THE TIDAL WAVE SYSTEM IN THE CHINESE MARGINAL SEAS

M. Su\textsuperscript{1,2}, M.J.F. Stive\textsuperscript{1}, C.K. Zhang\textsuperscript{2}, P. Yao\textsuperscript{1,2}, Y.P. Chen\textsuperscript{2}, Z.B. Wang\textsuperscript{1,3}

Abstract

A 2D large-scale tidal wave model is set up for the Chinese marginal seas and it is proved to simulate the tidal motion in this large domain well. Based on the model, sensitivity analyses have been carried out to investigate the influences of various factors on the tidal wave system. According to the results, the effect of river discharges and the tidal generating force on the whole tidal wave system is not obvious, but they do have influence in the shallow water area. In addition, the results show that sea level rise will impact on the China coast more than on the west coast of Korea. Furthermore, this paper demonstrates that the Shandong Peninsula is not the crucial reason for the formation of the radial tidal current off Jiangsu coast. A better insight into the propagation mechanism of the tidal wave in the Chinese marginal seas is obtained.

Key words: Chinese marginal seas, tidal wave, tidal current, radial sand ridges, Jiangsu coast, Delft 3D

1. Introduction

In the Chinese marginal seas, tide is an important driving force for the morphological processes, since wave action is rather weak. Jiangsu coast, located between the Xiuzhen Estuary and the Yangtze River Estuary, is about 954 km long (Figure 1). The radial sand ridge field is located in the central of the Jiangsu coast, which is made up of more than 70 sand ridges and tidal troughs. The main characteristics of the Jiangsu coast are the fine sediments and the gentle slopes. Silt-clayey coast accounts for 93\% of Jiangsu coast (Chen et al., 2010). In order to gain a better understanding of the hydrodynamic features along the Jiangsu coast, it is necessary to understand the tidal wave system in the whole Chinese marginal seas first. Also, a large-scale model with high resolution can provide boundary conditions for a more detailed model for the Jiangsu coast.

The formation mechanism and propagation characteristics of tidal wave in this area have been a focus for many years. The first research can be traced back to 1933, which was done by Ogura (1933). There are many studies and various numerical models afterward (Table 1). Some use observed data to establish a first understanding of the tidal wave system (Fang, 1986). Others use numerical models to simulate the tidal wave propagation in different regions. However, the resolution of some models is low and most of them only focus on a local area and ignore the influence of some factors.

In numerical models, the open boundary conditions are used to describe the tidal forcing. In addition, for a large-scale model, the tidal generating forces should not be neglected since the contribution of the gravitational forces on water motion increases considerably. However, some of the previous researches did not take the tidal generating force into account (Yanagi and Inoue, 1995; Wan et al., 1998). Furthermore, most of the models ignore the river discharges (Chen, 2008; Ye, 2012). An (1977) assumed that the potential effect of the tidal generating forces on the M2 constituent in a large region is less than 3\%. Nevertheless, there is little research on the quantitative analysis of the influence of the tidal generating force and river discharge on such a large-scale model.
Figure 1 The domain of the Chinese marginal seas and the distribution of the main rivers

Figure 2 The grid and bathymetry of the Chinese marginal seas

Table 1. Summary of the some tidal models

<table>
<thead>
<tr>
<th>Authors</th>
<th>Domain</th>
<th>Tide</th>
<th>Resolution</th>
<th>TGF</th>
</tr>
</thead>
<tbody>
<tr>
<td>An (1977)</td>
<td>BY</td>
<td>M2</td>
<td>11km</td>
<td>Yes</td>
</tr>
<tr>
<td>Zhao (1994)</td>
<td>BYE</td>
<td>4</td>
<td>15'×15'</td>
<td>Yes</td>
</tr>
<tr>
<td>Wan (1998)</td>
<td>BYE</td>
<td>M2</td>
<td>5'×5'</td>
<td>No</td>
</tr>
<tr>
<td>Kang (1998)</td>
<td>YE</td>
<td>M2</td>
<td>4'×5'</td>
<td>Yes</td>
</tr>
<tr>
<td>Choi (2007)</td>
<td>Y</td>
<td>8</td>
<td>5'×5'</td>
<td>Yes</td>
</tr>
<tr>
<td>Cheng (2009)</td>
<td>BYE</td>
<td>4</td>
<td>5'×5'</td>
<td>Yes</td>
</tr>
<tr>
<td>Choi (1980)</td>
<td>BYE</td>
<td>4</td>
<td>12'×15'</td>
<td>No</td>
</tr>
<tr>
<td>Yanagi (1995)</td>
<td>BYE</td>
<td>4</td>
<td>25 Km</td>
<td>No</td>
</tr>
<tr>
<td>Guo (1998)</td>
<td>BYE</td>
<td>4</td>
<td>12.5km</td>
<td>No</td>
</tr>
<tr>
<td>Zhu (2000)</td>
<td>BYE</td>
<td>M2</td>
<td>10'×10'</td>
<td>Yes</td>
</tr>
<tr>
<td>Chen (2008)</td>
<td>BYE</td>
<td>8</td>
<td>4'×4'</td>
<td>Yes</td>
</tr>
<tr>
<td>Ye (2012)</td>
<td>Y</td>
<td>8</td>
<td>-</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Notes: in the column of Domain: B = the Bohai Sea, Y = the Yellow Sea, E = the East China Sea; in the column of Tide: 4 = M2, S2, K1 and O1 tidal constituents, 8 = + N2, K2, P1 and Q1 tidal constituents; TGF = tidal generating forces; Dash in the blank = cannot get it from literatures.
In recent years, some researchers pay attention to the change of mean sea level. Yan et al. (2010) gave a chart of variation trend of the Chinese marginal seas and it shows that the mean sea level in this area is rising. According to IPCC report, the global mean sea level will rise about 66 cm to 110 cm in the next 100 years (Yu et al., 2007). Chen et al. (2009) simulated the 8 principal tide constituents after mean sea level rise and paid attention to the co-tidal chart differences of the Jiangsu coast. While some other research studies about the effect of mean sea level rise on the Chinese marginal seas only consider 4 principal tidal constituents (Du, 2005; Gao, 2008).

According to the previous studies, the incoming tidal wave from the East China Sea reaches the Shandong Peninsula and then reflects. The meeting of the reflected tidal wave and the incoming tidal wave can generate a standing tidal wave (Zhang et al., 1998; Wang et al., 2012). In these studies the geographical location of Shandong Peninsula is considered to be a key factor in the formation mechanism, but it is still an hypothesis. Xing et al. (2012) assumed that the tidal waves off Jiangsu coast are characterized by the meeting of a Kelvin wave and a Poincare wave. But the propagating route of Kelvin wave is still uncertain.

In this paper, the propagation mechanisms behind the tidal wave propagation in the Chinese marginal seas is updated and analyzed based on a numerical model with high resolution. The influences of various factors have been investigated by a series of sensitivity experiments, including the role of Shandong Peninsula in the formation of radial tidal current off Jiangsu coast.

2. Model Set Up and Performance

2.1. Model set up

This model is based on Delft3D modeling system (Deltas, 2012) and mainly focuses on the study of tide propagation mechanism in the Chinese marginal seas, especially around the Jiangsu coast. The domain of this model covers an area bounded by the latitudes 24° - 41°N and longitudes 117° - 131°E with two open boundaries (Figure 1). The resolution of the model is from 0.7′×0.7′ to 2.8′×2.8′ approximately, relatively higher in the Yellow Sea, Bohai Sea and lower near open boundaries (Figure 2a). The bathymetry data of this model is generated by GEBCO bathymetry data (Figure 2b).

In this model, 13 tidal constituents are considered, including 8 principle tidal constituents (M2, S2, N2, K2, K1, O1, P1 and Q1) and 5 other constituents (MF, MM, M4, MS4 and MN4), which are also important in the study area. This model takes the influence of tidal generating force and river discharges into account (the details are in the section 3.2.1). For initial conditions, a uniform value 0 is used for the water level and current velocity of the whole domain (cool start). This simulation period is set to be two months (from August 1st to October 1st, 2006) for the validation (the first 7 days data are considered as a spin-up period and omitted in the analysis). The time step is 1 minute.

2.2. Model performance

2.2.1. Verification of the water level

The water level from the model is compared to observations using the harmonic constants at 190 observation points for the calibration and verification. In order to show the comparison between the simulation and the measured values more clearly, observation points are divided into 10 groups and numbered in the clockwise direction (Figure 3). Harmonic constants of 8 principal tidal constituents in these stations have been collected from world tidal database, admiralty tidal tables and some other literatures (Zhang, 2005; Tao et al., 2011).

With the aim of giving a more graphical and visualized analysis, we put the amplitude ratio (the simulated amplitude divided by the measurement) and the phase-lag difference (the simulated phase-lag minus the measurement) of a tide constituent into a circular bar chart. Here we only take the bar chart of M2 constituent as an example to analyze the performance of the model (Figure 4). The outer circle represents the number of the observation points, while middle circle represents amplitude ratio comparison, and inner circle represents phase-lag difference. The letters “A-J” represent the ten regions of the observation points, respectively. In general, the averaged amplitude ratio and the averaged phase-lag error of the M2 constituent are 1.05 and 6.69°, respectively. Although the number of tidal gauges is almost 200,
the amplitude and phase-lag differences are still quite small. In conclusion, this model can reproduce the tidal wave system well in the Chinese marginal seas.

Figure 3 Distribution of the 190 observation points in the domain

Figure 4 Harmonic constants comparison between measured and computed values of the M2 constituent (Green line means the difference less than 0.1 for amplitude ratio or 10° for phase-lag; Orange line represents the difference less than 0.2 for amplitude ratio or 20° for phase-lag; Red line means the difference more than 0.2 for amplitude ratio or 20° for phase-lag)
2.2.2. Verification of the tidal current
Furthermore, tidal current velocities at 14 observation stations (Figure 3) are verified, in which 10 stations are located in the middle of the sea. Here we only take Lianqingshi Fishing Port (N33.50°, E123.51°) and Haizhou Bay Fishing Port (N35.00°, E121.00°) as an example to show the agreement of the tidal current. The verification data are the predicted value from the Tide Table (National marine data and information service, 2005). The verification periods are 10 days. The comparison results are shown in Figure 5. The minimum velocity magnitude of these two stations has a little difference at some time points, however, the velocity directions match very well. In general, the calculated values (both the magnitude and direction of the tidal current velocity) are in good agreement with the field data.

![Figure 5 The comparison of the tidal current velocity with the predicted value from the Tide Table](image)

3. Results
3.1. Co-tidal charts and tidal current field
Figure 6 shows the co-tidal chart and tidal ellipses of the M2 constituent. The tidal current fields generated by this model are displayed in Figure 7, which represent the ebb tide and flood tide at the radial sand ridges respectively. The co-tidal charts of 8 principal tidal constituents, as well as the tidal current field in the whole domain generated by the model show a good agreement with the Marine Atlas of the Bohai Sea, Yellow Sea and East China Sea (Atlas of the Oceans Editorial Board, 1993). Additionally, the position of the amphidromic points in the Yellow Sea are compared with some previous research results (Table 2) and they also show good accordance with previous researches (Shen, 1980; Fang, 1986; Zhang, 2005; Ye, 2012).
Figure 6 The co-tidal chart (a) and tidal ellipses (b) of the M2 constituent

Figure 7 The simulated tidal current vector field of the Chinese marginal seas during ebb (left) and flood (right) tide in radial sand ridge field

Table 2. The position of amphidromic points in the Yellow Sea

<table>
<thead>
<tr>
<th>Author</th>
<th>North point (M2 constituent)</th>
<th>South point (M2 constituent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This paper</td>
<td>123°24'E;37°45'N</td>
<td>121°33'E;34°48'N</td>
</tr>
<tr>
<td>Shen (1980)</td>
<td>123°15'E;37°38'N</td>
<td>121°12'E;34°35'N</td>
</tr>
<tr>
<td>Fang (1986)</td>
<td>123°05'E;37°30'N</td>
<td>121°40'E;34°40'N</td>
</tr>
<tr>
<td>Zhang (2005)</td>
<td>123°12'E;37°35'N</td>
<td>121°26'E;34°34'N</td>
</tr>
<tr>
<td>Ye (2012)</td>
<td>-</td>
<td>121°26'E;34°48'N</td>
</tr>
</tbody>
</table>

Table 3. Summary of the main experiments

<table>
<thead>
<tr>
<th>Sensitive factors</th>
<th>Reference run</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal generating force</td>
<td>11</td>
<td>No force</td>
</tr>
<tr>
<td>River discharge</td>
<td>14</td>
<td>No river</td>
</tr>
<tr>
<td>Mean-sea-level rise</td>
<td>No rise</td>
<td>80cm rise</td>
</tr>
<tr>
<td>Shandong Peninsula</td>
<td>Present</td>
<td>Not present</td>
</tr>
</tbody>
</table>
3.2. Parameters sensitive analysis

In this numerical model for the tide in the Chinese marginal seas several parameters are considered, such as the river discharges, tidal generating force etc. In order to present the sensitivity of these factors, a series of experiments are carried out (Table 3). The semi-diurnal tide, especially the M2 constituent is the main significant component in this research area. So, in this paper, the tidal wave motion of M2 constituent of each experiment is compared with the reference simulation to elaborate the influence of each parameter.

3.2.1. Tidal generating force and river discharges
Generally, for a small local model, the influence of tidal generating force is relatively small. However, it is essential for a large scale model, such as the Chinese marginal seas which contains a very huge area from the deep ocean (Okinawa Trough) to the shallow water basin (Bohai Bay). In this condition, the gravitational force on the water motion increases considerably and cannot be neglected. This model considers the tidal generating forces for 11 tidal constituents (8 principle tides, MF, MM and SSA constituents). The results of the experiment ignoring all tidal generating forces are compared with the results of the reference run for the M2 constituent in Figure 8. In general, no obvious changes can be found and the error for the phase-lag and amplitude are less than 3° and 5%, respectively. However, in order to get a more accurate simulation, it is better to take the tidal generating force into account.

Most of the former Chinese marginal seas models do not consider the influence of river discharges. 14 rivers which spread along China and Korea coastline are chosen as main river discharge boundaries in this model (Figure 1), whereas in the experiment 2, rivers are not taken into account. The influence of river discharges on phase-lag and amplitude of M2 constituent are shown in Figure 9. The differences are small and mainly occur near the Yangtze River Estuary, as the Yangtze River with large discharge is the most important one among the 14 rivers considered in the model.

In summary, the tidal generating force and the river discharges do not impact the model results substantially. However, they are the real existed parameters and the consideration of them is necessary for a more accurate result, especially when considering the shallow area.

3.2.2. Mean sea level rise 80 cm
Global warming and mean sea level rise have drawn a lot of attention. According to IPCC report (Yu et al. 2007) and Yan et al. (2010), rising about 80 cm could represent the worst situation of Jiangsu coast after 100 years (without considering the influence of land subsidence). Here experiment 3 with a mean sea level rise of 80 cm is used to analyze the influence of mean sea level rise. Figure 10 shows the influence of mean sea level rise 80 cm on the phase-lag and amplitude respectively. In Figure 10a, the red line represents the result of the model simulation and the blue line stands for the result of experiment 3. It can be seen that, for the M2 constituent, the phase-lag becomes smaller along the China coast, while it changes little along the Korea coast. The amplitude in the most part of the China coast increases after the mean sea level rise, whereas the amplitude near the Yangtze River Estuary decreases 0.1 m at most (Figure 10b). The rise of the mean sea level will influence the amplitude and phase-lag more on the China coast compared than on the west Korea coast.
Figure 8 The changes of the phase-lag (°) and amplitude (m) if ignoring tidal generating force

Figure 9 The influence of river discharge on the phase-lag (°) and amplitude (m)

Figure 10 The influence of mean sea level rising 0.8m on the phase-lag (°) and amplitude (m)
4. Discussion

The special geographic position of Shandong Peninsula is always considered to be the main reason causing the rotating tidal wave system in the Southern Yellow Sea. According to the previous studies on the tidal wave system in the South Yellow Sea, the incoming tidal wave from the East China Sea reaches the Shandong Peninsula and then reflects. The meeting of incoming wave and reflected wave can generate the rotating tidal wave system (Wang et al., 2012; Zhang et al., 1998).

Figure 11: The domain of the experiment of removing the Shandong Peninsula

Figure 12: The co-tidal chart of M2 (a) and the tidal ellipses (b) of the experiment of removing the Shandong Peninsula

An experiment of removing Shandong Peninsula from original model is set up to analyze the influence of Shandong Peninsula on the tidal wave system and the formation of radial tidal current pattern (Figure 11). The new bathymetry for Shandong Peninsula is using the linear interpolation of the depth in surrounding seas. The simulation results are shown in the Figure 12.

Figure 12a presents the co-tidal charts for the M2 constituent of this experiment. It is found that Shandong Peninsula impacts more on the Yellow Sea than on the Bohai Sea and the East China Sea. The location of the two amphidromic points of M2 tidal constituent in the Yellow Sea changes greatly. Both of
them move to the west and the amphidromic point in the Southern Yellow Sea has moved southwest to the Jiangsu coast, near the Sheyang estuary. It should be noted that according to previous studies, if the Shandong Peninsula is removed, the rotating tidal wave system in the Southern Yellow Sea will disappear or move northward correspondingly. However, our results show that without the Shandong Peninsula the amphidromic point in the Southern Yellow Sea would still exist and only move westward. That is to say, the reflect effect of the Shandong Peninsula is not as great as the former studies suggested.

Figure 12b shows the tidal ellipses of this experiment. It can be observed that the radial tidal current still exists without Shandong Peninsula and the difference between the results from the two model runs is the ellipticity. In the experiment without Shandong Peninsula, the radial tidal current has a relatively large ellipticity compared with the mostly rectilinear radial tidal current in the original model (Figure 6b). According to the previous analysis, we can draw the conclusion that Shandong Peninsula is not the crucial factor to the radial tidal current off Jiangsu coast and just plays a minor role, such as the small ellipticity.

Based on the results of this experiment, a kind of tidal wave propagation mechanism in the Chinese marginal seas can be derived as follows (Figure 13a and Figure 13b): before the tidal waves propagate to Korea Strait and Yangtze Shoal, the phase-lag lines in the East China Sea are parallel (Figure 6a and Figure 12a). Nevertheless, after the tidal waves moves to the 60° phase-lag lines, they are divided into two branches because the topography of the Yangtze Shoal is relatively high and it hinders the propagation. The right branch will propagate along the coastline (the order is the west coast of Korea, Liaodong Peninsula, Bohai Strait, Shandong Peninsula and the Jiangsu coast in the end). When spreading to the West Korean Bay, it encounters the reflected tidal wave from the Liaodong Peninsula. So that a rotating tidal wave system is formed in the Northern Yellow Sea. When it propagates to the Jiangsu coast, it meets the left branch of the tidal wave systems from the East China Sea and the rotating tidal wave in the Southern Yellow Sea is created.

It cannot be denied that the left branch tidal wave from the East China Sea will reflect when it comes to the Shandong Peninsula and the reflected tidal wave will meet the progressive tidal wave in the center of the Jiangsu coast. But, the reflected tidal wave caused by Shandong Peninsula is just one of the reasons forming the rotating tidal wave in the Southern Yellow Sea based on our experiments. Furthermore, it can be demonstrated that, as to the formation of the radial tidal current off Jiangsu coast, the reflected tidal wave is not the only reason nor the crucial factor.

![Figure 13 The schematic diagram of the tidal wave propagation mechanism](image)
5. Conclusion

Firstly, this study provides a two-dimensional numerical model for tidal wave propagation in the Chinese marginal seas. The new model has a relatively high resolution and considers many factors which have been ignored in the previous researches, such as the river discharges, tidal generating force. Through the comparison of harmonic constant and tidal current, it is indicated that this model can well reproduce the real tidal system in this large domain.

Secondly, in order to analyze the influence of several factors, three experiments were carried out and compared with the reference model run. The influences of river discharges and tide generating force are important on some areas along the coast. In order to get more accurate results, these two elements are better to be taken into account. The sea-level rise appears to impact China coast more than West coast of Korea.

Furthermore, the experiment of removing Shandong Peninsula is set up to analyze the formation mechanism of rotating tidal wave system in the Southern Yellow Sea and the radial tidal current off Jiangsu coast. The results show that the radial tidal current still exists even if Shandong Peninsula would not be there. This experiment shows that the encounter of the reflected wave from Shandong Peninsula and the progressive tidal wave from the East China Sea is not crucial for the formation mechanism of the radial tidal current here. Besides, a new propagation mechanism of the tidal wave in the Chinese marginal seas is suggested based on the model results.

Acknowledgements

The first author is financially supported by the China Scholarship Council. This work is supported by the 111 Project of the Ministry of Education and the State Administration of Foreign Experts Affairs, China (Grant No. B12032).

References