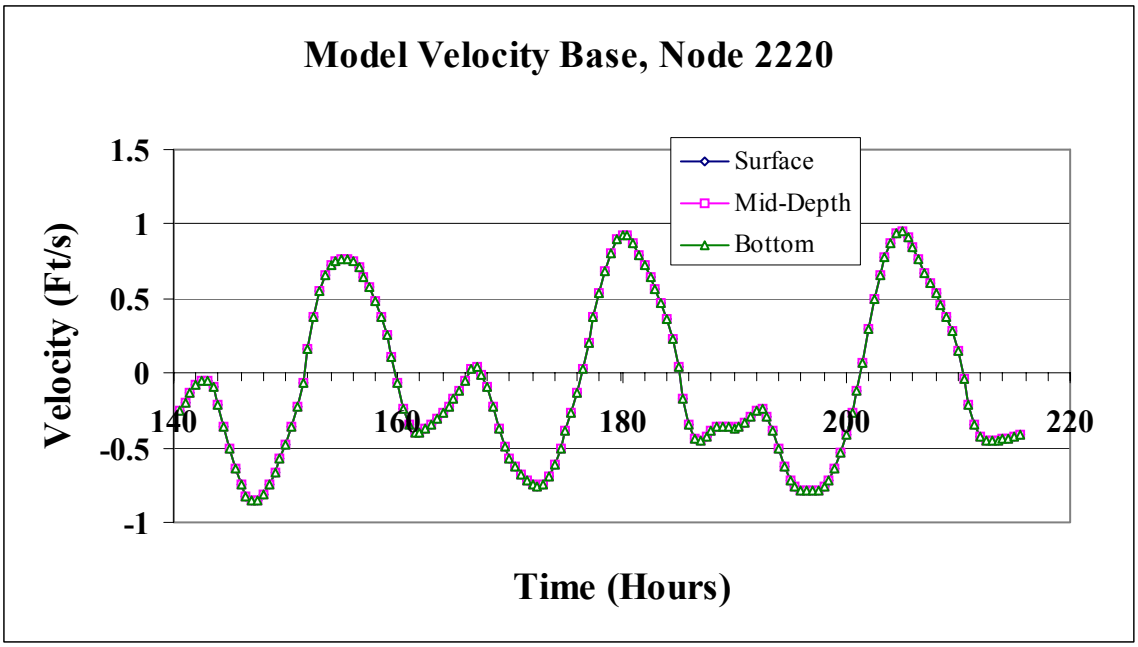
For Base and Plan

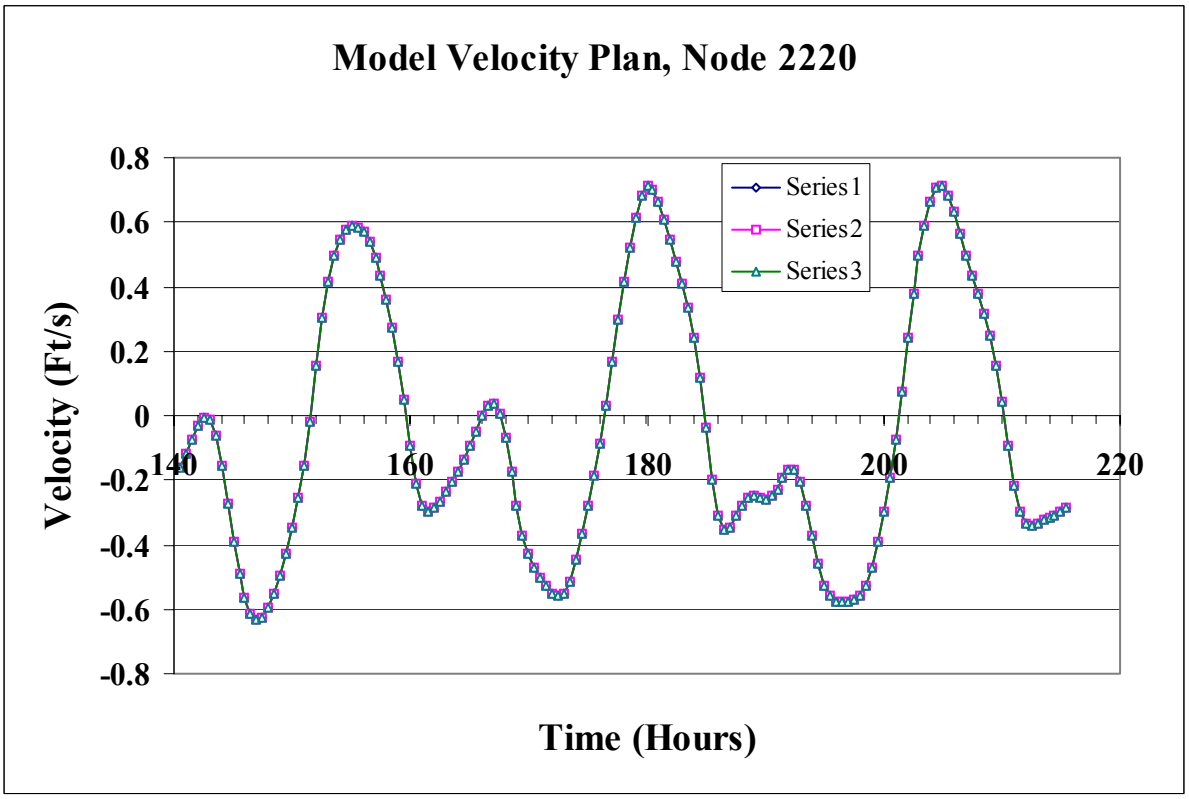

Model Velocity Base, Node 707
0.15
0.1
0.05
0
-0.05
-0.1
140
160
180
200
220
Velocity (Ft/s)
Time (Hours)
Surface
Mid-depth
Bottom

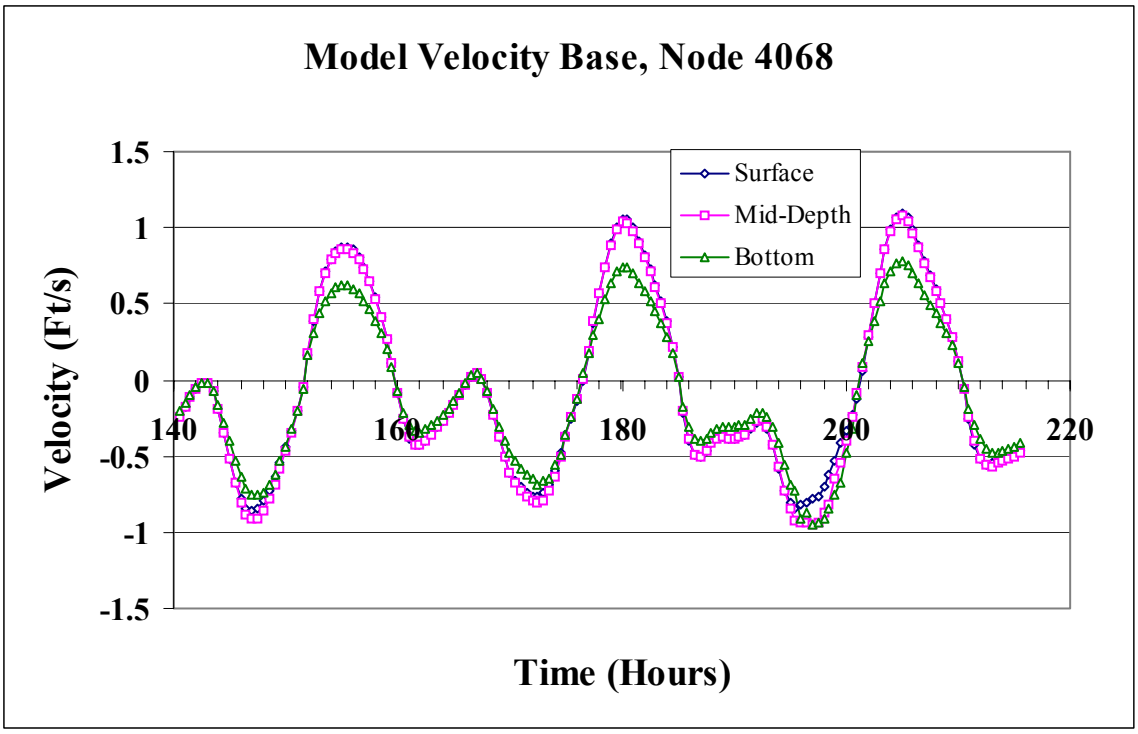

Model Velocity Plan, Node 707
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Velocity (Ft/s)
Time (Hours)
Surface
Mid-Depth
Bottom

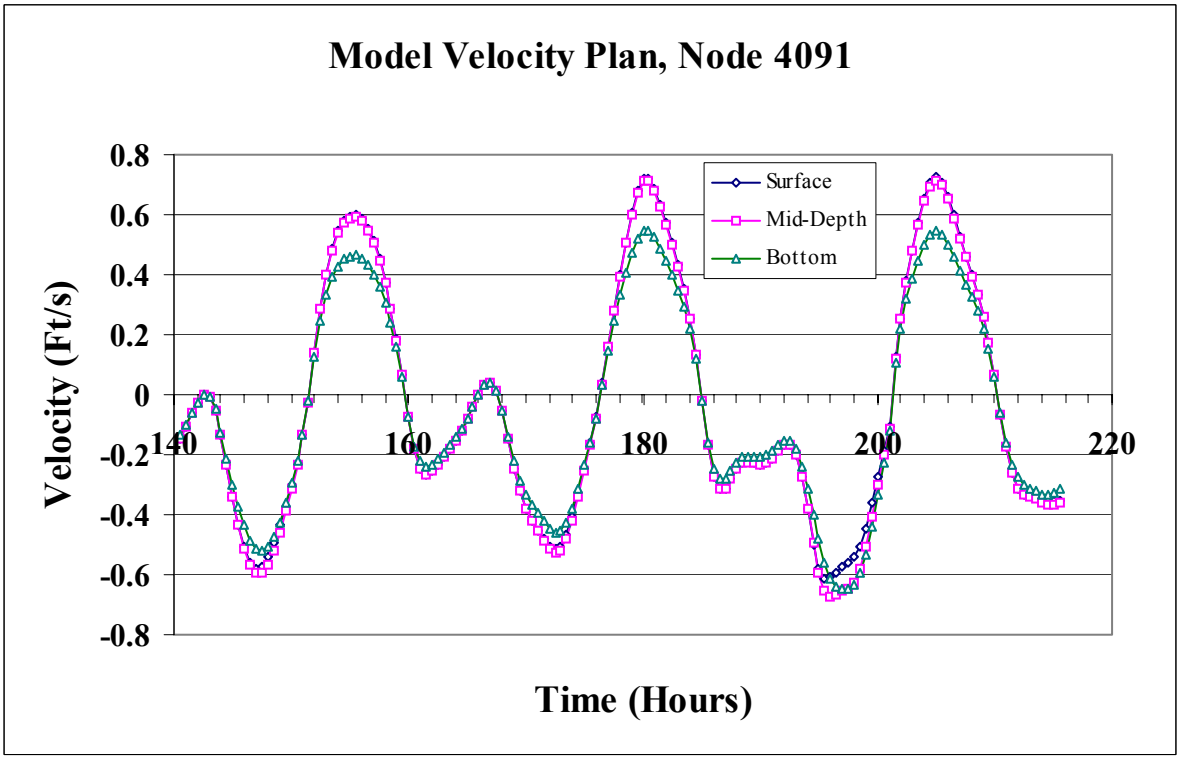

Model Velocity Base, Node 1574
Velocity (Ft/s)
0.15
0.1
0.05
0
-0.05
-0.1
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

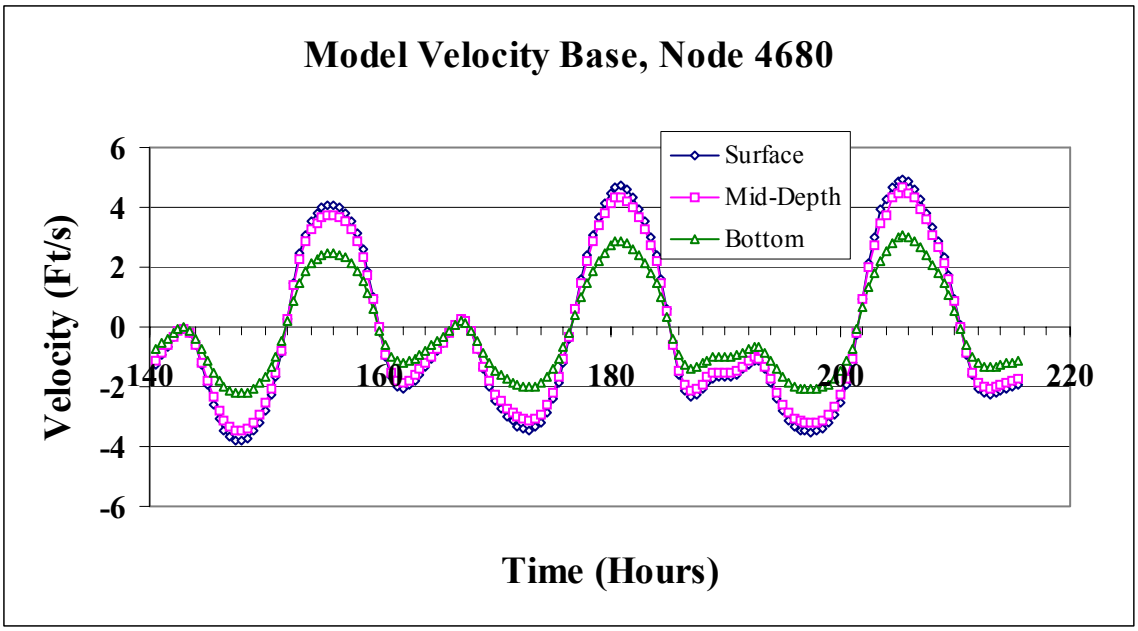

Model Velocity Plan, Node 1574
Velocity (Ft/s)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

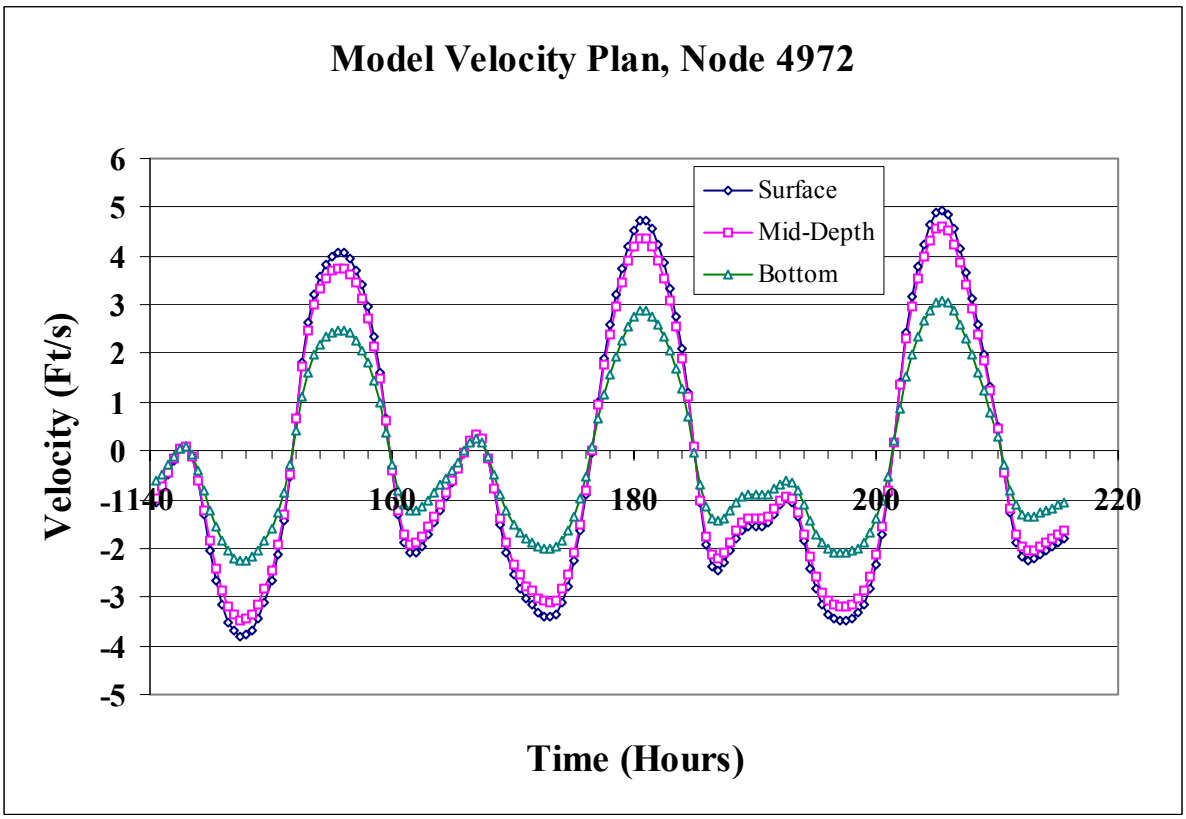

Model Velocity Base, Node 2220
Velocity (Ft/s)
1.5
1
0.5
0
-0.5
-1
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

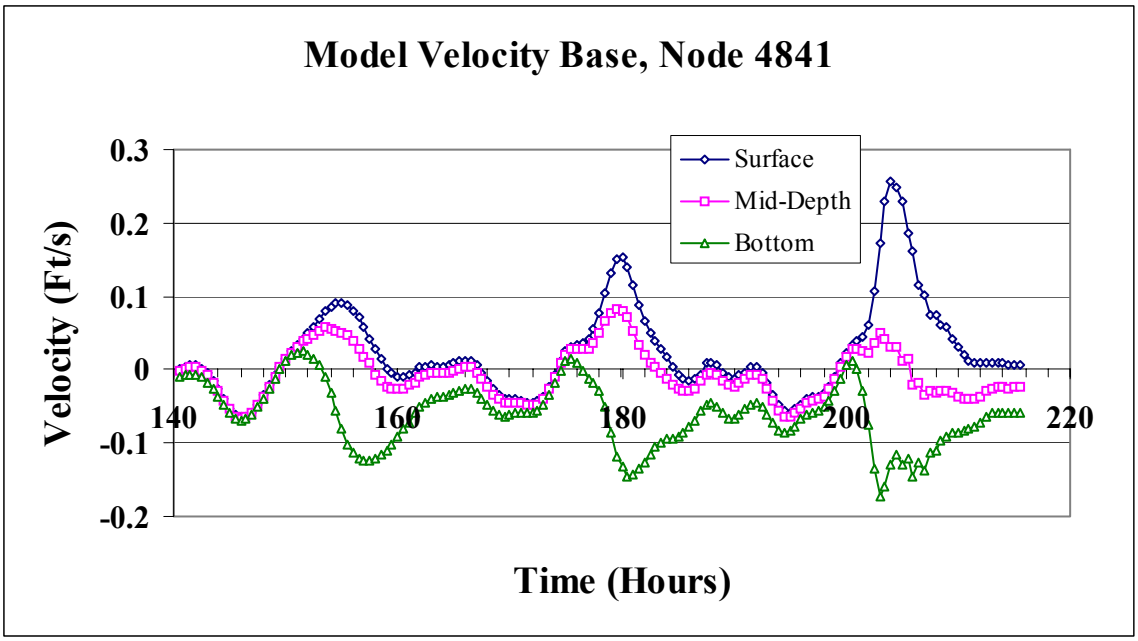

Model Velocity Plan, Node 2220
Velocity (Ft/s)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
140
160
180
200
220
Time (Hours)
Series1
Series2
Series3

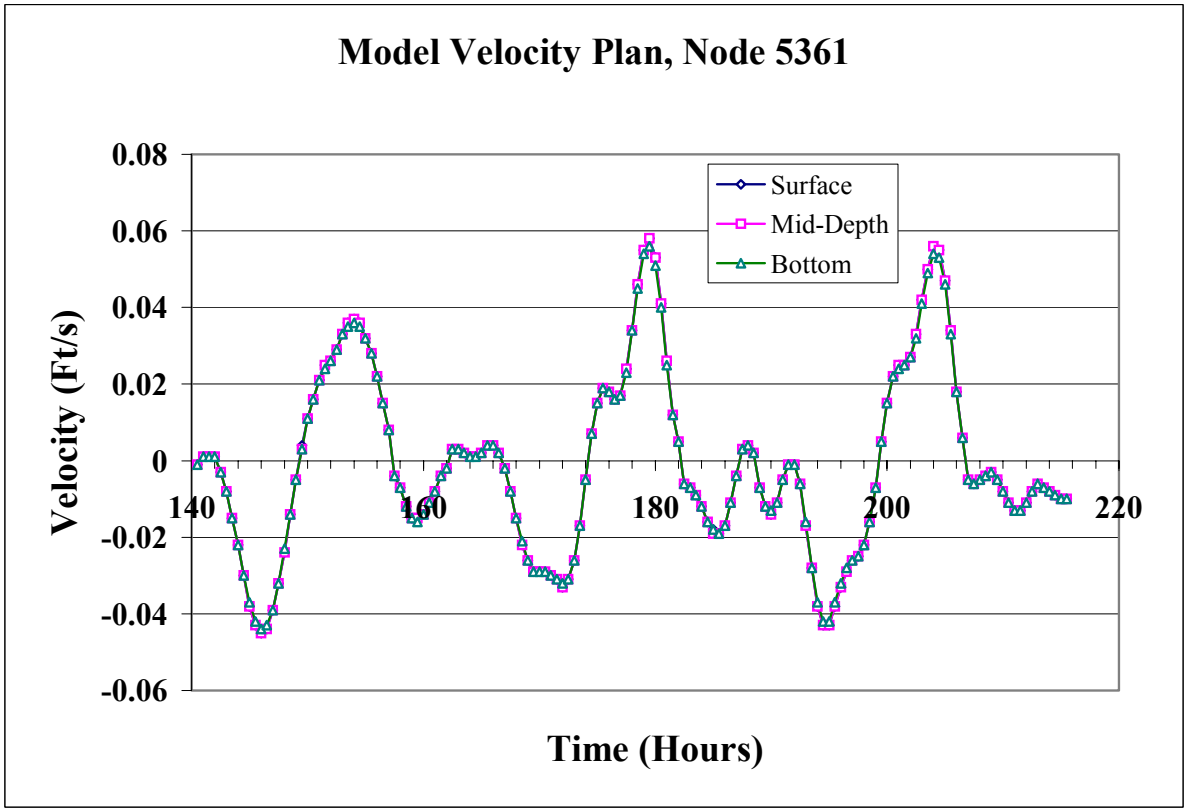

Model Velocity Base, Node 4068
Velocity (Ft/s)
1.5
1
0.5
0
-0.5
-1
-1.5
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

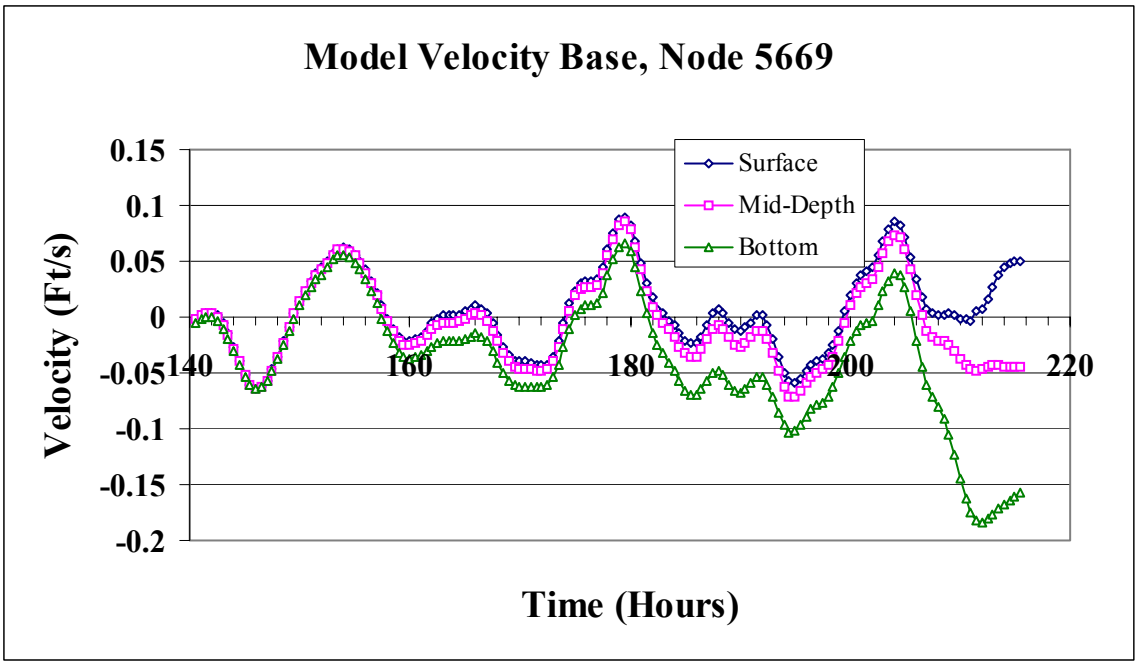

Model Velocity Plan, Node 4091
Velocity (Ft/s)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

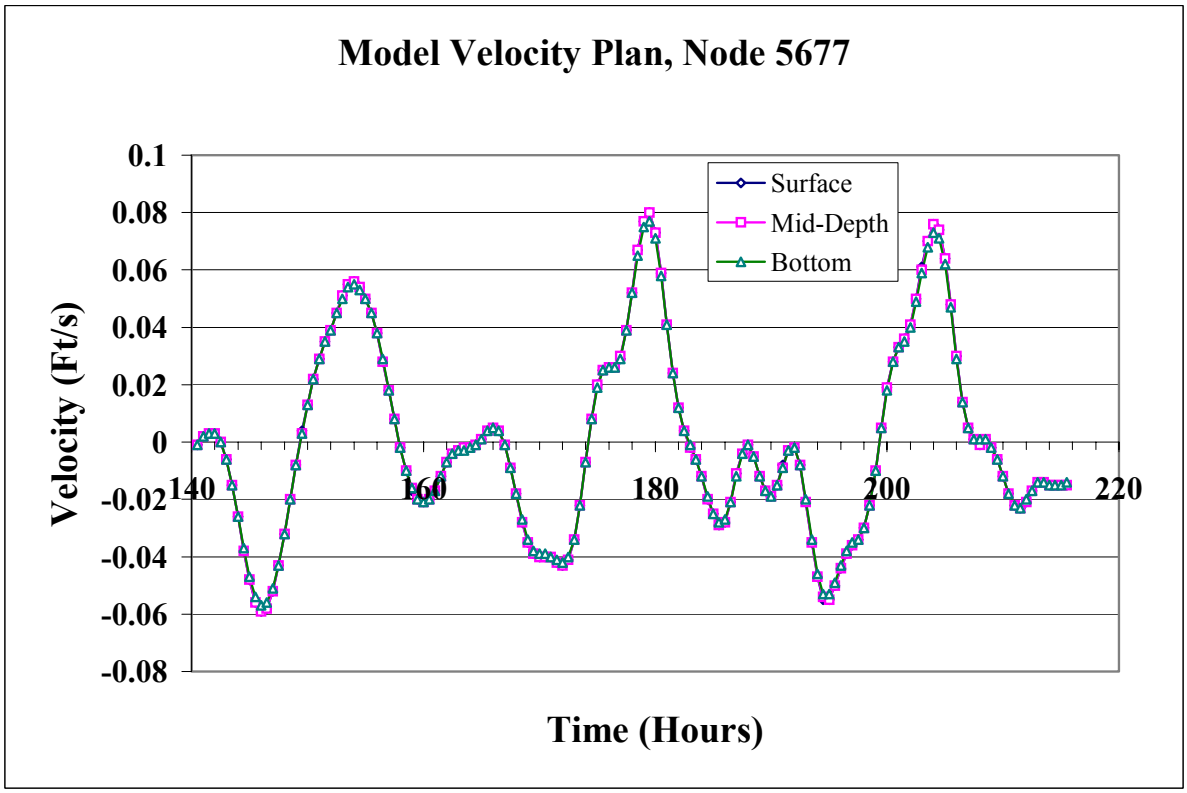

Model Velocity Base, Node 4680
Velocity (Ft/s)
6
4
2
0
-2
-4
-6
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

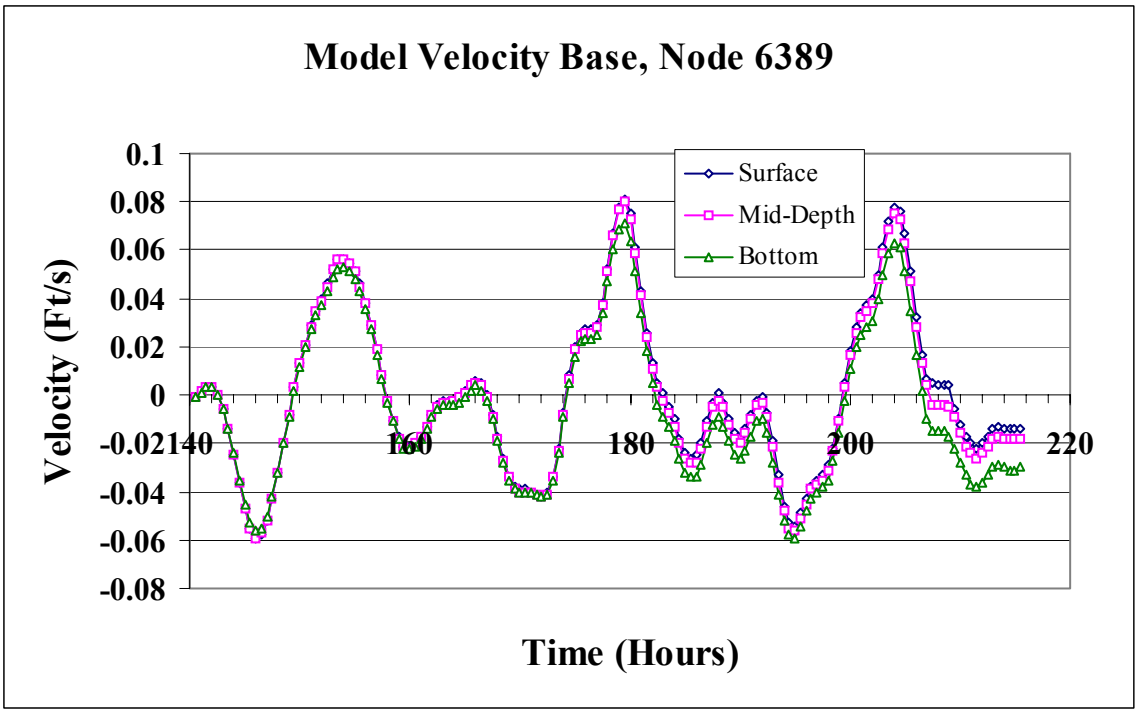

Model Velocity Plan, Node 4972
Velocity (Ft/s)
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

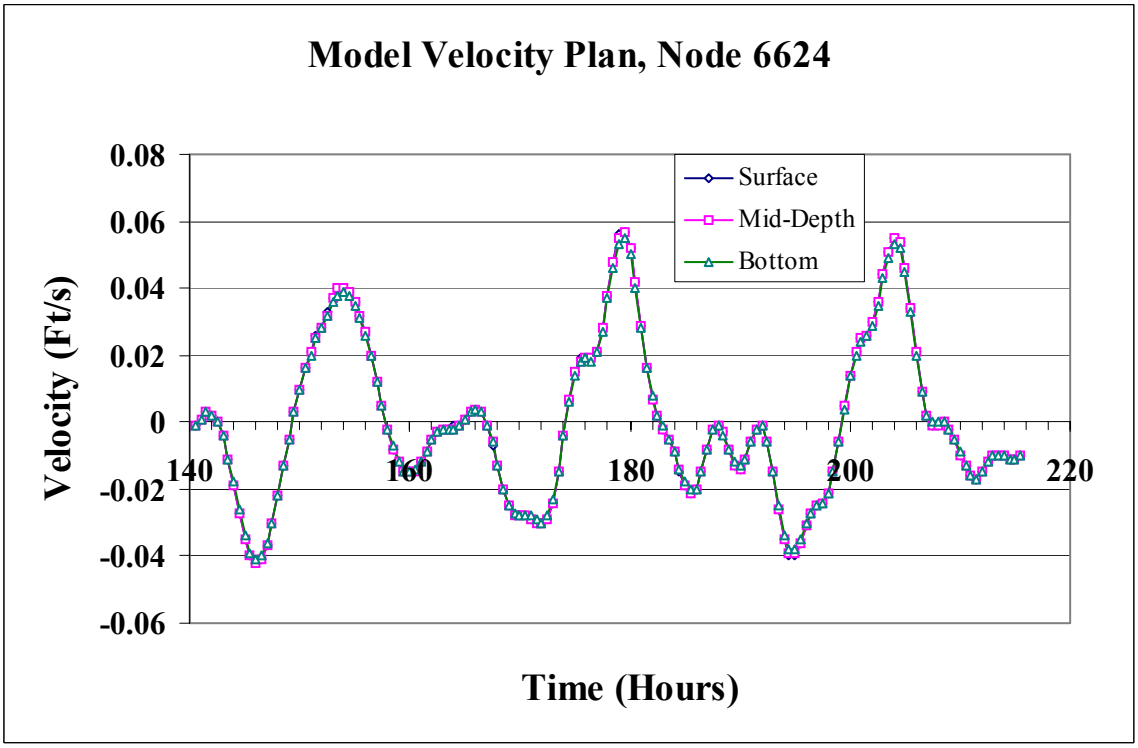

Model Velocity Base, Node 4841
Velocity (Ft/s)
0.3
0.2
0.1
0
-0.1
-0.2
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

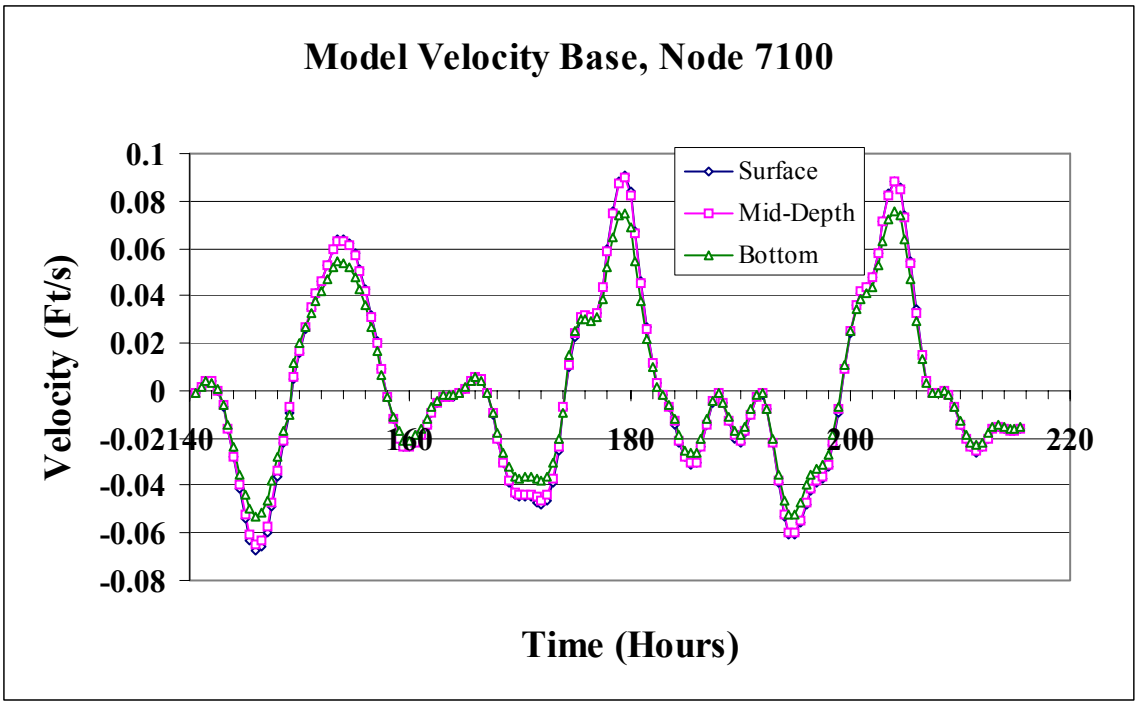

Model Velocity Plan, Node 5361
Velocity (Ft/s)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

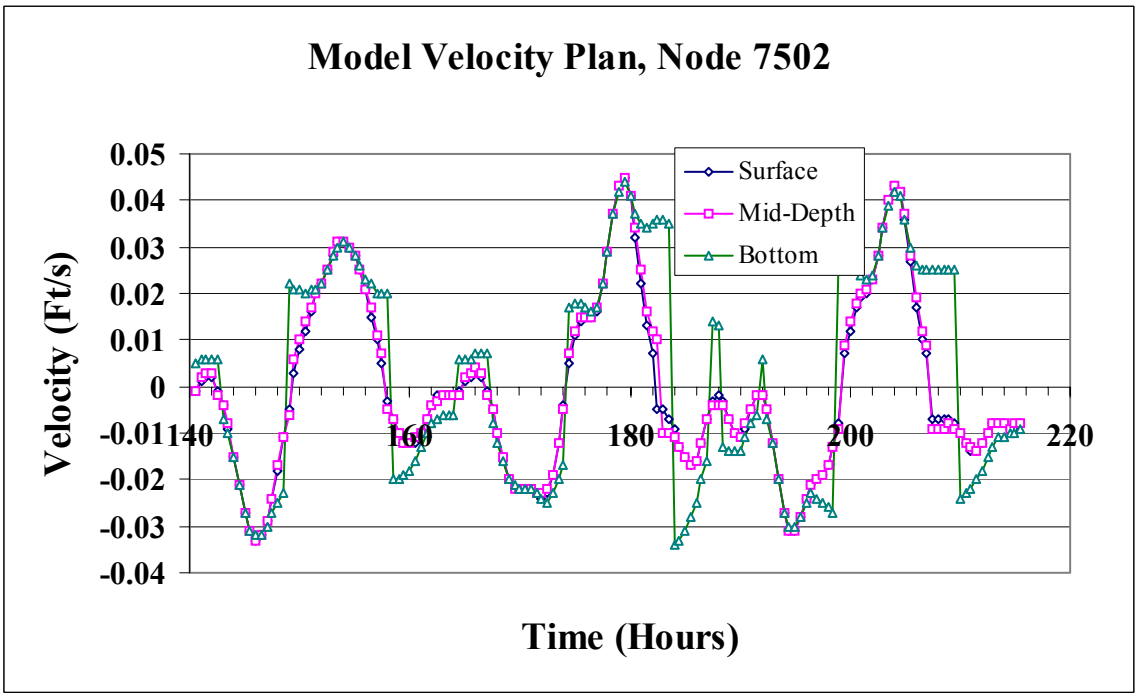

Model Velocity Base, Node 5669
Velocity (Ft/s)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

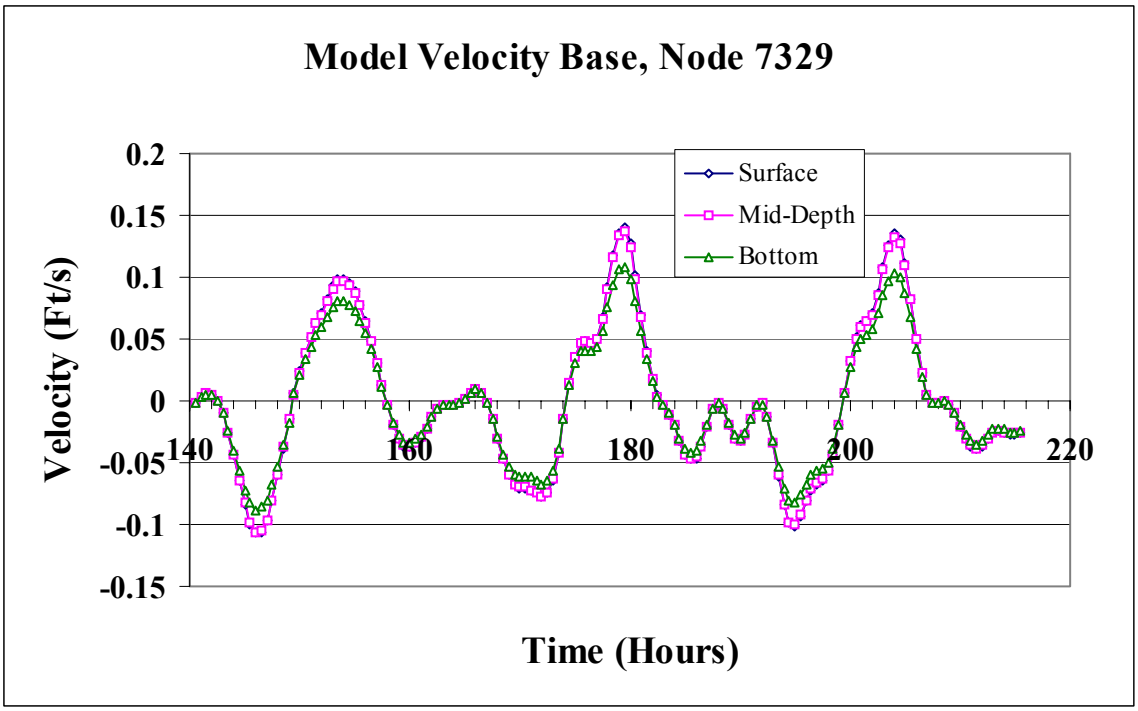

Model Velocity Plan, Node 5677
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

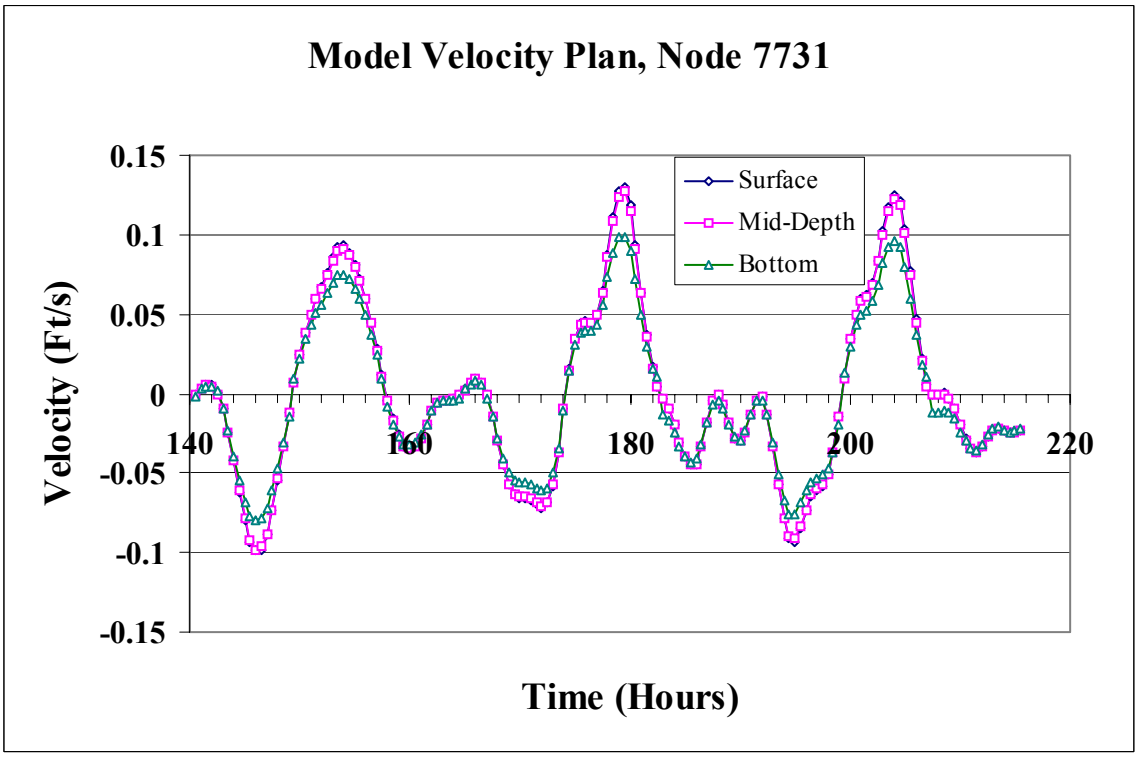

Model Velocity Base, Node 6389
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Surface
Mid-Depth
Bottom
Time (Hours)


Model Velocity Plan, Node 6624
Velocity (Ft/s)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
140
160
180
200
220
Surface
Mid-Depth
Bottom
Time (Hours)

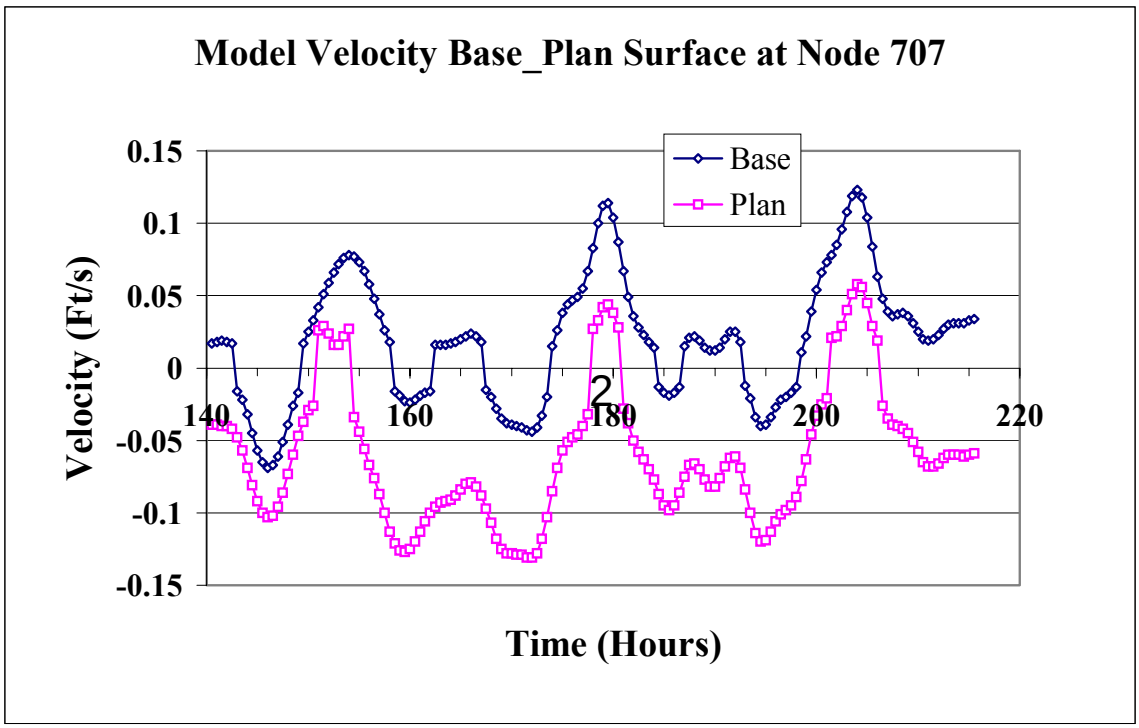

Model Velocity Base, Node 7100
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

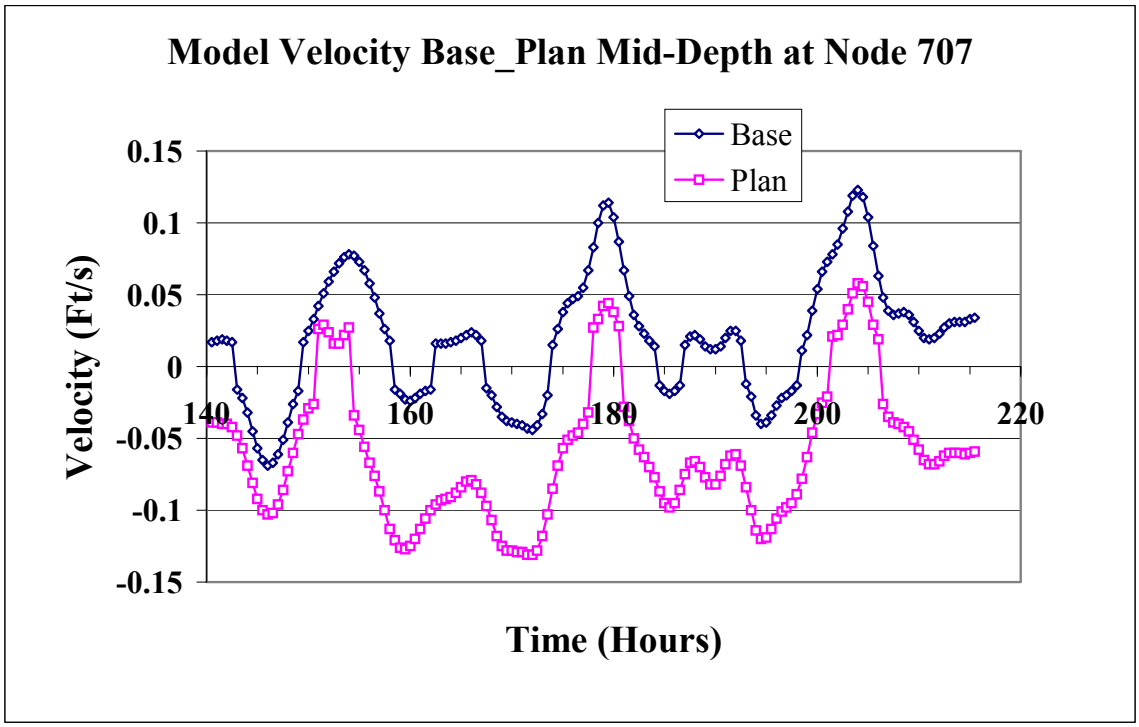

Model Velocity Plan, Node 7502
Velocity (Ft/s)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

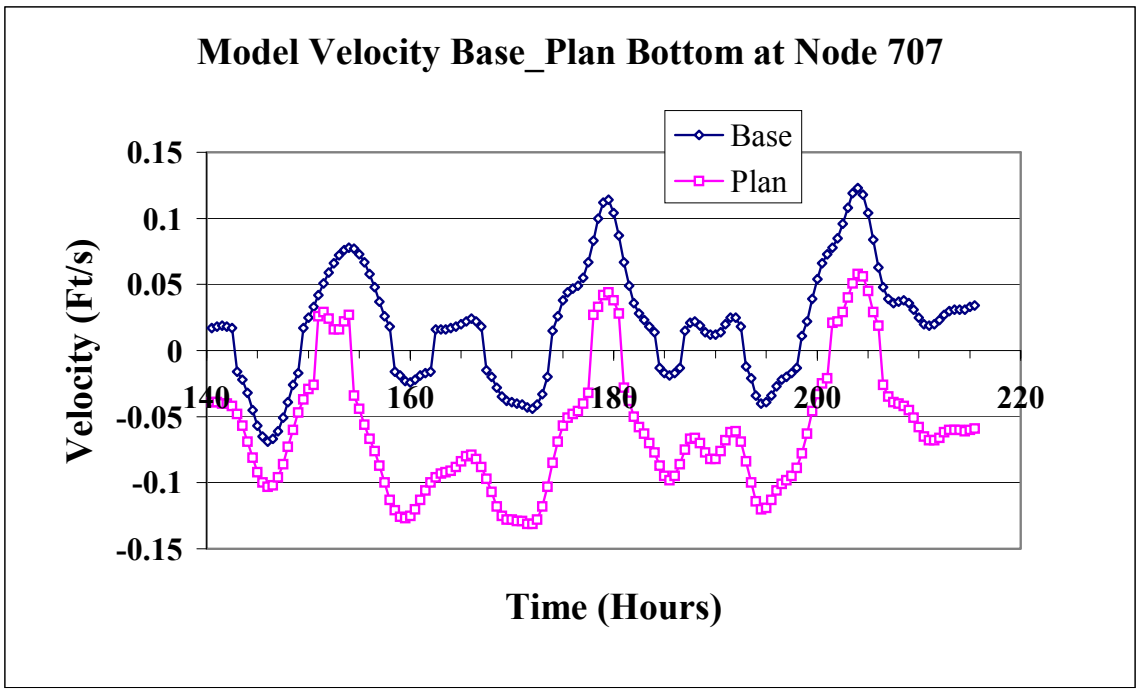

Model Velocity Base, Node 7329
Velocity (Ft/s)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

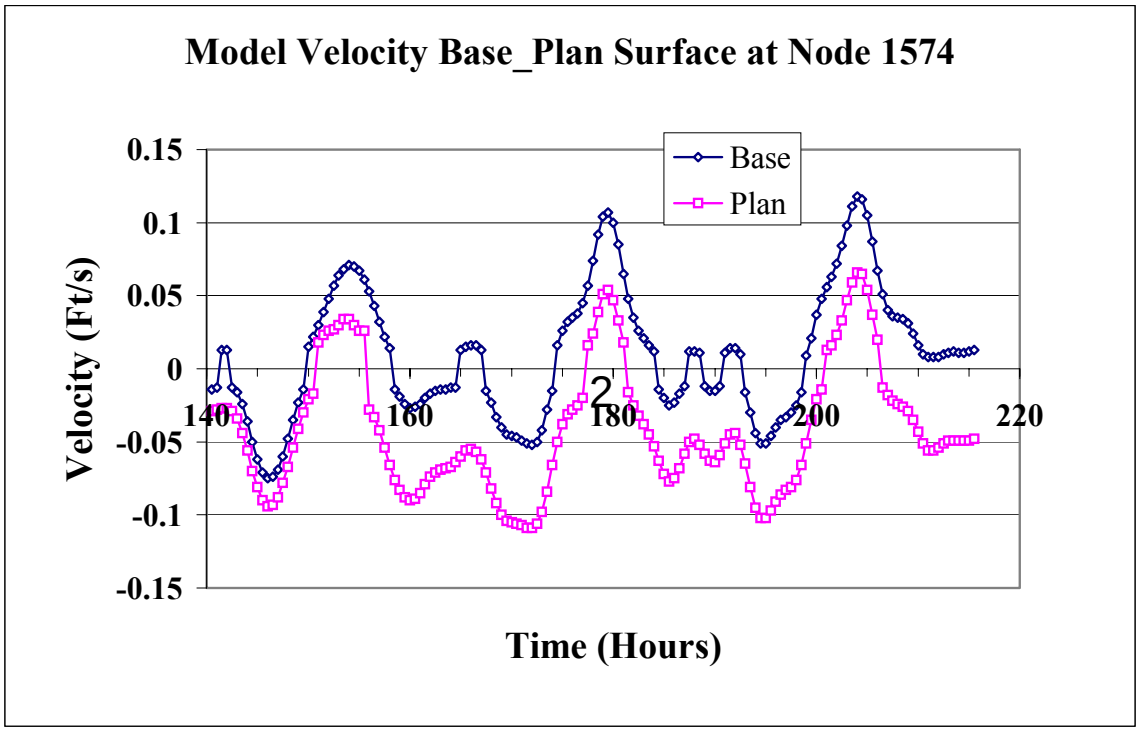

Model Velocity Plan, Node 7731
Velocity (Ft/s)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Time (Hours)
Surface
Mid-Depth
Bottom

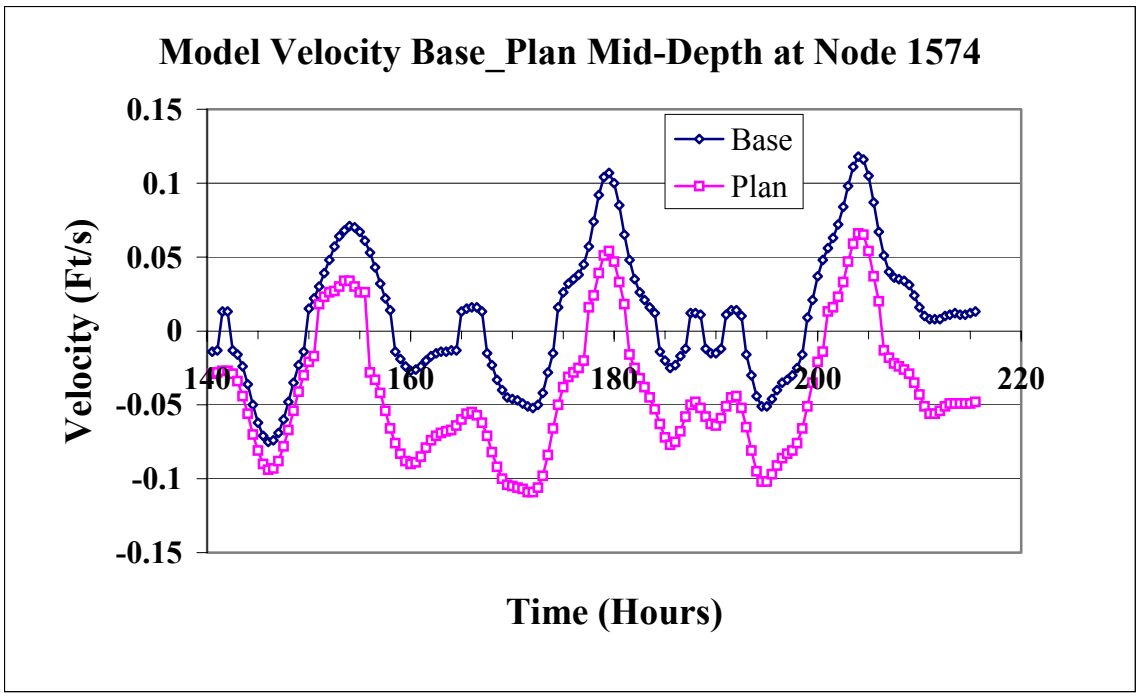
Appendix 5
Superposition of Base and Plan Velocities at Surface, Mid-Depth and Bottom
<u>From 3D Numerical Model</u>

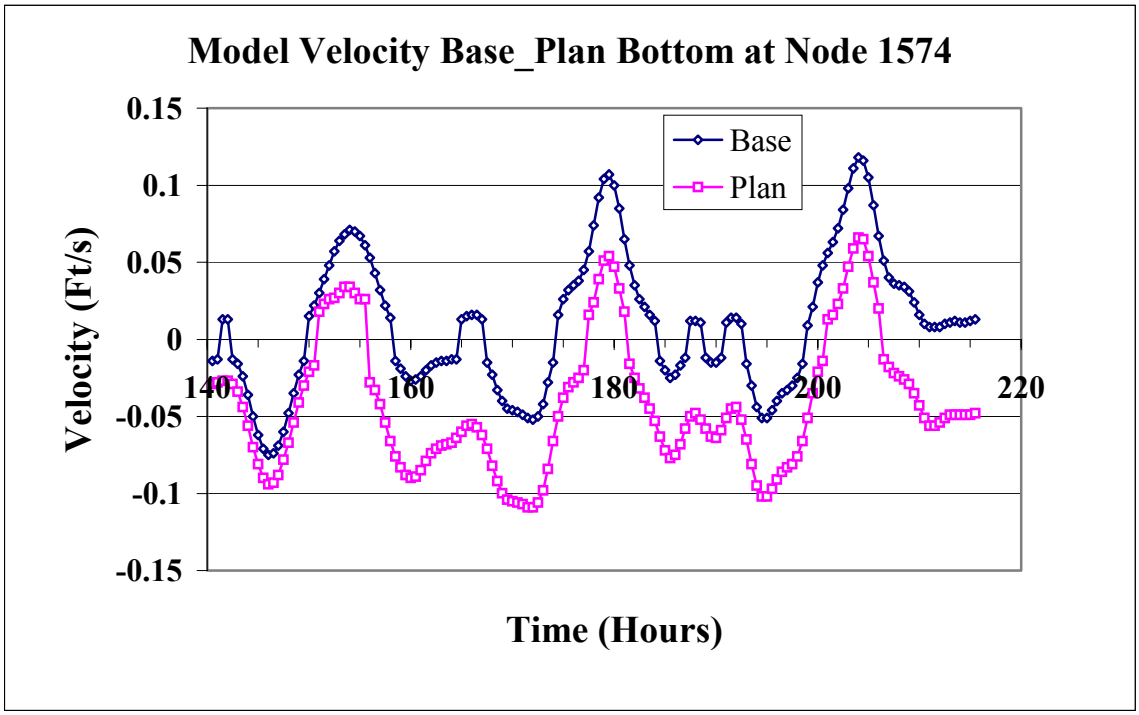

Model Velocity Base_Plan Surface at Node 707
Base
Plan
Velocity (Ft/s)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Time (Hours)

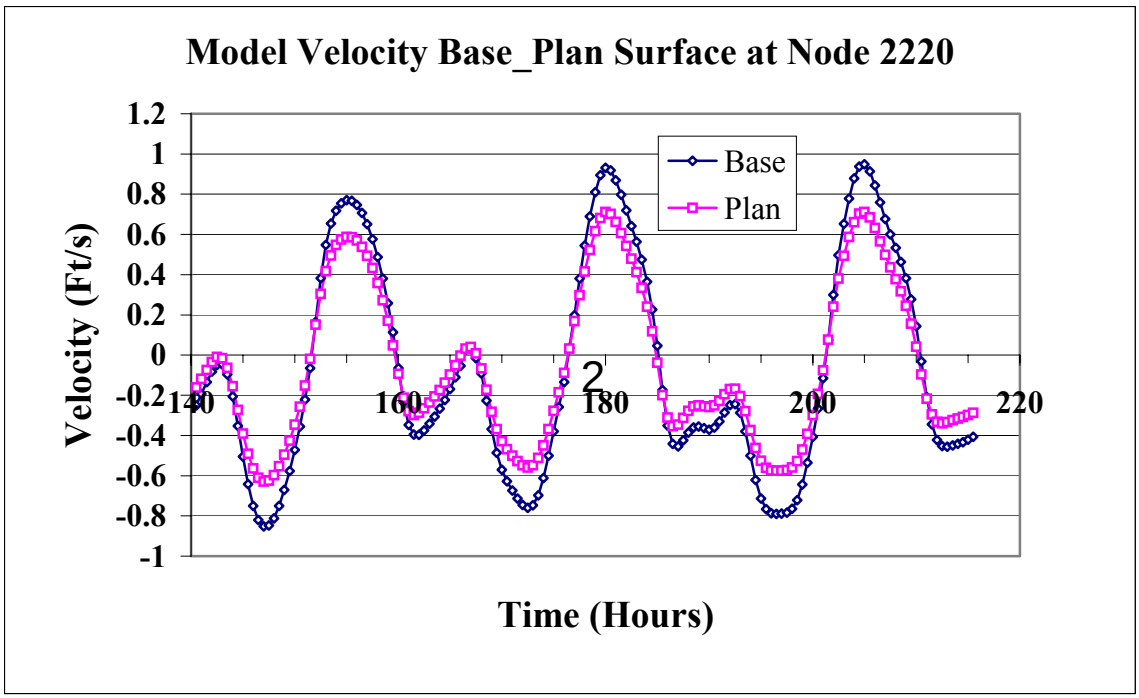

Model Velocity Base_Plan Mid-Depth at Node 707
Base
Plan
Velocity (Ft/s)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Time (Hours)

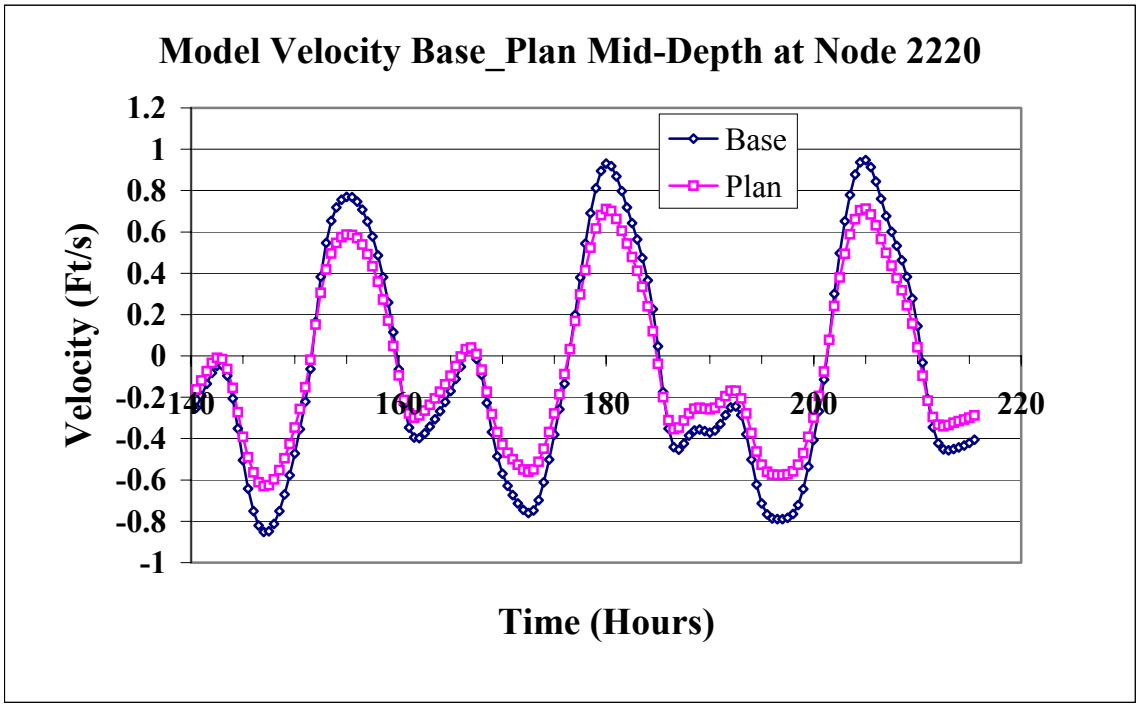

Model Velocity Base_Plan Bottom at Node 707
Base
Plan
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Velocity (Ft/s)
Time (Hours)

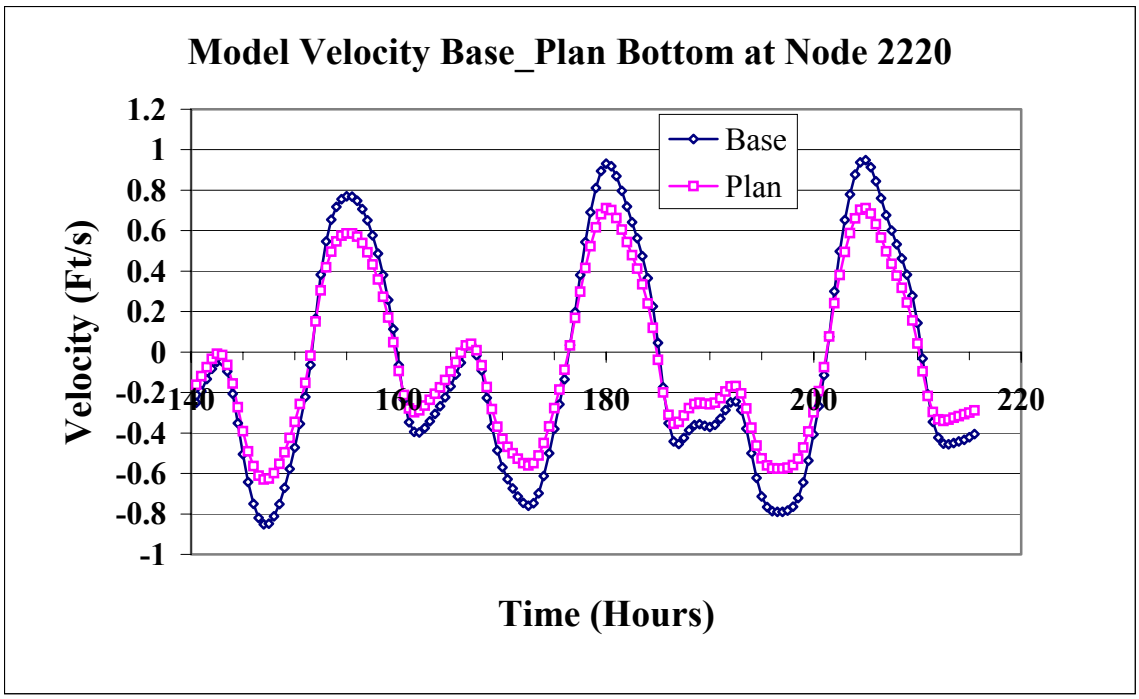

Model Velocity Base_Plan Surface at Node 1574
Base
Plan
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Velocity (Ft/s)
Time (Hours)

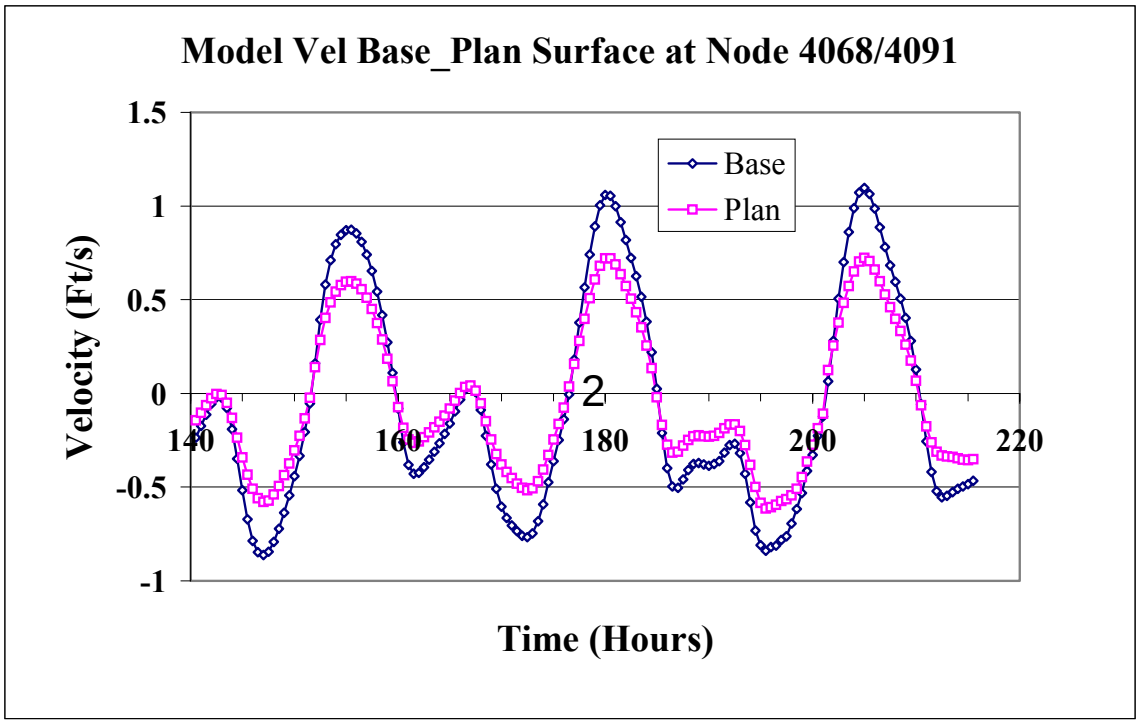

Model Velocity Base_Plan Mid-Depth at Node 1574
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Velocity (Ft/s)
140
160
180
200
220
Time (Hours)
Base
Plan

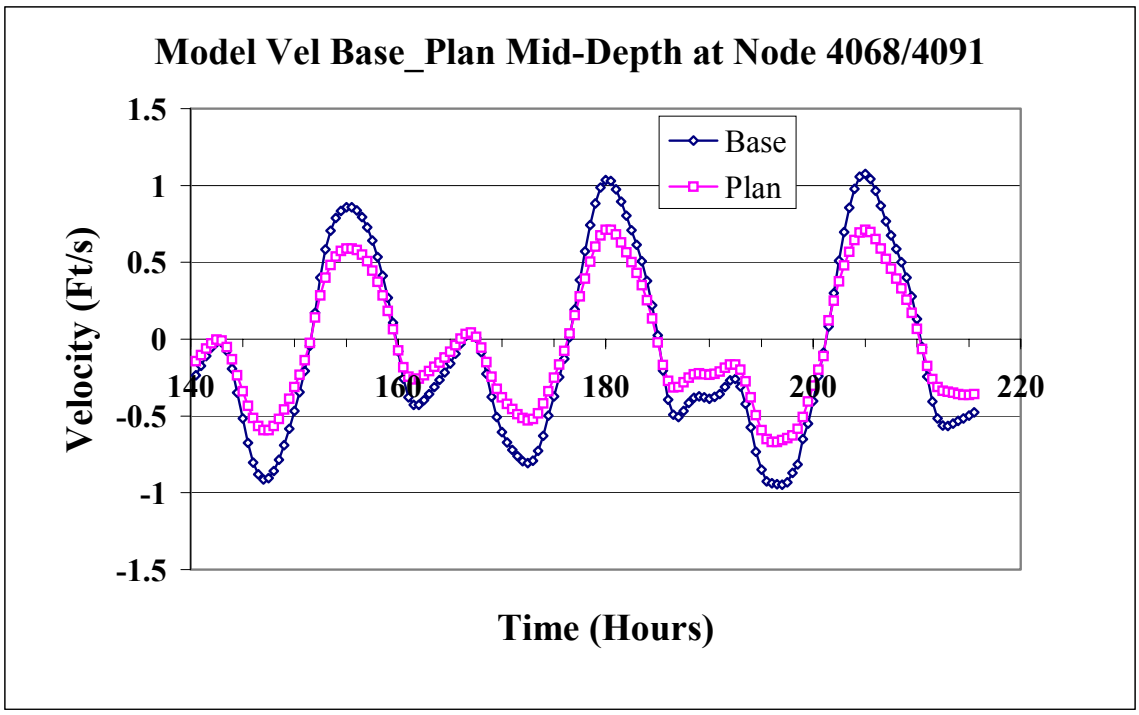

Model Velocity Base_Plan Bottom at Node 1574
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Velocity (Ft/s)
140
160
180
200
220
Time (Hours)
Base
Plan

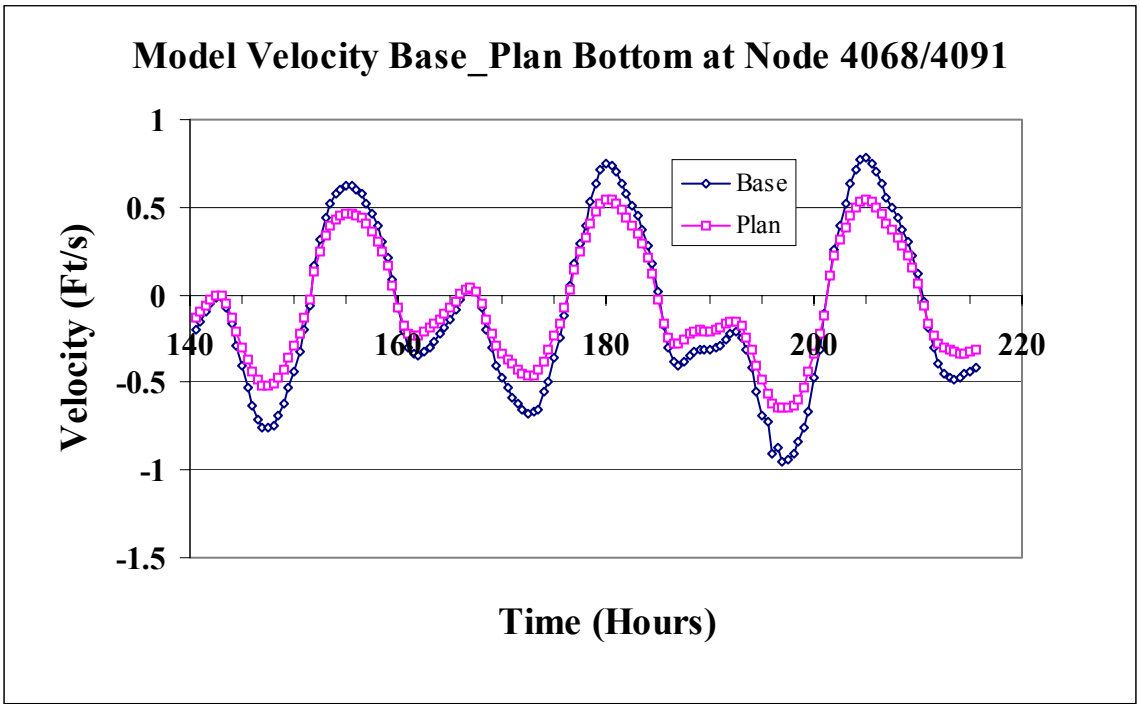

Model Velocity Base_Plan Surface at Node 2220
Velocity (Ft/s)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
140
160
180
200
220
Base
Plan
Time (Hours)

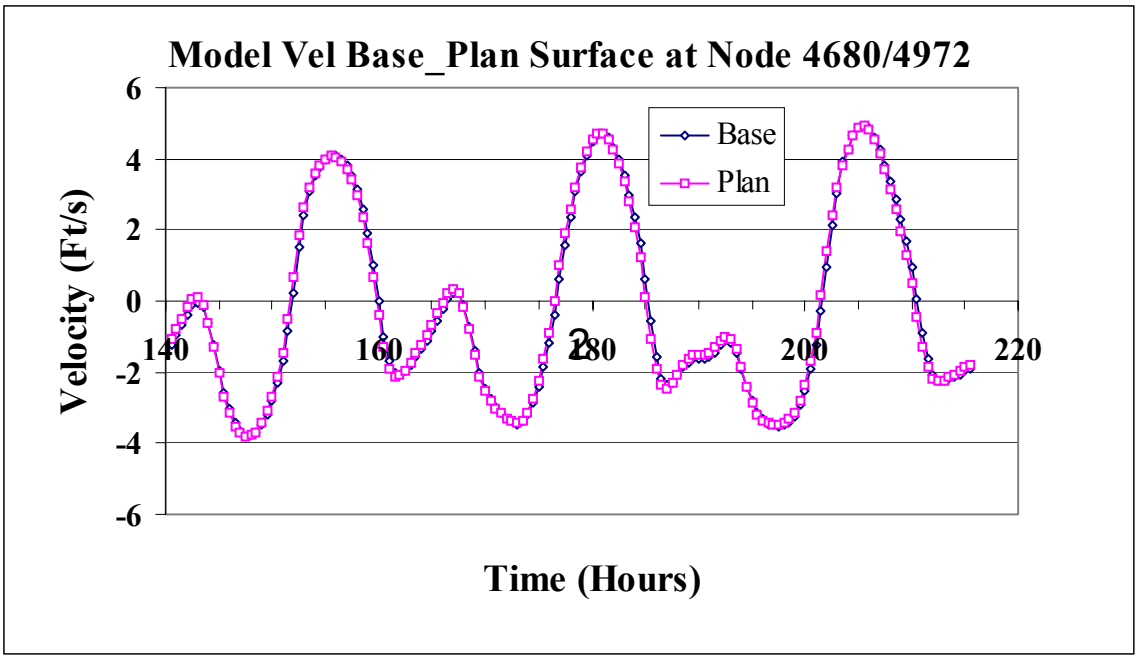

Model Velocity Base_Plan Mid-Depth at Node 2220
Velocity (Ft/s)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
140
160
180
200
220
Base
Plan
Time (Hours)

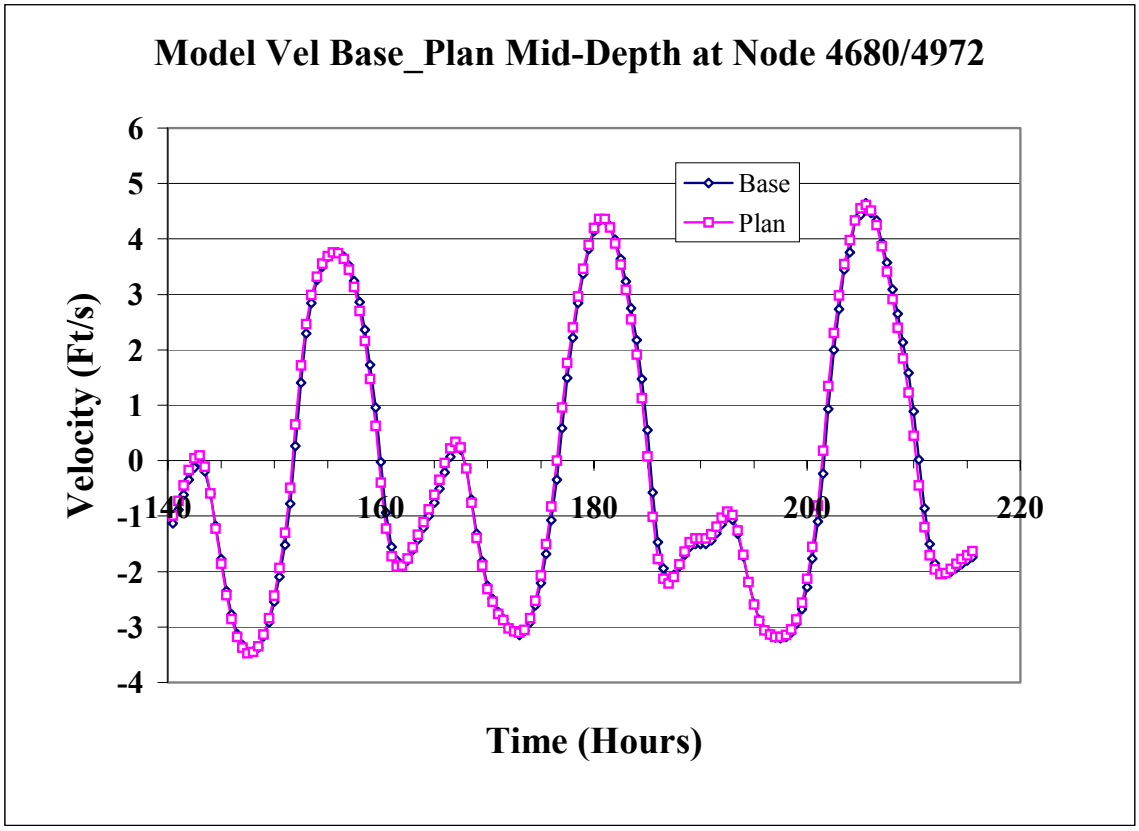

Model Velocity Base_Plan Bottom at Node 2220
Velocity (Ft/s)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
140
160
180
200
220
Base
Plan
Time (Hours)

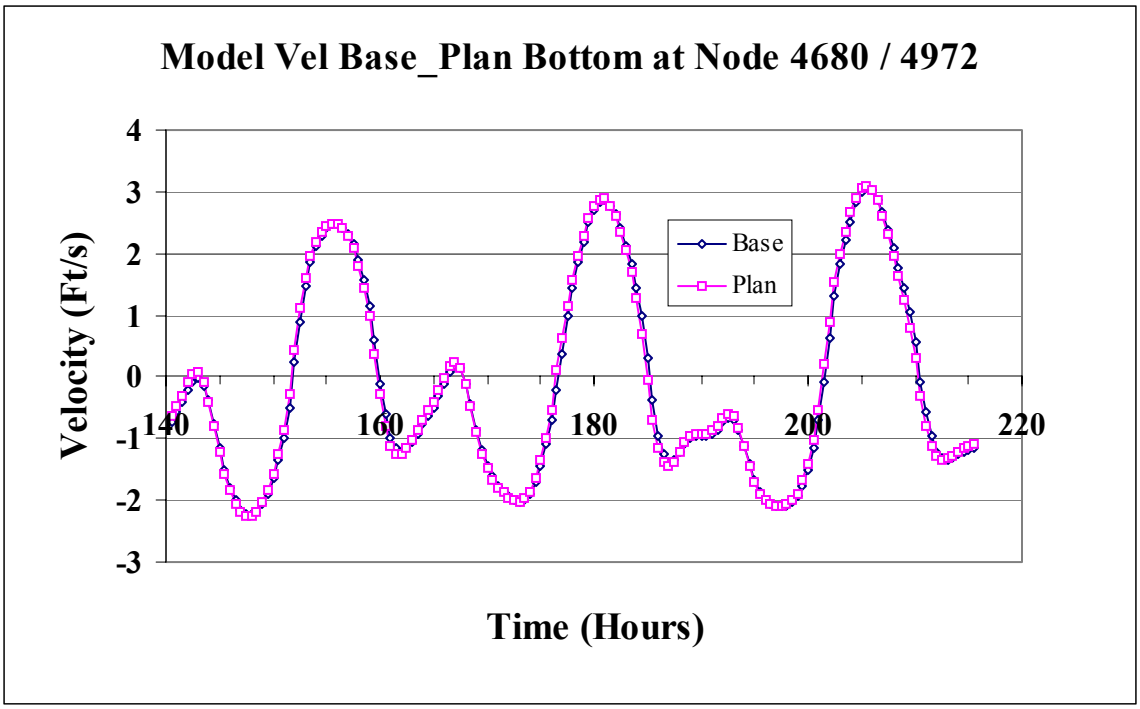

Model Vel Base_Plan Surface at Node 4068/4091
Velocity (Ft/s)
1.5
1
0.5
0
-0.5
-1
140
160
180
200
220
Base
Plan
Time (Hours)

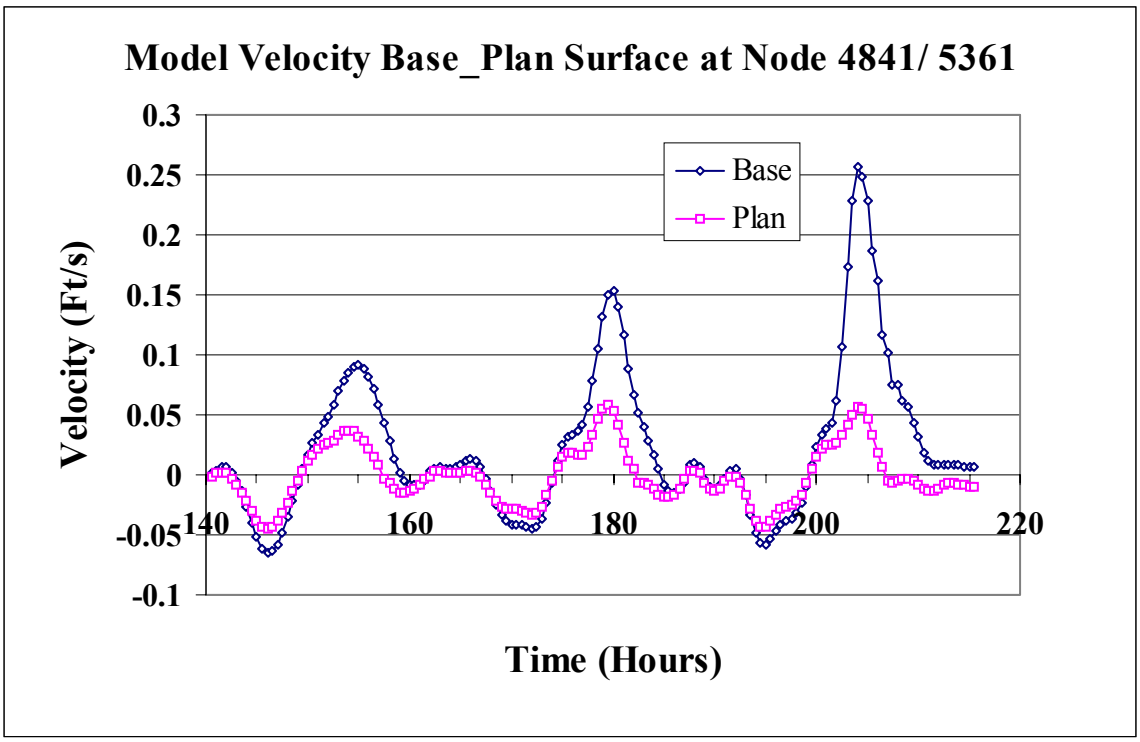

Model Vel Base_Plan Mid-Depth at Node 4068/4091
Velocity (Ft/s)
1.5
1
0.5
0
-0.5
-1
-1.5
140
160
180
200
220
Base
Plan
Time (Hours)

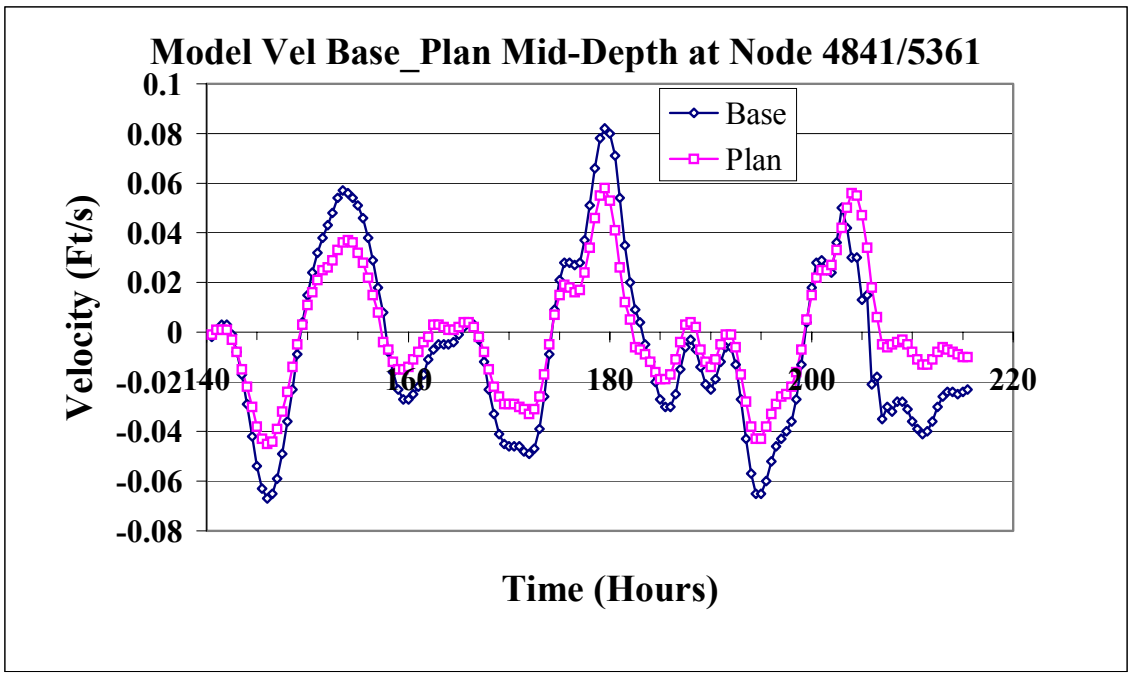

Model Velocity Base_Plan Bottom at Node 4068/4091
Velocity (Ft/s)
1
0.5
0
-0.5
-1
-1.5
140
160
180
200
220
Base
Plan
Time (Hours)

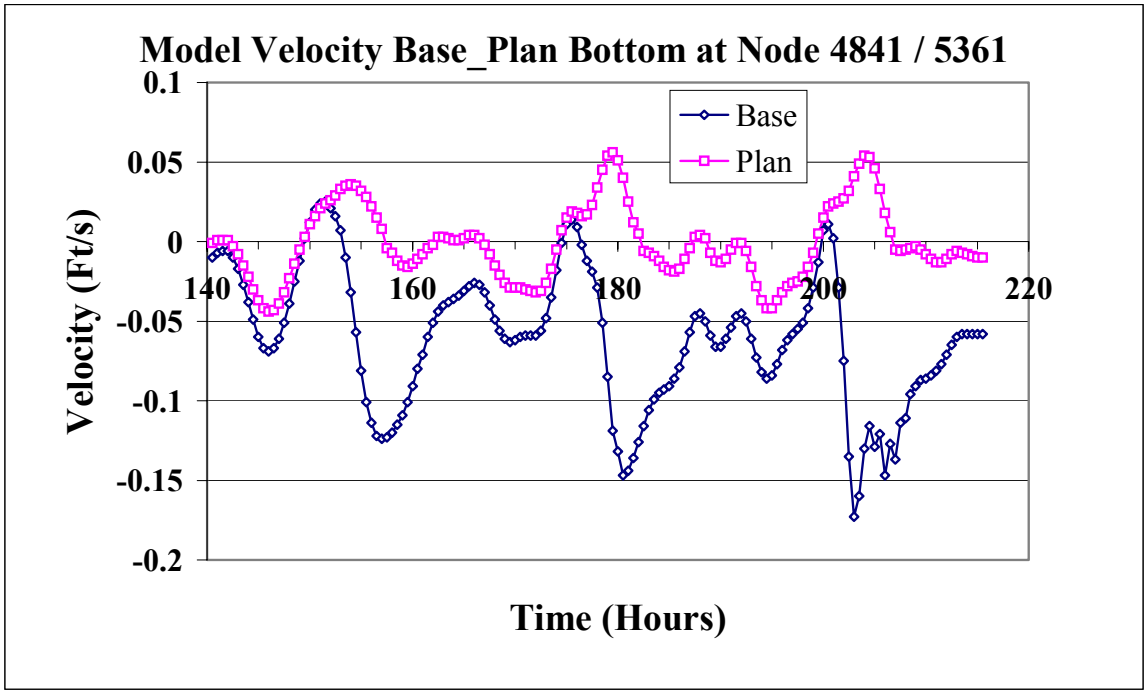

Model Vel Base_Plan Surface at Node 4680/4972
Velocity (Ft/s)
6
4
2
0
-2
-4
-6
140
160
180
200
220
Base
Plan
Time (Hours)

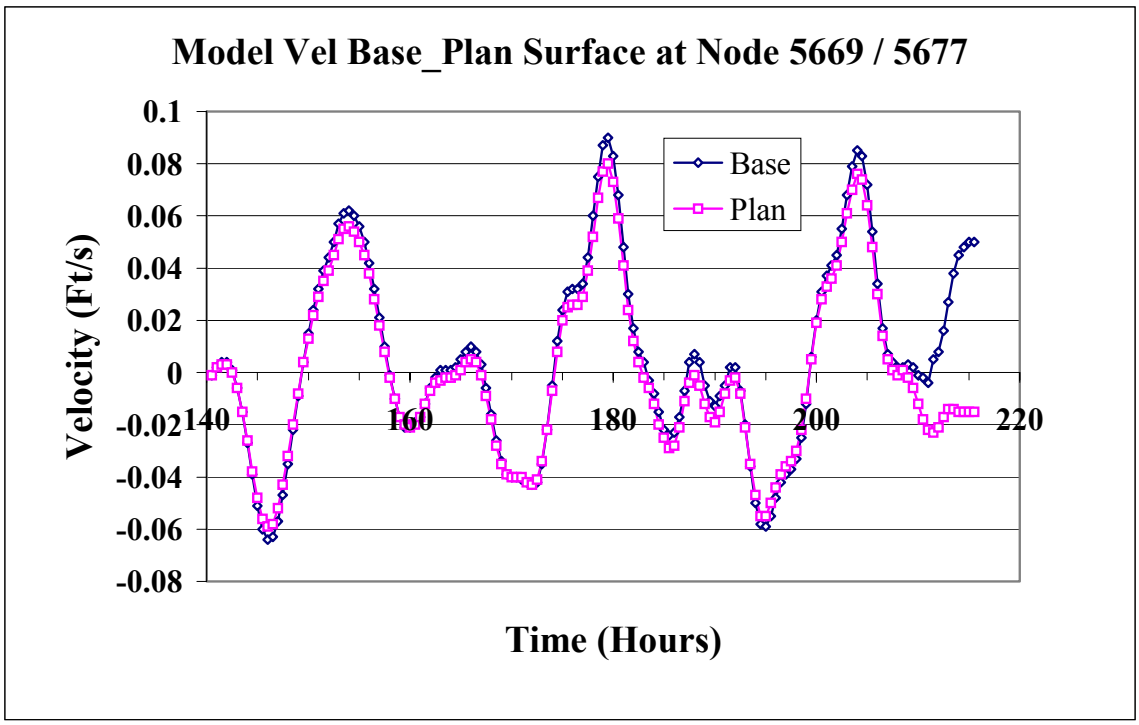

Model Vel Base_Plan Mid-Depth at Node 4680/4972
Velocity (Ft/s)
6
5
4
3
2
1
0
-1
-2
-3
-4
140
160
180
200
220
Base
Plan
Time (Hours)

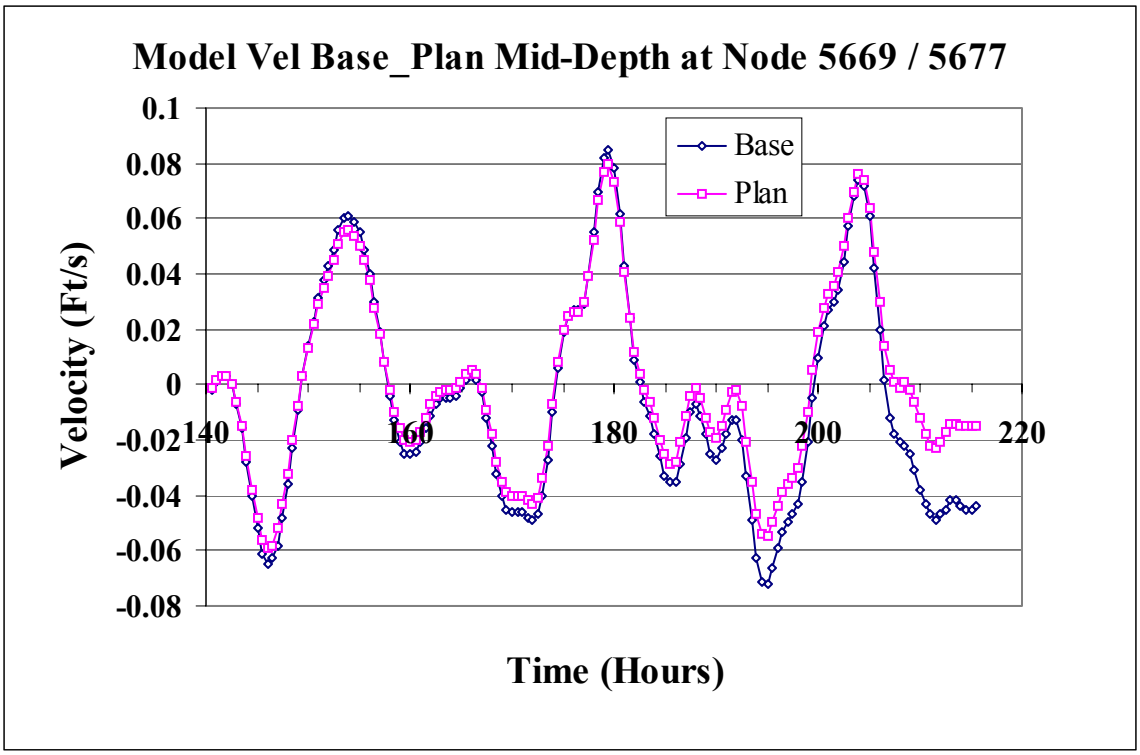

Model Vel Base_Plan Bottom at Node 4680 / 4972
Velocity (Ft/s)
4
3
2
1
0
-1
-2
-3
140
160
180
200
220
Base
Plan
Time (Hours)

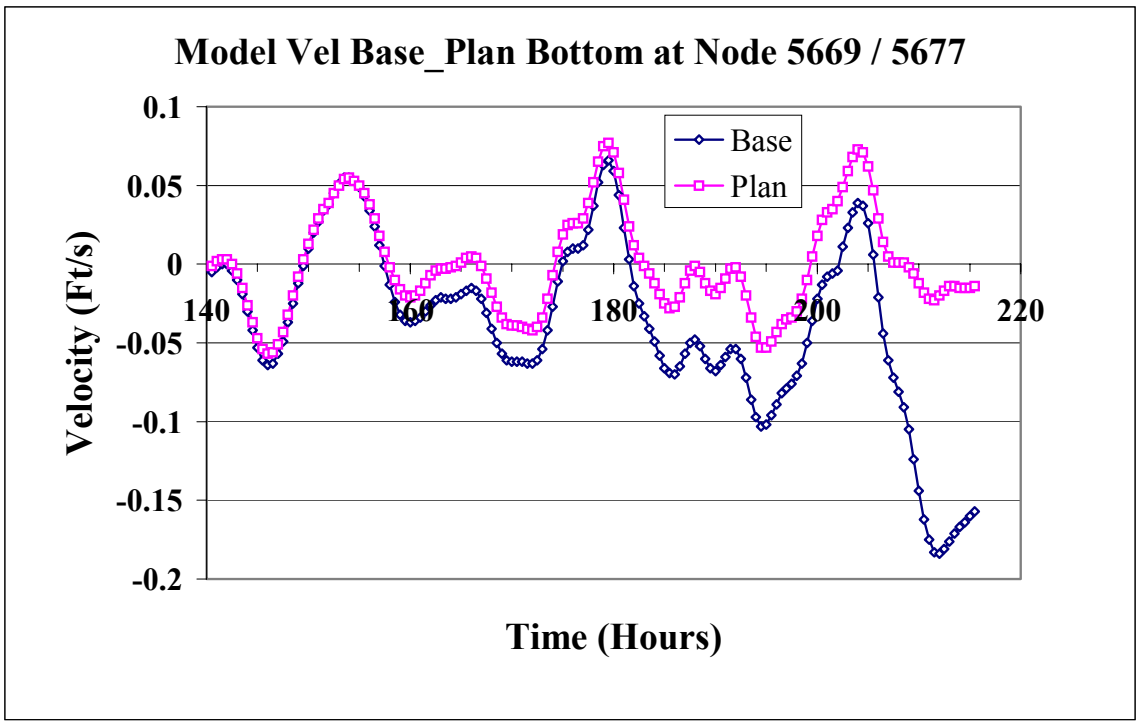

Model Velocity Base_Plan Surface at Node 4841/ 5361
Velocity (Ft/s)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
140
160
180
200
220
Base
Plan
Time (Hours)

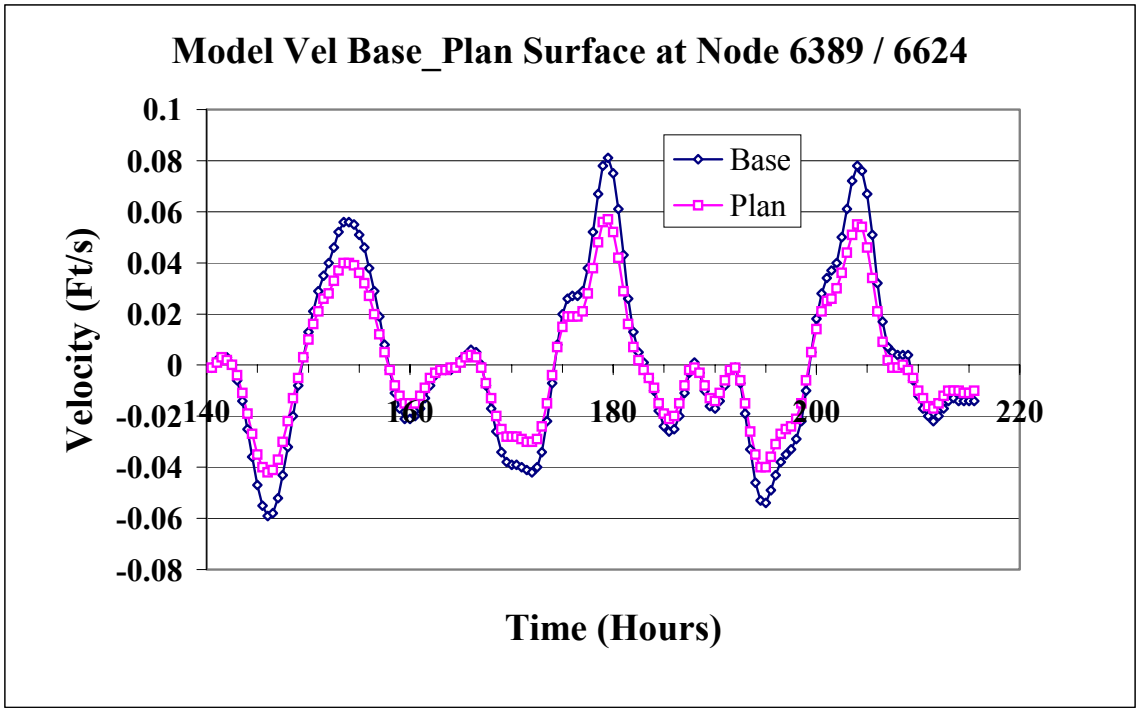

Model Vel Base_Plan Mid-Depth at Node 4841/5361
Base
Plan
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)

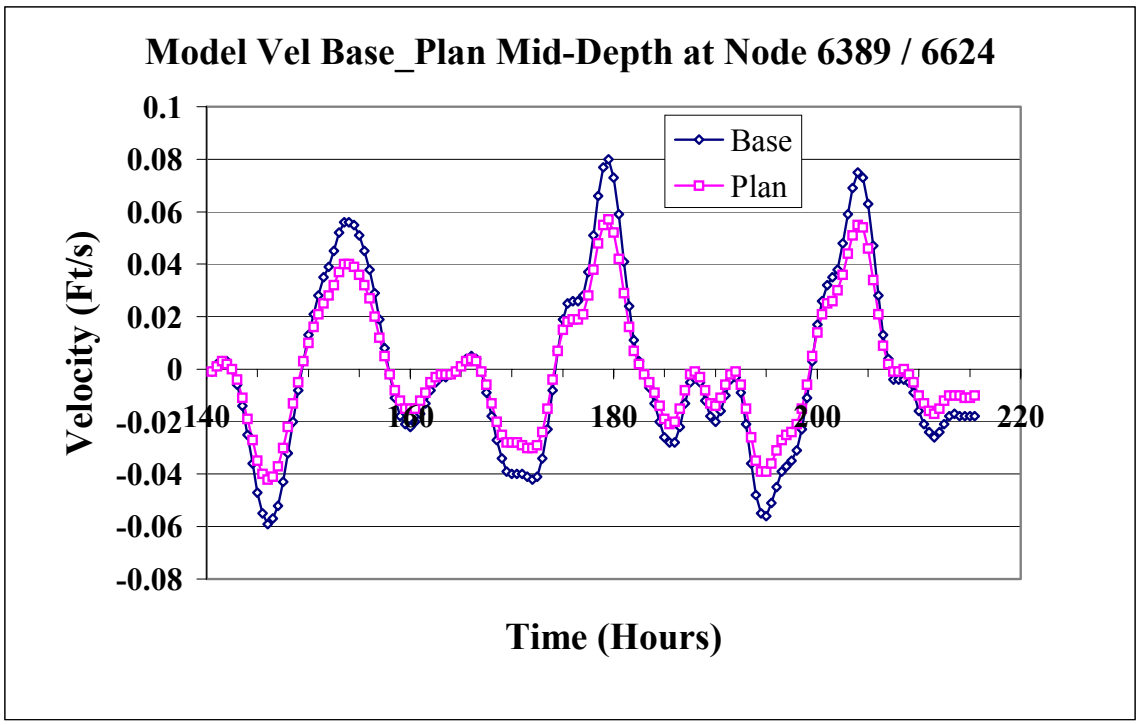

Model Velocity Base_Plan Bottom at Node 4841 / 5361
Base
Plan
Velocity (Ft/s)
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
140
160
180
200
220
Time (Hours)

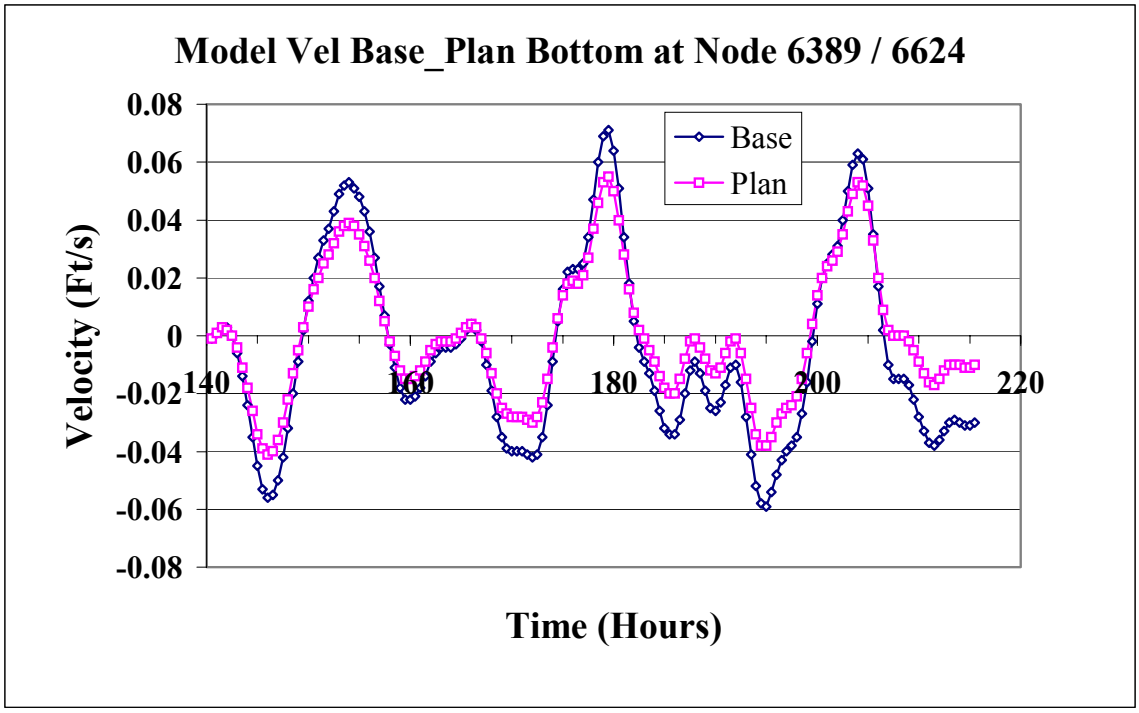

Model Vel Base_Plan Surface at Node 5669 / 5677
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Base
Plan

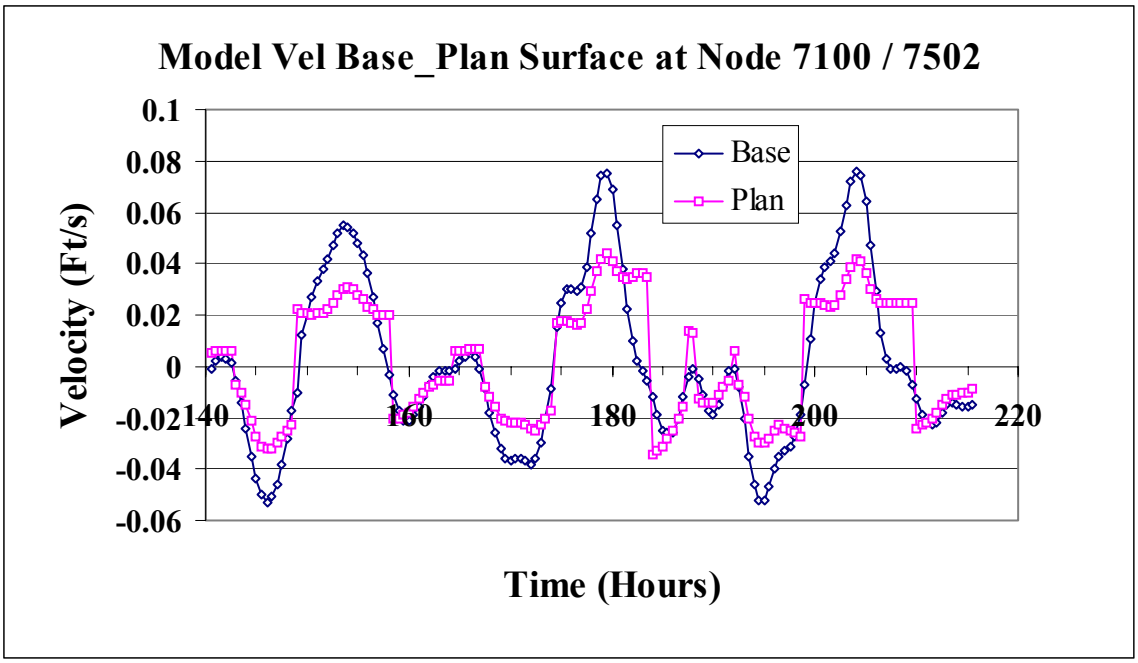

Model Vel Base_Plan Mid-Depth at Node 5669 / 5677
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Base
Plan

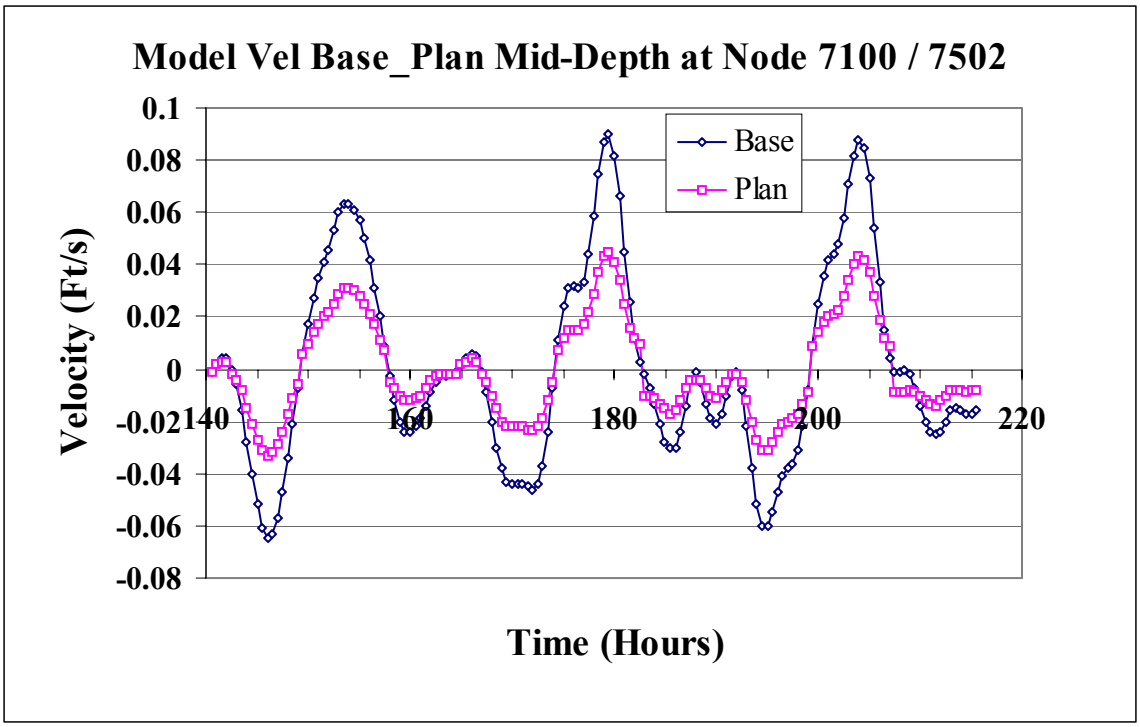

Model Vel Base_Plan Bottom at Node 5669 / 5677
Velocity (Ft/s)
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
140
160
180
200
220
Time (Hours)
Base
Plan

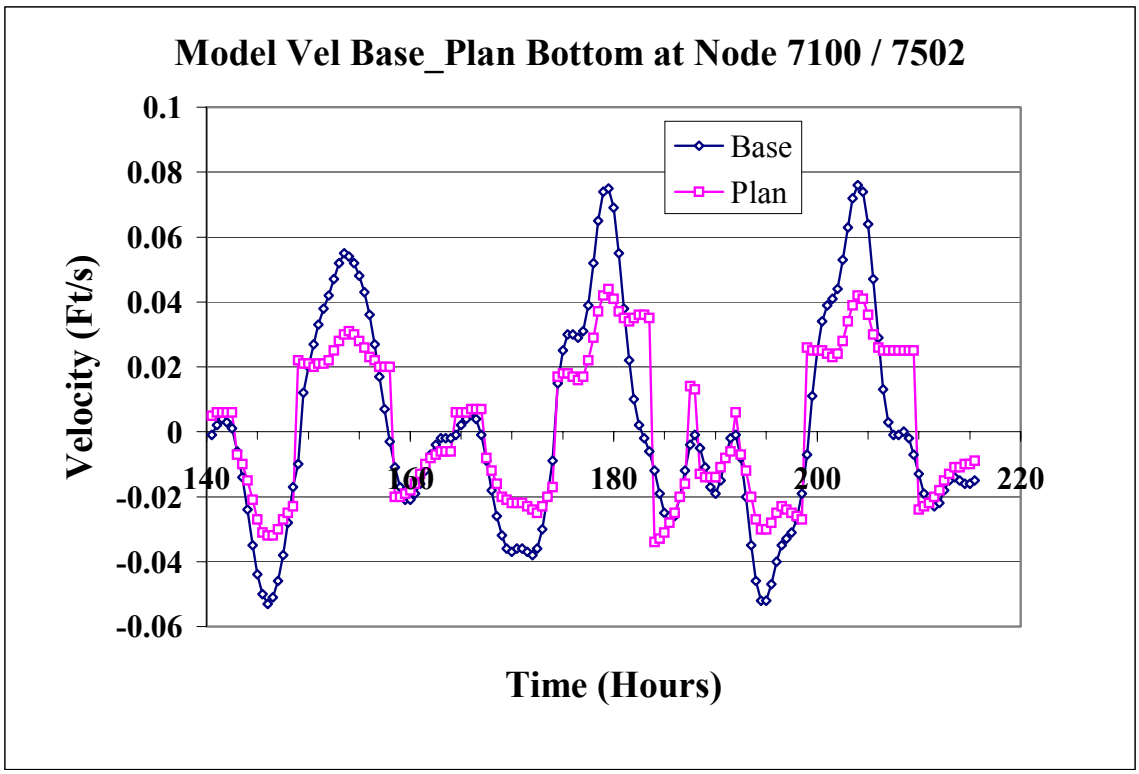

Model Vel Base_Plan Surface at Node 6389 / 6624
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Base
Plan

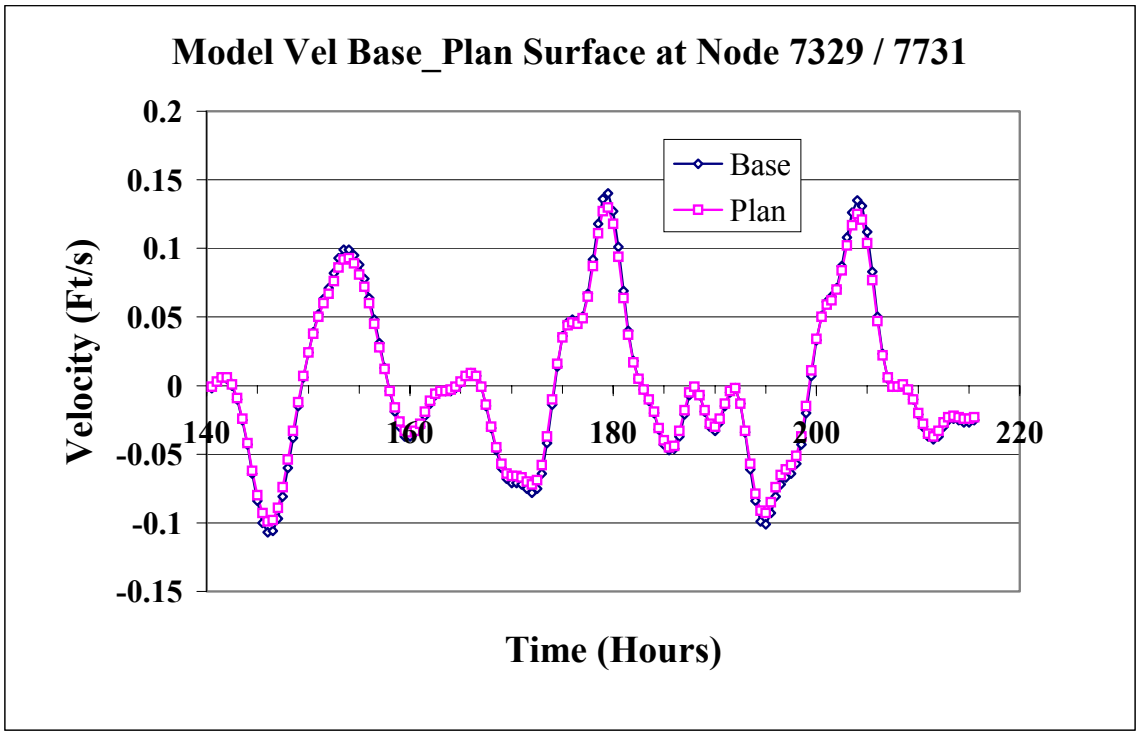

Model Vel Base_Plan Mid-Depth at Node 6389 / 6624
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Base
Plan

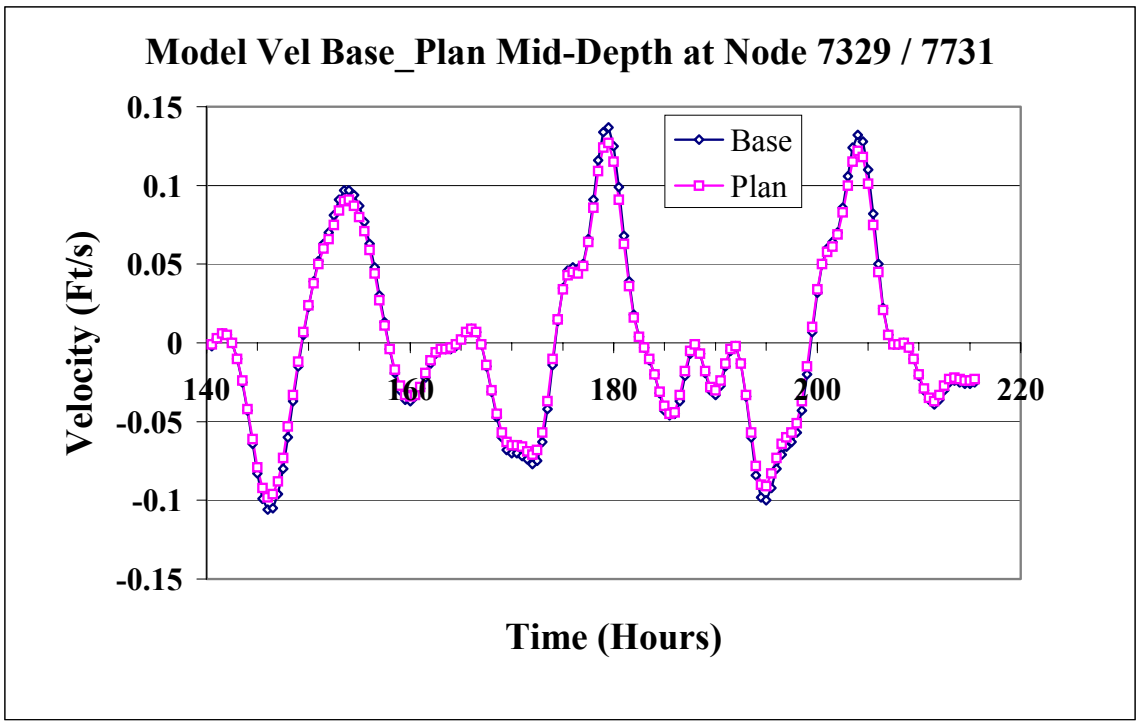

Model Vel Base_Plan Bottom at Node 6389 / 6624
Velocity (Ft/s)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Base
Plan

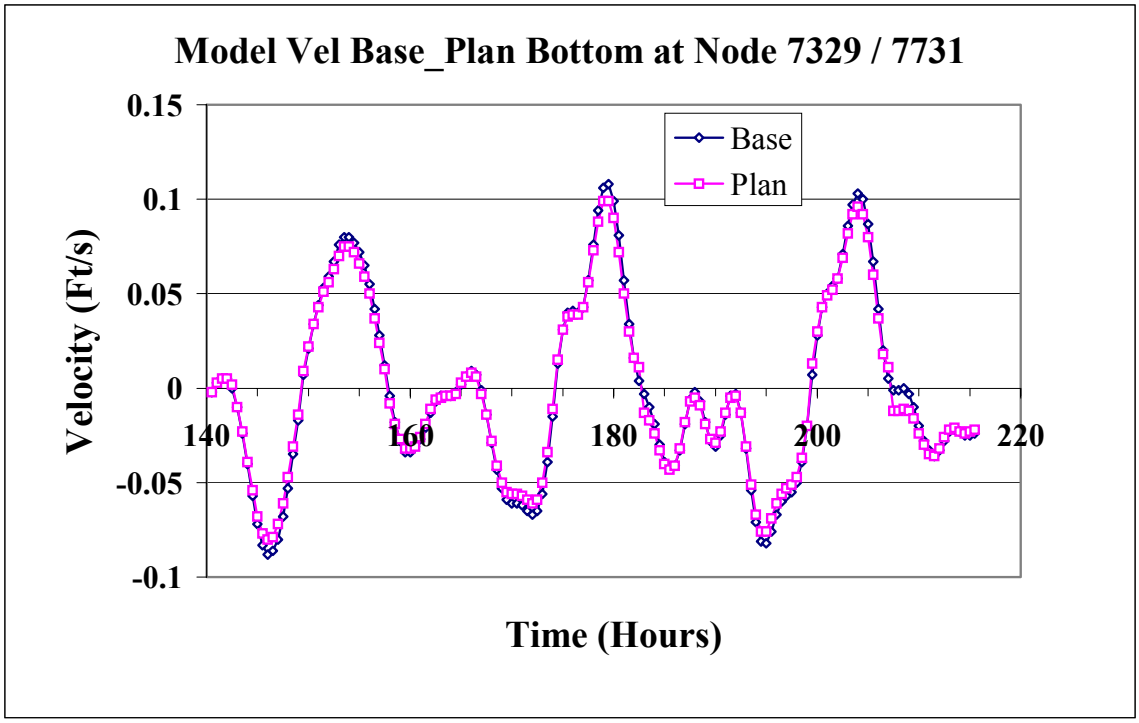

Model Vel Base_Plan Surface at Node 7100 / 7502
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
140
160
180
200
220
Time (Hours)
Base
Plan


Model Vel Base_Plan Mid-Depth at Node 7100 / 7502
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
140
160
180
200
220
Time (Hours)
Base
Plan


Model Vel Base_Plan Bottom at Node 7100 / 7502
Velocity (Ft/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
140
160
180
200
220
Time (Hours)
Base
Plan


Model Vel Base_Plan Surface at Node 7329 / 7731
Velocity (Ft/s)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
140
160
180
200
220
Time (Hours)
Base
Plan


Model Vel Base_Plan Mid-Depth at Node 7329 / 7731
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Velocity (Ft/s)
140
160
180
200
220
Time (Hours)
Base
Plan


Model Vel Base_Plan Bottom at Node 7329 / 7731
0.15
0.1
0.05
0
-0.05
-0.1
Velocity (Ft/s)
140
160
180
200
220
Time (Hours)
Base
Plan