Numerical Simulation of Tidal Current Energy in Yangtze Estuary-Hangzhou Bay, China

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Abstract: Tidal current power generation system extracts energy by transferring the kinetic energy of tidal movement to the motion of power turbines. The long coastline of China contains abundant tidal energy, but not all coastal area worth exploiting. It is generally considered that a mean spring peak tidal current of at least 2 *m/s* is required for tidal current power exploitation. Thus we choose to evaluate the tidal kinetic energy of East China Sea coastal area where 95 waterways contained, accounting for 78.6% of China's tidal kinetic energy. Considering the interaction between the Yangtze Estuary and Hangzhou Bay, a high resolution model with unstructured 3D grid system FVCOM (finite volume coastal ocean model) has been applied to simulate tidal motion in the Yangtze Estuary-Hangzhou Bay. The numerical results of the refined model has been validated with: (a) measured tidal currents data after harmonic analysis; (b) measured tide level hydrograph and velocity which were observed by China's coastal physical oceanography and marine meteorological special investigation on the East China Sea during August, 2014. It is also noticed that the area where power density larger than 10 kW/m^2 are mainly distributed over North Port of Yangtze Estuary and north of Hangzhou Bay, and the maximal value of the possible maximum velocity of the tidal current reaches 3.0-3.5 *m/s* at Hangzhou Bay.

Key words： Yangtze Estuary；Hangzhou Bay；tidal kinetic energy；FVCOM

1 INTRODUCTION

The tide is the regular and predictable change in the surface level of an ocean or estuary with time. Tides are driven by the gravitational and rotational forces between the earth, moon, and sun, which cause the flow on the earth's surface to move in different directions. Tidal currents (or tidal streams) are the movement of water driven by changes in the tidal height, with high flow velocity which can attain to 2m/s~3m/s. The density of water is 800 times as large as the density of air, the generation of tidal current is more efficient than the energy extracted by windmills from the wind. As a kind of renewable energy source, it can supply energy in the future more effective and towards commercialization.

Yangtze River is the biggest river in China with a complex terrain estuarine. It has been shown that the natural period of the Yangtze Estuary is slightly larger than the 12.42 *h* period of the dominant semi-diurnal lunar tide – the M_2 tide[1]. The resulting near-resonance is responsible for driving the high tides. The annual average tidal range in Zhongjun station near the entrance attains to 2.66 *m*, and 4.62 *m* in the maximum value. Flared terrain makes the Hangzhou Bay harbours some of the world's highest tides, reaching over 6m in amplitude in the channels of Zhoushan[2]. The tides contain a large amount of energy. In 1989, Chinese Coastal and Rural Ocean Energy Resources Regional Planning has got the statistics about 130 waterways in China. The reason why we choose to evaluate the tidal kinetic energy of East China Sea coastal area is that 95 waterways are contained, accounting for 78.6% of China's tidal kinetic energy. This has encouraged the discussion of tidal power in the region for nearly 100 years.

2 REFINEMENT OF HYDRODYNAMIC MODEL

The unstructured grid finite volume coastal ocean model (FVCOM) is a state of the art open source community model that has been applied to global/basin/regional scale ocean, coastal, and estuarine studies.

2.1 The primitive equations of unstructured grid 3D FVCOM

The governing equations consist of the following momentum, continuity, temperature, salinity, and density equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-\frac{1}{\rho_o}\frac{\partial P}{\partial x}+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right)+F_u \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1}{\rho_o}\frac{\partial P}{\partial y}+\frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right)+F_v \quad (2)$$

$$\frac{\partial P}{\partial z}=-\rho g \quad (3)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial z}\left(K_h\frac{\partial T}{\partial z}\right)+F_T \quad (5)$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial z}\left(K_h\frac{\partial S}{\partial z}\right)+F_S \quad (6)$$

$$\rho=\rho(T,S) \quad (7)$$

where x, y, and z are the east, north, and vertical axes in the Cartesian coordinate; u,v and w are the x, y, z velocity components; T is the potential temperature; S is the salinity; ρ is the density; P is the pressure; f is the Coriolis parameter; g is the gravitational acceleration; K_m is the vertical eddy viscosity coefficient; and K_h is the thermal vertical eddy diffusion coefficient. Here, F_u, F_v, F_T, and F_S represent the horizontal momentum, thermal, and salt diffusion terms[3].

2.2 Estimation of tidal stream energy

The fluid swept through the plane of unit area by a flow speed of U has a mass of $M=\rho U$, in which ρ is the density of seawater and is generally assumed to be about 1025 kg/m^3; U is the horizontal component of the flow velocity normal to the plane in m/s; and M is the mass of seawater in kg. Therefore, the instantaneous maximum fluid power $P_{\max}$ is given by

$$P_{\max}=\frac{1}{2}MU^2=\frac{1}{2}\rho U^3 \quad (8)$$

This quantity of $P_{\max}$ represents the flow of kinetic energy per square meter of turbine aperture due to the tidal stream[4].

Using the time integral, the potential mean power ($\bar{P}$) over an arbitrary period (T) can be expressed as

$$\bar{P}=\frac{\rho}{2T}\int_{t_0}^{t_0+T}\int_0^L\int_{-H}^0 U^3\mathrm{dydzdt} \quad (9)$$

Over a full spring–neap tide cycle, T is usually equated to 15.5 days, and for a mean spring tide cycle in the estuary, T is generally equated to 12.4 *h*. What's more, t_0 is initial time (*s*), and $L(y)$ is section width(*m*); $H(z)$ is section depth(*m*)[5].

3 NUMERICAL MODEL AND SETTINGS

3.1 Study domain and grid generation

The hydrodynamic processes in the Yangtze Estuary and Hangzhou Bay are highly complex due to the irregular land boundaries, the extraordinarily uneven bed topography and the extremely high tidal range.

The total study domain was divided into 10222 unstructured triangular cells in plane and 6 layers in vertical, with the minimum grid resolution of 200 *m* in the inner Hangzhou Bay and the maximum grid resolution of 5 *km* between each of 45 open boundary nodes (see Fig.1). All these grids are established and modified with the implementation of SMS (surface-water modeling system) version 9. 0, which is of great function for quality control and grid adjustment, being easily transformed grid information to the input file of the FVCOM[6].

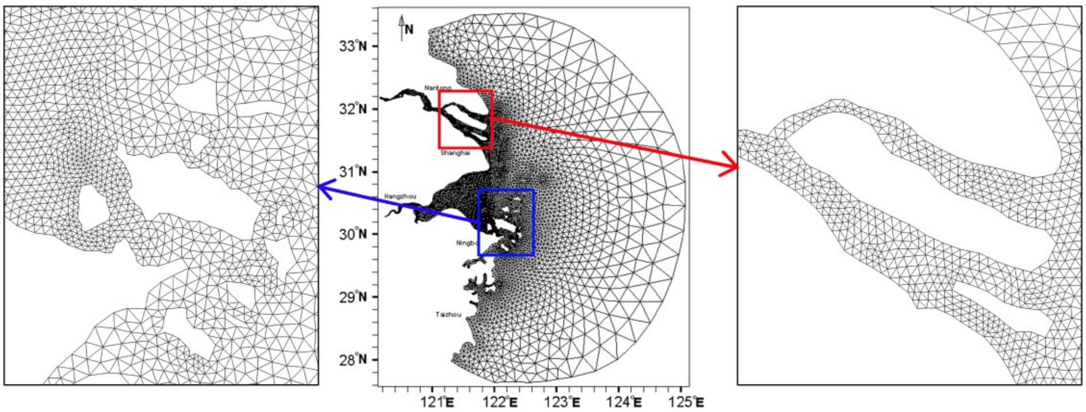

Figure.1 Mesh definition of computational domain

3.2 Initial field and boundary conditions

The initial patterns of current velocity and elevation respond to the dynamic force quickly,so they are set to zero value. The model is drivan by elevation at open boundary with the prediction of eight main pattial tides S_2, M_2, N_2 , K_2 , K_1 , P_1 , O_1 and Q_1, whose harmonic constants are downloaded from OSU tidal data inversion. Prediction using the T-TIDE MATLAB software package by Pawlowicz et a1. (2002) provides water level time series for 92 *d* from July 1st, 2014 to September 30*th*, 2013 (Greenwich time)[7]. The Changjiang runoff is specified by a parameter of 20000 m^3/s on behalf of runoff during dry season. Wind field from WRF provides surface momentum input, whose update data are available at every integral time point. The sponge boundary condition serves as a function reducing and absorbing the energy diverting from inner region[8].

4 RESULTS AND ANALYSIS

4.1 Harmonic analysis

In harmonic analysis, The phase of M_2 ranges from 240° to 360° through the southeast area to the northwest area, which illustrates the propagation direction of M_2. Amplitude is increasing as the tide bulge goes offshore, especially near the summit of the Hangzhou Bay,which can be up to 1.5-2.0 *m* (see Fig.2). By comparison and verification, the maximum absolute error of amplitude is 7 *cm*, and the tidal epoch's maximum absolute error is 20° .

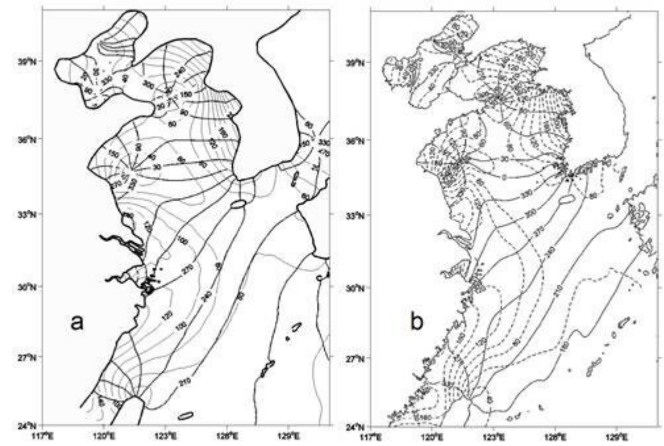

Figure.2 Cotidal chart and isc-amplitude line of M_2 (a is simulation results for the model and b is the measured results from Jiliang Xuan et al., 2014)

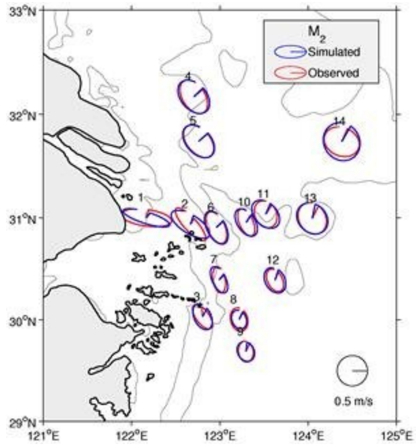

Figure.3 Distribution of M_2 ellipse in East China Sea

We can draw a current ellipse distribution map of M_2 (see Fig.3) after the harmonic analysis with currentvelocity, which showing a strong trend of reverse current.

4. 2 Current flow rate verification

China's coastal physical oceanography and marine meteorological special investigation on the East China Sea has finished a journal in the Yangtze Estuary and Hangzhou Bay and its adjacent seas for a comprehensive marine survey, from 18th August, 2014 to 5 th September, 2014. Measured tide level hydrograph and velocity using an acoustic Doppler current profiler(LADCP). The model simulation time for the validation of tidal currents was for a period of about 90 h, commencing at 5:30 pm on 17th August, 2014 and finishing at 11:30 am on 21th August, 2014. The hydrodynamic results show that the correlations between the predicted and measured data were relatively good.

5 ESTIMATION OF TIDAL CURRENT

5.1 The possible maximum flow rate

Velocity is the key factor in site selection of tidal current energy power station, which can determine current density[9]. Besides, a mean spring peak tidal current of at least 2 *m/s* is required for tidal current power exploitation.

The results show that rectilinear is the main feature of the tidal current and the maximal value of the possible maximum velocity of the tidal current reaches 3.0-3.5 *m/s* at Hangzhou Bay(see Fig.4-5).

As can be seen from the figures, the place with large reserves of tidal current energy located in Zhoushan Islands and North Port of Yangtze river estuary[10]. So we choose those seven channels to estimate tide current energy of Yangtze Estuary and Hangzhou Bay(see Fig.6). The results are showed in table 1. According to the computational results, the area where power density larger than 10kW/m^2 are mainly distributed over North Port of Yangtze Estuary(10.33 kW/m^2) and south of Hangzhou Bay(28.79 kW/m^2).

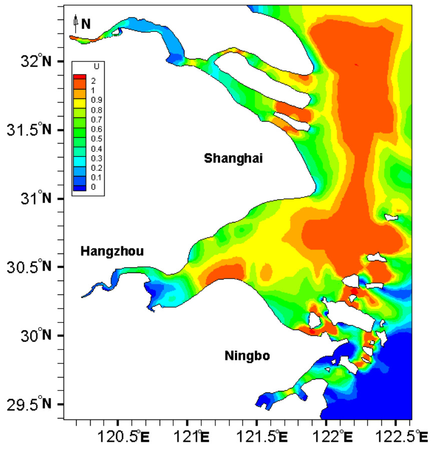

Figure.4 Distribution of horizontal velocity u during flood tide

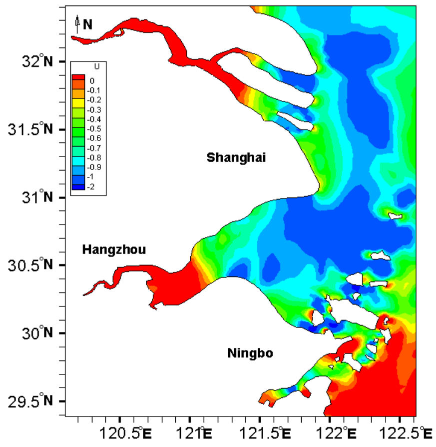

Figure.5 Distribution of horizontal velocity u during ebb tide

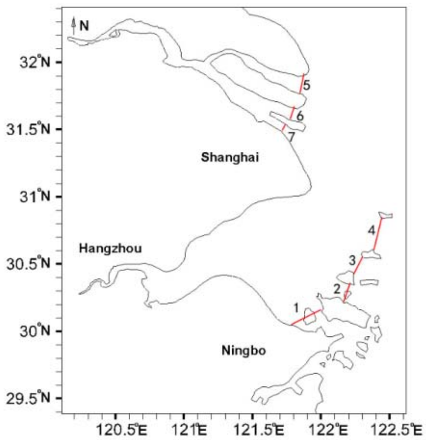

Figure.6 Distribution of calculated channels

Table.1 Reserves of tidal current energy in every channels

Water Channel		Average power In theory（MW）
1	Zhenhai-Zhoushan	64.23
2	Zhoushan-Daishan	455.26
3	Daishan-Qushan	129.15
4	Qushan-Shengsi	725.22
5	North Port	34.19
6	North Trough	87.67
7	South Trough	79.22

6 CONCLUSIONS

According to the related study, not all of this power can be converted in practice due to the Betz limit and many other potential losses in the power extraction such as hydrodynamic losses, transmission losses, and generator losses[11]. As a result, we should take effective impact factors of environment into consideration (SIF)[12]. The value of SIF varies with the current exchange way, and tidal current energy which can be developed in Yangtze Estuary-Hangzhou Bay attains to 700 *MW* when SIF is 20%.

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