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Assessment of Tidal Hydrodynamics Along Taiwan Coast

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ABSTRACT.

A large scale numerical model covering the entire Taiwan coastline has been developed to understand the tidal hydrodynamics, under the India-Taiwan programme of cooperation in Science and Technology. In this study, a finite difference based numerical model, Delft3D-FLOW is used to simulate the tidal levels and currents along the east and west coast of Taiwan. The steep bathymetry along the east coast and shallow and narrow Taiwan straight on its western side lead to a unique tidal pattern along Taiwan coastline. Estimation of tidal levels and associated currents along the east coast of Taiwan is challenging, as it is influenced by global circulation patterns and strong reflective nature of steep sea bed contours. The numerical model was forced with global tidal constituents along the offshore boundary. The simulated model results are validated with the collected water level and currents from various existing literature. The comparison of water level and currents are found to be in good agreement. The details of numerical model, methodology, field measurements and results are discussed in this paper.

KEYWORDS: Taiwan coast, Tidal Hydrodynamic, Delft3D, Currents

INTRODUCTION

The gravitational pulls of the moon and the sun cause a periodic, up and down motion of the ocean tide. Tides are predictable in the surface level, which cause the flow on the Earth's surface to move in different directions. Tidal currents are the movement of water driven by changes in tidal height. These current are small in the deep waters but it often increases in nearshore areas.

Taiwan is located between the continental shelf of China and the west side of the Pacific Ocean. This country has a different geographical formation and climate scenario along the east and west coasts. The steep bathymetry along the east coast and shallow and narrow Taiwan straight on its western side lead to a unique tidal pattern along Taiwan coastline. Estimation of tidal levels and associated currents along the east coast of Taiwan is challenging, as it is influenced by global circulation patterns and strong reflective nature of steep sea bed contours. The process based numerical modelling tools are extensively used to understand the various coastal processes, including tidal hydrodynamics in gulfs and continental shelf.

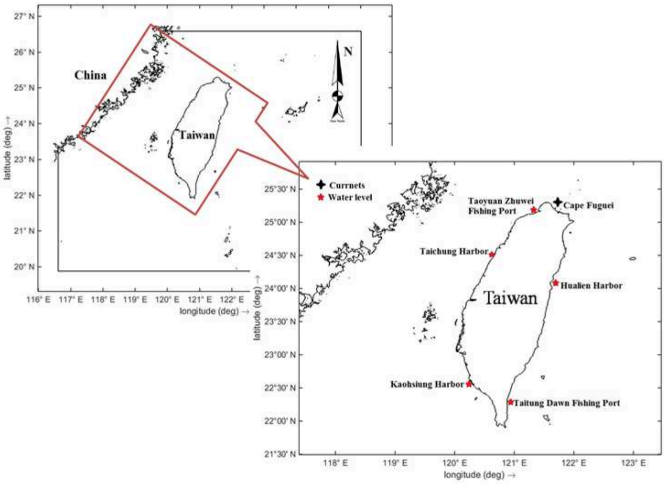

Fig 1 Model domain with observation stations

It is a cost-effective method of evaluating the marine environment as they require limited data collection and may be utilized to access tidal hydrodynamics and other processes. Already several researchers has been extensively used various numerical modelling techniques across the world. Notably, Yu, H., et al (2015) found asymmetric M2 tidal amplitude in the cross shore direction of Taiwan Strait using finite difference numerical model. Lin, X., et al (2016) developed Taiwan Strait Nowcast/Forecast system (TFOR) using Regional Ocean Modeling System, which includes both tide and circulation processes. Liu, W.C., et al (2015) developed a two-dimensional finite element based numerical to investigate the tide-surge interaction along the Taiwan coast. Tsai, C.H., et al (2015) estimated the tidal current energy potential at Cape Fuguei through field measurements of tidal current data using ADCP and X-band radar techniques. Wang, A., et al (2014) studied cohesive sediment behaviours and their time-variability along the northern Taiwan Strait using acoustic Doppler velocimeter (ADV), upward acoustic Doppler current profiler (ADCP) and a Seapoint turbidity sensor. [Satheeshkumar and Balaji (2015), Kumar, S and Balaji (2015)] developed a two-dimensional hydrodynamic model based on finite element and difference techniques along the Gulf of Khambhat, India implemented spatially varying bottom friction coefficients. This study aims at modelling tides hydrodynamics using a two-dimensional finite difference model for the entire Taiwan coastal region. Measurements available from literature were used for the validation of results of the developed numerical model.

STUDY AREA

Taiwan is located between the continental shelf of China and the west side of the Pacific Ocean (Fig. 1). It is subject to severe sea-state and often affected by typhoons during summer and autumn seasons. Taiwan has a typical geographical formation, the east coast which faces the Pacific Ocean consists of rocks and gravels and the west coast along the Taiwan Strait consists of finer sands. The Taiwan Strait is located between the East China Sea and South China Sea and forms part of China's continental shelf. The depth of strait is shallower than 60m. Due to the variation in depth contours, the strait is dominated by strong current circulation patterns. Apart from the circulation of the water mass, the tidal current also plays an important role in the hydrodynamics in estuarine, coastal and shelf environments. The semidiurnal M2 tide is by far the most predominant one (Wang et al 2003).

NUMERICAL MODEL DESCRIPTION

Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. These equations are solved over an orthogonal curvilinear grid using finite difference technique, with appropriate initial and boundary conditions.

The continuity (1) and momentum equations in x (2) and y (3) directions are:

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}(d+\eta)u+\frac{\partial}{\partial y}(d+\eta)v=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \eta}{\partial x}-fv+\frac{\tau_x}{\rho_w(d+\eta)}-\frac{F_x}{\rho_w(d+\eta)}-\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=0 \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial \eta}{\partial y}-fv+\frac{\tau_y}{\rho_w(d+\eta)}-\frac{F_y}{\rho_w(d+\eta)}-\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)=0 \tag{3}$$

where u, v, are the flow velocities in x, y, directions respectively; f is the Coriolis parameter; ρ_w is the reference density of water; τ_x and τ_y are bottom stress parameters; F_x and F_y are the external forces in x and y direction, respectively; ν is the vertical eddy viscosity.

For two-dimensional depth-averaged flow, the bottom stress induced by the flow in Eq. (2) and Eq. (3) is governed by a quadratic friction law, given by:

$$\tau_x=\frac{\rho g u\,|u|}{C^2} \tag{4}$$

where u is the depth-averaged velocity in x direction, and C is the Chezy's coefficient.

Similarly, for y direction, the bottom stress formulation is given as:

$$\tau_y=\frac{\rho g v\,|v|}{C^2} \tag{5}$$

Under the shallow water assumption, which is valid for large horizontal scales, the vertical momentum equation is reduced to the hydrostatic pressure equation. Vertical accelerations due to buoyancy effects or sudden changes in bottom topography are neglected, and only gravitational acceleration is taken into account. The hydrostatic pressure equation depicts pressure forces being balanced by weight of the water column, and is given by: where v is the depth-averaged velocity in y direction.

$$\frac{\partial P}{\partial z}\cong-\rho g \tag{6}$$

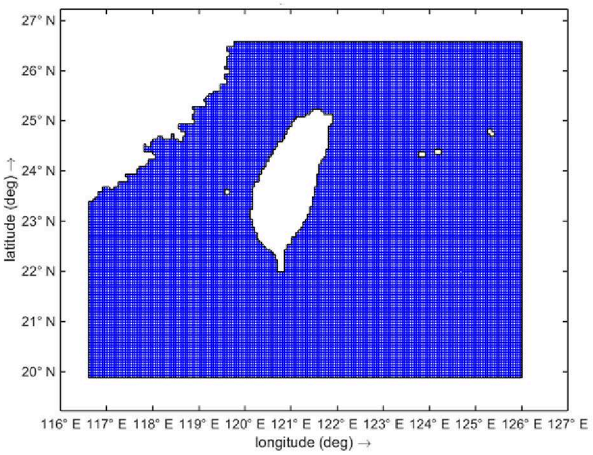

Fig 2 Computational model grid

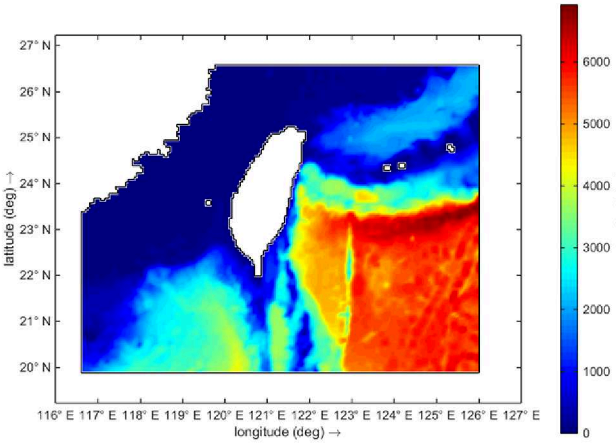

Fig 3 Bathymetry variations of model domain

MODELLING METHODOLOGY

The numerical model domain, in this study, covers the entire Taiwan located between the continental shelf of China and the west side of the

Pacific Ocean, as shown in the Fig. 2. The model domain was discretized in a small rectilinear part with a spatial resolution of 150m along the entire domain. For the horizontal discretization the Arakawa C-grid was used (Arakawa et al., 1983), a staggered grid in which water levels ζ are defined in the center of the grid and velocities are computed at the mid points of grid cell faces, respectively. The bathymetry of the present study was extracted from GEBCO global bathymetry dataset. The depth contours of the model domain various from 0m to 6000m as shown in Fig. 3. The offshore boundary of the model domain was forced with thirteen tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4 and MN4), extracted from a global tidal model TPXO 7.2 (Egbert et al., 1994). Other simulation parameters such as Chezy's bottom friction and horizontal eddy viscosity were also used for this simulation.

RESULTS AND DISCUSSION

In order to validate the tidal levels and currents, estimated from the numerical model, comprehensive collection of various data sets, from available literatures, was carried out. The location of collected data was shown in Fig. 1.The model simulation has been carried out to the respective measurement period of collected datasets. As spin-up period is essential to ensure the initial conditions do not affect the numerical results during the validation period, 15 days was chosen for the spin-up period for all simulations. Fig. 4 shows the comparison of water level between simulated and collected data from the 25 Sept to 1 Oct 2008, indicating a reasonable agreement between each others. Fig. 5 and 6 shows the comparison of current velocity at Cape Fuguei during 21 to 25 July 2013 and on 19 Sept 2013.It is clear from the figure that the model demonstrates its capabilities to predict the tidal levels and current velocity along the study domain.

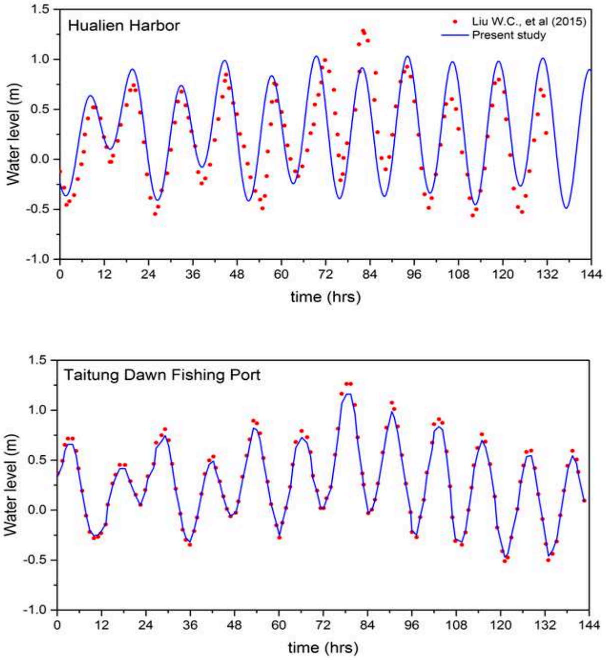

Fig 4 Time series comparison of water levels during 25 Sept to 1 Oct 2008

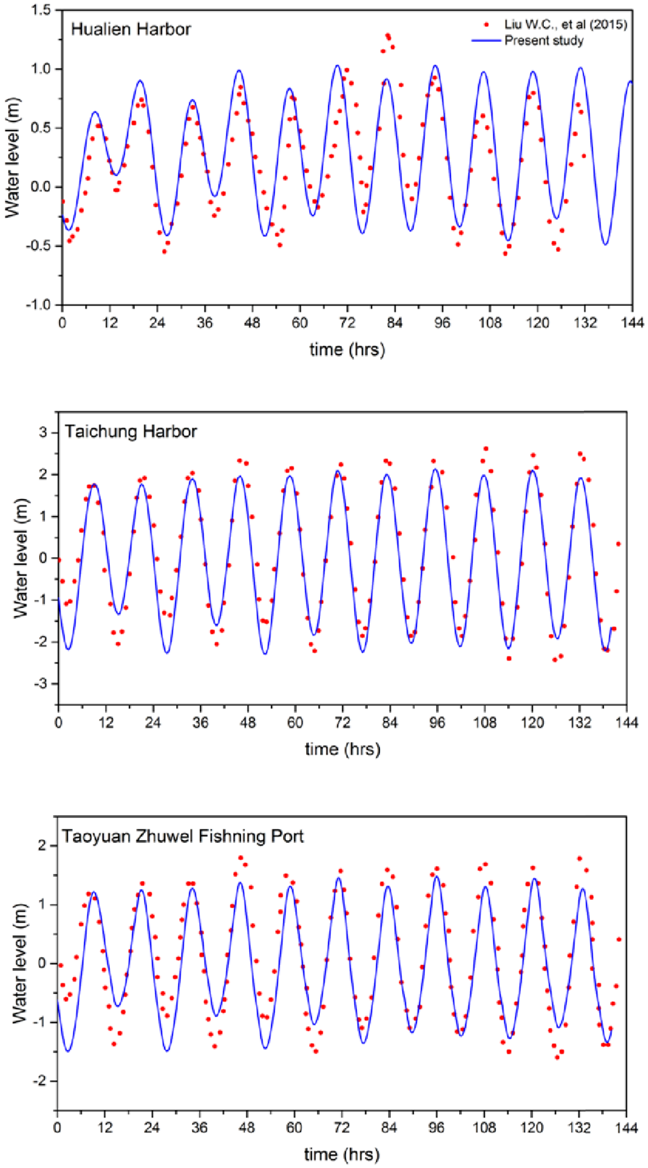

Fig 4 Continued

Further, the estimation of tidal level and velocity across the study domain, the spatial variation of hydrodynamic parameters extracted from simulated model results. Fig. 7 and 8 shows the typical spatial variations of water level and current velocity across the domain during mid-flood and mid-ebb on spring and neap tidal cycles. It is clear from that figures the maximum current velocity during spring and neap tidal cycles are 2.6m/s and 1.8m/s respectively.

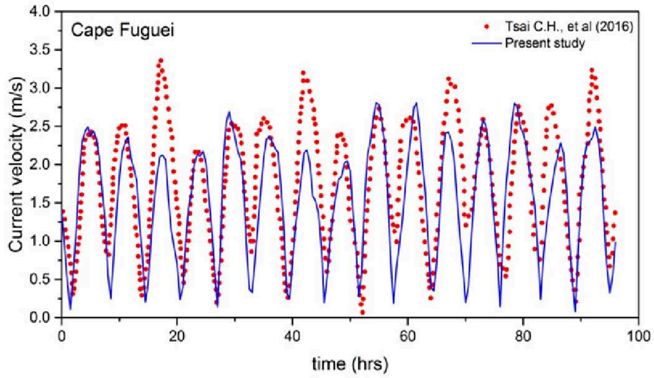

Fig 5 Comparison of current velocity during 21-25 July 2013

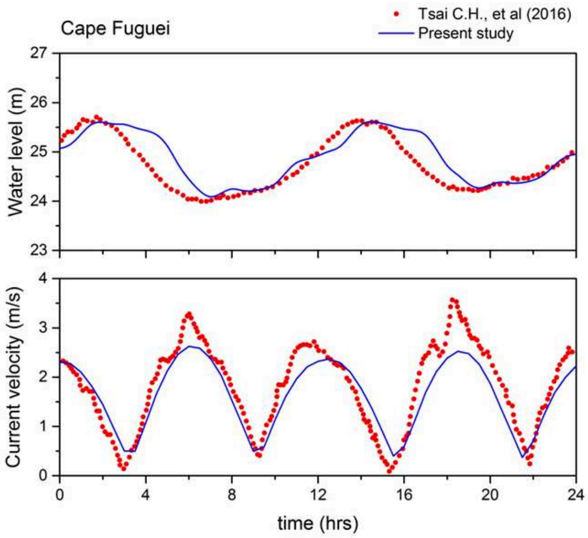

Fig 6 Comparison of water level and velocity at Cape Fuguei on 19 Sept 2013

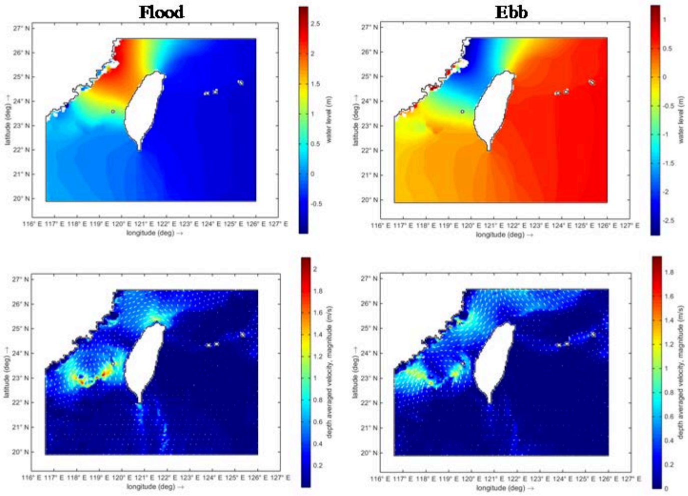

Fig 7 Typical variations of water level and currents during spring tidal cycle

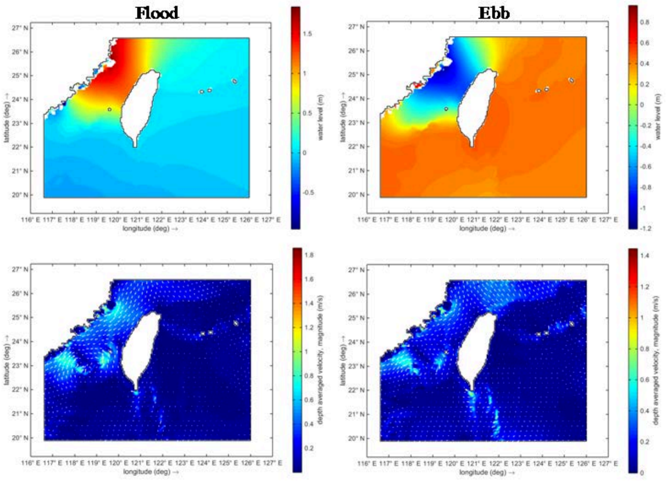

Fig 8 Typical variations of water level and currents during neap tidal cycle

CONCLUSION

A finite difference based hydrodynamic model has been developed to study a hydrodynamic characteristic along the Taiwan coastline. The study domain covers the entire coast of Taiwan. The model was forced with tidal constituents as an offshore boundary condition and the simulated model results are validated with the existing available literature based collected water levels and current data. The validated results shown the model can well enough to reproduce the hydrodynamic characteristics along the Taiwan Coastline. The maximum estimated values of tidal current velocities are of the 2.6m/s and 1.8m/s during spring and neap tidal cycles respectively.

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