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Numerical simulation of saltwater intrusion and storm surge effects of reclamation in Pearl River Estuary, China

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ABSTRACT

This study aims to simulate and predict the influence of reclamation on saltwater intrusion and storm surge in the Pearl River Estuary, China by using the FVCOM Surface Wave Module (FVCOM-SWAVE). The study shows that the reclamation has a great influence on tidal velocity and direction, especially in some areas where narrow waterways are formed. Reclamation resulted in an increase in salinity due to impeded runoff, and reduced significant wave height in the nearby sea area. It has a positive effect on reducing storm surge disasters. However, the geographic scope of impact has been small and there is almost no change away from the reclamation area.

1. Introduction

The Pearl River Estuary (PRE) area is the predominant source of economic and social development in Guangdong Province and is the most densely populated and most economically developed urban agglomeration in Guangdong Province. The Pearl River Delta (PRD) region has witnessed rapid economic development and frequent human activity. In particular, activities such as coastal reclamation and bridge and port construction have caused the PRE coastline to continuously advance toward the sea, with the type and length of the coastline having undergone great changes as a result. In the past two decades, the total length of the PRE coastline has increased by 149.2 km while coastal land has increased by 251.76 km^2 [1–5].

Saltwater intrusion refers to the phenomenon that the high salinity seawater on the oceanic continental shelf of the estuary enters the river section along the river with tide, which causes the phenomenon that the water bodies in the upstream rivers become salty. Storm surge is a catastrophic natural phenomenon. Abnormal seawater rises and falls occur due to the severe atmospheric disturbances, such as strong winds and sudden changes in pressure, which are usually caused by severe weather systems such as typhoons and tropical cyclones. In recent years, due to continuous dry water and river course changes in the PRE, the impact of saltwater intrusion has increased [6] and has seriously threatened the water supply in the PRD region, including Macao and Zhuhai. Rising sea levels due to climate warming combined with increasing storm surge will affect people's productivity and life through land loss.

In recent years, many scholars have conducted in-depth research on this issue. For example, some scholars have studied the relation between urban water supply and saltwater intrusion, and establish a model to achieve the purpose of optimizing water resources and further improve the shortage of fresh water caused by saltwater intrusion [7–9]. Mao et al. used the data from several cruises and observation stations in the PRE to study tidal dynamics and found that salt water intrusion largely occurred via the eastern channel in the estuary [10]. Coates et al. [11] and Cuthbertson et al. [12] studied the saltwater intrusion using theoretical and experimental methods. From the viewpoint of agricultural production, Nguyen et al. [13] studied the effects of saltwater intrusion on Red River Delta rice yield and found that saltwater intrusion will reduce the yield. Kang et al. [14] evaluated farmland losses from sea level rise and storm surges in the PRD region under global climate change. In economic terms, Williams [15] studied the impact of saltwater intrusion on the local economy after Hurricane Katrina. In addition, in the numerical simulation, Guo et al. [16,17] used numerical models to simulate the hydrodynamics in the Qiantang Estuary and storm surge in Hangzhou Bay. Kuang et al. [18] established a numerical model of the Yangtze Estuary to predict the morphological evolution process of the Yangtze Estuary for the next 20 years. Bao et al. [19] established a two-dimensional storm surge model to study the process of storm surge enhancement in the PRE. Lee et al. [20] used a

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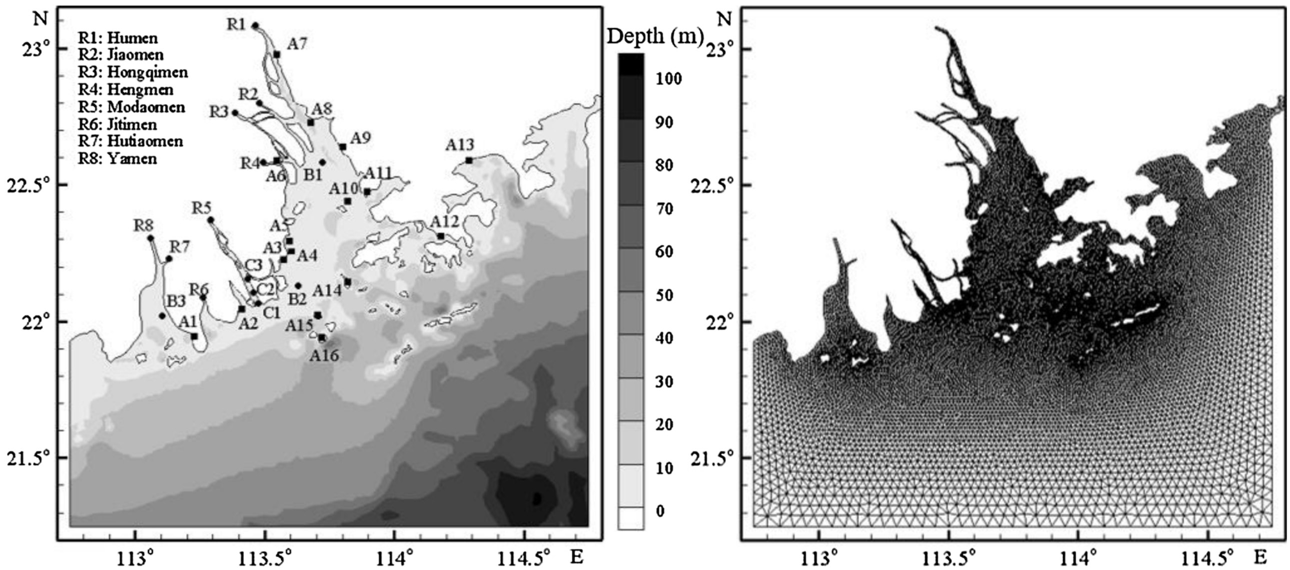

Fig. 1. The topography and locations of the observation stations (a) and the grid (b) of Pearl River Estuary (A1–A16: the tide level measured stations; B1–B3 and C1-C3: the tide current and salinity measured stations).

two-dimensional numerical model to study the relation between runoff and saltwater intrusion distance in the Terengganu Estuary. Abdullah et al. [21] established a saltwater intrusion prediction model for the Shatt al-Arab Estuary. Wang et al. [22] used a three-dimensional numerical model to study the saltwater intrusion in the Modaomen waterway, and Yin et al. [23] used an ADCIRC-SWAN coupled model to study the effects of sea level rise and typhoon intensity on storm surge and waves.

However, there have been a few studies on the impact of the reclamation projects on saltwater intrusion and storm surge rise. This study uses a well-validated model to systematically simulate and analyze the influence of coastline variations from reclamation on saltwater intrusion and storm surge in the PRE. The results of this study can contribute toward better decision-making for development of marine resources and engineering design.

2. Model setup and verification

This study is based on FVCOM Surface Wave Module (FVCOM-SWAVE) to simulate the saltwater intrusion and storm surge and predict the influence of reclamation in Pearl River Estuary. FVCOM is a three-dimensional, primitive equation coast and ocean model using a finite volume method [24,25]. This model features a non-overlapping unstructured triangular grid in the horizontal and a generalized terrain-following coordinate in the vertical, and solves the integral form of the governing equations by second-order accurate flux-based finite-volume methods.

2.1. Grids setup

A three-dimensional unstructured triangular grid model is built as shown in Fig. 1. The topography data are based on the NOAA-ETOPO1 database, and the data resolution is $1/6^{\circ} \times 1/6^{\circ}$. The minimum grid length is 100 m. The grid has 29,881 elements and 15,908 nodes, covers the Pearl River Estuary and nearby sea waters within 21.25°–23.15 °N, 112.75°–114.8 °E. Mesh encryption processing was performed in the near shore and estuary areas to ensure the accuracy of the simulation.

2.2. Boundary conditions

For the tide boundary, tidal prediction software China Tide is used to calculate the nine tidal constituents (S_a, O_1, Q_1, K_1, P_1, N_2, M_2, S_2, and K_2) under given latitude and longitude coordinates by interpolation calculation and numerical calculation. According to Eq. (1), the software automatically calculates the required time-period tide series.

$$\eta = \sum_{i=1}^{n} f_i h_i \cos(\sigma_i t + v_{0i} + u_i - g_i), \quad n = 9, \tag{1}$$

where η is the tide level; h_i and g_i are the tidal harmonic constants (amplitude and retardation); σ_i is the angular velocity of the tide; t is the time; f_i is the tidal intersection factor; v_{0i} is the first phase of astronomical tide; u_i is the tide intersection point of correction.

For the river boundary, the PRD region has a distinctive "convergence of three rivers and eight estuaries into the sea" characteristic, i.e., the main rivers Xijiang, Beijiang, and Dongjiang converge to the delta region, and through a total of eight estuaries, the Yamen, Hutiaomen, Jitimen, Modaomen, Hengmen, Hongqimen, Jiaomen, and Humen, drain into the South China Sea. Data on runoff and temperature over time were set at the eight estuaries and used as river boundaries.

For the temperature and salinity boundary, the temperature and salinity data of the open boundary of the Pearl River Estuary model are set to change with time and space. It comes from the global 1/12° reanalysis data on the CMEMS database. The temperature and salinity data on the CMEMS database at the boundary point were used to extract the boundary temperature and salinity data of the Pearl River Estuary model.

For the sea surface boundary, the data are based on ECMWF database, and the data accuracy is $0.25^{\circ} \times 0.25^{\circ}$, including wind, temperature, relative humidity, clearness coefficient, evaporation, and precipitation.

2.3. Model parameters

The simulation time of the model is from December 21, 2008 to January 1, 2011, during which the data were available to verify the model. The time steps used were 5 s for the external mode and 30 s for the internal mode. Ten uniform sigma layers were set. Dry and wet grid technology was used. The initial tidal level and flow velocity were defined as 0 m and 0 m/s, respectively. The initial temperature and salinity were defined as monthly mean data.