Wave Forecast System of Hualien Harbour

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ABSTRACT

In this paper, an establishment of wave forecast system of Hualien Harbour was introduced. WAM for global wave forecast, SWAN for nearshore wave forecast, and a harbour oscillation model have been combined to predict the wave condition inside the harbour during the severe weather. Refer to the characteristics of WAM and SWAN which output the spectral energies of each component wave and the principal wave direction at each specified node, the harbour oscillation model was simulated in long crested random waves with different wave direction at each node on pseudo boundary. With this system, wave conditions around the Hualien Harbour during typhoon period can be predicted.

1. INTRODUCTION

Wave conditions around a harbour are the major concern in harbour planning and design, and also in harbour operation. The evaluations of wave condition around the harbour in planning and design stages are always carried out in both the numerical simulations and the hydraulic model tests in wave flume and wave basin. However, all the simulations can only be done by some specific incident wave conditions where the wave period, wave height and wave direction were partly obtained from field measurement, but mostly from wave hindcast via wind records. On the other hand, for the harbour operation, the information of wave conditions around the harbor is helpful for safety maneuvering. Due to lack of proper tool, the wave conditions can only be estimated from experiences of harbor manager with the reference of observed or predicted weather or sea state.

In Taiwan, monsoon in winter and typhoons in summer can induce large wave height along the coastline and cause worse tranquility inside a harbour. The worse problem is that some of our harbours might cause long period oscillations inside the harbour, such as Su-Ao harbor and Hua-Lien harbor at the east coast of Taiwan, and the ships had always been asked to evacuate during typhoon period.

In order to enhance the wave forecast ability around a harbour for the operation purpose, a new tool which combined the TaiCOMS model (WAM+SWAN) established by the Institute of Harbour and Marine Technology and the harbour tranquility model (hereafter, the harbour model) with finite/infinite element method proposed by Lin (1995) to establish a prediction model of wave conditions around a harbour is discussed. By employing the predicted wind field of NW Pacific and around Taiwan, wave field that covers the NW Pacific ocean was calculated through the WAM model. Then a nested SWAN model was connected to calculate the wave fields around Taiwan and outside a harbour with different grid size. After the wave data at the nodes along the pseudo boundary were obtained, the harbour tranquility model was ignited to simulate

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the wave condition around the harbour. With such tool, harbour tranquility during severe weather can be predicted when the wind fields were analyzed and forecasted.

In the following paragraph, we will briefly describe the theory of the work, and the predicted wind fields during the period of typhoon Longwang between 2005/09/30 and 2005/10/04 was employed for the calculations of wave conditions around Hualien harbour at the east coast of Taiwan as an example.

2. TAICOMS WAVE MODEL

TaiComs (Taiwan Coastal Operational Modeling System) is one of the wind wave predictions models around Taiwan area which developed and operated by the Center of Harbour and Marine Technology, Institute of Transportation for the safety navigations in Taiwan water zone. As shown in Fig. 1, a WAM and a SWAN models are employed. Table 1 shows their computational area and their spatial resolutions.

The needed wind fields are supported by CWB. As shown in Fig. 2, there are three numerical wind fields, RC, MC and HC, which covers different area with different grid resolutions of 0.45°×0.45°, 0.15°×0.15° and 0.05°×0.05°, respectively. The numerical topography is extracted from either ETOPO5 from NGDC, NOAA (National Geographic Data Center, National Oceanic and Atmospheric Administration, USA) with grid resolutions of 5’×5’ or TaiDBMv5 from National Ocean Science Center, Taiwan with grid resolutions of 0.05°×0.05°.

TABLE I. RELATED INFORMATION IN TAICOMS MODEL

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Cover area</th>
<th>Grid size</th>
<th>Wind field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far field</td>
<td>WAM</td>
<td>Lat.: 10°N ~ 35°N</td>
<td>0.2°×0.2°</td>
<td>RC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lon.: 110°E ~ 134°E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near field</td>
<td>SWAN</td>
<td>Lat.: 21°N ~ 26°N</td>
<td>0.04°×0.04°</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lon.: 119°E ~ 123°E</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig1. Computational area and topography in TaiComs Model
3. THE HARBOUR TRANQUILITY MODEL

The model employed in the study is a finite/infinite element model developed by Lin and Chen (1996)[2], Lin (1995)[1] gives the full theory of the model. Figure 3 shows the definition sketch of the model. An arbitrary shape and bathymetry harbour is considered. The water zone are divided into two domains: \( \Omega_1 \) and \( \Omega_2 \), where \( \Omega_1 \) is a finite domain which bounded by the solid boundary around the harbour \( \Gamma_1 \), free water surface, sea bottom, and pseudo boundary \( \Gamma_2 \); and \( \Omega_2 \) is a semi-infinite domain which bounded by two semicircle pseudo boundaries: \( \Gamma_2 \) and \( \Gamma_3 \), and coastline \( \Gamma_3 \), free water surface and arbitrary sea bottom, where \( \Gamma_4 \) is located at infinite; \( \Gamma_2 \) is set at certain distance outside the harbour.

The governing equation of the model is mild slope equation modified by Chen (1986) as shown in Eq. (1),

\[
\nabla \cdot \left( \lambda \mathbf{C}_g \nabla \phi \right) + \mathbf{C}_g k^2 \phi = 0
\]

(1)

Here the wave is simple harmonic and long crested. The symbol \( \mathbf{v} = \left( \partial / \partial x, \partial / \partial y \right) \) is the horizontal gradient operator; \( \mathbf{c}(x, y) \) is the complex velocity potential; \( \cdot \) is the scalar product operator; \( C = L/T \) is the wave celerity; \( L \) is the wave length; \( T \) is the wave period; \( C_g = nC \) is the group velocity; \( n(x, y) = \left( 1 + 2kh / \sinh 2kh \right) / 2 \); \( h(x, y) \) is the still water depth; \( k(x, y) = 2\pi / L \) is the wave number; and \( \omega = 2\pi / T \) is the angular frequency. The wave number \( k \) and the angular frequency \( \omega \) satisfy the dispersion relation, \( \omega^2 = gk \tanh kh \), where \( g \) is the gravitational acceleration. On taking account the sea bottom friction, Chen (1986) proposed a friction factor \( \lambda = \left( 1 + (i\beta \alpha / h \sinh kh) e^{\gamma} \right)^{1} \), where \( i = \sqrt{-1} \) is the imaginary unit; \( \beta \) is the friction coefficient which is a dimensionless quantity and may vary spatially; \( \gamma \) is the phase angle and \( \alpha \) is the incident wave amplitude.

The boundary conditions are set as follows:

\[
\frac{\partial \phi_{\Omega_1}}{\partial n_{\Omega_1}} - \alpha \phi_{\Omega_1} = 0 \quad \text{on solid boundary } \Gamma_1
\]

(2)

\[
\frac{\partial \phi_{\Omega_2}}{\partial n_{\Omega_2}} = \frac{\partial \phi_{\Omega_1}}{\partial n_{\Omega_1}} \quad \text{on pseudo boundary } \Gamma_2
\]

(3)
\[ \frac{\partial \phi_{\Omega_2}}{\partial n_{\Omega_2}} - \alpha \phi_{\Omega_2} = 0 \] on solid boundary \( \Gamma_3 \) \hspace{1cm} (4)

where \( \alpha = ik \left[ \left( 1 - K_R \right) / \left( 1 + K_R \right) \right] \), \( K_R \) is the reflection coefficient, and \( n_{\Omega_1} \) and \( n_{\Omega_2} \) are the unit normal vectors directed outwards from the domain \( \Omega_1 \) and \( \Omega_2 \) respectively. On pseudo boundary \( \Gamma_4 \), the scatter waves \( \phi_S \) should satisfy the Sommerfeld radiation condition

\[ \lim_{r \to \infty} \sqrt{r} \left( \frac{\partial}{\partial r} - \frac{ik}{\sqrt{\lambda}} \right) \phi_S = 0 \] \hspace{1cm} (5)

By applying the first variation theory, the functional \( F(\phi) \) of the entire area can be constructed.

\[
F(\phi) = \frac{1}{2} \int_{\Omega_1} \left( \lambda CC_g \nabla^2 \phi_{\Omega_2} - CC_g k^2 \phi_{\Omega_2}^2 \right) dA \\
+ \frac{1}{2} \int_{\Omega_2} \left( \lambda CC_g \nabla^2 \phi_S - CC_g k^2 \phi_S^2 \right) dA \\
- \frac{1}{2} \int_{\Gamma_1} \alpha \lambda CC_g \phi_{\Gamma_1}^2 dL + \int_{\Gamma_2} \lambda CC_g \frac{\partial \phi_0}{\partial n_{\Omega_1}} \phi_{\Omega_2} dL \\
- \frac{1}{2} \int_{\Gamma_3} \alpha \lambda CC_g \phi_S^2 dL - \frac{1}{2} \int_{\Gamma_4} ik \frac{CC_g}{\sqrt{\lambda}} \phi_S^2 dL 
\] \hspace{1cm} (6)

After introducing the finite/infinite elements into the discretization of equ (6). The stationary of the functional \( F(\phi) \) implies that

\[ \frac{\partial F}{\partial \phi_i} = 0, \quad i = 1, 2, \ldots, N \] \hspace{1cm} (7)

where \( N \) is the number of nodal point. The velocity potential at each node of entire area can then be solved.

Fig 3. Definition sketch of the harbour tranquility model
4. THE CONNECTION OF THE MODELS

Figure 4 shows the conceptual model of this study. The incident waves on the pseudo boundary of the harbour tranquility model are calculated from the ocean wave model and TaiComs model was employed for this purpose. The SWAN model will directly connected to the harbour model and the necessary incident wave data in harbour model is extracted from SWAN model. There are several concerns when doing such connection and are discussed as follow.

4.1 The Incident Waves on Pseudo Boundary of Harbour Model

The incident wave information needed in harbour tranquility model are wave heights, periods and their directions which be input at the nodal points along the pseudo boundary $\Gamma_2$ as sketched in Figure 3. We may notice that, for all harbour tranquility models, the wave height and direction can be different between the nodes along the pseudo boundary, but the wave periods must be the same.

When revising the output results from SWAN model, one may found there are several types of output can be chosen. Those are representative wave (including wave heights, periods, directions and others), 1-D spectrum or 2-D spectrum at each specific point.

Although taking the representative waves as incident waves of harbour model is the most easy way, but this cannot be happened because the representative wave period at each node is different due to the periods are derived from spectra in SWAN model. With such concern and considering the time consuming problem, this study takes the 1-D spectrum as incident wave spectrum, and executes the irregular wave simulations. One benefit of doing so is the component wave frequencies of the output spectrum at all nodes are the same, and we can use directly.

4.2 The discussion of the grid size of SWAN

When connecting the ocean model and harbour model, the grid size of the calculation is always a problem. Since the grid size of ocean model is always taken more than a kilometer to save the memory and computation time due to a very large area is calculated. For example, in TaiComs model, as shown in Table 1, the grid size of WAM model is $0.2^\circ \times 0.2^\circ$ (i.e. 20km $\times$ 20km, approximately), and the grid size of SWAN is $0.04^\circ \times 0.04^\circ$ (i.e. 4km $\times$ 4km, approximately). However, the length of element in a harbour model is always less than 50m and the pseudo boundary $\Gamma_2$ is very close to the coastline. Our experiments shown that nodal points on pseudo boundary $\Gamma_2$ in harbour model were be treated as “Land” node and no data were output because by comparing the distance (around 4km) of two nodes in SWAN model, the radius of pseudo boundary $\Gamma_2$ (less than 1km) is “really’ too close to land.

In order to solve the problem, this study introduced a nested-SWAN to connect the TaiComs model and harbour model. The grid size of the nested SWAN is $0.001^\circ \times 0.001^\circ$ to obtain the nodal spectra along the pseudo boundary.
The experiments were carried out on wave conditions around Hualien harbour at east Taiwan. Figure 5 shows the location, Figure 6 shows the layout of the harbour, and Figure 7 shows the numerical mesh and contours of Hualien harbour.

Table II shows the related information of the model. Three layers of nested ocean wave models were involved in the calculation, Firstly, WAM model for NW Pacific Ocean; secondly, SWAN model for Taiwan water zone, and thirdly, a nested SWAN for the water area around Hualien harbour. The analyzed/predicted wind fields during the period of strong typhoon Longwang between 2005/09/30 and 2005/10/03 was employed in the calculations. The maximum wind speed near the typhoon center is around of 51 m/s, Figure 8 shows the path.

From Figure 9 to Figure 12 show only part of the results of RC and MC wind fields, WAM’s wave field and KD contour around the harbour at 2005/10/01 12:00. The KD contour in Figure 12 can be transferred into wave height distribution by multiplying the incident wave height.

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Cover area</th>
<th>Grid size</th>
<th>Wind field</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW pacific Ocean</td>
<td>WAM</td>
<td>Lat.: 10°N–35°N</td>
<td>0.2° × 0.2°</td>
<td>RC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lon.: 110°E–134°E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taiwan water zone</td>
<td>SWAN</td>
<td>Lat.: 21°N–26°N</td>
<td>0.04° × 0.04°</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lon.: 119°E–123°E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hualien water zone</td>
<td>nested</td>
<td>Lat.: 23.9°N–24.0°N</td>
<td>0.001° × 0.001°</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td>SWAN</td>
<td>Lon.: 121.6°E–121.65°E</td>
<td></td>
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</tbody>
</table>
Fig 5. Location of Hualien harbour, Taiwan

Source: Web site of Hualien Harbour

Fig 6. Layout of Hualien Harbour, Taiwan

Fig 7. Numerical mesh and contours
Fig8. Path of Longwang Typhoon (2005/09/29-2005/10/03)

Fig9. RC Wind field of 2005/10/01 12:00

Fig10. MC wind field of 2005/10/01 12:00

Fig11. WAM wave field of 2005/10/01 12:00
6. DISCUSSIONS AND CONCLUSIONS

In this study, taking Hualien harbour as an example, a prediction model of wave conditions around a harbour was created. One WAM model for far wave field, two nested SWAN models for nearshore wave field around Taiwan and around Hualien harbour, and a harbour tranquility model is employed to simulate the wave conditions around the harbour under the predicted wave field action. Once the wind fields are predicted, the wave condition inside the harbour can also be obtained.

From the experiments of wave calculations around Hualien harbour during the typhoon Longwang intrusion period from 2005/09/30 to 2005/10/03, we had experienced:

1. Such model can compensate the shortcoming of ocean wave model that cannot fully reflect the wave diffraction effect. And the wave conditions behind an island or an artificial structure, or inside a harbour can be simulated.

2. Due to the different demand of grid size in either ocean wave model or harbour model, the node along the pseudo boundary in harbour model might be misinterpreted as land node and no wave data is offered from the nested SWAN model, finer nested ocean wave models are needed to adjust the difference of the grid sizes.

3. Due to the accuracy of the predicted wind field mostly manipulates the correctness of all wave model results, and the wind field around Taiwan Island is affected by the complex topography and caused worse accuracy, more improvements must be done in wind field analysis and predictions.

4. Due to the wave conditions around the harbour was calculated in irregular wave cases, the simulation is time consuming when using a personal computer with Intel Core 2 Duo CPU E6550 @ 2.33GHz with 2.33GHz 3 GB RAM and Microsoft XP OS, the total computational time needed for one single time step is around 1 hour. Unless the hardware can be improved, otherwise this model is not suitable for wave forecast. On the contrary, due to it can simulate the wave fields at offshore, nearshore and outside/inside the harbour, such tool is currently suitable for the wave hindcast in harbour planning and design stages.

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