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# Hydrodynamic impact assessment of coastal reclamation project in semi-enclosed bay

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## ABSTRACT

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A two-dimensional numerical model of depth-integrated tidal motion in an orthogonal boundary-fitting curvilinear coordinate was developed and the engineering sedimentation method was used to study the possible impact of the coastal reclamation project of Mazucheng in the Meizhou Bay upon the tidal motion and the sediment siltation intensity in the vicinal sea area. The momentum equations were rewritten in the Lagrangian form and the convection term in the momentum equations was discretised by the Eulerian-Lagrangian method instead of the explicit upwind finite differences. The improved Double-Sweep-Implicit method was used to improve the computational stability and accuracy. Three comparative cases were studied on the basis of the satisfactory model verifications with field data. Computations show that the maximum change of tidal discharge would be smaller than 0.8% of that of the whole Meizhou Bay, indicating that the change of the situation of shoals and channels in the Meizhou Bay would be small. Based on numerical computations an optimum layout of the coastal reclamation project was recommended. For the recommended scheme, comparisons of the velocity field before and after the project revealed that there were a bit of changes in the vicinity of the project; the annual siltation intensity was smaller than 0.08m nearby the project site while that was smaller than 0.003m at the locations of main harbours and the navigation channel.

**ADDITIONAL INDEX WORDS:** *Tidal motion, Sediment siltation, Numerical model, Meizhou Bay*

## INTRODUCTION

The Meizhou Bay is located in the middle part of Fujian province, China which has a coastal line of 187km long, a water area of 516 $km^2$ and the tidal discharge of $2.42\times10^9$ $m^3$ under the mean tidal level. The Meizhou Bay is a long and narrow half-enclosed bay with a complex coastal topography and the water depth of most area is larger than 10m, in which there are a lot of islands such as the Meizhou Island and the Dazhu Island. Due to the shelter of these islands, the predominant hydrodynamics in the inner bay is the tidal motion. According to the statistical analysis of the tidal level in the Xiuyu station, the mean tidal range is 5.11m. The averaged annual runoff emptying into the Meizhou Bay is about $4.00\times10^8 m^3$, and the Fengtian Stream is the maximum river with the total length of 30km and the averaged annual runoff of $1.09\times10^8 m^3$. The landward-originated annual sediment discharge is $2.90\times10^6$ tons, whereas the seaward-originated one is $2.00\times10^7$ tons. The analysis of the field data at the Douwei-Dazhu-Dongwu section illustrated the sediment transported by the ebb tide out to the Taiwan Strait is $2.28\times10^7$ tons per year. The annual sediment discharges out and in the Meizhou Bay are balanceable on the whole. The primary mode of the sediment transport in the Meizhou Bay is the suspended load with the mean concentration of 0.012~0.020 $kg/m^3$ in general and the maximum one varying between 0.072 to 0.080 $kg/m^3$ for special case. The data from hydrometric measurements in 1999 after the consecutive gale showed the mean concentration during the spring tide is 0.054$kg/m^3$ and that during the neap tide is 0.029 $kg/m^3$ (WANG, 1999).

With rapid development in the economy of Putian City, Fujian Province in the past few decades, the larger land resources are required and a coastal reclamation project called Mazucheng, which will enclose the tidal flat of about 5 $km^2$ in northern Meizhou Bay, is put forward as shown in Fig.1. Although the coastal reclamation is a valid path to meet the demand of land resources, when the coastal reclamation project is constructed, however, the circumjacent conditions of the tidal motion and the sediment transport will be changed accordingly. The potential hydrodynamic impact problem of this coastal reclamation project draws the attention of the relevant departments.

In this study, a two-dimensional numerical model covering the whole Meizhou Bay is developed of depth-integrated tidal flow in an orthogonal boundary-fitting curvilinear coordinate and the engineering sedimentation method is used, to study the possible impact of the coastal reclamation project upon the tidal motion and the sediment siltation intensity in the vicinal sea area.

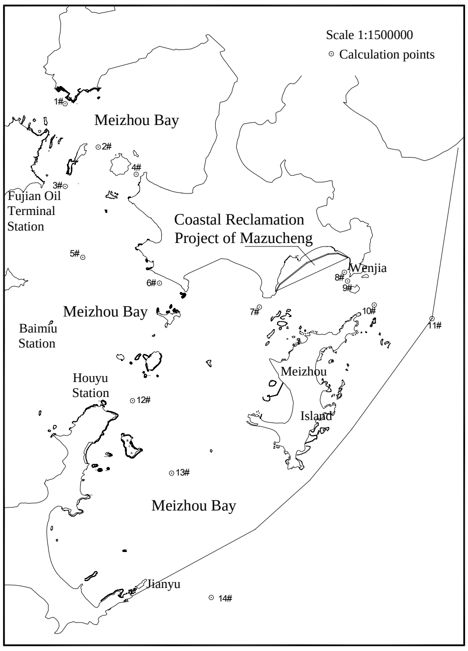

Figure 1. Layout of coastal reclamation project of Mazucheng in Meizhou Bay.

# NUMERICAL MODEL

## Governing Equations

The depth-integrated conservation equation of mass in the orthogonal boundary-fitting coordinate systems can be written as follows.

$$\frac{\partial \zeta}{\partial t}+\frac{1}{C_\xi C_\eta}[\frac{\partial}{\partial \xi}(C_\eta Du)+\frac{\partial}{\partial \eta}(C_\xi Dv)]=0 \qquad (1)$$

where $\zeta$ is water surface elevation; $D=h+\varsigma$ is the total water depth, in which *h* is the still water depth; *u* and *v* are the velocity components in the $\eta$ and $\xi$ directions, respectively; $C_\eta=\sqrt{x_\eta^2+y_\eta^2}$ and $C_\xi=\sqrt{x_\xi^2+y_\xi^2}$ are the Lame coefficients in the $\eta$ and $\xi$ direction, respectively; *t* is time.

The momentum equations for the tidal motion in the $\eta$ and $\xi$ horizontal coordinate directions can be written as

$$\frac{\partial u}{\partial t}+\frac{u}{C_\xi}\frac{\partial u}{\partial \xi}+\frac{v}{C_\eta}\frac{\partial u}{\partial \eta}-\frac{v^2}{C_\xi C_\eta}\frac{\partial C_\eta}{\partial \xi}+\frac{uv}{C_\xi C_\eta}\frac{\partial C_\xi}{\partial \eta}$$

$$=fv-\frac{g}{C_\xi}\frac{\partial \zeta}{\partial \xi}+A_H(\frac{1}{C_\xi}\frac{\partial A}{\partial \xi}-\frac{1}{C_\eta}\frac{\partial B}{\partial \eta})-\frac{g\sqrt{u^2+v^2}}{C^2D}u \qquad (2)$$

$$\frac{\partial v}{\partial t}+\frac{u}{C_\xi}\frac{\partial v}{\partial \xi}+\frac{v}{C_\eta}\frac{\partial v}{\partial \eta}-\frac{u^2}{C_\xi C_\eta}\frac{\partial C_\xi}{\partial \eta}+\frac{uv}{C_\xi C_\eta}\frac{\partial C_\eta}{\partial \eta}$$

$$=-fu-\frac{g}{C_\eta}\frac{\partial \zeta}{\partial \eta}+A_H(\frac{1}{C_\xi}\frac{\partial B}{\partial \xi}-\frac{1}{C_\eta}\frac{\partial A}{\partial \eta})-g\frac{\sqrt{u^2+v^2}}{C^2D}v \qquad (3)$$

where $A=\frac{1}{C_\xi C_\eta}[\frac{\partial}{\partial \xi}(C_\eta u)+\frac{\partial}{\partial \eta}(C_\xi v)]$; $B=\frac{1}{C_\xi C_\eta}[\frac{\partial}{\partial \xi}(C_\eta v)-\frac{\partial}{\partial \eta}(C_\xi u)]$; *f* is Coriolis parameter; *g* is the acceleration due to gravity; $A_H$ is the depth mean (horizontal) eddy viscosity coefficient of turbulent flow; *C* is the Chezy bed roughness coefficient.

## Numerical Scheme

The Double-Sweep-Implicit finite-difference scheme (YAN *et al.*, 1999) is adopted to solve the momentum and continuity equations, which employs a space-staggered grid with the velocities located at the edge of the grid cell and with the other main variables being located at the centre of the cell. In order to improve the computational stability and accuracy, the left-hand side of the momentum equations is rewritten in the Lagrangian form and the convection term in the momentum equations is discretised by the Eulerian-Lagrangian method instead of the explicit upwind finite differences (ZHENG *et al.*, 2002). The improved Double-Sweep-Implicit finite differential equations are written as

$$\begin{cases}\varsigma^*-\varsigma+\Delta t\frac{\delta_\eta}{\Delta\eta}\left(Du^{n+1}\right)+\Delta t\frac{\delta_\xi}{\Delta\xi}\left(Dv\right)=0\\ u^{n+1}-u+g\Delta t\frac{\delta_\eta}{\Delta\eta}\varsigma^*-\Delta t\left(fv+TR_\eta-u\frac{\partial u}{\partial\eta}-v\frac{\partial v}{\partial\xi}\right)=0\end{cases} \qquad (4)$$

$$\begin{cases}\varsigma^{n+1}-\varsigma^*+\Delta t\frac{\delta_\xi}{\Delta\xi}\left(Dv^{n+1}\right)-\Delta t\frac{\delta_\xi}{\Delta\xi}\left(Dv\right)=0\\ v^{n+1}-v+g\Delta t\frac{\delta_\xi}{\Delta\xi}\varsigma^{n+1}+\Delta t\left(fu^{n+1}-TR_\xi+u\frac{\partial u}{\partial\eta}+v\frac{\partial v}{\partial\xi}\right)=0\end{cases} \qquad (5)$$

where $\varsigma^*$ is an intermediate tidal level value; $\delta_\eta$ and $\delta_\xi$ are differential operators; $TR_\eta$ and $TR_\xi$ are turbulence terms in the $\eta$ and $\xi$ directions respectively.

The finite-difference equations, which are a tri-diagonal matrix, can be resolved by TDMA method. Since there is a large area of tidal flat in the Meizhou Bay, a moving boundary treatment is considered so that the flooding mass flux can be provided by the surface gradient at the water-land boundary when the water elevation at the seaward front is higher than the basement level at the adjacent landward grid. The numerical model with this scheme has been successfully applied to the hydrodynamic impact assessments on the reclamation project in the Shenzhen River Estuary (ZHENG, 2003), the large-scale reclamation project in Sansha Bay (ZHENG and WANG, 2004), the waterfront layout of the Xiuyu Harbour (ZHENG *et al.*, 2005), and the coastal highway project in the Meizhou Bay (ZHENG *et al.*, 2006).

# COMPUTATIONS AND ANALYSIS

## Verifications of Numerical Model

The computational domain covers the whole Meizhou Bay and extends to 12km away from the bay, in order to eliminate the potential influence of the engineering on the offshore open boundary conditions. The length in the south-northward direction is 45 km and that in the west-eastward direction 15 km. The minimum grid size is 11m. The number of grid nodes is 96695. The lateral boundary conditions were set to be zero of the flow normal to the shoreline. The given tidal data, which were obtained from the mathematical model of the East China Sea, are imposed along the offshore open boundaries.

For the verification of the present model, the tidal level data at the Oil Terminal Station, the Bainiu Station, the Houyu Station, the Jianyu Station, the Chongwu Station and the synchronous hydrometric measurements at nine points from 25th to 31st Jan., 1997 are employed. Comparisons of the field survey data and computations (Figures 2 and 3) demonstrate that a satisfactory agreement is obtained. Comparisons at other points have been described by ZHENG (2005) in detail. The time step is set to be

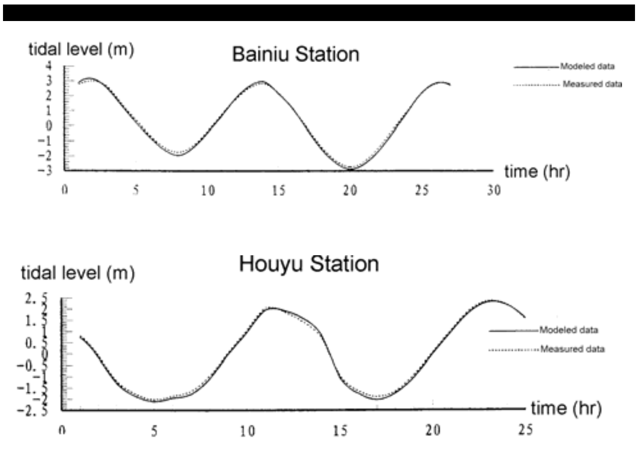

Figure 2. Comparisons of measured and modelled water level.

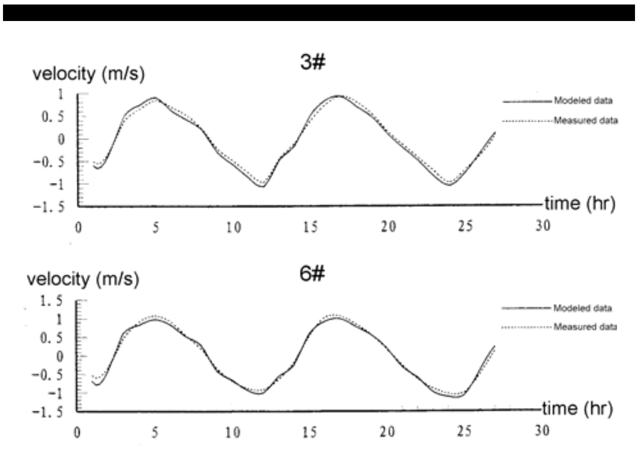

Figure 3. Comparisons of measured and modelled tidal current.

36s. The depth mean eddy viscosity coefficient is taken as 150 $m^{1/2}/s$. The Manning coefficient is determined to be 0.022.

Results demonstrate that the present model is efficient and capable of simulating the tidal motion in the Meizhou Bay.

## Study Cases

Three comparative schemes are considered in this study, as shown in Fig.1. In case 1, the reclamation area is 4.5 $km^2$ from Shanbing to Xiasha. In case 2, the reclamation area is 1.3$km^2$ from Shanbing to Xiasha. In case 3, the reclamation area is 5.0 $km^2$ from Shanbing to Xiasha.

## Changes of Tidal Discharge

Table 1 shows the tidal discharges through the Jianyu section on the natural status and after the project, which demonstrates the change of the tidal discharge of the whole Meizhou Bay. It is clear that the smaller the enclosed tidal flat area the smaller the impact upon the tidal discharge. The project-induced decreases of the amount of the flood tidal discharge in the spring tide through the Jianyu section for case 1 to case 3 are $0.187\times10^8m^3$, $0.103\times10^8m^3$ and $0.219\times10^8m^3$, account for 0.65%, 0.36% and 0.76% of the total flood tidal discharge in the Meizhou Bay and those in the neap tide are $0.118\times10^8m^3$, $0.054\times10^8m^3$ and $0.136\times10^8m^3$, account for 0.54%, 0.25% and 0.63% of the total flood tidal discharge in the Meizhou Bay.

Table 1: Changes of tidal discharge ($\times10^8m^3$) through Jianyu Section.

| | Spring Tide | | Neap Tid | |
|---|---|---|---|---|
| | Flood Tide | Ebb Tide | Flood Tide | Ebb Tide |
| Natural Status | 28.661 | 28.473 | 21.679 | 21.242 |
| Case 1 | 28.474 | 28.282 | 21.561 | 21.127 |
| Amount 1 | -0.187 | -0.191 | -0.118 | -0.115 |
| Percent 1 (%) | -0.65 | -0.67 | -0.54 | -0.54 |
| Case 2 | 28.558 | 28.367 | 21.625 | 21.186 |
| Amount 2 | -0.103 | -0.106 | -0.054 | -0.056 |
| Percent 2 (%) | -0.36 | -0.37 | -0.25 | -0.26 |
| Case 3 | 28.442 | 28.254 | 21.543 | 21.105 |
| Amount 3 | -0.219 | -0.219 | -0.136 | -0.137 |
| Percent 3 (%) | -0.76 | -0.77 | -0.63 | -0.64 |

## Changes of Tidal Velocity

In order to study the change of flow velocity quantitatively, a total of 14 calculating points are set within the concerning water area, as shown in Fig.1. Table 2 shows the changes in the most concerned locations of the mean velocity before and after the completion of the project in the spring tide. It can be found that the smaller the distance from the project the larger the impact of the project and the larger area of the enclosed tidal flat the greater the annual siltation intensity. Comparisons of the velocity field before and after the project showed that there were some changes in the vicinity of the project. Point 7 is located in the Wenjia channel. Points 8 and 9 are located in front of Wenjia Fishery Harbour and Wenjia Passenger terminals. Points 12 to 14 are located in the main navigation channel of the Meizhou Bay. The maximum decrease of the velocity was less than 0.005 m/s at locations of main harbours and the navigation channel such as point 1 and point 12.

## Project-induced Annual Siltation Intensity

The project-induced annual siltation intensity was calculated by the Formula recommended in the Hydrological Criterion of Seaport Engineering of China, in the following form (LIU and ZHANG, 1993).

$$p=\frac{\omega st}{\gamma_d}\left\{k_1\left[1-\left(\frac{V_2}{V_1}\right)^3\right]\sin\theta+k_2\left[1-\frac{V_2}{2V_1}\left(1+\frac{V_2}{V_1}\right)\right]\cos\theta\right\} \tag{6}$$

where $p$ is the annual siltation intensity (m/a); $\omega$ is the settling velocity of sediment (m/s); $s$ is the average sediment concentration ($kg/m^3$); $t$ is the time (s); $\gamma_d$ is the dry density of sediment ($kg/m^3$); $V_1$ and $V_2$ are the averaged velocities over semi-tide before and after the completion of the reclamation project respectively (m/s); $\theta m$ is the angle between the tidal flow and the channel; $k_1$=0.35 and $k_2$=0.13 are the siltation constant of the transversal and longitudinal currents respectively. On the basis of the analysis of the field data, the relevant parameters are determined as follows: (1) The average sediment concentrations of flood tide and ebb tide in the neap tide are 0.017$kg/m^3$ and 0.023$kg/m^3$; those in the median tide 0.024 $kg/m^3$ and 0.028$kg/m^3$; those in the spring tide 0.033$kg/m^3$ and 0.042$kg/m^3$. (2) The settling velocity of sediment

Table 2: Changes of current velocity (m/s) in spring tide.

| | 7# | | 8# | | 10# | | 12# | |
|---|---|---|---|---|---|---|---|---|
| | Flood Tide | Ebb Tide | Flood Tide | Ebb Tide | Flood Tide | Ebb Tide | Flood Tide | Ebb Tide |
| Natural Status | 0.408 | 0.331 | 0.104 | 0.238 | 0.344 | 0.377 | 0.712 | 0.742 |
| Case 1 | 0.424 | 0.341 | 0.088 | 0.179 | 0.333 | 0.361 | 0.711 | 0.742 |
| Amount 1 | 0.016 | 0.010 | -0.016 | -0.059 | -0.011 | -0.016 | -0.001 | 0.000 |
| Percent 1 (%) | 3.9 | 3.0 | -15.4 | -24.8 | -3.2 | -4.2 | -0.1 | 0.0 |
| Case 2 | 0.419 | 0.338 | 0.096 | 0.207 | 0.338 | 0.366 | 0.712 | 0.742 |
| Amount 2 | 0.011 | 0.007 | -0.008 | -0.031 | -0.006 | -0.011 | 0.000 | 0.000 |
| Percent 2 (%) | 2.7 | 2.1 | -7.7 | -13.0 | -1.7 | -2.9 | 0.0 | 0.0 |
| Case 3 | 0.432 | 0.348 | 0.081 | 0.167 | 0.329 | 0.355 | 0.711 | 0.741 |
| Amount 3 | 0.024 | 0.017 | -0.023 | -0.071 | -0.015 | -0.022 | -0.001 | -0.001 |
| Percent 3 (%) | 5.9 | 5.1 | -22.1 | -29.8 | -4.4 | -5.8 | -0.1 | -0.1 |

is 0.0004 m/s. (3) The dry density of sediment $\gamma_d$=1750$d_{50}^{0.183}$ kg/m$^3$. (4) The median diameter $d_{50}$ is 0.014mm.

Table 3 shows the project-induced annual siltation intensity for case 3, which is the most serious case. It is obvious that the smaller the distance from the project the larger the annual siltation intensity and the larger area of the enclosed tidal flat the greater the annual siltation intensity. In front of the Wenjia Fishery Harbour and the Wenjia Passenger terminals, the annual siltation intensities are largest, up to 0.076 and 0.031cm, respectively. In the main waterway of Meizhou Bay, the annual siltation intensity is smaller than 0.003 m. Since the water depth in the above two terminals and the main waterway is greater than 20m, and the sediment concentration in the Meizhou Bay is relatively small, the project-induced annual siltation intensity can be considered to have small influence on the utility of the main channel and terminals.

Table 3: Project-induced annual siltation intensity (m/a).

| | 8# | 9# | 10# | 11# | 12# |
|---|---|---|---|---|---|
| Case 3 | 0.076 | 0.031 | 0.022 | 0.011 | 0.003 |

## CONCLUSION

A two-dimensional orthogonal body-fitted finite difference numerical model of depth-integrated tidal flow was developed to study the possible impact of the coastal reclamation project of Mazucheng upon the tidal flow and the sediment siltation intensity in the vicinal sea area. Based on the satisfactory verifications, the project-induced impacts were studied of the tidal discharge and flow velocity in the Meizhou Bay. The annual siltation intensity was computed by using the formula recommended by the Hydrological Criterion of Seaport Engineering of China. Case 2 was recommended on the basis of the comparisons of the results of three cases. It was found that for the recommended case, the maximum change of tidal discharge would be smaller than 0.8% of that of the whole Meizhou Bay, indicating that the change of the situation of shoals and channels in the Meizhou Bay would be small. Comparisons of the velocity field before and after the project showed that there were some changes in the vicinity of the project. The maximum decrease of the velocity was less than 0.005 m/s at locations of main harbours and the navigation channel. The annual siltation intensity was smaller than 0.08m nearby the project while that was smaller than 0.003m at the locations of main harbours and the navigation channel.

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