Journal of
Marine Science and Technology

Volume 23 | Issue 6 Article 15

EVALUATION OF TIDAL STREAM ENERGY AROUND RADIAL SAND RIDGE SYSTEM IN THE SOUTHERN YELLOW SEA

Jinhai Zheng
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing. College of Harbor Coastal and Offshore Engineering, Hohai University, Nanjing., jhzheng@hhu.edu.cn

Jisheng Zhang
College of Harbor Coastal and Offshore Engineering, Hohai University, Nanjing.

Jun Wang
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing. College of Harbor Coastal and Offshore Engineering, Hohai University, Nanjing.

Aifeng Tao
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing. College of Harbor Coastal and Offshore Engineering, Hohai University, Nanjing.

Recommended Citation
Zheng, Jinhai; Zhang, Jisheng; Wang, Jun; and Tao, Aifeng (2015) "EVALUATION OF TIDAL STREAM ENERGY AROUND RADIAL SAND RIDGE SYSTEM IN THE SOUTHERN YELLOW SEA," *Journal of Marine Science and Technology*: Vol. 23: Iss. 6, Article 15.
DOI: 10.6119/JMST-015-0610-14
Available at: https://jmstt.ntou.edu.tw/journal/vol23/iss6/15

EVALUATION OF TIDAL STREAM ENERGY AROUND RADIAL SAND RIDGE SYSTEM IN THE SOUTHERN YELLOW SEA

Acknowledgements

This research work is financially supported by the National Science Fund for Distinguished Young Scholars (51425901), the National Natural Science Foundation of China (51479053, 51137002), the 111 Project (B12032), and the Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20130094110014).

DOI: 10.6119/JMST-015-0610-14

EVALUATION OF TIDAL STREAM ENERGY AROUND RADIAL SAND RIDGE SYSTEM IN THE SOUTHERN YELLOW SEA

Jinhai Zheng[1, 2], Jisheng Zhang[2], Jun Wang[1, 2], and Aifeng Tao[1, 2]

Key words: tidal stream energy, radial sand ridge system, numerical model, candidate sites.

ABSTRACT

Tidal stream energy as a new type of marine renewable energy attracts more and more attention of coastal engineers due to its advantages of great power density, long-term predictability and low environment impact. The radial sand ridge (RSR) system is located in the southern Yellow Sea off the Jiangsu coast, China, and it is characterized by a radial current field. The exploitation of tidal stream energy in the RSR system means great significance to the local industry and ecosystem of this region. In this study, a two-dimensional depth-averaged hydrodynamic model was established to predict one-year tidal hydrodynamics in the RSR system. The numerical results including water elevation and tidal current (speed and direction) were validated by the measured data, showing a reasonable agreement between simulation and measurement. Then, the validated model was applied to evaluate the tidal stream energy resources of the whole region with a concept consisting of total operating time (TOT), dispersion of operating time (DOT) and mean operating time (MOT), aiming to reveal the periodic interrupted working condition of tidal stream turbine. The distributions of TOT, DOT and MOT around the RSR system in one-year period are investigated, providing useful guide maps for the exploitation of tidal stream energy in this coastal area.

I. INTRODUCTION

In response to the enormous consumption of fossil fuel energy and its resulted environmental pollutions, marine renewable energy are favored by many countries as a great potential solution to offer clean and sustainable energy. Ocean makes up 71% of the earth's surface, and it supplies different forms of renewable energy with a total amount more than $2*10^3$ TW, including tide, wave, tidal stream, thermal, salinity gradients and biomass (Charlier and Finkl, 2009). Among these, tidal stream energy (water movements caused by forces of gravity between the sun, the moon and the earth) catches more and more attentions due to its advantages of the high energy density, long-time predictability and potentially large resource. Nowadays, tidal stream energy is yet a largely untapped resource with no commercial size application, although some demonstration projects are very close.

Energy potential needs to be accurately determined prior to the exploitation of tidal stream energy, and many efforts have been devoted to this challenge all over the world in recent years. For example, numerical simulations or direct measurements have been carried out for the estimation of tidal stream resources around the UK (Easton et al., 2012; Draper et al., 2014), USA (Define et al., 2012; Yang et al., 2013), Spain (Carballo et al., 2009; Ramos et al., 2013), Portugal (Pacheco et al., 2014), New Zealand (Stevens et al., 2012) and Iran (Rashid, 2012). As reviewed by Liu et al. (2011), the mainland China, with over 18000 km shorelines and thousands of islands, has abundant tidal stream energy resources, and the large-scale distribution of tidal stream energy was investigated by the Coastal and Rural Ocean Energy Resource Investigation (Wang et al., 2011). However, such a large-scale investigation cannot provide accurate details for energy assessment when an engineering project of tidal stream farm is designed in specific coastal area.

The radial sand ridge (RSR) system is located in the southern Yellow Sea off the Jiangsu coast, China. Significant rectilinear currents are formed in the northern RSR area, whereas rotary currents prevail in the southern RSR area. The transition between these two different currents is dominated by a locally generated trapped wave (Chen et al., 2009; Xing et al., 2011; Zhang et al., 2013a). The previous studies show a maximal tidal current velocity around the RSR system to be more than 2.5 m/s, indicating a promising potential of tidal stream energy in this coastal region. The assessment of tidal stream energy in this coastal area is still very limited. For

Paper submitted 12/12/14; Revised 02/02/15; Accepted 06/10/15. Author for correspondence: Jinhai Zheng (e-mail: jhzheng@hhu.edu.cn).
[1]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing.
[2]College of Harbor Coastal and Offshore Engineering, Hohai University, Nanjing.

example, Zhang et al. (2013b) proposed a new concept with three parameters (total operating time (TOT), dispersion of operating time (DOT) and mean operating time (MOT)) and applied their methods to analyze the TOT, DOT and MOT at three water channels during a relatively short period (72-hour). This study is to apply a two-dimensional depth-averaged hydrodynamic model with a more recent bathymetry to numerically evaluate the distribution of tidal stream resource around the whole RSR system mainly based on the concept of Zhang et al. (2013b) in one-year period.

II. HYDRODYNAMIC MODEL

1. Governing Equations

A two-dimensional depth-averaged model, based on the MIKE21 FM package, is developed to simulate the tidal hydrodynamics around the RSR system in the southern Yellow Sea. The incompressible Reynolds-Averaged Navier-Stokes (RANS) equations can be written as below:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=hS \tag{1}$$

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial h\bar{u}^2}{\partial x}+\frac{\partial h\overline{uv}}{\partial y}=f\bar{v}h-gh\frac{\partial \eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y}\right)+\frac{\partial}{\partial x}(hT_{xx})+\frac{\partial}{\partial y}(hT_{xy})+hu_sS \tag{2}$$

$$\frac{\partial h\bar{v}}{\partial t}+\frac{\partial h\bar{v}^2}{\partial y}+\frac{\partial h\overline{uv}}{\partial x}=-f\bar{u}h-gh\frac{\partial \eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)+\frac{\partial}{\partial x}(hT_{xy})+\frac{\partial}{\partial y}(hT_{yy})+hv_sS \tag{3}$$

where (x, y) are horizontal Cartesian co-ordinates; t is time; η is surface elevation; d is still water depth; $h = \eta + d$ is total water depth; u and v are velocity components in x and y directions; f is the Coriolis parameter ($f = 2\Omega\sin\phi$, in which Ω is angular rate of revolution and ϕ is geographic latitude); g is gravitational acceleration; ρ is density of water; S_{xx}, S_{xy}, S_{yx}, and S_{yy} are components of radiation stress tensor; p_a is atmospheric pressure; ρ_0 is reference density of water; S is magnitude of discharge due to point sources; (u_s, v_s) is velocity by which water is discharged into the ambient water; T_{ij} are lateral stresses including viscous friction, turbulent friction and differential advection; and over-bar indicates a depth-averaged value.

2. Computational Domain and Conditions

In the study, a computational domain covering the Jiangsu coast and its adjacent ocean areas is adopted with a distance of 394 km in longitude from east (123°29′35″E) to west (119°12′11″E) and a distance of 503 km in latitude from south (31°0′47″N) to north (35°29′48″N). The Beijing geodetic coordinate system 1954 is used in this study. A set of non-overlapping unstructured triangular grids are implemented in the domain, with a great ability to capture the complex coastline. Various grid sizes are carefully tested and the independency of numerical solutions on grid size is achieved in the simulation. The final mesh adopted in the simulation has 146603 nodes and 289674 elements, and the smallest grid in the coastline is about 20 m.

Time-dependent water surface elevation is clamped along open-sea boundaries (southern, eastern and northern boundaries of the computational domain), which is imposed as the main driving force of the hydrodynamic model. Flow discharge from the Yangtze River is provided by a long-term averaged discharge at the Xuliujing Station. At sea bottom, bottom shear stress induced by bottom friction is non-uniformly specified, and the coefficient of bottom roughness varies from 0.015 to 0.02. At sea surface, wind stress, surface net heat and moisture flux can be imposed but they are not considered in the simulation. Initial surface elevation is set as 0 m with zero velocity, and a spin-up period of 2-day is adopted to avoid the influence of initial conditions. The hydrodynamic model runs from 01/November/2009 to 31/October/2010 with a time step as 30-second.

III. ASSESSMENT METHODS OF TIDAL STREAM ENERGY

In the past years, traditional method of kinetic energy density was extensively used to assess the tidal stream energy. However, in the practical engineering application, the extraction of tidal stream energy is highly dependent on the operation abilities/parameters of tidal stream turbine, such as, cut-in speed, rated output flow speed and cut-out speed. The speed at which the tidal stream turbine starts to rotate and generate power is called the cut-in speed. As the flow speed rises above the cut-in speed, the level of electrical output level of tidal stream turbine rapidly rises and may reach the output limit. When the limit of turbine output is achieved, the flow speed at which it is reached is referred as rated output flow speed of turbine. Even though the flow speed is further increased, the output power remains this maximum level. There is a risk of damage to the turbine due to the extremely large force on the turbine structure when the flow speed increases above the rated output flow speed. When the cut-out speed of turbine is reached, a braking system is applied to bring the turbine rotor to a standstill. In this study, the cut-in speed, rated output flow speed and cut-out speed are taken as 1.3 m/s, 3.5 m/s and 4.5 m/s for an example (Benelghali et al., 2010).

The concept proposed by Zhang et al. (2013b) is employed to consider the influences of the operation ability of tidal stream turbine on the assessment of tidal stream energy in

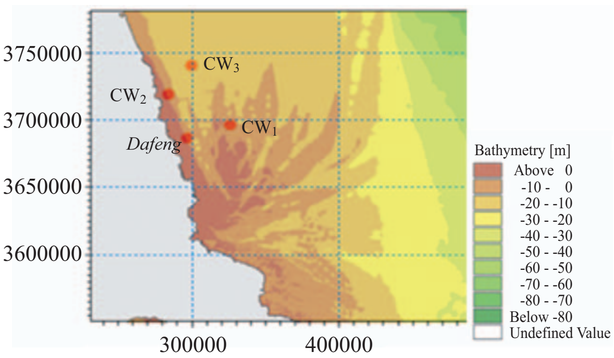

Fig. 1. Locations of stations for the measurement of water elevation.

terms of TOT, DOT and MOT. TOT is defined as the sum of operating time over a given period, indicating the duration of effective operation of tidal stream turbine:

$$\text{TOT} = \int_0^T P(V_t)dt,\ P(V_t) = \begin{cases} 0, V_t < 1.3 \\ 1, 1.3 \le V_t \le 4.5 \\ 0, V_t > 4.5 \end{cases} \tag{7}$$

where V_t is magnitude of current velocity and T is a given period. DOT is used to account the interruption number of turbine performance during a given period, which is calculated by counting the status shift from power-off (with a current velocity below 1.3 m/s or above 4.5 m/s) to power-on (with a current velocity between 1.3 m/s and 4.5 m/s) of tidal stream turbine:

$$\text{DOT} = \sum Q(V_t, t)(0 \le t \le T)$$

$$Q(V_t, t) = \begin{cases} 1, \lim\limits_{\delta \to 0} P(V_{t-\delta}) < \lim P(V_{t+\delta}) \\ 0, \textit{others} \end{cases} \tag{8}$$

MOT is defined as the ratio of TOT to DOT, indicating the average operating time of turbine in one continuous operation duration. It is noted that TOT is the most important indicator within this new concept concerning the operation process of tidal stream turbine as it is directly related to the total amount of electricity output.

IV. RESULTS AND DISCUSSION

1. Validation of Hydrodynamic Model

The numerical results of hydrodynamic model are compared with data of field measurement around the RSR system in the southern Yellow Sea, aiming to check numerical accuracy of the model. During November-December/2009, water surface elevation were measured by the WFH-2 Absolute Machinery Code water level meter at the Dafeng station (121°7′32″E, 33°22′49″N) and three temporary stations, CW$_1$ (121°7′32″E, 33°22′49″N), CW$_2$ (120°40′33″E, 33°34′35″N) and CW$_3$ (120°50′18″E, 33°46′14″N) (Fig. 1). Fig. 2 shows the comparison between simulated water elevation and measured data at these four stations. As listed in Table1, the maximal values of mean absolute error (MAE = 0.21 m) and root mean square error (RMSE = 0.26 m) can be identified at station CW$_2$, with a relatively small coefficient of determination (R^2 = 0.972).

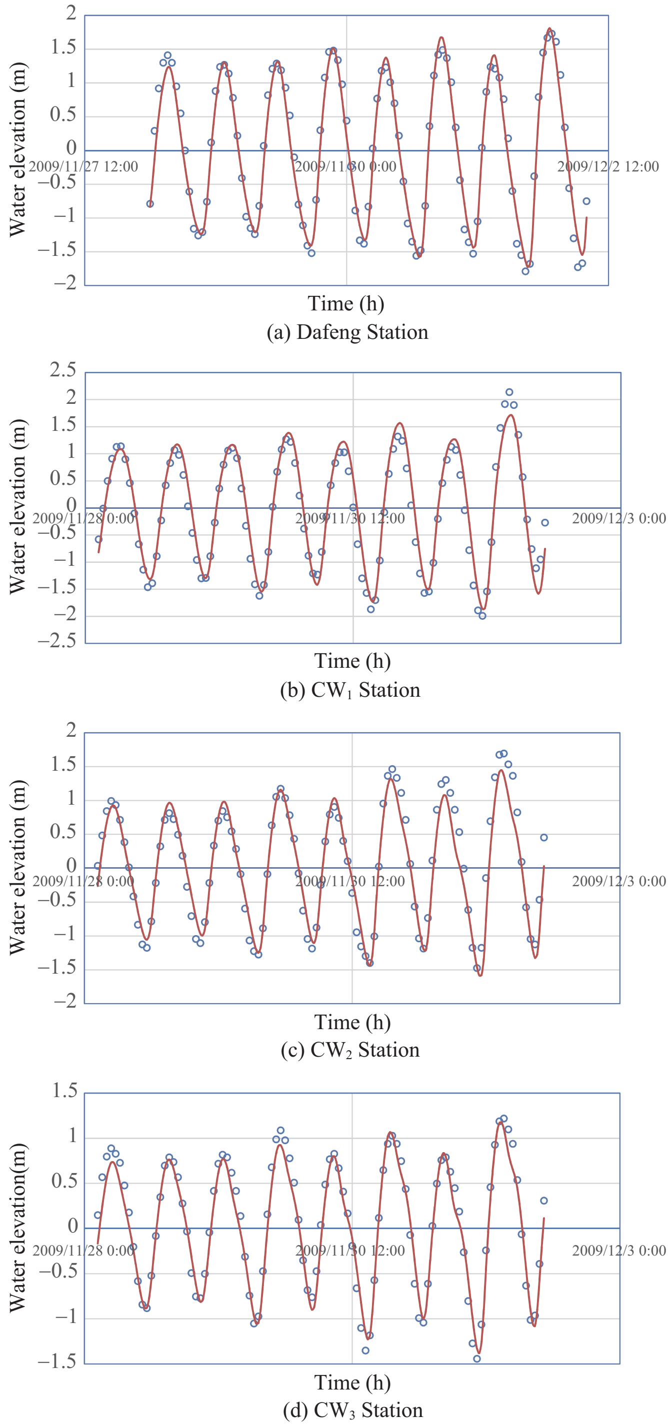

Fig. 2. Comparisons of simulated water elevation and measured data.

Table 1. Statistical error of the difference between simulated and observed water elevation.

	Dafeng	CW_1	CW_2	CW_3
MAE (m)	0.16	0.21	0.17	0.12
RMSE (m)	0.19	0.26	0.23	0.15
R^2	0.986	0.972	0.979	0.987

Note: MAE = mean absolute error, RMSE = root mean square error, R^2: coefficient of determination.

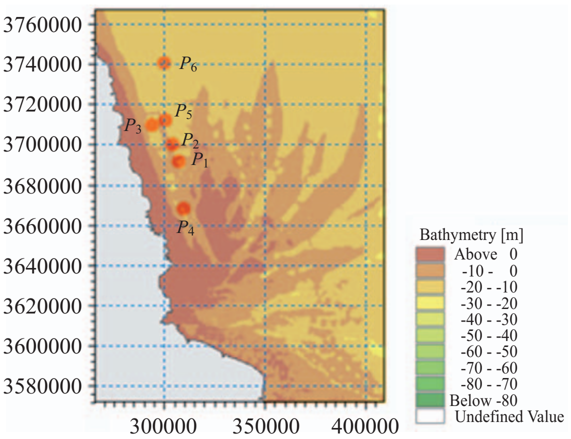

Fig. 3. Locations of stations for the measurement of tidal current.

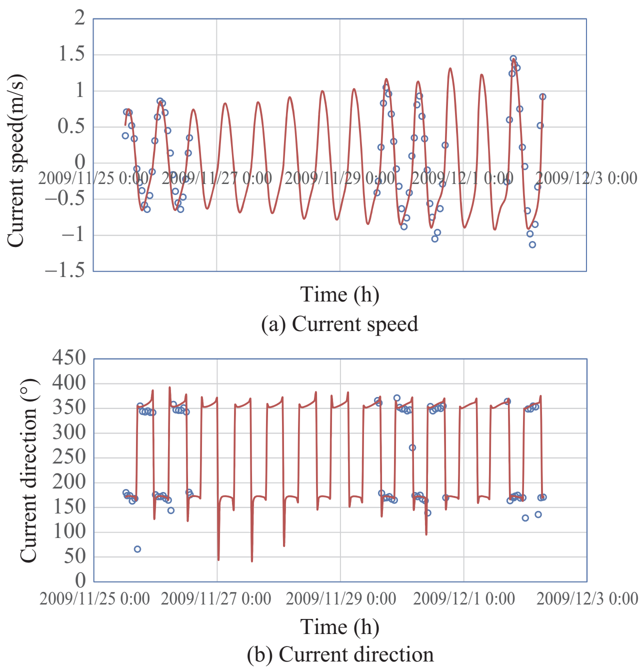

Fig. 4. Comparisons of simulated and measured depth-averaged current at P_2 station.

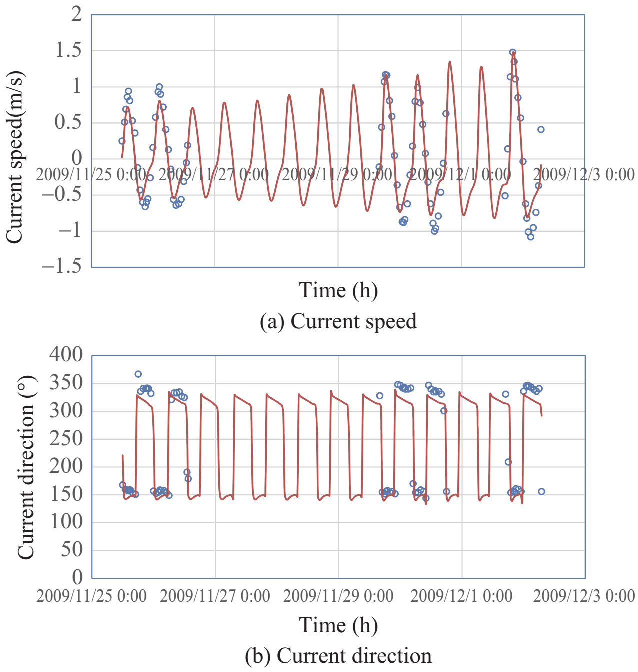

Fig. 5. Comparisons of simulated and measured depth-averaged current at P_4 station.

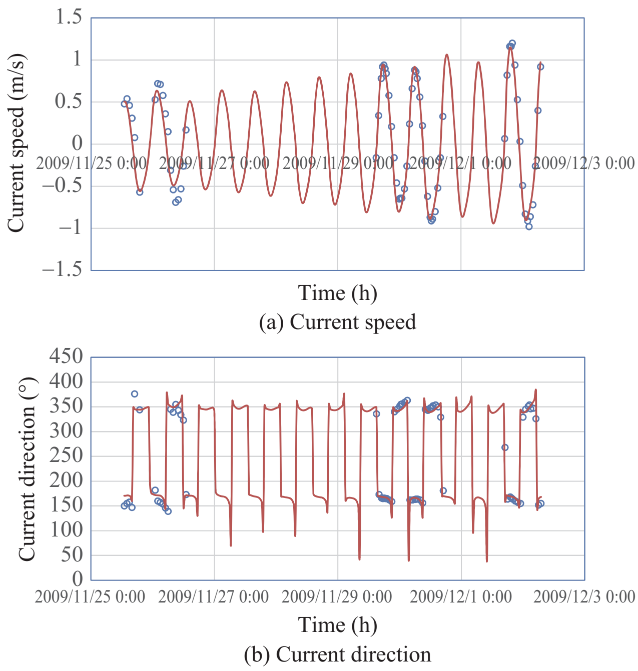

Fig. 6. Comparisons of simulated and measured depth-averaged current at P_6 station.

The flow currents were also measured by the ADCP (Acoustic Doppler Current Profiler) at six temporary stations, P_1 (120°55′44″E, 33°20′4″N), P_2 (120°53′50″E, 33°24′41″N), P_3 (120°46′44″E, 33°29′35″N), P_4 (120°57′34″E, 33°7′12″N), P_5 (120°51′4″E, 33°31′11″N) and P_6 (120°50′18″E, 33°46′14″N) between 12:00 25/November/2009 and 7:00 2/December/2009, and locations of these stations are shown in Fig. 3. Figs. 4-6 demonstrate the comparisons of depth-averaged tidal current between numerical simulation and field measurement at P_2, P_4 and P_6 stations, respectively. Table 2 lists mean absolute

Table 2. Statistical error of the difference between simulated and observed tidal current.

	P_1	P_2	P_3	P_4	P_5	P_6
Current Velocity						
MAE (m/s)	0.13	0.15	0.19	0.19	0.17	0.11
RMSE (m/s)	0.16	0.2	0.24	0.23	0.21	0.14
R^2	0.880	0.830	0.766	0.819	0.820	0.885
Current Direction						
MAE (°)	24.8	27.7	24.2	26.3	18.2	18.7
RMSE (°)	53.4	68.6	49.6	45.1	47.9	44.9
R^2	0.860	0.765	0.841	0.868	0.855	0.884

Note: MAE = mean absolute error, RMSE = root mean square error, R^2: coefficient of determination.

error, root mean square error and coefficient of determination at each station. It can be seen from the comparisons that the current peak and phase were faithfully reproduced by the model, although there are still some discrepancies in flow speed and current direction.

The differences between numerical simulation and field measurement are due to several reasons. The bathymetry around the RSR system consisting of tens of radial tidal channels is extremely complex, and it is difficult to be exactly presented in the computational domain. Meanwhile, a large amount of suspended sediment supplied by the Yangtze River to the RSR system (especially in the southern RSR area) may lead to a significant deposition (or erosion) within one tidal period, which is not considered in the hydrodynamic model. Although the coefficient of bottom roughness varies in space in the simulation, it does not change during the tidal cycle. The ignore of the impacts of flow acceleration and non-constant stress in tidal estuary on the specification of bottom shear stress may also be one of the reasons.

2. Assessment of Tidal Stream Energy

In this study, the numerical results between 01/November/2009 and 31/October/2010 (one-year) from hydrodynamic model are taken for the evaluation of tidal stream energy around the RSR system. Owing to the existence of cut-in speed, rated output flow speed and cut-out speed, tidal stream turbine will be periodically interrupted during its operation process. Such a kind of discontinuous operating condition obviously affects the power output of tidal stream turbine in practical application.

Figs. 7-9 show the distributions of TOT, DOT and MOT around the RSR system in one-year period, and the values of these three parameters in southern RSR area are generally greater than those in northern RSR area. It can be seen from Fig. 7 that the values of TOT in the vicinity of Huangshayang Channel, Xiaoyangkou Channel and Lanshayang Channel are between 2500-hour and 5000-hour. High values of TOT (more than 5000-hour) can also be identified at the Xiaomiaohong Channel and the entrance of North Branch of the Yangtze Estuary. As one can expect, the coastal area with a higher

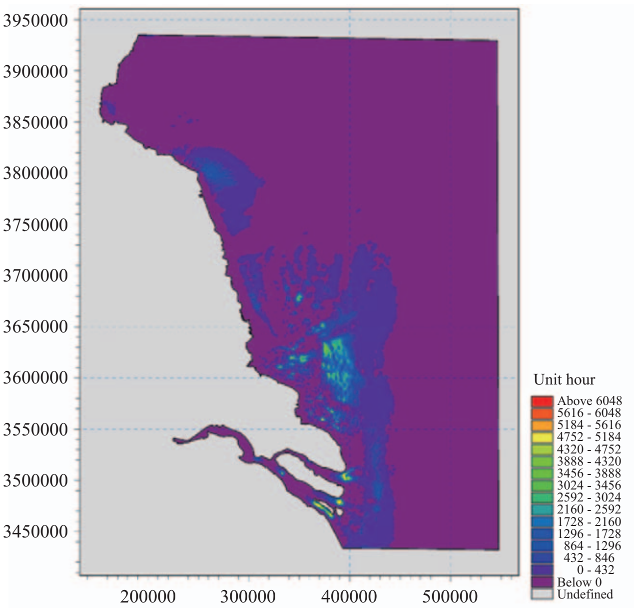

Fig. 7. Distribution of total operating time (TOT).

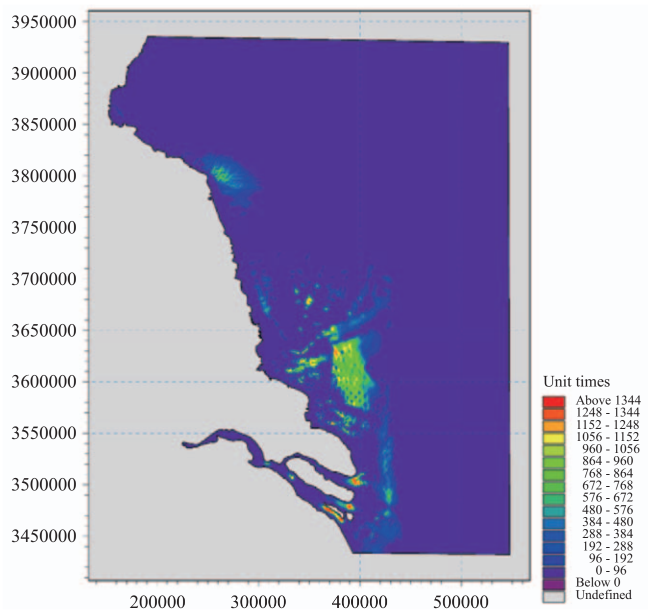

Fig. 8. Distribution of dispersion of operating time (DOT).

value of TOT is normally with more chance to be dispersed during the turbine operation (see Fig. 8). As shown in Fig. 9, the mean value of operation time, MOT, is generally in a range between 1.5 hour and 3.5 hour. It means that the tidal stream turbine with a cut-in speed being 1.3 m/s may averagely continue to work for 1.5-3.5 hour after it is switched-on by the tidal current.

A site (121°39′21″E, 32°9′29″N) with promising energy at Xiaomiaohong Channel is taken as an example to demonstrate the exploitation potential of tidal stream energy. The values of TOT, DOT and MOT in one-year period are 6336-hour, 1416

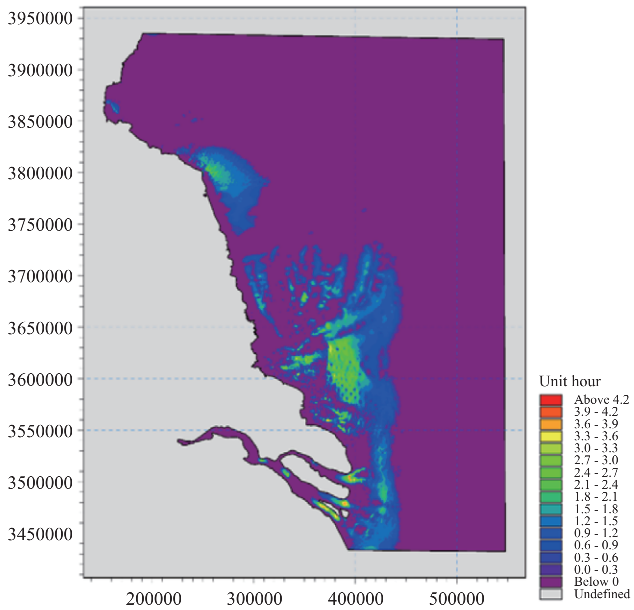

Fig. 9. Distribution of mean operating time (MOT).

and 4.47-hour at this site. If the generator SeaGen S (with a diameter of 16 m and a swept area of 402 m^2) was adopted to convert tidal stream energy to electricity power, the average power and annual energy output in the Xiaomiaohong would be roughly 566.7 kW and 4.96 GWh. It is worthy to mention that site selection for large-scale tidal stream farm is also dependent on the large-scale ocean space-use plan around the RSR system which aims to achieve a well balance between exploitation of ocean resources and environmental protection.

V. CONCLUSIONS

A two-dimensional depth-averaged hydrodynamic model was developed to simulate tidal hydrodynamics, and the concept of Zhang et al. (2013b) is adopted to evaluate tidal stream energy in one-year period around the RSR system in the southern Yellow Sea. The numerical results from hydrodynamic model generally agree with the data from field measurement during November-December/2009, indicating that this model well predicts tidal hydrodynamics around the RSR system. The detailed distributions of TOT, DOT and MOT between 01/November/2009 and 31/October/2010 around the RSR system are given, showing that the tidal stream energies within the southern RSR area are generally greater than those within the northern RSR area. If a tidal stream turbine with a cut-in speed being 1.3 m/s is installed in the southern RSR area, it can be expected to work 2500-5000 hours per year. The final site selection for large-scale exploitation of tidal stream energy is also dependent on the large-scale ocean space-use plan around the RSR system.

ACKNOWLEDGMENTS

This research work is financially supported by the National Science Fund for Distinguished Young Scholars (51425901), the National Natural Science Foundation of China (51479053, 51137002), the 111 Project (B12032), and the Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20130094110014).

REFERENCES

Benelghali, S., M. E. H. Benbouzid and J. F. Charpentier (2010). Comparison of PMSG and DFIG for marine current turbine applications. XIX International Conference on Electrical Machines, Roma, Italy.

Carballo, R., G. Iglesias and A. Castro (2009). Numerical model evaluation of tidal stream energy resources in the Ria de Muros (NW Spain). Renewable Energy 34(6), 1517-1524.

Charlier, R. H. and C. W. Finkl (2009). Ocean Energy: Tide and Tidal Power. Springer, Berlin.

Chen, K., Y. Wang, P. Lu and J. Zheng (2009). Effects of coastline changes on tide system of Yellow Sea off Jiangsu Coast, China. China Ocean Engineering 23(4), 741-750.

Defne, Z., K. A. Haas, H. M. Fritz, L. Jiang, S. P. French, X. Shi, B. T. Smith, V. S. Nearly and K. M. Stewart (2012). National geodatabase of tidal stream power resource in USA. Renewable and Sustainable Energy 16(5), 3326-3338.

Draper, S., T. A. A. Adcock, A. G. L. Borthwick and G. T. Houlsby (2014). Estimate of the tidal stream power resource of the Pentland Firth. Renewable Energy 63, 650-657.

Easton, M. C., D. K. Woolf and P. A. Bowyer (2012). The dynamic of an energetic tidal channel, the Pentland Firth, Scotland. Continental Shelf Research 48, 50-60.

Liu, H.W., S. Ma, W. Li, H. G. Gu, Y. G. Lin and X. J. Sun (2011). A review on the development of tidal current energy in China. Renewable and Sustainable Energy Reviews 15, 1141-1146.

Pacheco, A., O. Ferreira, R. Carballo and G. Iglesias (2014). Evaluation of the production of tidal stream energy in an inlet channel by coupling field data and numerical modeling. Energy 71, 104-117.

Ramos, V., R. Carballo, M. Alvarez, M. Sanchez and G. Iglesias (2013). Assessment of the impacts of tidal stream energy through high-resolution numerical modeling. Energy 61, 541-554.

Rashid, A. (2012). Status and potentials of tidal in-stream energy resources in the southern coasts of Iran: A case study. Renewable and Sustainable Energy Reviews 16(9), 6668-6677.

Stevens, C. L., M. J. Smith, B. Grant, C. L. Stewart and T. Divett (2012). Tidal energy resource complexity in a large strait: the Karori Rip, Cook Strait. Continental Shelf Research 33, 100-109.

Wang, S., P. Yuan, D. Li and Y. Jiao (2011). An overview of ocean renewable energy in China. Renewable and Sustainable Energy Reviews 15, 91-111.

Xing, F., Y. Wang and H. Wang (2010). Tidal hydrodynamics and fine-grained sediment transport on the radial sand ridge system in the southern Yellow Sea. Marine Geology 291-294, 192-210.

Yang, Z., T. Wang and A. E. Copping (2013). Modeling tidal stream energy extraction and its effects on transport processes in a tidal channel and bay system using a three-dimensional coastal ocean model. Renewable Energy 50, 506-613.

Zhang, C., J. Zheng, X. Dong, K. Cao and J. Zhang (2013a). Morphodynamic response of Xiaolangdi tidal channel to a coastal reclamation project in Jiangsu Coast, China. Journal of Coastal Research SI65, 630-635.

Zhang, J., J. Wang, A. Tao, J. Zheng and H. Li (2013b). New concept for assessment of tidal current energy in Jiangsu Coast, China. Advances in Mechanical Engineering 2013, 340501.