Study of high tide level changes in estuary area in response to coastline deformation in Wenzhou Bay

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Abstract. Wenzhou Bay, which is located in the southern coast of China with rich tidal flat resources, is frequently influenced by human activities, leading coastline deformation and high tide level changes in estuary area. A two-dimensional tidal numerical model of high resolution including Wenzhou Bay 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 high tide level changes under the development plan of coastline deformation. According to the simulating results, high tide level and tidal range in the Ou River and the Feiyun River estuary area will decrease about 0.01~0.13 m and 0.01~0.18 m, whether in dry season or flood season. Further analysis from tide wave point illustrates that weaken of the tidal system outside estuary area will occur after the coastline deformation. The direction of tidal propagation will change from vertical to parallel to coastline, causing weaken reflection, leading to the decreases of tidal range and high tidal level.

1. Introduction

Coast area in Zhejiang Province is rich in tidal flat resources and has been carrying out human activities historically such as sea reclamation, jetty building, and island expansion. During last 60 years, 2373.3 km² of near shoal area has been developed in this province, mainly distributed in estuary and bay along the coast. These activities may cause significant changes in high tide level, which will affect the construction standards of coastal seawalls. Therefore, it is very important to study high tide level changes for regional disaster prevention and reduction. There have been many studies on the changes of tidal waves caused by such activities. Due to different characteristics of sea areas where the activities are located, the influence on high tide level is quite different, and the reasons are also different. For example, the Qiantang River estuary is characterized by the narrowing of river channel and the reclamation of tidal flat, which have increased the tidal volume of unit width. Since there is a good correlation between the high tide level and the area of estuary reclamation, increasing of annual average high tide level in the Qiantang River estuary reaches 0.5 m from 1950 to 2010 [1-3]. Human activities on tidal flat in the Sammen Bay and the Xiangshan Harbour are distributed mainly in the inner part, leading to decreases of tidal prism and increases of high tide level [4,5]. Similarly, tidal prism and high tide level are also changed and tidal range of the M₂ tidal component is increased due to the dike building and reclamation in the Mokpo Bay in South Korea [6]. Some studies on tidal flat reclamation in the open coast have discussed tide variations through analysing the changes of
amplitudes of the tidal components [7-10]. Generally speaking, tidal component amplitudes in the nearshore area of seawalls will be increased or decreased, which will reflect the high tide level, but the reasons for these changes have not been fully explained.

Figure 1. Sketch of the study area.

There are three estuaries in Wenzhou Bay named as the Oujiang Estuary, the Feiyun Estuary and the Aojiang Estuary, and a large amount of suspended sediment deposits in the estuary area, forming rich tidal flat resources (shown in figure 1). Tidal flat between the Oujiang Estuary and the Feiyun Estuary is commonly known as the Oufei Tidal Flat, with the area of about 87 km² and the elevation between 0.0 m ~ -3.5 m (1985 National Height Datum). The scale of coastline deformation plan of the Oufei Tidal Flat is quite large and river channels of the Feiyun Estuary and the Oujiang estuary will extend to the sea side for 4 km. In this paper, a high-resolution tidal wave numerical model was established to simulate the changes of high tide levels and main tidal components in the estuaries and adjacent sea areas after the coastline deformation plan, so as to explore the causes of high tide level changes in these estuaries.

2. Numerical model

2.1. Study domain and model setup

A depth averaged tidal dynamics model was constructed using Mike21 FM, which includes the Wenzhou Bay and the East China Sea. The model ranges from 116° - 138°E and 19°- 42°N with 103505 flexible meshes and 56905 nodes and the smallest grid size is 50 meters in the study area (shown in figure 2).

In this model, the flux of the Oujiang River, Feiyun River and Aojiang River are controlled by river discharge, and a total of 10 primary tidal constituents including the main tidal components such as $M_2$, $S_2$, $K_1$, $O_1$, $N_2$, $P_1$, $K_2$, $Q_1$ and the long period tidal components such as $M_t$ and $M_n$ have been applied as the hydrodynamic boundary for tidal simulations [11]. Components with subscript 2 are semidiurnal tide variables and sub subscript 1 are diurnal tide variables. And $M_t$ and $M_n$ are generated from $M_2$ by the nonlinear interaction of shallow water. Dynamic time step length with 0.001~30 second was used to adapt the unstructured elements and the Manning coefficient was around 0.012~0.016 with spatial variation. The Horizontal eddy viscosity was calculated by Smagorinsky formulation and the initial
conditions were set with the cold start.

2.2. Model results validations

Measured data of tidal levels and tidal currents in April 2013 and the astronomic constants of tide obtained by multi-annual harmonic analysis were applied to validate the model, as showing in figures 3-5 and table 1. Locations of the observing stations are displayed in figure 1. The average deviations of high tide levels validations were smaller than 0.18 m and during the spring tide the errors smaller than 0.16 m. The average verifications of currents during flood period were less than 0.12 m/s with less than 0.10 m/s during ebb period. The relative deviations of the M2 tidal amplitudes were -6.8%~5.9% and average deviation of the tidal amplitudes and phases were 0.01m and 3°. While the verifications of K1 were -14.7%~3.6%, 0.01m and 2°. All the results of validations indicated a good performing and could be used to make more predictions and analyses.

Figure 2. The computational grid.

Figure 3. Verifications of high tide levels.
Table 1. Deviations of the astronomic constants of tide.

|                    | Kammenn | Longwan | Dongtou | Nanji |
|-------------------|---------|---------|---------|-------|
| Amplitudes of M₄ (m) | 0.02    | 0.12    | 0.05    | 0.06  |
| Phases of M₄ (°)   | 3       | 7       | 5       | 7     |
| Amplitudes of K₈ (m) | 0.00    | 0.01    | 0.00    | 0.00  |
| Phases of K₈ (°)   | 2       | 4       | 3       | 4     |

3. Results analysis

3.1. High tide level changes

Table 2. Changes along the Oujiang River (HTL), tide range (TR) and tide prism (TP).

|                    | Stations along the Oujiang River | Stations along the Feiyun River |
|-------------------|----------------------------------|---------------------------------|
|                   | Meiao xinyu     | Zhang yu     | Long wan | Qili kun | Ling wan | Mayu xiang | Xian hui | Ruian wang |
| Flood season HTL  | -0.02 -0.03     | -0.03 -0.03 | -0.03    | -0.04 -0.05 | -0.04    | -0.06 -0.07 | -0.06 -0.07 |
| with spring TR    | -0.03 -0.04     | -0.04 -0.04 | -0.04    | -0.05 -0.04 | -0.04    | -0.06 -0.08 | -0.10 -0.09 |
| tide              | -0.9% -0.5%     | -0.5% -0.5% | -0.6%    | 5.4% -15.4% | -2.0%    | -1.3% -1.3% | -1.2% -1.5% |
| Flood season HTL  | -0.01 -0.01     | -0.01 -0.01 | -0.01    | -0.01 -0.01 | -0.03    | -0.02 -0.02 | -0.02 -0.02 |
| with TR           | -0.02 -0.02     | -0.02 -0.02 | -0.02    | -0.02 -0.02 | -0.02    | -0.03 -0.04 | -0.03 -0.04 |
| neap tide TP      | -1.4% -0.9%     | -0.9% -0.6% | -0.7%    | 1.8% -7.2%  | -3.5%    | -1.7% -1.8% | -1.8% -1.7% |
| Dry season HTL    | -0.02 -0.03     | -0.03 -0.03 | -0.03    | -0.04 -0.04 | -0.04    | -0.06 -0.07 | -0.06 -0.07 |
| with spring TR    | -0.03 -0.03     | -0.04 -0.04 | -0.04    | -0.05 -0.05 | -0.04    | -0.06 -0.09 | -0.09 -0.09 |
| tide              | -0.4% -0.2%     | -0.4% -0.5% | -0.5%    | 5.3% -15.4% | -1.1%    | -0.8% -1.2% | -1.0% -1.5% |
| Dry season HTL    | -0.01 -0.01     | -0.01 -0.01 | -0.01    | -0.01 -0.01 | -0.02    | -0.02 -0.02 | -0.02 -0.02 |
| with TR           | -0.02 -0.02     | -0.02 -0.02 | -0.02    | -0.02 -0.02 | -0.02    | -0.03 -0.04 | -0.03 -0.04 |
| neap tide TP      | -0.9% -0.7%     | -0.7% -0.7% | -0.7%    | 1.8% -7.4%  | -1.5%    | -1.4% -1.6% | -1.6% -1.6% |

Notes: tide level and tide range: m; tide prism: %; +: increase, -: decrease.

To simulate the influence of the plan of coastline deformation, different discharges during flood and dry season were applied in this model. The flux upstream during flood season in the Oujiang River are 965 m³/s and 287 m³/s, while 229 m³/s and 66.7 m³/s during dry season. The downstream conditions of
tide levels were based on the 10% high tide level (2.99 m) of the cumulative frequency of the Dongtou Station as the spring tide, and the 90% high tide level (1.62 m) as the neap tide. Changes of high tidal level, tidal range and tidal prism in some stations along the Oujiang River and the Feiyun River are shown in table 2 and changes of high tide level and tide range during dry season are shown in figures 6-7.

It can be seen that the tidal prism entering the Oujiang River and the Feiyun River will change after the implementation of coastline deformation, and the tide levels at stations along the rivers will also change accordingly. During the flood period, high water levels along the Oujiang River will decrease slightly, and the range is within 0.05 m. The tidal range of each station will decrease, and the tidal prism will decrease too except for the Qili station. The high water level along the Feiyun River will decrease about 0.07 m. From the distribution along the river, decrease values are the largest between Xianjiang Station and Shangwang Station, and the tidal range and prism in each station are all reduced. This situation is similar in the dry season.

According to figures 6 and 7, the high tidal level under spring tide in dry season outside the seawalls will decrease 0.10–0.13 m, and 0.01–0.07 m around sea area in the Oujiang Estuary and the Dongtou Island, and about 0.08 m in the Feiyun River, and within 0.05 m in the northern sea area of the Oujiang Estuary. The tidal range under spring tide in dry season will also decrease, mainly distribute in the sea area outside the seawalls, which is about 0.18 m, and 0.01–0.10 m in the Oujiang Estuary and the Dongtou Island sea area, and 0.04–0.06 m in the Feiyun River and the Aojiang River estuary. The implementation of the coastline deformation project in the dry season will reduce the high tide level along the estuary. As the estuary being prolonged, the tidal prism will decrease, the tidal power will get weakened, leading decrease of high tide level. And the decrease of high tide level outside the estuary will aggravate the decline of high tide level inside this estuary. During the flood period, high tide level in the upstream of the river will slightly increase, and decrease in the estuary section.

**Figure 6.** Changes of the high tide level under spring tide in dry season (unit: m; +: increase, -: decrease).

**Figure 7.** Changes of the high tide range under spring tide in dry season (unit: m; +: increase, -: decrease).

### 3.2. $M_2$ and $K_1$ changes under conditions of the coastline deformation

In order to explore the causes of these changes in estuary area, it is necessary to analyze the influence of the coastline deformation on the main astronomic constants of tide such as $M_2$ and $K_1$. Water depth gradually becomes shallower from Nanji Island to near shore area in Wenzhou Bay. After the tide wave of the Western Pacific propagating into the neritic tidal flat area, the low tide level is affected by seabed, and the amplitude of the tidal wave decreases rapidly. Amplitude lines of the $M_2$ tidal wave
will change greatly after the plan being implemented, as shown in figures 8 and 9. The amplitude lines outside seawalls will migrate landward more significantly than other sea areas, leading decreases of the tidal component amplitudes, as shown in figures 10 and 11. The $K_1$ tidal wave range is only one-tenth of the $M_2$ tidal wave, and the magnitudes of changes are smaller.

In current situation, the phase lines are mostly vertical to coastline in sea area of the Wenzhou Bay, but parallel in tidal flat area, as shown in figures 12 and 13. This phenomenon illustrates that the tidal wave propagates along the coast in sea area and cross the coast in tidal flat area.

After the implementation of coastline deformation, the phase lines in Wenzhou Bay will change obviously especially outside seawalls. First, the phase lines will move southward, and significantly around the coastline deformation area. The propagation distance of the tidal wave will be shorter so the tidal wave speed will be accelerated. Second, the phase lines will be greatly deflected, and the coastline reflection will get weakened. Situation of the phase lines with the coastline is parallel before the plan and basically perpendicular after the plan, especially in the southern part of seawalls. So it can be seen that the decreases of high tide level and the tidal range after the coastline deformation are mainly caused by the weakening of the tidal wave reflection in the front of seawalls.
4. Conclusion
A depth averaged tidal dynamics model was constructed to predict the changes of high tidal level under the plan of coastline deformation. Simulation results show that the high tide level and tide prism will decrease during the flood season and the dry season. Due to the special tidal wave phenomenon in southeast sea of the Zhejiang Province, the tidal wave propagates along the coastline in deep sea, and spreads across the tidal flat. The tidal wave reflection in front of seawalls will get weakened after the coastline deformation, which will reduce the tidal range. The decreases in the high tide level in the outer sea area will also lead to the decreases of the flood level upstream in the estuary area. Tidal flats would always develop under natural conditions if there are adequate sediment sources from the sea or the river. And this may take several years or decades. Once the hydrodynamic environment changes, sediment distribution will change correspondingly and thus influence the topography trend around the near shore. So this could be the next study of simulations and predictions.

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