Bayport Flare Hydrodynamic Study for Ship Simulation

Jennifer N. Tate and Cassandra G. Ross

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

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Abstract

The Bayport flare area of the Houston Ship Channel is a large deep zone of approximately 72 acres designed for deep draft vessels to safely make the turn in and out of the Bayport Channel. These turns require multiple-tug assist, but engineered modifications to the flare could make turning easier and improve navigational safety in the area. However, this deep area acts as a sediment trap due to local velocity patterns, so modification plans to improve navigation should also consider the potential impacts to shoaling.

The US Army Engineer District, Galveston (SWG) requested the Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) to perform hydrodynamic modeling of several plan alternatives to provide data for ship simulation studies in which pilots will test the navigational effects of these plans. Ship simulation was the primary focus of the hydrodynamic modeling, but sediment simulations were also performed. These modeling scenarios will provide information on how the proposed modifications to the Bayport flare will impact current velocities and sedimentation in the area.
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Preface

The model investigation presented in this report was authorized and funded by the US Army Corps of Engineers, Galveston District, under Military Interdepartmental Purchase Request MIPRW45VAK13324247, “ERDC Bend Easing Hydrodynamic Study,” dated 2 December 2011. The study was conducted by Ms. Jennifer Tate (Coastal and Hydraulics Laboratory) and Ms. Cassandra Ross (Contractor). Field data were collected by Mr. Chris Callegan, Mr. Charles Ellis, Mr. Mike Kirklin, Mr. Thad Pratt, Mr. Tommy Kirklin, and Mr. Trey Davis (all of Coastal and Hydraulics Laboratory).

The work was performed at the Coastal and Hydraulics Laboratory, US Army Engineer Research and Development Center (ERDC-CHL), Vicksburg, MS, under the general direction of Dr. William D. Martin, Director; and Mr. Jose Sanchez, Deputy Director, ERDC-CHL. Direct supervision was provided by Mr. Bruce A. Ebersole, Chief, Flood and Storm Protection Division (CEERD-HF); Dr. Robert McAdory, Chief, Estuarine Engineering Branch (CEERD-HF-E); and Mr. Pat McKinney, Chief, Field Data Collection and Analysis Branch (CEERD-HF-F).

COL Kevin J. Wilson was Commander and Executive Director of ERDC and Dr. Jeffery P. Holland was Director.
# Unit Conversion Factors

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1 Introduction

Background

The Bayport flare is the area where the Houston Ship Channel joins the Bayport Channel approximately 20 miles north of Bolivar Roads at the Gulf of Mexico. This area is composed of a large, deep zone of approximately 72 acres in order for deep draft vessels to safely make the turn in and out of the Bayport Channel. Currently, these turns require multiple tug assist. Modifications to the size of the Bayport flare have the potential to improve the turning capabilities and navigational safety in this area. However, this deep area acts as a sediment trap due to the velocity patterns in the area. Although these modifications to the flare are for navigational operation, the impacts to shoaling should also be considered.

The US Army Corps of Engineers (USACE), Galveston District (SWG) requested the Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) to perform hydrodynamic modeling of several plan alternatives to provide data for ship simulation studies in which pilots are able to test the navigational effects of these plans. Ship simulation was the primary focus of this research. However, in addition to the hydrodynamic modeling effort, sediment simulations were performed as a secondary effort. These modeling scenarios will provide information on how the proposed modifications to the Bayport flare will impact current velocities and sedimentation in the area.

Objective

The objective of this study was to develop a hydrodynamic numerical model of the Bayport flare and surrounding area to test proposed modifications to the flare geometry to ease vessel maneuvering in the area. Further analysis also was performed to determine how the proposed modifications would impact shoaling in the flare.

Approach

The Houston Ship Channel area has been studied by ERDC-CHL in several previous efforts. Berger et al. (1995) performed a model validation and analysis for hydrodynamics and salinity. This study included plan alternatives for enlarging the Houston Ship Channel. Carrillo et al. (2002) used
the previously validated model to study the effects of adding barge lanes along the Houston Ship Channel. Tate et al. (2006) looked into possible reasons for increased shoaling in the ship channel by analyzing vessel effects and sediment properties in the area. In Tate et al. (2008), the sediment model was validated using the same hydrodynamic model, and the results included the effects of vessel transport on the sedimentation patterns.

This study utilizes the previously validated TABS-MDS model that includes the Galveston Bay, Trinity Bay, and Houston Ship Channel (Berger et al. 1995). Figure 1-1 shows the area of interest. The model domain includes the area from the Gulf of Mexico to the head of tides, or the location farthest upstream that is affected by tidal fluctuations, near Houston. The previous model was validated for sediment to the bay areas between approximately Red Fish Reef and Morgan’s Point, whereas the hydrodynamics and salinity were validated to areas from the entrance at Bolivar Roads to the Tabb’s Bay area upstream of Morgan’s Point. The area of the model domain north of Morgan’s Point is included for tidal storage in order to ensure accurate velocities and discharges in the study area.
The model was modified to include newly collected bathymetry data in the Bayport flare and surrounding area as well as higher mesh resolution in the flare and Bayport Channel. Additional velocity and discharge data were collected along the Houston Ship Channel and the Bayport Channel in order to ensure accurate representation of the current velocity magnitudes and directions in the model.

The model was run using data collected in 2010. The hydrodynamic model is initially run to provide data to the ERDC Ship/Tow Simulator\(^1\) for pilot analysis. A vessel transport simulation was performed so that the effects of the vessel movement could be included in the sediment model simulations for each plan alternative. Using these simulation results for each plan, the sediment model was run, coupling the hydro results with the vessel results

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in order to determine the combined effects on the shoaling patterns in the flare and surrounding area.

Chapter 2 discusses the modification made to the previous model based on field data comparisons and the purpose of this study. It also defines the boundary conditions for the hydrodynamic and sediment model. Chapter 3 documents the field data comparisons for the model check, including discharges and velocity magnitudes and direction, in both two and three dimensions. Chapter 4 focuses on the plan alternatives and the comparisons of these modifications to the Base (or present) condition for hydrodynamics and sedimentation. Chapter 5 provides the conclusions of this modeling study.
2 Model Development

A numerical model was developed to analyze the alternative plans for any changes to the Bayport flare area and to provide hydrodynamic data for ship simulation studies. The model was developed such that the natural driving forces of the system are included – winds, tides, salinity, freshwater inflows, and friction effects. The model is compared to field data collected during the simulation period to ensure an accurate representation of nature. The validated model was then applied to determine how any navigation infrastructure changes affect the hydrodynamics and sediment transport within the area.

Numerical model

The TABS-MDS code was used for the design alternatives tested under this study. Full details of the code are given in Appendix A. TABS-MDS is a two-dimensional/three-dimensional (2D/3D) finite-element code that simulates hydrodynamics, salinity, and sediment transport. The code solves the basic physics of hydrodynamics and salinity transport through the use of the laws of mass and momentum conservation. A similar version of this code was used in a previous study of the Houston Ship Channel (Tate et al. 2008). The current work builds from the previous studies. The mesh resolution was increased for the new work and a new model comparison check was performed. This code has been used successfully on many estuarine systems, including the Cape Fear River, the Lake Pontchartrain – Lake Borgne area, New York Harbor, and San Francisco Bay.

The sediment modeling is also performed using TABS-MDS. This modeling is not necessary for the ship simulation study, and was performed uncoupled from the hydrodynamics (i.e., the sediment model results do not impact the hydrodynamic results). Because this area experiences high volumes of vessel traffic daily, the effect of this traffic on the sedimentation changes due to the plan alternatives is important. The vessel simulations were performed using Adaptive Hydraulics (AdH). This is a 2D code that allows for the movement of a vessel — based on its size, draft, and speed — to impact the surrounding waterway. The shear stresses from the vessel simulations are incorporated into the sediment model so that the effects of the vessel movement and the effects of the hydrodynamics are both included in the sediment-transport predictions. The sediment model was not
revalidated under this study, so the parameters as set in Tate et al. (2008) were maintained and this study focuses on Base/plan comparisons only, not absolute magnitudes of shoaling.

**Mesh development**

The model domain is taken from previous work performed at ERDC-CHL (Tate et al. 2008). This model was previously used to study hydrodynamics, salinity, and sediment transport in the Houston Ship Channel and bay areas beginning in the early 1990s. The work performed in this project focuses on the Bayport flare, so additional data collection and model comparisons were necessary.

The model comparison process (see Chapter 3) showed that additional storage areas are necessary to accurately represent the velocity directions and discharge values. Areas to the north of Morgan’s Point were added based on aerial images, as is a connection of the Bayport Channel with Clear Lake to the south. Storage area is added in this southern area to match field data and account for several small channels that join in this general area. In a tidal environment these storage areas are important to accurately represent the tidal prism, which can greatly alter flow directions and magnitudes. Elevation data for these added storage areas are unknown, so estimates are made based on known elevations around the area and comparison to field data.

Figure 2-1 and Figure 2-2 below show the initial mesh domain and the final mesh domain, respectively. Resolution is added in the Bayport flare area and into the turning basin in order to provide better results for use in the ERDC Ship/Tow Simulator. The resolution of the original mesh and the modified mesh are shown for the Bayport flare area in Figure 2-3 and Figure 2-4. The final mesh consists of nearly 69,000 nodes and 27,400 elements covering approximately 2,070 square miles, whereas the original mesh had approximately 43,400 nodes and 18,000 elements. The channel areas and side slopes are three dimensions, with four layers defining the vertical. Along the outside of the channels, two layers define the vertical mesh. Other areas of the bay region are three dimensional, with only one vertical layer. Since TABS-MDS elements are quadratic, one layer is equivalent to three linear layers.
Figure 2-1. Initial mesh domain.

Figure 2-2. Final mesh domain, with added storage areas.
Figure 2-3. Original mesh resolution in the Bayport flare.

Figure 2-4. New mesh resolution in the Bayport flare.
Farther away from the area of interest and near inflow locations, 2D computations were performed such that the velocity and salinity results were depth averaged. These areas do not require the detail that a 3D computation yields due to their specified boundary condition or shallow depths.

Figure 2-5 shows the spatial coverage of the vertical layer definitions for the mesh domain.
During field data collection in September 2010, a multibeam survey was made in order to provide accurate bed elevations for the model mesh in the Bayport flare and surrounding area. Figure 2-6 shows the location and values of the survey data, in NAVD 88\(^2\) feet.

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Boundary conditions

The boundary conditions for this study are set up in the same manner as the previous work performed for this model domain (Tate et al. 2008). Tidal water surface elevations and salinity are applied at the ocean boundary. Winds are included throughout the model domain. Freshwater inflow is applied for the Trinity River and the San Jacinto River, as well as at other inflow locations to account for ungaged flows in the area, based on the same method used in the initial model setup (Berger et al. 1995). All inflow locations are labeled in Figure 2-7.
Freshwater inflows

Figure 2-8 shows the inflow discharge for the Trinity River and San Jacinto River. The San Jacinto River flows are determined from a rating curve using the stage elevations at Lake Houston near Sheldon, TX (USGS 8072000). The Trinity River flows are taken from data at Romayor, TX (USGS 8066500).

The ungaged flows are determined from known field data flows at several locations within the system based on data provided by the Texas Water Development Board (TWDB) during the original model validation docu-
mented in Berger et al. (1995). The final flows are grouped together so that the additional flows are applied at the nine locations, as shown in Figure 2-9.

**River Inflow**

![River Inflow Graph](image1)

*Figure 2-8. River inflows.*

**Ungaged Inflow**

![Ungaged Inflow Graph](image2)

*Figure 2-9. Ungaged inflow values.*
**Tidal boundary conditions**

In addition to freshwater inflows, a tidal boundary is applied at the ocean boundary of the mesh. These data are taken from Pleasure Pier (NOS/NOAA 877-1510) and shifted 1.31 hours in order to transfer the data the necessary 26 miles offshore to the boundary location. Periods less than 3 hours are filtered from the data in order to remove any possible noise from the boundary condition. The elevation for the tidal boundary is shown in Figure 2-10. Salinity is also applied at the model’s Gulf of Mexico tidal boundary. The salinity used in this model is the same as that from the previous model studies and based on 15 year monthly averages. Figure 2-11 shows the salinity at the Gulf boundary during these model simulations.

![Water Surface Elevation at Model Boundary](image)

*Figure 2-10. Tidal elevation at model boundary.*
Wind conditions

Wind data are applied to the model for the purpose of including wind effects on the velocity and water surface elevations. The Wu method (Wu 1969) is used for the hydrodynamics in this modeling application. The Wu method is good for areas of deeper water, greater than 2 – 3 meters. The wind speed is obtained from the Air Force Combat Climatology Center’s 14th Weather Squadron for the Houston Intercontinental Airport. Although this site is located farther inland and north of the area of interest, the initial model setup and validation in Berger et al. (1995) provides a correlation for the data to a gage that had been located in the bay so that the airport data can be used in the Houston Ship Channel area. The equation that converts the airport wind data to appropriate bay wind data, in miles per hour, is

\[
\text{windspeed}_{\text{bay}} = 0.85 \times (\text{windspeed}_{\text{airport}} \times 1.15) + 5.92 .
\]

The wind speed is provided in Figure 2-12, and the wind direction toward which it is blowing, measured counterclockwise from east, is given in Figure 2-13. The wind data are also filtered to remove high-frequency signals (less than 3 hour period) that indicate noise in the data. The wind is applied over the entire model domain, and the shoreline boundary is defined to allow erosion as is natural in the field.
Sediment model boundary conditions

The sediment model is driven by the estuarine and vessel motion hydrodynamic modeling results from the previous simulations. The boundary conditions for the sediment modeling include grain characteristics, bed
definitions, and sediment loads. The same conditions established from the previous sediment model validation (Tate et al. 2008) are used, and the inflow sediment and bed materials are divided into 50% silt material and 50% cohesive material. The sediment-specific parameters are given in Table 2-1.

Table 2-1. Sediment parameters and values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Critical shear for deposition of the cohesives</td>
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</tr>
<tr>
<td>Critical shear for erosion of the cohesives</td>
<td>0.1 Pa</td>
</tr>
<tr>
<td>Settling velocity of the cohesives</td>
<td>0.05 mm/s</td>
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<tr>
<td>Particle erosion constant for the cohesives</td>
<td>3.84x10^-5</td>
</tr>
<tr>
<td>Critical shear for deposition of the silts</td>
<td>0.1 Pa</td>
</tr>
<tr>
<td>Critical shear for erosion of the silts</td>
<td>0.67 Pa</td>
</tr>
<tr>
<td>Settling velocity of the silts</td>
<td>0.22 mm/s</td>
</tr>
</tbody>
</table>

Sediment loads are applied to the two major rivers in the area: the Trinity River and the San Jacinto River. These loads are determined from a rating curve correlating discharge with concentration generated using data from the US Geological Survey (USGS) as documented in Tate et al. (2008). The sediment loads for each river for this 2010 simulation period are provided in Figure 2-14.

Figure 2-14. Inflow suspended sediment concentrations for the Trinity and San Jacinto Rivers.
Vessel modeling conditions

The vessel modeling performed using AdH for the sediment portion of this study consisted of a single day of vessel traffic. This representative day was repeated daily in the sediment model. The AdH simulation includes only the bay portion of the model domain and does not have any boundary conditions (i.e., no tide or inflow conditions). The only effects on the water body are due to vessel movement. This is necessary since all other necessary hydrodynamic effects are modeled in the TABS-MDS hydrodynamic simulations. Forty-eight vessels of different dimensions and paths were included in these simulations. These are the same vessel definitions used in the previous sediment studies in the Houston Ship Channel area. Table 2-2 gives the range of dimensions for the 48 vessels being simulated. The numerical model mesh used for vessel modeling contains much more resolution than the TABS-MDS model mesh due to the necessity of having several elements overlap a single vessel. Figure 2-15 shows the mesh resolution for the start of the vessel simulations. The added base resolution, along with the automatic mesh adaption that occurs during the model run, ensures appropriate resolution for calculating the ship waves. The time-step size is also much smaller for these simulations so that the actual speed and progression of the wave, and therefore bed shear stresses, are computed correctly. Figure 2-16 shows a snapshot of velocity magnitudes from the vessel simulation. The figure represents five vessels of various sizes, speeds, and paths moving in the system. Again, details of the vessel inclusion in the sediment model validation can be found in Tate et al. (2008).

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
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<tr>
<td>Length</td>
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<tr>
<td>Beam</td>
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</tr>
<tr>
<td>Speed</td>
<td>15 – 25 ft/s</td>
</tr>
<tr>
<td>Travel Path</td>
<td>Starting and ending at Sea, Bayport, Barbour’s Cut, and Baytown</td>
</tr>
</tbody>
</table>
Figure 2-15. Initial AdH vessel simulation mesh.

Figure 2-16. Vessel velocity magnitudes at a single time during the day long simulation.
The movement of the vessel generates a return current that moves out and around the vessel and returns to the channel behind the vessel. The return currents alone can be significant enough to cause erosion of the channel, and the resulting long waves that move into the shallows can cause erosion of those areas as well. The AdH simulation generates the velocity pattern around the vessel caused by the return current and into the surrounding shallows. As the long wave generated by the vessel propagates into the shallows, it will form a bore. This occurs where the vessel speed is greater than the free surface wave speed. This wave speed is approximately \((gh)^{1/2}\). Here \(g\) is the acceleration associated with gravity and \(h\) is the water depth. In shallow water this free surface wave speed, or celerity, is slower than in deeper water, thus resulting in a bore. These simulations with moving vessels are only appropriate for the areas immediately outside of the channel and beyond. The solutions directly in the channel are not accurate because the vessel propeller effects are not included and the model is hydrostatic.

These AdH simulations provide the vessel-induced shear stress on the bed. This stress field can then be applied to the TABS-MDS sediment model so that the shear stresses caused by the vessels are included with those generated by the hydrodynamics, including freshwater flow, tide, and wind. Therefore, the TABS-MDS hydrodynamic model is run and the AdH vessel model is run, then the hydrodynamic results and the additional vessel shear stresses are used to drive the TABS-MDS sediment model.
3 Hydrodynamic Model Field Data Check

TABS-MDS model validation for all previous work on the ERDC-CHL Houston Ship Channel model used hydrodynamic and salinity data from 1990 – 1991 in the bay portions of the domain, and sediment data from 1994 – 1995 in the navigation channel and the bay. Due to the time lapse between the early TABS-MDS model validation and this new work focusing on the Bayport flare, additional data collection and model comparisons were necessary. Model domain modifications for the current work were discussed in Chapter 2.

Figure 3-1 shows the location of ADCP velocity and discharge field data collection. This data collection occurred over 24 hours on 14–15 September 2010, with data collected for each of the five transects every hour. Details of the ADCP transects are provided in Appendix B.

Figure 3-2 – Figure 3-6 show the model results as compared to the field data for discharge. Positive values indicate flood-directed flow, or flow toward Houston or Bayport; and negative values indicate ebb-directed flows, or flows toward the Gulf of Mexico or out of the Bayport turning basin. The solid line represents the model data, and the points are the field data over time. Each line is identified by number in Figure 3-1. The model may not pick up the absolute highs and lows as shown in the field data for each location, but the overall discharge trend and direction of flow are represented well by the model for all transects over the 24 hour sample period.

Figure 3-7 – Figure 3-11 show the model comparison to the depth-averaged velocity magnitudes and directions at the center of the channel for each transect location over the sampling period. Therefore, the closest transect point to the model-analysis point is compared for each line, removing any comparisons to areas where the velocities are extremely small or outside of the main navigation channel. The channel itself is of greatest importance for ship-simulation studies, making this type of analysis appropriate. The model results are the solid lines, and the field data are the dots. These comparisons are made to the model each hour, on the hour, which does not correspond directly with each transect time since the transects are taken over the course of the entire hour. The velocity values are

3 ADCP: Acoustic Doppler Current Profiler.
positive for flow in the flood direction and negative for flow in the ebb direction, as defined for the discharge comparisons. The model does not reproduce every velocity value exactly, but it does show agreement with the direction, timing, and location of velocity changes overall and indicates that the model reasonably represents the behavior of the system. ADCP velocity data can be spurious at times, which is visible in the rapid variation in the data points at times. This type of behavior may be a response to local phenomena occurring during data collection, and are not replicated in the model. Therefore, the combination of several analysis methods is used to judge model accuracy for adequately representing the system.

An additional analysis was performed to determine how the 3D representation of the system compares to the field data. This comparison is not directly necessary for the ship-simulation aspect of this study but can be important for sediment transport since the highest concentrations of sediment move along the channel bottom. The ADCP transects take data at constant intervals into the water column. Since this is a 3D model, comparisons over the depth can be made at each transect over the 24 hour period. The model contains fewer computation points in the vertical than the field data collection, but the comparison is still beneficial. Figure 3-12 – Figure 3-21 show these comparisons for each line at two times during the comparison period — maximum surface flood and maximum surface ebb — in units of feet per second. The left side of the figure is the field data and the right side is the model-computed result. Yellow, orange, and red areas indicate flood-directed flow, and grays and blues indicate ebb-directed flows. The transects are shown as cross sections along the line from south to north at line 1 and west to east at lines 2 – 5. Therefore, when observing these figures, the reader is looking in the flood direction. These transects show times of stratified flow during the time of the model/field data comparison when bottom flows are flood-directed and surface flows are ebb-directed. Overall, the variation of flow magnitude and direction with depth is maintained in the model results.

Data for ship simulation is the priority of this study, making surface flow directions and magnitudes important. For the secondary sediment modeling effort, the bottom flows are important to determine accurate shear stresses for erosion or deposition of sediment. Based on the model/field data comparisons the model, as updated for use in the Bayport flare vicinity, is deemed adequate to address questions about the effects of proposed channel improvements.
Figure 3-1. Bayport ADCP transect locations.

Figure 3-2. Line 1 model/field discharge comparison.
Figure 3-3. Line 2 model/field discharge comparison.

Figure 3-4. Line 3 model/field discharge comparison.
Figure 3-5. Line 4 model/field discharge comparison.

Figure 3-6. Line 5 model/field discharge comparison.
Figure 3-7. Line 1 model/field velocity comparison.

Figure 3-8. Line 2 model/field velocity comparison.
Figure 3-9. Line 3 model/field velocity comparison.

Figure 3-10. Line 4 model/field velocity comparison.
Figure 3-11. Line 5 model/field velocity comparison.
Figure 3-12. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 1 at 13:30 CST.
Figure 3-13. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 1 at 1:00 CST.
Figure 3-14. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 2 at 18:30 CST.
Figure 3-15. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 2 at 1:00 CST.
Figure 3-16. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 3 at 20:00 CST.
Figure 3-17. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 3 at 1:00 CST.
Figure 3-18. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 4 at 20:00 CST.
Figure 3-19. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 4 at 2:00 CST.
Figure 3-20. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 5 at 13:00 CST.
Figure 3-21. Field (left)/model (right) data comparison of 3D flood (+)/ebb (-) velocity for line 5 at 1:00 CST.
4 Alternative Simulations

SWG provided six different plans for simulation of hydrodynamics and sedimentation, including two flare radii and two bend wideners. The maximum flood and ebb velocity fields for each alternative and the Base condition were provided for use in the ERDC Ship/Tow Simulator. These simulations were performed 6 months — 1 January 2010 through 30 June 2010 — for both the hydrodynamic and sediment simulations.

Model scenarios

The Base and six alternative geometry conditions are given in the list below along with a schematic of the alternatives provided by SWG (see Figure 4-1). The existing channel and flare outline is shown in blue. The planned radii are shown in black and green and, the two planned wideners are shown in green and red. The domain boundaries are shown in brown. Figure 4-2 – Figure 4-8 show bathymetry for the Base and six plan alternatives as defined in the model mesh.

- Base — maintain the present status of the Bayport flare as determined from the September 2010 bathymetric survey (Figure 4-2)
- R4000 — increase the southern Bayport flare radius to 4000 ft and apply design elevations of 53 ft in the flare and 57 ft in the Bayport Channel (Figure 4-3)
- **R4000-W1** — increase the southern Bayport flare radius to 4000 ft, include a 250 ft maximum width by 3500 ft length widener on the eastern side of the Houston Ship Channel, and apply design elevations of 53 ft in the flare and 57 ft in the Bayport Channel (Figure 4-4)
- **R4000-W2** — increase the southern Bayport flare radius to 4000 ft, include a 300 ft maximum width by 4500 ft length widener on the eastern side of the Houston Ship Channel, and apply design elevations of 53 ft in the flare and 57 ft in the Bayport Channel (Figure 4-5)
- **R5375** — increase the southern Bayport flare radius to 5375 ft and apply design elevations of 53 ft in the flare and 57 ft in the Bayport Channel (Figure 4-6)
- **R5375-W1** — increase the southern Bayport flare radius to 5375 ft, include a 250 ft maximum width by 3500 ft length widener on the eastern side of the Houston Ship Channel, and apply design elevations of 53 ft in the flare and 57 ft in the Bayport Channel (Figure 4-7)
- **R5375-W2** — increase the southern Bayport flare radius to 5375 ft, include a 300 ft maximum width by 4500 ft length widener on the eastern side of the Houston Ship Channel, and apply design elevations of 53 ft in the flare and 57 ft in the Bayport Channel (Figure 4-8)
Figure 4-3. R4000 flare elevation, NAVD88 ft, zero = 100 ft.

Figure 4-4. R4000-W1 flare elevation, NAVD88 ft, zero =100 ft.
Figure 4-5. R4000-W2 flare elevation, NAVD88 ft, zero =100 ft.

Figure 4-6. R5375 flare elevation, NAVD88 ft, zero =100 ft.
Figure 4-8. R5375-W2 flare elevation, NAVD88 ft, zero = 100 ft.
Hydrodynamic results

The plan alternatives are limited to geometry changes in the Bayport flare as are their effects on the hydrodynamic results. It is expected that the larger flare radius and channel wideners will allow for a slightly larger flow volume to pass through this area and therefore modify the discharge some based on the area adjustment for each plan. The total discharge over time at the same five lines used for the model to field comparison (see Figure 3-1) are compared for each plan alternative. Line 1 lies west of the flare in the Bayport channel. Lines 2 through 5 cross the Houston Ship Channel from south to north beginning just downstream of the flare and ending just upstream of the flare. Figure 4-9 through Figure 4-13 show these discharge comparisons for a representative 7 days during the six-month simulation period – May 20 through May 27, 2010 – with positive values indicating flood-directed flow and negative values indicating ebb-directed flows. As expected, the change in discharge is small given that the area adjustment due to the plans is not large. The greatest impacts on the discharge are at lines 1, 2, and 3. These locations are in the Bayport Channel and on the southern side of the flare where the geometry modifications are made, so the largest impact is expected in these areas. At those locations, the discharge variations are observable on the plots although the details of each line are difficult to decipher. Lines 4 and 5 show less of an effect on the discharge results as compared to the Base.

Discharge is a product of cross-sectional area and velocity. Lines 4 and 5 are located away from any geometric changes to the channels, so any changes in discharge at those locations can be attributed to changes in average velocity. Given that Lines 4 and 5 show very little change from the Base for discharge, it is likely that the area modifications of the channels are generating most of the change in discharge at Lines 1, 2, and 3.
Figure 4-9. Discharge comparison for Line 1, flood (+)/ebb (-).

Discharge, Line 1

Discharge, cfs

Date


Discharge, Line 2

Discharge, cfs

Date


Figure 4-10. Discharge comparison for Line 2, flood (+)/ebb (-).
Figure 4-11. Discharge comparison for Line 3, flood (+)/ebb (-).

Figure 4-12. Discharge comparison for Line 4, flood (+)/ebb (-).
Due to the difficulty in determining the effects of the plan modifications on the total discharge at each location in the above figures, an average discharge analysis was performed. The average discharge at each line for the Base condition is given in Table 4-1.

<table>
<thead>
<tr>
<th>Average Discharge (cfs)</th>
<th>Line 1</th>
<th>Line 2</th>
<th>Line 3</th>
<th>Line 4</th>
<th>Line 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>-1306</td>
<td>2829</td>
<td>2685</td>
<td>3522</td>
<td>2754</td>
</tr>
</tbody>
</table>

Again, positive values indicate flows toward Houston or Bayport (flood-directed) and negative values indicate flows toward the gulf (ebb-directed). Figure 4-14 shows the average discharge change from the Base for each alternative (Plan – Base) over the entire six-month simulation. The averages over the simulation more easily show any variation among the plans than the seven-day time history figures above (Figure 4-9 through Figure 4-13), although the peak variations—which could be on the order of 5,000 cfs for some plans and times based on the time history figures—are lost in the averaging process. Average discharge change values that have the same sign as the Base average discharge indicate that the plan alternative has a higher average discharge magnitude; differing signs
indicate that the plan alternative has a lower average discharge magnitude. Lower values were only observed for the R5375 plans at Line 1.

Figure 4-14 indicates that the R4000 plan produces higher-magnitude discharges than any of the other alternatives at all lines except Line 2 (adding the average Base discharge to the average discharge change to get total discharge magnitude) and also the largest variation from the Base condition at all lines except Lines 1 and 2. At Line 1, the R4000 plans generate larger average discharges than the Base condition, whereas the R5375 plans show a slight reduction in average discharge from the Base (given that the Base average discharge is in the ebb, negative direction). The location of the connection of the southern flare boundary to the ship channel can have an impact on the results depending on how close an analysis location is to this tie-in.

It is also interesting to note that the wideners have very little effect on the comparisons. Once the flare is enlarged by the radius change, the effect of each widener is almost negligible, especially for the R4000 plans. The
wideners do have a larger effect at Lines 2 and 3 due to their location near the widener placement.

At Line 2, the R4000 plans generate less of a change from Base than the R5375 plans. The direct opposite is observed at Line 3. Again, this variation is likely due to the size of the two radius plans and where they connect back to the navigation channels. The larger radius, R5375, extends farther down the Houston Ship Channel near Line 2, therefore producing larger changes from the Base at Line 2. The smaller radius, R4000, does not extend as far to the south and therefore does not generate the same changes at Line 2. However, it does impact Line 3 more than the R5375 plans.

The larger changes from the Base condition are greatest for analysis locations close to the area of modification, such as for Lines 1, 2, and 3. Line 4 shows a large change with the initial radius increase to 4,000 ft, but then the effects reduce some and remain nearly constant with all additional changes. This line is to the north of the modifications and less impacted by the changes taking place to the south. Line 5 indicates less change from the Base condition as well as little change among alternatives, as expected due to its position farthest north along the Houston Ship Channel.

The greatest variation in the plan alternatives compared to the Base is at locations closest to the modifications. Lines 1, 2, and 3 indicate the greatest impact. This is an expected area of change due to the enlarged southern radius of the flare in the alternative conditions. Lines 2 and 3 lie across the Houston Ship Channel along the downstream section of the flare. The wideners are placed near Line 3. These lines show variations from the Base total discharge. Lines 4 and 5 lie across the Houston Ship Channel along the upstream section of the flare and show less variation from the Base average discharge. These results indicate that the plan alternatives for the Bayport flare will not generate significant changes to the total discharge in the area, and any changes that are generated remain in the vicinity of the modifications (i.e., closer to Lines 1–3). These generally small variations in discharge indicate that the effects of adding wideners to help ship navigation are insignificant to the hydrodynamics when compared to the initial effect of modifying the southern flare radius.

**Sediment results**

The sediment simulations were run over the same six-month period as the hydrodynamics, and the vessel transport effects are included. The Bayport
flare is a known sediment trap, so the effect of enlarging this area on the shoaling is important for weighing the overall benefits of each plan. The shoaling, however, must take into account the larger area of availability. In other words, it can be misleading to consider only shoaling volumes since the additional area of the flare will automatically produce larger total volumes. Instead, a unit shoal depth was determined such that the total volume of material settling is divided by the computation area. This way the increased area is removed from the results. This calculation was performed for the flare and a section of the Houston Ship Channel, labeled as “combined,” and for the flare only. Figure 4-15 shows the areas included in these computations in red. Figure 4-16 shows the percentage of change from the Base condition of the unit shoal depth for each plan alternative, both for the combined area and the flare-only area. Positive-percentage changes mean that the plan produces a larger unit shoal depth when compared to the Base, and negative-percentage changes mean that the plan produces a smaller unit shoal depth.

Increasing the flare radius alone, as in R4000 and R5375, increases the combined shoaling depth in the area. However, by adding the wideners the total area increases even more, yet the unit shoaling does not respond proportionally. The wideners actually show a decrease in unit shoaling when compared to the Base for all widener plans. The wideners are located along the Houston Ship Channel, so vessel traffic will likely keep material suspended.

![Figure 4-15. Unit shoaling computation areas: (a) combined, (b) flare only.](image)
Although the widener plans show a decrease in unit shoal depth when compared to the Base, the flare itself is the location of historically high shoaling. R4000 is the only plan that shows an increase in unit shoaling for the flare alone; all other plans show the flare shoaling less than the Base condition on a unit depth basis. This reduction in unit shoal depth indicates that the material is still settling in this area but not at the same rate by which the area of the flare was increased. The larger radius, 5,375 ft, shows an even smaller change of unit shoal depth given the increase in area. Shoaling still occurs, and over time this area will need to be dredged, but the only plan that may require more frequent dredging than is presently taking place in the flare is R4000.

Furthermore, these analyses look at average unit shoaling depth, but it is likely that some areas within the footprint of the flare or combined areas will shoal differently than others. R4000 and R5375 show increases in unit shoal depth when the Houston Ship Channel is included, indicating that there is some additional material settling outside of the flare. The slight changes in hydrodynamics are transporting suspended material differently, so that some material is settling in a different location than in the Base condition. This is not unexpected, and the overall increases when the entire “combined” region is considered are less than 10 percent, as shown above in Figure 4-16.
This sediment analysis is limited, based on a six-month simulation period and the unit shoal changes over a defined area. Although the simulation period was January through June and included the times of high spring flows, an entire year-long cycle will include all seasonal effects. It is known that this 2010 simulation period represents one of high flows on the Trinity River based on USGS data. Therefore, this analysis does provide an opportunity to observe the effects of the plan conditions on the shoaling in the flare given that higher flows yield higher sediment loads supplied to the system. The unit shoaling analysis indicates that the frequency of dredging will likely decrease. It is not certain if the total volume of material will decrease over time, but given that the flare would have a larger footprint, there is more area for material to settle onto the bed before reaching the threshold elevation where dredging is required. In other words, a set volume of material will yield a lower depth of shoaling for an increased flare area than for the current conditions.
5 Conclusions

This report documents the comparison of model to field data of the Houston-Galveston hydrodynamic model for the Bayport flare. Six plan alternatives were provided for testing to determine the effects of the planned modifications on hydrodynamics and sedimentation in the flare and surrounding area. Included in the model simulations are tides, salinity, freshwater river inflows, sediment loads, winds, and vessel effects.

The hydrodynamic simulations indicate that the proposed plan conditions produce changes in average discharge in the flare area of as much as 37% for R5375-W1 at Line 2, and as little as 5–8% for all plans at Line 5. At Line 1, the average discharge actually drops by approximately 12% for the R5375 plans when compared to the Base. The various plan conditions have the effect of redistributing the flows in and around the flare.

The sediment simulations indicate that some of the proposed changes actually reduce the unit shoaling depth over the flare area. The overall change of the unit shoaling is less than 10% for all plans over the six month simulation period, but some plans provide more positive results than others. The wideners show the best sediment results since the added channel area results in a decrease in unit shoaling. The larger radii also show good improvement from the Base since the unit shoaling depth does not increase proportionally to the increase in flare area. The unit shoaling analysis indicates that the frequency of dredging will likely decrease, although it is not certain from these sediment analyses whether or not the total volume of material to be dredged will decrease over time.

The hydrodynamic results were provided to the ship simulation study where pilots test the proposed modifications while steering the design vessels for the waterway. The ship simulation study and results will be presented in a separate report and should be considered when reviewing the conclusions presented here.
References


Introduction

A model of a particular estuary, river, or reservoir consists of several parts. There is the geometric description that not only includes the $X$, $Y$, and $Z$ locations of points chosen, but also the delineation of bed cover such as grasses, sands, etc. There is also the specification of boundary conditions, including all of the forcing mechanisms, tides, wind, inflow, and any constituents. The third part is numerical code. This code has, at its core, the basic laws of physics, in particular the relationship between force and acceleration. A consistent model code is a faithful representation of these equations, for sufficient resolution. Since these equations are universal, the range of applicability of the code is limited by the additional empirical relationships to describe turbulent processes, bed roughness, equations of state, and wind stress, and by any simplifying assumptions made in the equations.

There is some degree of uncertainty associated with the geometric description, the boundary conditions, and the numerical code. Often the error indicated by these uncertainties is highest for the specification of the boundary conditions, followed by the geometric description, with the numerical code providing the least of the error. The error in the accuracy of input values of inflow, wind, and rainfall/evaporation is often very large, particularly in estuarine models. The inflows, for example, are often determined by gages far upstream from the estuary, and they leave out large ungauged downstream areas. Also, at the location of the gage, the relation between gage elevation and discharge is far from perfect. This relation changes over time and flow conditions.

These errors can be minimized by careful model calibration. Also, modelers can use sound testing procedures to eliminate much of the error from the decision process. These techniques include plans to base comparisons and sensitivity analysis.
In this appendix, the TABS-MDS hydrodynamic code is described. The Galerkin-based finite-element model TABS-MDS is an ERDC adaptation of the RMA-10 code developed by King (1993)\textsuperscript{4}. This code computes time-varying open-channel flow and salinity/temperature/sediment transport in one, two, and three dimensions. It invokes both the hydrostatic-pressure and mild-slope assumptions. Vertical turbulence is supplied using a Mellor-Yamada Level II (Mellor and Yamada 1982) $k-\varepsilon$ approach modified for stratification by the method of Henderson-Sellers (1984). The RMA2 code is a predecessor to TABS-MDS, but is limited to at most two-dimensional (2D) cases. The formulation is similar to TABS-MDS, so the only descriptions reported herein will be those of TABS-MDS.

**TABS-MDS theoretical development**

**3D equations**

We have six unknowns ($u$, $v$, $w$, $h$, $s$, $\rho$). Therefore, we require six equations.

**Navier-Stokes equations (i.e., conservation of fluid momentum)**

\[ \rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} + \nabla \mathbf{p} + \mathbf{g} = \mathbf{f} \]

\[ + \frac{\partial \tau_x}{\partial x} = 0 \]  

\[ \rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{g} = \mathbf{f} \]

\[ + \frac{\partial \tau_y}{\partial y} = 0 \]  

\[ \rho \frac{\partial \mathbf{w}}{\partial t} + \rho \mathbf{w} \cdot \nabla \mathbf{w} = \mathbf{f} \]

\[ + \frac{\partial \tau_z}{\partial z} = 0 \]

---

\*References cited in this appendix are listed at the conclusion of the text.*
Volume continuity equation

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  \hspace{1cm} (4)

Advection-diffusion equation

\[
\frac{\partial s}{\partial t} + u \frac{\partial s}{\partial x} + v \frac{\partial s}{\partial y} + w \frac{\partial s}{\partial z} = - \frac{\partial}{\partial x} \left( D_x \frac{\partial s}{\partial x} \right) - \frac{\partial}{\partial y} \left( D_y \frac{\partial s}{\partial y} \right) - \frac{\partial}{\partial z} \left( D_z \frac{\partial s}{\partial z} \right)
\]  \hspace{1cm} (5)

\[ - \theta_s = 0 \]

Equation of state

\[ \rho = F(s, t) \]  \hspace{1cm} (6)

where:

\[ \tau = \text{applied forces (e.g., wind stress, bed shear stress, Coriolis force)} \]
\[ \theta_s = \text{salinity source/sink term} \]

Now we reduce the number of unknowns requiring a simultaneous solution from six to three.

Assuming that the influence of vertical momentum on the system is small and may be neglected, equation 3 reduces to the following equation:

\[ \frac{\partial p}{\partial z} + \rho g = 0 \]  \hspace{1cm} (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:

\[
\int_{a}^{z} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) d\eta = - \int_{a}^{z} \frac{\partial w}{\partial z} d\eta = -w_s + w_b
\]  \hspace{1cm} (8)
where:

\[ w_s = \text{the vertical velocity at the water surface} \]
\[ w_b = \text{the vertical velocity at the bed} \]

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:

\[ u_s, v_s = \text{the surface horizontal velocity components} \]
\[ u_b, v_b = \text{the near bed horizontal velocity components} \]
\[ z_b = \text{the bed elevation} \]

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 \( \rho \) 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 four equations (1, 2, 8, and 5) and four unknowns (\( u \), \( v \), \( h \), and \( s \)) to be solved simultaneously. In practice, however, the solution is broken up into two 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 four equations and unknowns.
Hence, the solution of a system of four equations and four unknowns becomes the solution of a system of three equations (1, 2, and 8) and three unknowns (u, v, and h), followed by the solution of one equation (5) and one unknown (s).

**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.

\[ \frac{h}{(z - z_b)} = \frac{(b - a)}{(Z - a)} \]  

(11)
\[ z = \frac{(Z - a)}{(b - a)} h + z_b \] 

(12)

Hence:

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

(13)

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

**Momentum equations**

\[
\begin{align*}
\rho \left[ h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} \right] + \rho g h \frac{\partial z}{\partial x} + \rho g h \frac{\partial z}{\partial x} + h \frac{\partial p}{\partial x} + \rho g h \frac{\partial z}{\partial x} & = \frac{1}{(b - a)} \frac{\partial T_z}{\partial t} = 0 \\
\end{align*}
\]

(14)

\[
\begin{align*}
\rho \left[ h \frac{\partial v}{\partial t} + hv \frac{\partial v}{\partial x} + hv \frac{\partial v}{\partial y} + \frac{\partial v}{\partial z} \right] + \rho g h \frac{\partial z}{\partial y} + \rho g h \frac{\partial z}{\partial y} + h \frac{\partial p}{\partial y} + \rho g h \frac{\partial z}{\partial y} & = \frac{1}{(b - a)} \frac{\partial T_y}{\partial t} = 0 \\
\end{align*}
\]

(15)

**Volume continuity equation**

\[
\begin{align*}
\int_a^b \left[ h \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} - \frac{\partial T_z}{\partial x} \right) - \frac{\partial u}{\partial z} \frac{\partial T_x}{\partial z} - \frac{\partial v}{\partial z} \frac{\partial T_y}{\partial z} \right] dz \\
+ u_s \frac{\partial (z_b + h)}{\partial x} + v_s \frac{\partial (z_b + h)}{\partial y} + \frac{\partial (z_b + h)}{\partial t} - u_b \frac{\partial z_b}{\partial x} - v_b \frac{\partial z_b}{\partial y} - \frac{\partial z_b}{\partial t} & = 0 \\
\end{align*}
\]

(16)
Advection-diffusion equation

\[
\begin{align*}
\left[ \frac{\partial h}{\partial t} + h \frac{\partial \vec{v}}{\partial x} + hv \frac{\partial \vec{v}}{\partial y} + h \frac{\partial \vec{v}}{\partial z} \right] & \left( w - u \frac{\partial \vec{v}}{\partial x} - v \frac{\partial \vec{v}}{\partial y} - (z-a) \frac{\partial \vec{v}}{\partial z} \right) \\
\left[ \frac{\partial h}{\partial x} \right] & - h \frac{\partial}{\partial y} \left( D_x \frac{\partial \vec{v}}{\partial x} \right) - (b-a) \frac{\partial}{\partial z} \left( D_z \frac{\partial \vec{v}}{\partial z} \right) - h \theta_s \\
\end{align*}
\]

\( \frac{1}{(b-a)} = 0 \) (17)

where:

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

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

\[
h_D = \frac{(b-z)h}{(b-a)} \\
(20)
\]

2D equations

Vertically averaged equations

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

\[
\begin{align*}
\rho(b-a) \left[ \frac{\partial \vec{u}}{\partial x} + h \frac{\partial \vec{u}}{\partial x} + hv \frac{\partial \vec{u}}{\partial y} \right] \\
- h(b-a) \frac{\partial}{\partial x} \left( \varepsilon_{xx} \frac{\partial \vec{u}}{\partial x} \right) - h(b-a) \frac{\partial}{\partial y} \left( \varepsilon_{xy} \frac{\partial \vec{u}}{\partial y} \right) \\
+ \rho gh(b-a) \left( \frac{\partial z_b}{\partial x} + \frac{\partial h}{\partial x} \right) + (b-a) \frac{gh^2}{2} \frac{\partial \vec{u}}{\partial x} - h(b-a) \tau_x \\
\end{align*}
\]

\( \frac{1}{(b-a)} = 0 \) (21)

Similarly, the continuity equation reduces to:
\[ h \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} + \frac{\partial h}{\partial t} = 0 \]  
\text{(22)}

And the advection-diffusion equation reduces to:

\[ \begin{align*}
&\left\{ h(b-a) \frac{\partial \hat{s}}{\partial t} + h(b-a)u \frac{\partial \hat{s}}{\partial x} + h(b-a)v \frac{\partial \hat{s}}{\partial y} \\
&- h(b-a) \frac{\partial}{\partial x} \left( D_x \frac{\partial \hat{s}}{\partial x} \right) - h(b-a) \frac{\partial}{\partial y} \left( D_y \frac{\partial \hat{s}}{\partial y} \right) - h(b-a) \frac{\partial \theta}{\partial s} \right\} \\
&\quad \frac{1}{(b-a)} = 0
\end{align*} \]
\text{(23)}

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 \( c \) be 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:

\[ \begin{align*}
&\rho \left[ \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hu \frac{\partial z}{\partial x} \left( b-a \right) \left( \frac{b-a}{a} \frac{\partial h}{\partial a} - \frac{\partial z}{\partial x} \right) \\
&- h \frac{\partial}{\partial x} \left( \epsilon_{xx} \frac{\partial u}{\partial x} \right) - \left( b-a \right) \frac{\partial}{\partial z} \left( \epsilon_{xx} \left( \frac{b-a}{a} \right) \frac{\partial u}{\partial z} \right) \\
&+ \rho gh \frac{\partial z}{\partial x} + \rho gh \frac{\partial h}{\partial x} + h \frac{\partial p}{\partial x} + \rho gh \frac{\partial h}{\partial x} - h \tau_x \\
&\quad \frac{c}{(b-a)} = 0
\end{align*} \]
\text{(24)}

Similarly, the continuity equation reduces to:

\[ \int_{z}^{b} \left[ \frac{h}{(b-a)} \left( \frac{\partial u}{\partial x} + u \frac{\partial c}{\partial x} \right) - c \frac{\partial u}{\partial z} T_x \right] dz \]

\[ + cu_s \frac{\partial (z_b + h)}{\partial x} + \frac{\partial (z_b + h)}{\partial x} - cu_b \frac{\partial a}{\partial x} - \frac{\partial z_b}{\partial t} = 0 \]  
\text{(25)}

And the advection-diffusion equation reduces to:
1D 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 to be trapezoidal, with allowance made for off-channel storage.

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

\[
\begin{aligned}
\left\{ \begin{array}{l}
\frac{\partial}{\partial t} \left[ \frac{\partial}{\partial x} \left( \frac{\partial A}{\partial x} + A \frac{\partial u}{\partial x} \right) \right] \\
- A \frac{\partial}{\partial x} \left( \frac{\partial A}{\partial x} \right) \\
+ \rho g A \frac{\partial z u}{\partial x} + \rho g A \frac{\partial h}{\partial x} + \frac{g A h}{2} \frac{\partial \rho}{\partial x} - A \tau_x
\end{array} \right. \\
= 0
\end{aligned}
\]

(27)

Similarly, the continuity equation reduces to:

\[
A \left( \frac{\partial u}{\partial x} \right) + u \frac{\partial A}{\partial x} + \frac{\partial (A + A_{oc})}{\partial t} = 0
\]

(28)

And the advection diffusion equation reduces to:

\[
\left\{ \begin{array}{l}
(A + A_{oc}) \frac{\partial s}{\partial t} + A \frac{\partial s}{\partial x} - A \frac{\partial}{\partial x} \left( D_x \frac{\partial s}{\partial x} \right) - A \theta_x
\end{array} \right. \\
= 0
\]

(29)

where:

- \( A \) = The main channel cross-sectional area
- \( A_{oc} \) = The off-channel storage cross-sectional area
Finite element formulation

In order to generate the finite-element equations, we must integrate each of the equations over the element volume (for 3D), area (for 2D), or length (for 1D), 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 $N$:

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

This can be rewritten as:

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

(30)

Then, it can be integrated by parts:

$$N \frac{\rho g}{2(b-a)} \frac{\partial h^2}{\partial x} = \frac{\partial}{\partial x} \left( N \frac{\rho gh^2}{2(b-a)} \right) \cdot \frac{\partial N}{\partial x} \left( \frac{\rho gh^2}{2(b-a)} \right)$$

$$- N \frac{gh^2}{2(b-a)} \frac{\partial \rho}{\partial x} - N \frac{\rho gh^2}{2(b-a)^2} \frac{\partial a}{\partial x}$$

(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.

Time derivative solution method

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

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

(33)
where:

\[ \beta_t = \text{any of the unknown variables at time } t \]
\[ \Delta t = \text{the time step} \]

**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 comprise the stiffness matrix, and are used to drive the residual (i.e., the integral of each equation across an element) to 0.

\[
\begin{bmatrix}
X_u & Y_u & Z_u \\
X_v & Y_v & Z_v \\
X_h & Y_h & Z_h
\end{bmatrix}
\begin{bmatrix}
u \\
v \\
h
\end{bmatrix}
=
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

(34)

**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 three expressions can be used, depending upon the instantaneous value of the depth/roughness height ratio \( \frac{d}{k} \). The expressions are as follows (given for the X-direction only):

\[ \tau_x = \frac{\rho g |v_x|}{L^{2/3}d^{2/3}} \quad \text{where } L = \frac{6.46 \sqrt{g}}{k^{1/3}} \]  

(35)

\[ \tau_x = \frac{\rho g |v_x|}{M^{2/3}d^{1/3}} \quad \text{where } M = \frac{8.25 \sqrt{g}}{k^{1/6}} \]  

(36)

\[ \tau_x = \frac{\rho g |v_x|}{N^{2/3}d^{1/6}} \quad \text{where } N = \frac{13.18 \sqrt{g}}{k^{1/12}} \]  

(37)

where:
\( \tau_x \) = the bed shear in the X-direction  
\( k \) = the roughness height  
\( d \) = the local depth  
\( v \) = the local velocity  
\( g \) = the gravitational constant  
\( \rho \) = the density of water

\( k \) is found as a function of Manning’s \( n \) from the following expression:

\[
k = \left( \frac{8.25 \sqrt{g \ n \ 1.486}}{\n} \right)^6
\]

(38)

**Wind stress**

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

\[
\tau_{wx} = \rho_a C_w V_w^2 \cos \theta_w
\]

(39)

where:

\( \tau_{wx} \) = the wind stress in the X-direction  
\( \rho_a \) = the density of air  
\( V_w \) = the wind velocity  
\( \theta_w \) = 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):

\[
C_w = \frac{0.8 + 0.065 \times V_w}{1000}
\]

(40)

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

\[
C_w = \left( \frac{0.4}{16.11 - 0.5 \ln(d) - 2.48 \ln(V_w)} \right)^2 \times \left( 1 - \frac{1.118 \cdot e^{-6(d-2)}}{\sqrt{V_{wi}}} \right)
\]

(41)
where:

\[ \begin{align*}
    d &= \text{the local water depth (in meters)} \\
    d_1 &= \text{the maximum of the local water depth (in meters) and 2 meters} \\
    V_{w1} &= \text{the maximum of the wind velocity (in m/s) and 5.063 m/s}
\end{align*} \]

**Horizontal turbulent mixing and diffusion**

Horizontal turbulent mixing can be specified directly, or it can be controlled by the method of Smagorinsky (1963). 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:

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

\[ 
    k = \text{Smagorinsky coefficient, usually given a value ranging from approximately 0.005 for rivers to 0.05 for estuaries and lakes (Speziale 1998, Thomas et al. 1995)}
\]

\[ 
    A = \text{the surface area of the element}
\]

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

\[
S_{\text{Emin}} = \text{TBMINF} \times \rho \alpha \sqrt{A}
\]  

(46)

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

\[
S_{\text{Dmin}} = \text{TBMINFS} \times \alpha \sqrt{A}
\]  

(47)

where

- \( \text{TBMINF} \) = minimum turbulent mixing factor (default = 1.0)
- \( \text{TBMINFS} \) = minimum diffusion factor (default = 1.0)
- \( \alpha \) = a coefficient, given as \( 5.00 \times 10^{-3} \) ft/sec or \( 1.52 \times 10^{-3} \) m/s, depending on the unit system being used in the simulation.

The \( \text{TBMINFS} \) 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 of 0.2 ft/sec.

Also, if \( |V| < \text{TBMINF} \times V_{\text{min}} \), then \( S_{\text{Emin}} \) 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.

**Vertical turbulent mixing and diffusion**


The Mellor-Yamada expressions for vertical eddy viscosity and diffusion are given as follows:
\[ E_{xz} = E_{yz} = \rho S_m l_m q \] (48)

\[ D_z = S_h l_m q \] (49)

where:

\[ l_m = 0.4(z - a) \left| 1 - \left( \frac{z - a}{h} \right)^{\frac{3}{2}} \right| \] (50)

\[ q = b_1 l_m^2 S_m \left[ \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 \right]^{\frac{1}{2}} \] (51)

and

\[ S_m = 0.393 \]
\[ S_h = 0.494 \]
\[ b_1 = 16.6 \]

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:

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

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

\[ E_z = \frac{E_{zo}}{1 + 0.74R_i} \] (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:

$$D_z = \frac{D_{zo}}{\left(1 + 37R_i^2\right)}$$  \hspace{1cm} (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).

References


Appendix B: ADCP Transect Information

The starting and ending times and locations for every ADCP transect is provided in this appendix. The date/time is given in the local system, Central Standard Time (CST). The start and end times are given in Greenwich Mean Time (GMT), which is 5 hours later than CST. The starting and ending locations are given in feet for the NAD 83, Texas South Central State Plane system.

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## ABSTRACT

The Bayport flare area of the Houston Ship Channel is a large deep zone of approximately 72 acres designed for deep draft vessels to safely make the turn in and out of the Bayport Channel. These turns require multiple-tug assist, but engineered modifications to the flare could make turning easier and improve navigational safety in the area. However, this deep area acts as a sediment trap due to local velocity patterns, so modification plans to improve navigation should also consider the potential impacts to shoaling.

The US Army Engineer District, Galveston (SWG) requested the Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) to perform hydrodynamic modeling of several plan alternatives to provide data for ship simulation studies in which pilots will test the navigational effects of these plans. Ship simulation was the primary focus of the hydrodynamic modeling, but sediment simulations were also performed. These modeling scenarios will provide information on how the proposed modifications to the Bayport flare will impact current velocities and sedimentation in the area.

## SUBJECT TERMS

TABS-MDS, numerical modeling, Bayport flare, Houston Ship Channel, ERDC Ship/Tow Simulator