Character of extreme high tide level variations response to coastline deformation in Taizhou Bay

X Liu1,2, C P Kuang1,3, J B Mu2 and S C Huang2
1Department of Hydraulic Engineering, College of Civil Engineering, Tongji University, Shanghai, China
2Zhejiang Institute of Hydraulics & Estuary, Hangzhou, China
E-mail: cpkuang@tongji.edu.cn

Abstract. Taizhou Bay, which locates in the southern coast of China, is frequently influenced by human activities, leading coastline changes frequently in coastline changes visible from space. Coastline deformation in this area will obviously affect the character of extreme high tide level variations in Jiaojiang River and Estuary especially during flood and typhoon periods. Statistic data showed that 54.5% of the extreme high tide levels of Jiaojiang River were caused by typhoon and 27.3% by flood in the past twenty-two years. So, a two-dimensional (2-D) hydrodynamic numerical model including Jiaojiang River and East China Sea was established based on the Mike21 FM model. The model was calibrated with field data and then was employed to predict the extreme flood and storm high tide level changes under three different assumption plans of coastline deformation. 100-year return discharge upstream with 2-year return tide level downstream conditions were set in the model to simulate extreme flood level changes, while Typhoon 0414 with actual discharge upstream were considered to simulate extreme storm high tide level variations. According to the flood level changes simulating results, an increase of 0.01~0.03 m in extreme flood level will happen in river section and estuarine section and a decrease of 0.01~0.06 m will occur outside estuarine section. Predictions of the typhoon conditions show that an increase of 0.01~0.15 m in extreme storm high tide level will happen in both river and estuarine sections with a decrease of 0.01~0.03 m outside of the Jiaojiang Estuary. Further analysis from tide wave point illustrates that propagation direction of nearshore tide wave in Taizhou Bay will be turned by coastline deformation, thus reflection effect of tide wave will be weakened, while distribution of storm tide currents field changes shows that tidal influx of Jiaojiang Estuary increases due to the blocking effect of the seawalls, causing this kind of special extreme high tide level changing formation.

1. Introduction
Coastline deformation caused by human activities in Zhejiang Province is frequently occurred in recent years especially in estuary areas. It will obviously change the hydrodynamic characters including tide, current, sediment and wave, and will further change the topography and coast physical structure in these areas. There are three major estuaries in Zhejiang Coast, which are the Qiantangjiang Estuary, the Jiaojiang Estuary and the Oujiang Estuary. These estuaries separately create three interfaces between rivers and bays, which are the Qiantangjiang River and the Hangzhou Bay, the Jiaojiang River and the Taizhou Bay, the Oujiang River and the Wenzhou Bay (shown in figure 1). A number of studies have been conducted to evaluate the changing situation of hydrodynamic and tidal
flat in these areas. Many studies in the Qiantangjiang Estuary focusing on flood level, suspended sediment concentration and topography changes [1-3], which show that changes of coastline in Hangzhou Bay will cause an increase of flood level and river channel siltation. Reclamation in Wenzhou Bay will prevent the tidal influx flowing from East China Sea into Oujiang Estuary, leading a decrease of current speed and high tide level [4-6]. Distribution characteristics of the storm high tide level changes in Wenzhou Bay are mainly depended on the typhoon landing paths [7] Human activities including reclamation and sand extraction in the Taizhou Bay and Jiaojiang Estuary are happening with high frequency in the last 50 years, which result in redistribution of the erosion and deposition situations in this estuary area [8]. Predictions of water level and sediment transport changes due to reclamation projects have been researched [9-11], and variations of high storm tide level caused by reclamation plans are simulated [12].

![Figure 1. Sketch of the study area.](image)

The coastline changes influence on hydrodynamic and sediment in the Qiantangjiang Estuary and the Oujiang Estuary are studied more and more comprehensively. However, most of the studies in Jiaojiang Estuary had only paid attention to the normal hydrodynamic phenomenon and focused on the estuary area, without a systematic research of the extreme high tide level variations and the whole study of river section and estuary section. The extreme high tide levels in Jiaojiang river and estuary area are generally caused by flood and storm tide in Zhejiang Coast and have a serious influence on flood protection and seawall design along the river. Thus, the effects of coastline deformation on extreme high tide level variations in estuarine and river zone are worth studying. In this study, a series of numerical simulations were carried out in order to predict the distribution of extreme high tide level variations response to coastline deformation in Taizhou Bay, aiming to provide academic references for coastal disaster prevention and mitigation in Zhejiang Province.

2. Basic data
Taizhou Bay locates in the southern coast of China and exchanges a large amount of water with Jiaojiang River through the Jiaojiang estuary every year. Since the tidal flat resources are very rich in Taizhou Bay and land resources are extremely deficient in Taizhou City, reclamation activities are happened frequently in recent years, and new tidal flat outside the seawalls cannot grow to a certain size in a short time, leading the coastline deformation in space scale.
Statistic data in Linhai Station upstream showed that 54.5% of the extreme high tide levels of Jiaojiang River were caused by typhoon and 27.3% by flood in the past twenty-two years. At the same time, the first to the ninth place are caused by typhoons in the top 10 of the annual extreme high tide level in Haimen Station downstream. In general, the storm surge always encounters rainstorms in typhoon seasons, causing the extreme high tide level along river and estuary areas. According to the analysis of relationship between the synchronized tidal levels at the Linhai and Haimen stations with the discharge in the Baizhiao Station, the probability of high water level at the Linhai station is 59.1% under the flood peak in the Baizhiao Station, while 27.3% at Haimen station. And most of the flood peak in the Baizhiao Station is affected by typhoons. So, it can be considered that the high tide levels of the Jiaojiang River are controlled by typhoons.

In this study the effects of three coastline deformation plans on the extreme high tide level during flood period and Typhoon 0414 (Rananim) were investigated (shown in figure 1). The three assuming coastline deformation plans are designed by combining tidal flat and islands through seawalls and breakwaters based on current coastline. Based on the prediction of land requirements in Taizhou City, these three plans will shape artificial coastlines with 24.8 km, 26.8 km, 33.5 km and include total areas of 67 km$^2$, 80 km$^2$, 120 km$^2$. The first and the second plans are mainly composed by seawalls, while the third plan adds a breakwater in the south area, and the length of coastline deformation and reclamation area are increasing from the first plan to the third plan. Typhoon 0414 landed in the south of Taizhou bay and brought serious storm surge and rainstorm to Jiaojiang River, causing extreme high water level in the Linhai Station and Haimen Station.

3. Numerical model

3.1. Study domain and model grids
The two-dimensional (2-D) hydrodynamic numerical model was established based on the Mike21 FM model, covering the Jiaojiang River and the whole East China Sea from 116°E to 138°E and 19°N to 42°N. There are 134541 unstructured elements and 70749 nodes in the model and the smallest space scale of the elements is 30 meters (shown in figure 2). The upstream boundaries of the Jiaojiang River are controlled by discharge of the Shaduan Station and Baizhiao Station, and the open boundary on the east of the grid is determined by hydrostatic pressure drop and astronomical tide level provided by the global tide model TPXO6$^{[13]}$. 

Figure 2. Model grids for the study domain.
Parametric wind models are frequently used for wind forcing in numerical models. In this paper, the wind and pressure model of Jelesniansk is selected to simulate the wind field and atmospheric pressure. The model equations are as follows:

\[
W = \begin{cases} 
\frac{r}{r+R} \left( V_0 \mathbf{i} + V_0 \mathbf{j} \right) & (0 < r \leq R) \\
\frac{R}{r+R} \left( V_0 \mathbf{i} + V_0 \mathbf{j} \right) & (r > R) 
\end{cases}
\]

\[
P_e = \begin{cases} 
P_0 + \frac{1}{4} (P_e - P_0) \left( \frac{r}{R} \right)^2 & (0 < r \leq R) \\
P_0 - \frac{3}{4} (P_e - P_0) \frac{R}{r} & (r > R)
\end{cases}
\]

where \( R \) is the radius of maximum wind velocity; \( r \) is the distance from the calculating point to the center of typhoon; \( V_0 \) is the moving velocity of typhoon; \( W_R \) is the maximum wind velocity at the radius \( R \); \( A = [(x-x_c) \sin \theta + (y-y_c) \cos \theta] \); \( B = [(x-x_c) \cos \theta - (y-y_c) \sin \theta] \); \( (x_c, y_c) \) is the coordinate of the typhoon center; \( \theta \) is the flow angle; \( P_0 \) is the atmospheric pressure at the center of typhoon; \( P_e \) is the peripheral atmospheric pressure; \( \beta \) is the attenuation coefficient of wind in distance.

3.2. Model verifications

Field data of water levels and currents in July 2016 and storm tidal levels during Typhoon 9711 and Typhoon 0414 were used to verify the model, with results showing in figures 3-5. Positions of the measurement stations are shown in figure 1. The deviations of water levels verifications are less than 0.10 m and currents verifications less than 0.15 m/s, and the average deviation of the storm tidal levels is about 0.14 m, which indicates that the model performs well in Zhejiang coastal area and is suitable for making further predictions.

Figure 3. Verifications of high tide levels.

Figure 4. Verifications of current velocity magnitudes and current directions.
4. Results analysis

4.1. Flood level changes under the plans of coastline deformation
To simulate flood level changes, 100-year return discharge upstream with 2-year return tide level downstream conditions were set in the model. The 100-year return discharge conditions in the Shaduan Station and Baizhiao Station are 5298 m$^3$/s and 9990 m$^3$/s, while the 2-year return tide level conditions in the Dachen Station is 3.1 m. So, the flood peak will always encounter the high tide level under this calculation condition, aiming to form an extreme flood level. Results under the three plans of coastline deformation are shown in figures 6-8.

Figure 6. Distribution of the extreme flood level variations under the first plan.  
Figure 7. Distribution of the extreme flood level variations under the second plan.
It can be seen that an increase of 0.01 m in extreme flood level will happen in river section and estuarine section under the first plan, and 0.01–0.02 m under the second plan, and 0.01–0.03 m under the third plan. A decrease of 0.01–0.05 m will occur outside estuarine section under the first plan, while 0.01 m–0.06 m under the second and the third plans. So the third plan will present the highest tidal level because it has the maximum reclamation area. The increasing area of extreme flood level is mainly in the estuarine section between Sanjiangkou and Baishawan because the floodwater and tide current meets in this area and coastline deformation plans will extend the estuarine section outward, intensifying the backwater effect. The decreasing area of extreme flood level mostly distributes in the east side of the seawalls that will construct in the three plans. Further analysis from tide wave point illustrates that propagation direction of nearshore tide wave is parallel to the coastline in deep water area of Taizhou Bay and nearly perpendicular to the coastline in the tidal flat areas, resulting in the reflection effect of tide wave. Under the influence of the coastline deformation plans, new tidal flat outside the seawalls cannot grow to a certain size in a short time, thus the propagation direction of nearshore tide wave will be turned and the reflection effect of tide wave will be weakened, causing this kind of special extreme high tide level changing formation.

4.2. Storm high tide level changes under the plans of coastline deformation

Based on the statistical data since 1950, there are about 4 typhoons affecting the Taizhou Bay every year, and Typhoon 0414 results the greatest storm surge since 2000. Hence this typhoon was chosen to simulate extreme storm high tide level variations with actual discharge upstream in Shaduan Station and Baizhiao Station. Simulation results are shown in figures 9-11.

During the landing of Typhoon 0414, most areas of the Jiaojiang Estuary and Taizhou Bay are located at the maximum wind speed radius, so the influence of the coastline deformation plans is magnified. An increase of 0.01–0.05 m in extreme storm high tide level will happen in river section and estuarine section under the first plan, and 0.01–0.10 m under the second plan, and 0.01–0.15 m under the third plan. A decrease of 0.01–0.03 m will occur outside estuarine section. So the third plan will cause the greatest impact similarly to the distribution of the extreme flood level variations. Under the influence of typhoon storm surge, the storm tide current can spread further upstream the Jiaojiang River. Thus, the increasing area of extreme storm high tide level is mainly in the river section and estuarine section between Linhai and Haimen. In current coastline situation and during flood tide period, the storm tide currents spread from north to south through the waterway between Baishawan and Toumen Island and divide into two branches. One of the branches flows into the Jiaojiang Estuary, and the other continues spreading southward through the tidal flat areas outside the Eleventh Jiaojiang
Seawalls. After the coastline deformation plans, the branch of storm tide currents that moving southward through the tidal flat areas will deflect to southwest due to the blocking effect of the seawalls, and then flow into the Jiaojiang Estuary, which causes the increase in tidal influx of Jiaojiang Estuary and finally results in a higher extreme storm high tide level.

Figure 9. Distribution of the extreme storm high tide level variations under the first plan.

Figure 10. Distribution of the extreme storm high tide level variations under the second plan.

Figure 11. Distribution of the extreme storm high tide level variations under the third plan.

The decreases of extreme storm high tide level outside estuarine section are also due to weaken of the reflection effect of tide wave, but with a smaller area than the flood level changes simulation.

5. Conclusion
A two-dimensional (2-D) hydrodynamic numerical model was established to predict the extreme flood and storm high tide level changes under three plans of coastline deformation. Simulating results show that increases in extreme flood and storm high tide level will happen in river section and estuarine section, while decreases will occur outside estuarine section. Causation analysis illustrates that propagation direction of tide wave will be turned by coastline deformation and reflection effect will be weakened. On the other side, tidal influx of Jiaojiang Estuary will increase due to the blocking effect
of the seawalls. The simulating results could be used by urban planning department of Taizhou City. In general, the tidal flat will gradually develop with sufficient sediment supplies on the front of the new-building seawall in several years or decades. Sediment from the Yangtze River into the East China Sea provides 96% sediment supply for the Zhejiang Coast, which is about 226 million t every year. And there are amount of deposited sediment outside the Yangtze Estuary and Zhejiang Coast, maintaining the shoal siltation processes in the Zhejiang Coast [14]. So, more effort could be made to predict topography changes near the study area and extreme high tide level variations under new bottom boundary.

References

[1] Pan C H and Zhu J Z 1999 Numerical simulation of flow field for Jianshan first phase reclamation project in Qiantang Estuary Ocean Eng. 17 40-8
[2] Cao Y and Zhu J Z 2000 Numerical simulation of effects on storm-induced water level after contraction in Qiantang Estuary Journal of Hangzhou Institute of Applied Engineering S1 24-9
[3] Ni Y Q and Lin J 2003 The effects of regulation and reclamation in Qiantang Estuary on Hangzhou Bay Ocean Eng. 21 73-7
[4] Lu Y J, Li H L and Dong Z 2002 Effects of the reclamation projects on hydro-dynamic environment in a strong tide estuary Ocean Eng. 20 17-25
[5] Mu J B, Huang S C and Lou H F 2013 Study on hydro-dynamic environment of the large-scale reclamation projects at the estuary Journal of Sichuang University (Engineering Science Edition) 45 61-6
[6] Xu T and You X Y 2017 Numerical simulation of suspended sediment concentration by 3D coupled wave-current model in the Oujiang River Estuary China Cont. Shelf Res. 137 13-24
[7] Huang S C, Xie Y L, Liu X and Zhao X 2015 Changes of storm high tide level responses to predicted change of coastline in Wenzhou Bay ICEC2015 (Fifth International Conference on Estuaries and Coasts) p 40
[8] Ni M 2012 Impacts of human activities on riverbed evolution of Jiaojiang River Estuary in recent 50 years (Zhejiang Normal University)
[9] Zhang Q, Tao J F, Zhang C K, Dai W Q and Xu F 2015 Effect of the large-scale reclamation of tidal flats on the hydrodynamic characteristics in the Taizhou Bay Mar. Sci. Bull. 34 392-8
[10] Guo C 2016 Response of Jiaojiang Estuary to coastal reclamation (Zhejiang University)
[11] Sun Z L, Huang S J, Jiao J G, Nie H and Lu M 2017 Effects of cluster land reclamation projects on storm surge in Jiaozhou Estuary, China Water Sci. Eng. 10 59-69
[12] Sun Z L, Nie H, Huang S J, Huang W R, Zhu L L and Gao Y Y 2014 Effects of sea level rise on coastal reclamation projects in Jiaozhou Estuary, China J. Coastal Res. 68 74-9
[13] Gray D E and Svertlana Y E 2002 Efficient inverse modeling of barotropic ocean tides J. Atmos. Ocean. Tech. 19 183-204
[14] Hu C H, Wang Y G, Chen S M and He Q 2012 The variation of coastal-sediment on the coast line in Zhejiang Province and its impact on the variation of shoals Zhejiang Hydrotechnics 6 1-4