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# The Interaction between Tides and Storm Surges for the Taiwan Coast - A Modeling Investigation

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## ABSTRACT

An unstructured grid, two-dimensional hydrodynamic model was established and applied to the coast of Taiwan to investigate the tide-surge interaction. The model was calibrated and verified with the observed tidal levels at four tidal stations for seven typhoon events to ascertain the capability and feasibility of the model. The validated model was then applied to investigate the impacts of tide-surge interaction on phase, water levels, and storm surge height. We found that the tide-surge interaction influenced both the magnitude and timing of the surge, which depended on the typhoon path. The water level rise due to the storm surge during high tide was greater at neap tide than at spring tide. Changing tidal ranges altered the prediction of the surge enough to induce the changes in peak water levels.

KEY WORDS: Tide-surge interaction; Storm surge prediction; ADCIRC model; Typhoon; Model calibration and validation.

## INTRODUCTION

Storm surge is increasingly severe as the intensity of storms increase recently because of climate change (Lowe and Gregory, 2005). The damages caused by storm surge have increased every year. Storm surges correspond to abnormal variations in the ocean free-surface driven by atmospheric forcing associated with extra-tropical storms or tropical hurricanes and typhoons (Flather, 2001).

Taiwan is located between the continental shelf of China and the west side of the Pacific Ocean. It is often subject to severe sea states induced by typhoons generated during the summer and autumn seasons in either the South China Sea or the Northwest Pacific Ocean near the Philippine islands, resulting in extensive loss of life and property.

When a typhoon approaches Taiwan, its strong wind and low atmospheric pressure often cause storm surges that result in severe damage to coastal areas, especially on the low-lying lands near river mouths because of the double effects of the river floods by typhoon-brought rains and the backward uplifting seawater floods from storm surges. Therefore, it is necessary to develop a reliable model to predict the height of typhoon-induced storm surge and to understand the tide-storm surge interaction for coastal management and hazard mitigation.

Tide-surge interactions are one of the most important problems and affect the prediction of storm surges. The main objectives of this study are to apply an unstructured grid, two-dimensional hydrodynamic model to simulate the tide and storm surges along the coast of Taiwan. The numerical model was calibrated and verified with the observed water levels at tidal stations for seven typhoon events to ascertain the capability and feasibility of the model. The validated model was then applied to investigate the tide-surge interactions along the coast of Taiwan.

## DESCRIPTION OF NUMERICAL MODEL

### Storm-surge model and global tidal model

The advanced storm surge and circulation model, Advanced Circulation (ADCIRC) (Luettich et al., 1992; Westerink et al., 1994a) is used to simulate the response of water levels and currents along the Taiwan coast with several typhoon events. The two-dimensional version of ADCIRC solves the depth-integrated, nonlinear momentum and continuity equations in the time domain. Numerous applications of the model by the US Army Corps of Engineers and other institutions have been reported in the literature (e.g., [Bacopoulos et al., 2012; Bhaskaran et al., 2013; Chen et al., 2008; Dietrich et al., 2011; Keen et al., 2004; Murty et al., 2014; Westerink et al., 1994b]). To simulate tidal propagation in the ADCIRC model, the driving tidal forces at the open boundaries are necessary. The TOPEX/Poseidon Global Inverse Solution (TPXO) is adopted for further simulations in the present study.

### Cyclone model

The meteorological driving forces underlying storm surges consist of wind stress and an atmospheric pressure gradient. Therefore, determining the wind field and the pressure field of a tropical cyclone is indispensable for conducting cyclone surge calculations. To simplify the numerical calculation, the pressure fields and wind fields are derived from the independent formulas. In the present study, the atmospheric pressure field for the cyclone was calculated using the equation expressed below (Holland, 1980; Jakobsen and Madsen, 2004):

$$p_a = p_c + \Delta p \cdot \exp[-(\frac{r}{r_m})^{-B}],\quad \Delta p = p_e - p_c \quad , \quad r > 0 \tag{1}$$

where $P_c$ is the central pressure of the cyclone; $P_e$ is the ambient pressure or environmental pressure; $\triangle p$ is the pressure drop or pressure deficit; $r$ is the radius, which is the distance from the typhoon center; $r_m$ is the radius to maximum wind speed; and $B$ is the shape parameter, which can be estimated by an empirical relationship, $B = 0.1397(\Delta p)^{0.288}$, $r > 0$ (Jakobsen and Madsen, 2004).

An asymmetric wind field model for a moving cyclone was developed by Jelesnianski (1965) and is widely used in many tropical cyclone surge models (Roy, 1995; Salisbury and Hagen, 2007). This model, which was adopted to calculate the wind field, is described as follows:

$$W = \frac{r}{r_m + r}(U_w i + V_w j) + W_m \frac{1}{r}\left(\frac{r}{r_m}\right)^{3/2}(ai + bj), \quad 0 < r \le r_m \qquad (2a)$$

$$W = \frac{r_m}{r_m + r}(U_w i + V_w j) + W_m \frac{1}{r}\left(\frac{r_m}{r}\right)^{1/2}(ai + bj), \quad r > r_m \qquad (2b)$$

$$a = -r_\lambda \sin\theta - r_\varphi \cos\theta, \quad b = r_\lambda \cos\theta - r_\varphi \sin\theta$$

where $(i, j)$ are unit vectors in longitude and latitude; $U_w$, $V_w$ are the components of the translation velocity of the cyclone center; $W_m$ is the maximum wind; $r_\lambda$ and $r_\varphi$ are the components of the vector; and $\theta$ is the inflow angle of range 0-30$^o$.

## Model implementation

The computational domain in the Asian marginal seas and the western Pacific Ocean includes the region within the longitudes 117°E to 125°E and the latitudes 21°N to 28°N. The Digital Terrain Model (DTM) bathymetric data were obtained from the Global Topography data bank of the University of California, San Diego (Eakins et al., 2006), and from the Ocean Data Bank of the National Science Council, Taiwan (Wu et al., 2010). Figure 1 show the bathymetric map and the locations of the tidal gauge stations on the east coast of Taiwan. To save on computational time and to fit the coastline, coarse grids were generated in coastal seas, whereas fine grids were used in shallow areas close to the coastline. The modeling domain consists of 18,543 unstructured triangular elements and 9,560 nodes.

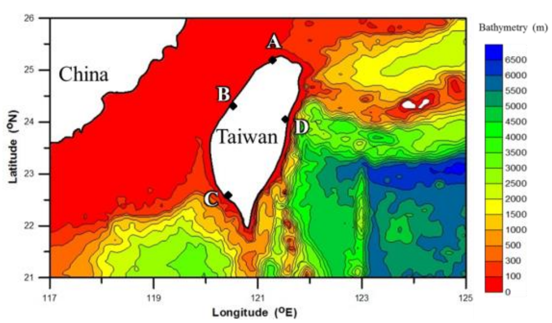


Fig. 1 Bathymetric map and locations of tidal gauge stations along the coast of Taiwan, A is Taipei Danshui River Mouth; B is Taichung Harbor; C is Kaohsiung Harbor; D is Hualien Harbor.

## Indices of simulation performance

To evaluate the performance of the storm surge model, two criteria were adopted to compare the predicted results and the observational data, which are the mean absolute error (MAE) and root mean square error (RMSE). These criteria are defined by the following equations:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|(Y_m)_i - (Y_o)_i\right| \qquad (3)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[(Y_m)_i - (Y_o)_i]^2}, \qquad (4)$$

where $N$ is the total number of data points; $Y_m$ is the predicted water level; and $Y_o$ is the observational water level.

## MODEL CALIBRATION AND VALIDATION

Seven data sets of the historical typhoon events collected from the Central Weather Bureau, Taiwan were used to determine the practical accuracy of the model and to ascertain its predictive capabilities. Typhoon Dujuan (2003), Typhoon Nanmadol (2004), Typhoon Mindulle (2004), and Typhoon Sepat (2007) were adopted for model calibration, and Typhoon Wipha (2007), Typhoon Jangmi (2008), and Typhoon Morakot (2009) were used for model validation. From the model calibration procedure, the horizontal eddy viscosity parameter is set to 5.0 m$^2$/s. A constant minimum bottom friction coefficient of $Cf_{min}$=0.003, break depth of $H_{break}$=10m, and two dimensionless parameters of α=10 and β=1/3 were used. These parameters adopted in this study are in the reasonable ranges that can be found in Luettich et al. (1992).

Table 1 shows the MAE and RMSE for model validation at different locations. The maximum MAE and RMSE values are 0.267 m and 0.354 m, respectively, for Typhoon Jangmi at the Taichung Harbor. It can be observed that the model prediction of water level has difficulty matching the observed water level at the Taichung Harbor for the model calibration and validation. Cheng et al. (1991) reported that the bottom topography is an important factor in modeling the flow properties of the environment. An accurate representation of the bottom topography by the model grids is the fundamental requirement in a successful modeling study. The reason may be due to the horizontal resolution 200m x 200m of the bathymetry data collected from the Ocean Data Bank of the National Science Council to generate the grids which can not accurately reflect the bathymetry along the coast of Taiwan. The other one reason is the wave-induced surge height which is not taken into account, resulting in significant differences between model results and observed water levels at some locations.

Table 1 Mean absolute error (MAE) and root mean square error (RMSE) of the difference between the computed and observed water levels for model validation

| Tidal station | Typhoon Morakot | | Typhoon Jangmi | | Typhoon Wipha | |
|---|---|---|---|---|---|---|
| | RMSE (m) | MAE (m) | RMSE (m) | MAE (m) | RMSE (m) | MAE (m) |
| Taipei Danshui River Mouth | 0.162 | 0.135 | 0.202 | 0.163 | 0.174 | 0.122 |
| Taichung Harbor | 0.222 | 0.178 | 0.354 | 0.267 | 0.279 | 0.234 |
| Kaohsiung Harbor | 0.156 | 0.128 | 0.136 | 0.112 | 0.125 | 0.100 |
| Hualien Harbor | 0.228 | 0.185 | 0.153 | 0.116 | 0.126 | 0.102 |

## MODEL APPLCATIONS TO INVESTIGATE TIDE-STORM SURGE INTERACTION

The validated model was used to investigate the influences of tide-surge interaction through the region. Typhoon Jangmi (2008) served as the case study because this typhoon was classified as a strong typhoon by the Central Weather Bureau, Taiwan.

Five simulations used in the experimental studies reported in this paper included the following datasets: (A) Tidal boundaries only; (B) Tidal boundaries + Atmospheric forcing (including wind stress forcing); (C) No tidal boundaries + Atmospheric forcing (including wind stress forcing) ; (D) Tidal boundaries (of decreasing amplitude range from 100% to 0% at 10% intervals) + Atmospheric forcing (including wind stress forcing); and (E) Tidal boundaries + Atmospheric forcing (including wind stress forcing) (with an artificial typhoon that had the same strength as Typhoon Jangmi but at spring tide and at neap tide)

### Effect on phase shifts

To investigate the influence of tide-surge interaction on the phase shifts, three simulation experiments, A, B, and C, were run for the Typhoon Jangmi event, which occurred on the 28th and 29th September, 2008. Figure 2 shows the modeling results for simulations A, B, and C. The water levels with simulation B minus simulation A, designated as the storm surge height, are also present in the figure. It shows that the timing of peak storm surge height is quite different from the timing of peak water level under simulations A and B. This characteristic demonstrates the phase shifts due to the tide-surge interactions. This is not due in part to the fact that the tidal range is significantly larger than the storm surge height and thus dominates the peak water levels. However, storm surge heights at the Kaohsiung Harbor present no significant changes because the typhoon path is far from these two stations. It should be noted that the storm surge heights are different with simulation C and simulation B minus simulation A. This is due to the nonlinear advection and bottom friction effect, which have been confirmed by Bernier and Thompson (2007) and Zhang et al. (2013).

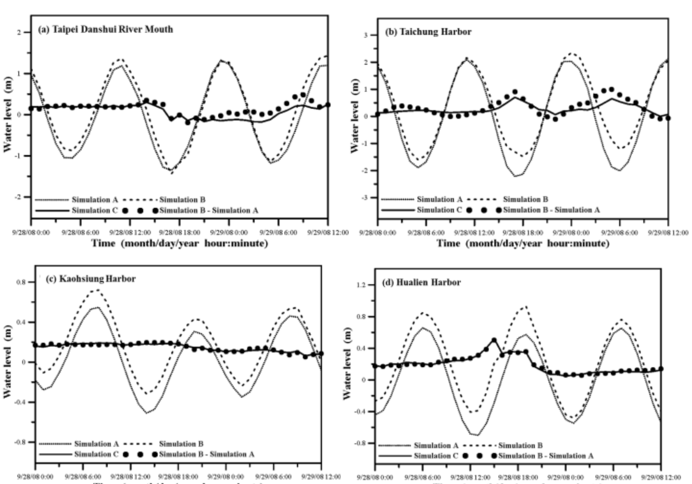


Fig. 2 Predicted water level with different simulations at the (a) Taipei Danshui River Mouth, (b) Taichung Harbor, (c) Kaohsiung Harbor, and (d) Hualien Harbor

### Effect of tidal range

The model was run with simulation D, which has the tidal boundaries decreasing over a range in amplitude from 100% to 0% at 10% intervals, for the Typhoon Jangmi event. Figure 3 plots the RMSE between the storm surge prediction and those given with changes in the tidal range, shown with a dashed line, at different tidal stations. The change in the peak water levels relative to water level prediction is shown by the solid line. The RMSE and peak level appear to increase linearly with a reduction in tidal range. The similar pattern was also found by Quinn et al. (2012). This figure also reveals that when the decrease in tidal range reaches its maximum (100%), the changes to elevation in RMSE and peak level are higher at the Taichung Harbor than those at the other five stations. This is likely due to the fact that the Taichung Harbor has the highest tidal range among the tidal stations. As mentioning in the storm surge calibration validation, the Taichung Harbor also has the highest error.

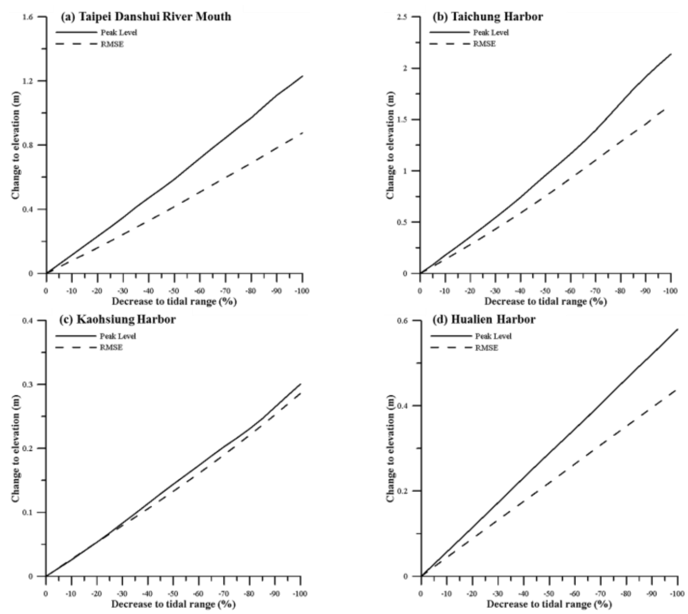


Fig. 3 The influence of the alteration to the tidal range on water level with simulation D at the (a) Taipei Danshui River Mouth, (b) Taichung Harbor, (c) Kaohsiung Harbor, and (d) Hualien Harbor

### Effect of spring tide and neap tide

To probe the influence of tide, the simulation E was conducted with an artificial typhoon that had the same strength as Typhoon Jangmi (2008) but at spring tide and at neap tide. Figure 4 presents the comparison of storm surges at spring tide and neap tide at the Taichung Harbor. It shows that the difference between the curve of storm surge and tides and that of only tides near high tides was larger at neap tide than at spring tide. Because the water surface elevation during the high tide was greater at spring tide than at neap tide, the surge height was greater at neap tide than at spring tide. This study shows that the combined effects of storm surge and tides along the coast of Taiwan can impact the storm surge height, especially when influenced by spring and neap tides.

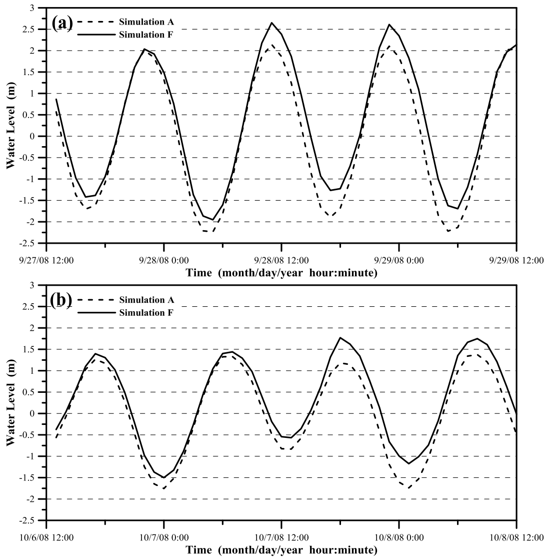


Fig. 4 The comparison of storm surges at (a) spring tide and (b) neap tide simulations at the Taichiung Harbor

## CONCLUSIONS

The hydrodynamic model was then applied to investigate the interactions of tides and storm surges along the coast of Taiwan. The results indicated that the tide-surge interaction influenced both the magnitude and timing of the surge, which depended on the typhoon path. The influence of predicted tidal levels was assessed by altering the tidal range. The results indicated that the RMSE and peak level appeared to increase linearly with a reduction in the tidal range. When the decrease in tidal range reaches its maximum, the changes to water surface elevation in RMSE and peak level are higher at the Taichung Harbor than those at the other five stations. We also found that the storm surge height during high tide was greater at neap tide than at spring tide.

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