Calibration of a finite element surge prediction model for the east coast of India

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Real time simulation of storm surges using numerical models requires calibration and validation of the model before being used for operational forecasts. The main objective of this paper is to present the calibration studies carried out on an operational level storm surge prediction model developed at NIOT using finite element method. The primary requirement for calibration of surge prediction model is the actual data on bathymetry, past cyclones and the observed surges. The bathymetric contours along the shelf of east coast of India were digitized from the hydrographic charts and the data on cyclones which crossed the east coast of India for the past fifty years were collected from India Meteorological Department. The sensitivity studies showed that the wind stress coefficient is the key sensitive parameter for the model and so the model is calibrated for this parameter. The surge simulations using the calibrated parameter compare very well with the observed surges and illustrate the predictive capability of the model.

[Key words: Storm surge, finite element method, calibration]

Coastal regions are generally vulnerable to storms and associated surges and the inundation caused by the surges have devastating impacts. To minimize damages, it is essential to have a forecasting model for storm surges and for estimation of coastal inundation.

Among the various numerical methods available for surge prediction1–5, the finite element method is the most suited due to its flexibility to represent irregular boundaries and complex topographies with greater accuracy. Though finite element models for surge prediction were developed in the past3,6, to reduce the computation significantly, an efficient model using explicit finite element scheme for surge simulation was developed at NIOT7,8 and benchmarked using the international standard software MIKE21 of Danish Hydraulic Institute. Then sensitivity studies were carried out on the model9 and the wind stress coefficient was found to be the key calibrating parameter.

This finite element model needs to be calibrated before it is used for operational forecasts. Calibration of the numerical model requires actual data of all the inputs that go into the model. The objective of this paper is to present the calibration carried out on the finite element model using actual data of bathymetry of the domain and cyclones that crossed east coast of India over the last fifty years (Fig. 1).

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Materials and Methods

Governing equations

The vertically integrated form of the shallow water equations governing the ocean flow field in an ocean shelf, in a Cartesian co-ordinate frame fixed to the rotating earth, are the continuity equation.

\[ q_{xx} + q_{yy} + \zeta_{,y} = 0, \quad \ldots \ (1) \]

and the momentum equations in the x and y directions:

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Fig. 1 — Study area in the ocean shelf region along the east of coast of Sri Lanka and India.
Here the origin of the coordinate system was chosen at the undisturbed sea surface and \(z\) was measured positive upwards. The pressure was assumed hydrostatic and the astronomical tide generating forces were neglected. The volume transport \((q)\) and volume transport components are defined as
\[
q_x = \int u \, dz \quad \text{and} \quad q_y = \int v \, dz,
\]
where the integration limits vary from \(-h\) to \(\zeta\); \((u, v)\) are the components of velocity in the \((x, y)\) directions respectively and \(t\) is the time. The suffixes preceded by comma indicate partial derivatives. \(H = h + \zeta\) is the total depth of water, \(h\) is the undisturbed depth of water and \(\zeta\) is the elevation of the sea surface, measured from the undisturbed sea surface; \(p_a\) is the atmospheric pressure, \(f\) is the Coriolis parameter, \(\rho\) is the density of water and \(g\) is the acceleration due to gravity; \((\tau_{ax}, \tau_{ay})\) and \((\tau_{bx}, \tau_{by})\) are the stresses at the air-sea interface (wind stresses) and at the bottom surface (bottom stresses) respectively.

**Wind field estimation**

The wind estimates based on pressure distribution over ocean regions are considered to be more reliable, since the pressure observations are relatively free from noise unlike wind observations. In the present surge simulation model, we used the pressure distribu-

<table>
<thead>
<tr>
<th>Area</th>
<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Between Sri Lanka &amp; Paradip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across the shelf</td>
<td>5.64</td>
<td>1.97</td>
<td>11.60</td>
</tr>
<tr>
<td>Along the shelf</td>
<td>8.76</td>
<td>6.35</td>
<td>17.20</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Between Paradip &amp; Bangladesh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across the shelf</td>
<td>6.52</td>
<td>1.97</td>
<td>15.00</td>
</tr>
<tr>
<td>Along the shelf</td>
<td>8.90</td>
<td>6.35</td>
<td>20.00</td>
</tr>
</tbody>
</table>

(\(^{\oplus}\) The grid spacing is large only at a few places along the coast, where the coast line is highly irregular)
tion given by Basu & Ghosh\textsuperscript{10} to derive the wind field, since it requires only one parameter ‘n’ to define the pressure distribution and for a fixed ‘n’ the wind field derived from this formulation coincided well with observed winds for past cyclones. Basu & Ghosh\textsuperscript{10} compared the computed and measured pressure distributions for four cyclones and observed that the parameter ‘n’ varies between 1.3 and 2. Fixing the value of ‘n’ as 1.7, they computed the maximum wind for thirty-seven past cyclones and found them to match well with observed maximum winds. Hence in this study, we used their formulation with the parameter ‘n’ as 1.7.

Explicit finite element method

In this model the finite element method\textsuperscript{11} was adopted and flow domain was first divided into 9-noded quadrilateral elements. The variables ($\zeta$, $q_x$, $q_y$)

Table 2 — Cyclone parameters and location of peak surges for past cyclones along the east coast of India

<table>
<thead>
<tr>
<th>Cyclone</th>
<th>Landfall (°N)</th>
<th>Location of peak surge observed</th>
<th>Peak surge distance from landfall (km)</th>
<th>$\Delta p$ (hPa)</th>
<th>Rad. of max wind (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machilipatnam (1949)</td>
<td>16.3</td>
<td>Machilipatnam</td>
<td>87</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td>Kakinada (1969)</td>
<td>16.7</td>
<td>Kakinada</td>
<td>49</td>
<td>45</td>
<td>25</td>
</tr>
<tr>
<td>Sriharikota (1972)</td>
<td>14.0</td>
<td>Sriharikota</td>
<td>33</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td>Divi (1977)</td>
<td>15.8</td>
<td>Machilipatnam</td>
<td>26</td>
<td>97</td>
<td>45</td>
</tr>
<tr>
<td>Kavali (1979)</td>
<td>14.8</td>
<td>Ongole</td>
<td>61</td>
<td>60</td>
<td>35</td>
</tr>
<tr>
<td>Sriharikota (1984)</td>
<td>14.0</td>
<td>Sriharikota</td>
<td>17</td>
<td>60</td>
<td>25</td>
</tr>
<tr>
<td>Kavali (1989)</td>
<td>14.8</td>
<td>Near Ongole</td>
<td>23</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>Divi (1990)</td>
<td>15.7</td>
<td>Machilipatnam</td>
<td>26</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Madras (1994)</td>
<td>13.0</td>
<td>Madras</td>
<td>14</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Kakinada (1996)</td>
<td>16.7</td>
<td>Kakinada</td>
<td>49</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>Paradip (1982)</td>
<td>20.7</td>
<td>Dhamra port</td>
<td>60</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Orissa (1985)</td>
<td>21.0</td>
<td>Chandbali</td>
<td>22</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>Orissa (1989)</td>
<td>21.8</td>
<td>Near Dariapur</td>
<td>75</td>
<td>40</td>
<td>33</td>
</tr>
</tbody>
</table>

Fig. 4 — Tracks of the cyclones which crossed (A) Tamilnadu coast (B) Andhra Coast and (C) Orissa Coast

Fig. 5 — Wind coefficient (Ka) vs. least square error of $K_a$. 

Latha et al.: Surge prediction model
Fig. 6—Surge envelopes for the cyclones that crossed (A) Tamilnadu coast, (B,C) Andhra coast and (D) Orissa coast. (Coastal stations are given as KRK—Karaikal, CDL—Cuddalore, MDS—Madras, ONG—Ongole, MCH—Machilipatnam, KAK—Kakinada, VSP—Visakhapatnam, PR—Puri, PDP—Paradip, DPT—Dhamra Port and SI—Sagar Island).
over the elements are represented by Lagrangian quadratic basis functions (i.e. piece-wise continuous polynomials) in the form,

\[
\zeta(x,y,t) = \sum_{j=1}^{N} \zeta_j(t) \phi_j(x,y)
\]

\[
q_x = \sum_{j=1}^{N} q_{xj}(t) \phi_j(x,y)
\]

\[
q_y = \sum_{j=1}^{N} q_{yj}(t) \phi_j(x,y)
\]

where, \(\zeta, q_{x}, q_{y}\) are the unknown nodal values of the dependent variables in an element, \(\phi(x,y)\) are the shape functions and \(N\) is the number of nodes in each element. The approximate solutions (Eqs. 5a-c) were substituted into the governing equations (Eqs.1-3) and the Galerkin's method of weighted residuals was employed to get the element equations. In this scheme, nine-noded Lagrangian isoparametric elements were used to discretise the variables in the problem. The use of Lagrangian interpolation functions in combination with Simpson's rule of integration of dependent variables over an element makes the coefficient matrices of the flow variables diagonal as against a banded matrix, which normally results from other forms of finite element schemes. This leads to an explicit time integration scheme avoiding matrix inversion and hence a reduction in computation, which is a primary requirement in real time storm surge prediction.

**Finite element grid generation**

The ocean shelf along the east coast of Sri Lanka and India, which is the analysis area for the storm surge prediction model, is shown in Fig. 1. The southern boundary of the analysis area is 6°N and the northern boundary is 22°N. The length and the average width of the shelf are nearly 2600 km and 50 km respectively.

The software “DIGI” (from MIKE21 Package) and “FASTTABS” were used to generate the finite element grid over the analysis area. Using the software “DIGI”, the depth contours 0 m (coastline), 5 m, 10 m, 20 m, 30 m, 50 m, 100 m, 150 m and 200 m, in the hydrographic charts were digitized and a bathymetry file was created. The bathymetry file forms the input to the software “FASTTABS”. Using this software, the finite element grid was generated interactively and the depth at the grid points was determined.

Initially the finite element grid was generated for the shelf region from Sri Lanka to Paradip consisting of 236 points along the shelf and 11 grid points across the shelf. The mesh consists of a total number of 2596 points. The statistics of the grid spacing for this stretch is shown in Table 1A. The finite element mesh for the shelf region between Paradip and Bangladesh was carried out separately as the width of the shelf in this region is high. The grid points across the shelf are 21 for the region from Paradip to Sagar islands and 17 beyond Sagar islands. Along the coast there are 27 points and the total number of nodes in this mesh is 514.

The grids used in the region near Krishna river delta and in the Palk Straight are shown exclusively below due to the following reasons:

1. In the Krishna river Delta the coast line has a deep curvature and the number of points across the shelf were reduced accordingly.
2. In the shelf region between Sri Lanka and Tamil Nadu, the Palk Strait is an open ocean region. Additional grid points were introduced to handle the open ocean condition.

Figure 2 shows the grid distribution used in the present model over the shelf region near the Krishna River delta. As this delta region extends into the shelf, only 7 grid points are considered across the shelf. The channel between Sri Lanka and Vedaranyam (Fig. 3) that connects the Bay of Bengal and the Palk Strait can be kept open or closed by switching on or off a parameter in the software. When the channel is kept open the software automatically generates 14 extra grid points in the Palk Strait region (Fig. 3).
Model calibration

While calibrating the surge model and then using it for forecasting, we have to be aware of the quality of the input data used in calibration experiments. Many uncertainties in the specification of cyclone parameters, which go as input to the surge model, are discussed below.

Pressure difference
- Determination of the maximum atmospheric pressure difference ($\Delta p$) from the T-number of a cyclone was based on an empirical relation between them. Error involved in the estimation of $\Delta p$ from the T-number of a cyclone is $\approx 10$ hPa, when T-number = 5.
- T-number estimation from satellite imagery of cloud pattern is subjective in nature.

Pressure and wind distribution
Empirical functions fitted to the pressure and wind fields are again subjective in nature. When wind fields were derived from the atmospheric pressure fields, approximate force balance relations were used.

Results and Discussion

The present model was calibrated using the data of 11 past cyclones which crossed the east coast of India in the stretch of Andhra and Tamil Nadu. The tracks of these cyclones are shown in Fig. 4 and the parameters of the cyclone are listed in Table 2. Using the finite element model, the peak surges generated by these cyclones were computed for values of $K_a$ varying from $2.8 \times 10^{-3}$ to $3.8 \times 10^{-3}$. The error in the surge estimates defined as the difference between the observed and the model predicted peak surges for each $K_a$ were computed for all the cyclones. The sum of squares of these errors over all the cyclones for each $K_a$ is shown in Fig. 5, and it can be seen that it has the least value for $K_a = 3.4 \times 10^{-3}$. Hence the value of $K_a$ was fixed as $3.4 \times 10^{-3}$ and the surge generated along the coast for the 11 past cyclones were computed. The surges caused by cyclones that crossed the Orissa coast are simulated using the same $K_a$ and the results are compared with the observed surges. The surge envelopes are shown in Fig. 6 and the peak surges are presented in Table 2.

The average error in the predicted surge by NIOT model when compared with the observed surge is 6% for 11 cyclones and it is 35% for the other three cyclones, over the coast of Tamil Nadu and Andhra. The average error for the Orissa cyclones is 12%. It may be noted that the observed surges of past cyclones are not instrument recorded values and they are based on post storm surveys. Also the uncertainties in the input parameters of an approaching cyclone are mentioned earlier. Even with all these limitations, Table 3 illustrates that the predictive capability of our model is good. So it is concluded that the model can be validated once the instrument recorded surge data is available and then it can be used for forecasting the surges.

References