7. Hydrodynamic modeling

7.1 Introduction

The professional modeling package MIKE21 developed by DHI Water and Environment is one of the well known numerical models which are currently available in the market. It is a two-dimensional simulation package and includes many different models applied to various coastal engineering problems. Though MIKE21 is very important for the complex bathymetries, its hydrodynamic models can be used effectively to simulate the current field. This model can also be used to investigate water quality, ecological systems, wave model and sediment transport by directly coupled with hydrodynamic model. In shallow waters, hydrodynamics are mainly influenced by tides, waves and winds. Tide induced currents are envisaged to be persistent and periodic and therefore are considered suitable to provide initial comparisons on the changes in hydrodynamics.

7.2 Model Description

The hydrodynamic module is based on the numerical solution of the two dimensional shallow water equation the depth –integrated incompressible Reynolds averaged Naviers – Stokes equation. Thus, the model consists of continuity, momentum, temperature, salinity and density equations. In the horizontal domain both Cartesian and spherical coordinates can be used. The spatial discretization of the primitive equation is performed using cell- centered finite volume method. The spatial domain is discretized by subdivision of the continuum into non- overlapping elements cells. In the horizontal plane an unstructured grid is used to comprise of triangles or quadrilateral elements. An approximate Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions.
Hydrodynamic module is a part of MIKE 21 Coupled FM Model. The hydrodynamic model in the MIKE 21 Flow Model is a general numerical modeling system of the simulation of water levels and flows in estuaries, bays and coastal areas. It simulates unsteady two-dimensional flow in one layer has been applied in a large number of studies.

The following equations are used to obtain the conservation of mass and momentum integrated over the vertical flow and water level variation.

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \tag{7.1}
\]

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial x} + \frac{gp\sqrt{p^2+q^2}}{c^2h^2} - \frac{1}{\rho_w} \left[ \frac{\partial}{\partial y} (ht_{xx}) + \frac{\partial}{\partial x} (ht_{xy}) \right] - \Omega_q - fVV_x + \frac{h}{\rho_w} \frac{\partial}{\partial x} (p_a) = 0 \tag{7.2}
\]

\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial y} + \frac{gq\sqrt{p^2+q^2}}{c^2h^2} - \frac{1}{\rho_w} \left[ \frac{\partial}{\partial y} (ht_{yy}) + \frac{\partial}{\partial x} (ht_{xy}) \right] - \Omega_p - fVV_y + \frac{h}{\rho_w} \frac{\partial}{\partial xy} (p_a) = 0 \tag{7.3}
\]

Where

- \( \zeta(x, y, t) \) - Water surface level above datum (m)
- \( p(x, y, t) \) - flux density in the x-direction \((m^3/s/m)\)
- \( q(x, y, t) \) - flux density in the y-direction \((m^3/s/m)\)
- \( h(x, y, t) \) - water depth (m)
- \( S \) - source magnitude per unit horizontal area \((m^3/s/m^2)\)
- \( S_{lx}, S_{ly} \) - source impulse in x and y-directions \((m^3/s/m^2.m/s)\)
- \( e \) - evaporation rate (m/s)
- \( g \) - gravitational acceleration \((m/s^2)\)
- \( C \) - Chezy resistance No. \((m^{1/2}/s)\)
\[ K_a = C_w \frac{\rho_{\text{air}}}{\rho_{\text{water}}} \]

- \( C_w \) - wind friction factor
- \( W, W_x, W_y(x, y, t) \) - wind speed components in \( x \) & \( y \) directions (m/s)
- \( p_a(x, y, t) \) - barometric pressure (kg/m/s^2)
- \( \rho_w \) - density of water (kg/m^3)
- \( \Omega_p \) & \( \Omega_q \) - Coriolis coefficient (latitude dependent) (s^{-1}) in \( x \) and \( y \) direction
- \( \varepsilon(x, y) \) - eddy or momentum dispersion coefficient (m^2/s)
- \( x, y \) - space coordinates (m)
- \( t \) - Time (s)

**Eddy viscosity**

In many applications a constant eddy viscosity is used for the horizontal stress terms. Alternatively, Smagorinsky (1963) has proposed sub grid scale transport by an effective eddy viscosity related to a characteristic length scale. The sub- grid scale eddy viscosity \( A \) is given by

\[
A = C_s^2 I^2 \sqrt{2S_{ij}^2} \tag{7.4}
\]

Where \( C_s \) is the constant, \( I \) is a characteristic length and deformation rate \( (S_{ij}) \) is given by

\[
S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) (i, j = 1, 2) \tag{7.5}
\]

**Bed resistance**

The bottom stress \( \tau_b \), is determined by a Quadratic friction law

\[
\frac{\tau_b}{\rho_0} = C_f \bar{u}_b |\bar{u}_b| \tag{7.6}
\]
Where $C_f$ is the drag coefficient, $\overline{u_b}$ is the flow velocity above the bottom and $\rho_0$ is the density of the water. For two dimensional calculation $|\overline{u_b}|$ is the depth averaged velocity and the drag coefficient can be determined from Chezy number, $C$ (m$^{1/2}$/s), or Manning number, $M$ (m$^{1/3}$/s) with water depth $h$.

$$C_f = \frac{g}{C^2}$$  \hspace{1cm} (7.7)

$$C_f = \frac{g}{(M h^{1/6})^2}$$  \hspace{1cm} (7.8)

**Wave radiation Stress**

The second order stresses due to breaking of short period waves can be included in the simulation. The radiation stress acts as a driving force for the mean flow and can be used to calculate the wave induced flow. A data file with the three components of the radiation stress which is divided by the density of the water, $S_{xx}$, $S_{yy}$ and $S_{xy}$ (m$^2$ s$^{-2}$), must be specified. The data file containing the wave radiation stresses can be generated by the wave models MIKE21 SW, MIKE21 NSW or MIKE 21 PMS.

**7.3 Model setup**

After gathering the input data, including boundary conditions and wind field, the geometry of the simulation shoreline area was added to the model in order to define the domain. Model grids were generated by MIKE Mesh Generator, which used bathymetry data and user defined grid limits. The recorded surface elevations of three wave recorder data from north of Godavari estuary to Uppada region, employed to provide the eastern and western lateral boundary conditions of the hydrodynamic model. The hydrodynamic model has a few physical parameters that require tuning during the model calibration. Various sensitivity tests were carried out to analyze the effect of variations of different parameters on the hydrodynamic model results, including boundary conditions, eddy viscosity, bed
resistance (bottom roughness) and wind friction coefficients, mesh resolution, and
time steps. This analysis revealed that the model was insensitive to time steps.
However, the outputs were sensitive to mesh resolution. After increasing the
resolution a few times, the outputs became insensitive to mesh resolution, i.e. mesh
independency. Flooding depth (water depth at which the point will be re-entered
into the calculation) was set at 0.05 m, and drying depth (minimum water depth
allowed in a point before it is taken out of the calculation) was set at 0.15 m to
capture the intertidal area appropriately in the model domain. Bed resistance can be
calculated either through the roughness height or quadratic roughness coefficient.
Examining the roughness heights as Chezy number of $72m^3/s$ was chosen.
Horizontal eddy viscosity coefficient is another important parameter defining the
turbulent mixing in the water. The Smagorinsky eddy viscosity with the coefficient
of 0.5 was adopted for the simulation. The wind shear stress was simply assumed
to be proportional to square of wind velocity through using the wind drag
coefficient. The drag coefficient depends on the wind speed and increased with the
increase of wind speed. Comparing the outputs with measurements, the drag
coefficient of 0.001255 (for wind speed of 7 m/s) and 0.0026 (for wind speed of 15
m/s and higher) was chosen.

**Boundary Conditions**

Boundary conditions of the hydrodynamic model were synthesized from
current and water level measurements were taken on either side of the scheme. In
flow model, tidal elevation data based on global tidal analysis were used
(Anderson, 1983). The time step was set at 5400 seconds considering the Courant–
Friedrichs–Lewy (CFL) condition criteria for stability of the model. The Courant
number was set to 0.9, which was within the prescribed limit for numerical
stability of the 2D implicit model. The numerical simulations were carried out by
imposing two open boundaries, viz., north and south of Kakinada port and the offshore boundary was considered to be zero cross flow. The model was driven by temporal variations in water level specified along the open boundaries and wind, to obtain realistic water elevation and flow patterns. The data was then split into the individual tidal cycle, temporally normalized to the mean tidal cycle length and current speeds with water depths averaged to give a mean tidal cycle. In order to force the progressive wave the water level was specified at the northern end and current velocities at the southern end. The offshore boundary was forced with current velocities, the forcing velocities varied along the offshore boundary, being interpolated between current velocities at the northern and southern boundaries. The simulation period was from the 14th - 29th July and 15th – 30th December 2009 of which was the period of the tide measurements. But the first simulations were run for a short period until the results were acceptable. Certainly so many simulations had to be run before finding the right parameters that running each of them for the whole period. So a period of a few days was taken for each simulation until the calibration was done, and then the model was verified for the whole period.

7.4 Results and Discussion

Hydrodynamic modeling is a prerequisite to the spectral wave modeling as it influences the sediment erosion and deposition processes in the coastal region. A modeling study has been carried out to understand the tidal currents and the effect of winds on the current system for the study area. Along the east coast of India tidal amplitude get increases from south to north. The tidal range of the southern tip of Kanyakumari is about 1.6 m and increases up to the northern end of Hooghly estuary with the height of 5.25m. This is mainly due to nonlinear shallow water
effects and the configuration of the Bay of Bengal. The tidal range of Kakinada coast with a maximum of 2.48 m, which normally occurs at mouth bay in December (NE monsoon), and the minimum level 0.16 m occurs on July 2009. The observed surface elevation is 1.81m and 2.48m during SW and NE monsoon respectively (Table 2). Further, the tidal signals are analyzed for major tidal constituents using the IOS method as described by Godin, (1972) and Foreman, (1977). The largest amplitude is observed in M2 constituent in the order of 0.48 and 0.52, which is followed by S2 with 0.18 and 0.21, respectively for SW and NE monsoon. The Greenwich phase of the tidal constituents is 65° - 85° for M2, 106°-340° for S2, 255°- 330° for K1 and 230°- 320° for O1 during both seasons. The determined constituents amplitude and phase are given in table 3 and 4. The importance of semidiurnal constituents depend on geographical positions which can be calculated by form number. The form number is the ratio of the sums of amplitudes of the two major diurnal (K1 and O1) and semidiurnal (M2 and S2) constituents (Pugh, 1987). The obtained form number are 0.25 and 0.23 during SW and NE monsoon, indicating the study area is dominated by semidiurnal tidal constituents throughout the year.

Table 2. Hydrodynamic parameter during North-east and South-west monsoon

<table>
<thead>
<tr>
<th>Location name</th>
<th>Tide (m)</th>
<th>U Velocity (m/s)</th>
<th>V Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Mean</td>
</tr>
<tr>
<td>SW Monsoon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offshore</td>
<td>1.81</td>
<td>0.17</td>
<td>0.86</td>
</tr>
<tr>
<td>Mouth of bay</td>
<td>1.75</td>
<td>0.23</td>
<td>0.86</td>
</tr>
<tr>
<td>Near Godavari</td>
<td>1.68</td>
<td>0.19</td>
<td>0.87</td>
</tr>
<tr>
<td>NE Monsoon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offshore</td>
<td>1.52</td>
<td>0.18</td>
<td>0.86</td>
</tr>
<tr>
<td>Mouth of bay</td>
<td>2.48</td>
<td>0.19</td>
<td>0.87</td>
</tr>
<tr>
<td>Near Godavari</td>
<td>1.65</td>
<td>0.16</td>
<td>0.87</td>
</tr>
</tbody>
</table>
Figure 7.1 Surface Elevation during (a) SW monsoon and (b) NE monsoon
Tidal currents are very prominent towards the coastal region. Tidal currents have been resolved into U components (east-west) and v-components (north-south) to get the dominant flow for the coastal environment, which is responsible for transport of sediment materials along or across the coast. Normally, for 8 months of the year, i.e., March to October the water flow is towards the north and from November to February it is towards south (NHO, 1991). Hence the east of India experiences 0.20 – 0.25 m/s for coastal current patterns with seasonal changes in direction. Analysis of the current speed and direction at measured locations during SW and NE monsoon are given in Table 5.

### Table 3. Amplitude of major tidal constituents at various locations.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>M₂ Amplitude (m)</th>
<th>S₂ Amplitude (m)</th>
<th>K₁ Amplitude (m)</th>
<th>O₁ Amplitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.48</td>
<td>0.50</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>0.49</td>
<td>0.52</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>0.48</td>
<td>0.51</td>
<td>0.19</td>
<td>0.21</td>
</tr>
</tbody>
</table>

### Table 4. Phase of major tidal constituents at various locations.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>M₂ Phase (Deg)</th>
<th>S₂ Phase (Deg)</th>
<th>K₁ Phase (Deg)</th>
<th>O₁ Phase (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65</td>
<td>71</td>
<td>119</td>
<td>111</td>
</tr>
<tr>
<td>2</td>
<td>66</td>
<td>82</td>
<td>127</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>79</td>
<td>85</td>
<td>138</td>
<td>106</td>
</tr>
</tbody>
</table>

### Table 5. Observed current magnitude and direction at measured locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>SW Monsoon</th>
<th>NE Monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (m/s)</td>
<td>Maximum (m/s)</td>
</tr>
<tr>
<td>1</td>
<td>0.21</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>0.13</td>
<td>0.72</td>
</tr>
<tr>
<td>3</td>
<td>0.26</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Figure 7.2 A flow of Current during SW monsoon (a) Flood tide and (b) Ebb tide
Figure 7.3 A flow of Current during NE monsoon (a) Flood tide and (b) Ebb tide
Figure 7.4 Comparison between modeled and measured Surface Elevation at offshore(a), north near bay mouth(b) and South near Godavari estuary(c) during SW monsoon
Figure 7.5 Comparison between modeled and measured Surface Elevations at offshore(a), north near bay mouth(b) and South near Godavari estuary(c) during NE monsoon
Figure 7.6 Comparison between modeled and measured U velocity at offshore(a), north- near bay mouth(b) and South near Godavari estuary(c) during SW monsoon
Figure 7.7 Comparison between modeled and measured U velocity at offshore (a), north near bay mouth (b) and South near Godavari estuary (c) during NE monsoon
Figure 7.8 Comparison between modeled and measured V velocity at offshore(a), north- near bay mouth(b) and South near Godavari estuary(c) during SW monsoon
Figure 7.9 Comparison of V velocity between modeled and measured for northeast monsoon at A) offshore B) north- near the bay mouth and C) South near Godavari estuary.
The maximum current speed has been observed as 0.88 m/s, near Godavari estuary, 0.72 m/s at mouth entrance and 0.5 m/s at offshore region during the SW monsoon. During the NE monsoon the maximum current speed varied with an average of 0.85 m/s, near Godavari estuary, 0.54 m/s at the mouth entrance and 0.51 m/s at offshore region. The magnitudes of current speed during the SW monsoon is observed to be higher compared to NE monsoon.

Near Godavari estuarine region, tidal range is less and supply of tidal current from the south is strong with relatively larger barrier systems have developed by influence of tides and tidal current (Sastry et al., 1991). Since tidal currents were weak and therefore an eroded materials tend to be deposited at the mouth entrance. The flood current reaches maximum velocity and flows in a southerly direction near Kakinada entrance channel and ebb current reaches maximum velocity at Godavari point in northern direction, flows along the sand spit (Sastry et al., 1991). The strong ebb current removes materials and have caused deepening of bay. The water level data are predicted using harmonic constituents which are compared very well with the simulated water level variation. The result indicates that these oscillations are associated with the semidiurnal pattern. As the 2D model result represents the current flow, the measured U – V components are compared with the model results, this shows that the current in the upper layer increases significantly under the influence of monsoonal winds (Vethamony and Babu, 2010). In shallow coastal region, the presence of oscillatory flow of wave results in the increase of bottom stress, which favors the remobilization of bed sediment. From the above observations, it is evident that the tidal currents are responsible for transport of sediment along the coast.