Proceedings of the 2nd Marine Energy Technology Symposium
METS2014
April 15-18, 2014, Seattle, WA

ARRAY OPTIMIZATION FOR TIDAL ENERGY EXTRACTION IN A TIDAL CHANNEL – A NUMERICAL MODELING ANALYSIS

Zhaoqing Yang[1]
Pacific Northwest National Laboratory
Seattle, WA 98109, USA

Taiping Wang
Pacific Northwest National Laboratory
Seattle, WA 98109, USA

Andrea Copping
Pacific Northwest National Laboratory
Seattle, WA 98109, USA

[1]Corresponding author: zhaoqing.yang@pnnl.gov

ABSTRACT

This paper presents an application of a hydrodynamic model to simulate tidal energy extraction in a tidal dominated estuary in the Pacific Northwest coast. A series of numerical experiments were carried out to simulate tidal energy extraction with different turbine array configurations, including location, spacing and array size. Preliminary model results suggest that array optimization for tidal energy extraction in a real-world site is a very complex process that requires consideration of multiple factors. Numerical models can be used effectively to assist turbine siting and array arrangement in a tidal turbine farm for tidal energy extraction.

INTRODUCTION

The desire for new sources of renewable energy has been rising because of the growing concerns of climate change and the strong demand for global reduction of greenhouse effects from human energy consumption. Harnessing in-stream tidal energy has received attention because tides have a high degree of predictability and the energy resources are often close to coastal regions with large population centers. However, tidal turbine arrangement in a tidal farm for optimal energy output is complicated and challenging because flow diversion and wake interaction between turbines alter the efficiency of power generation by a tidal farm. A number of theoretical studies have aimed to investigate the optimal array arrangement for maximum power generation. For example, Garrett and Cummins [1] used a theoretical model to show that a tidal fence with turbines placed side-by-side in a row would increase power generation in a uniform flow condition. Vennell [2] explored different turbine arrangements to maximize energy efficiency in a confined tidal channel. More recently, Draper and Nishino [3] extended quasi-inviscid Linear Momentum Actuator Disc Theory (LMADT) to two rows of tidal turbines in an idealized tidal channel with uniform flow field and found that the staggered arrangement would generate more power than the centered arrangement.

Numerical models have been widely used to support the development of in-stream tidal energy technology and its application to energy extraction in real world sites. A tidal device module in a three-dimensional unstructured-grid coastal ocean model for simulating in-stream tidal energy extraction was developed by the Pacific Northwest National Laboratory (PNNL) to assist assessment of tidal energy resource characterization and environmental impacts [4]. This paper describes the application of the PNNL tidal turbine model to evaluate the response of extractable tidal energy to different tidal turbine arrangements in a real-world site – Tacoma Narrows, Washington, USA.

METHOD

Hydrodynamic Model with Tidal Turbine Module

The hydrodynamics model used in this study is the finite volume coastal ocean model FVCOM [5]. FVCOM is an unstructured-grid model that solves the momentum governing equations using a finite-volume method and sigma-stretch coordinate transformation in the vertical direction. To simulate the effect of tidal energy extraction, a momentum sink approach was used to develop the tidal turbine module. The momentum governing equations for Reynolds-averaged turbulent flows with momentum sink terms due to energy extraction have the following general form:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_o}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) + F_x - F_x^M \qquad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_o}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) + F_y - F_y^M \qquad (2)$$

where (x, y, z) are the east, north, and vertical axes in the Cartesian coordinates; (u, v, w) are the three velocity components in the x, y, and z directions; (F_x, F_y) are the horizontal momentum diffusivity terms in the x and y directions; K_m is the vertical eddy viscosity coefficient; ρ is water density; p is pressure; and f is the Coriolis parameter. $\overrightarrow{F^M}$ = (F_x^M , F_y^M) are the added momentum sink terms corresponding to energy extraction that can be defined as follows:

$$\overrightarrow{F^M} = \frac{1}{2}\frac{C_e A}{V_c}|\vec{u}|\,\vec{u} \qquad (3)$$

where V_c is a control volume, C_e is momentum extraction coefficient, A is the flow-facing area of the turbines, or turbine swept area, and $\vec{u}$ is the velocity vector. Details on the tidal turbine module are given in [4].

Study Site – Tacoma Narrows, WA

Tacoma Narrows is a narrow strait with an approximate length of 9,000 m and width of 2,000 m. It is located in the southern basin of Puget Sound, WA (Figure 1). It is the only passage that connects the complex, multi-branch South Puget Sound to the Main Basin of Puget Sound. The average water depth in Tacoma Narrows is 35 m with the deepest portion over 75 m. Tidal currents in Tacoma Narrows are extremely strong because of the narrow channel width, relatively shallow depth, and the force of the water in large basins behind the sill. Tidal amplitudes for the dominant principal semi-diurnal tide M_2 and principal diurnal tide K_1 in Tacoma Narrows are approximately 1.2 m and 0.8 m, respectively [8]. The maximum tidal range can be as large as 4.5 m in Tacoma Narrows [7]. The average tidal channel power in Tacoma Narrows is over 100 MW [6]. Average maximum currents at flood tide and ebb tide are 2.2 m/s and 1.7 m/s respectively, and the maximum instantaneous flood current could be as high as 3.5 m/s near Pt. Evans in Tacoma Narrows according to NOAA observations [6]. Based on these attributes, Tacoma Narrows is considered as an ideal region for tidal energy production [6].

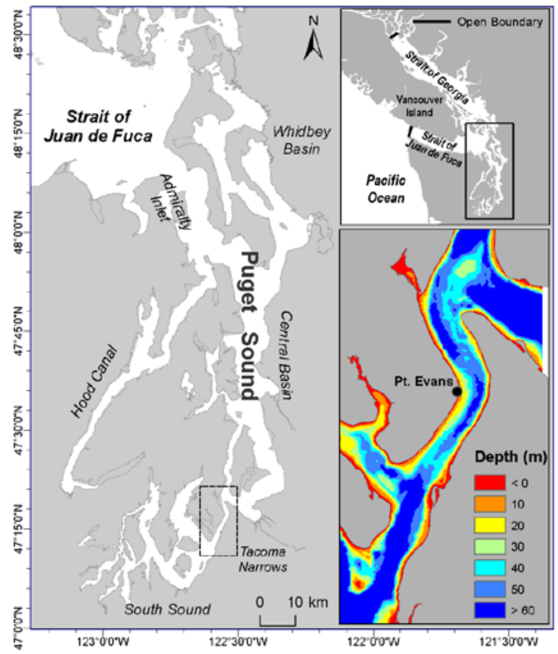

FIGURE 1. PUGET SOUND AND TACOMA NARROWS

Model Configuration

This study was based on an unstructured-grid coastal ocean model of Puget Sound from a previous study [7], with further refinement of the Tacoma Narrows region. The model grid covers the entire Salish Sea (Figure 1). The Salish Sea consists of Puget Sound, Strait of Juan de Fuca and the Strait of Georgia (the latter is not shown, but connects northern Puget Sound to the coast of British Columbia) (Figure 1). The model element size varies from approximately 200 m in the sub-basins of Puget Sound to 30 m in the more detailed area around Tacoma Narrows (Figure 2). The model consists of about 228,000 elements with 125,000 nodes in the horizontal plane. Ten vertical layers of uniform thickness were specified in the water column in a sigma-stretched coordinate system. The bottom friction is described by the quadratic law with the drag coefficient determined by the logarithmic bottom layer as a function of bottom roughness. A bottom friction coefficient of 0.0025 and a bottom roughness of 0.001 m were used in the model. The Smagorinsky multiplicative coefficient was set to

0.2, and a background value of vertical eddy viscosity of 10−6 m^2/s was used.

Open boundary conditions for the model were specified at the entrance of the Strait of Juan de Fuca and the north end of the Strait of Georgia using eight harmonic tidal constituents (S2, M2, N2, K2, K1, P1, O1, and Q1). The dominant tidal constituents in Puget Sound are the principal semi-diurnal tide M2 and principal diurnal tide K1. The Puget Sound hydrodynamic model has been validated with observations, including spatial distribution of M2 and K1 tides [8] and eight tidal constituents (S2, M2, N2, K2, K1, P1, O1, and Q1) at specific locations throughout Puget Sound [7]. River inflows as well as density-induced and wind-driven currents were not considered in this study.

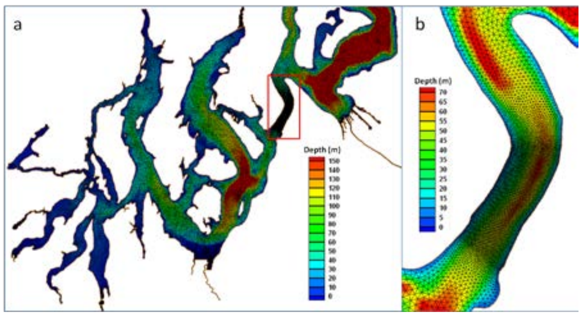

FIGURE 2. MODEL GRID AND BATHYMETRY IN (A) SOUTH PUGET SOUND AND (B) TACOMA NARROWS

A series of model simulations were conducted by deploying a tidal turbine farm in Tacoma Narrow with a varying number of turbines and different layouts. The location of the tidal turbine farm was selected based on the simulated distributions of depth-averaged maximum tidal current and power density over a spring-neap tidal cycle under baseline condition, i.e., without the presence of tidal turbines. The depth-averaged maximum velocity in Tacoma Narrows is shown in Figure 3. It can be seen that a high velocity region exists southwest of Pt. Evans in Tacoma Narrows, with a maximum velocity greater than 3.5 m/s. Water depths corresponding to this region are generally greater than 60 m (Figure 1). In this study, model simulations with tidal turbine farms were designed by deploying tidal turbines in a high tidal current area downstream of the Pt. Evans.

Turbine configurations were based on the Marine Current Turbine's SeaGen turbine [6], which has dual rotors with a diameter of 18 m and rotor tip to tip spacing of 46 m [6]. Turbines were deployed 30m below the sea surface. The turbine thrust coefficient was specified as 0.5 for all model runs. For simplicity, energy dissipated by the turbine foundation and supporting structure was not considered in this study.

Two sets of experiments with four different turbine layouts were simulated in the model. The first set of experiments has 6 turbines, representing a small commercial scale tidal farm, and the second set consists of 36 turbines, presenting a large commercial scale tidal farm. Each set of the experiments consists of centered, staggered, lateral and longitudinal arrangements of turbines. Array configurations for all the simulation cases are listed in Table 1. Examples of turbine layouts for Case 1 (centered 6-turbine), Case 2 (staggered 6-turbine) and Case 5 (centered 36-turbine) are shown in Figure 3.

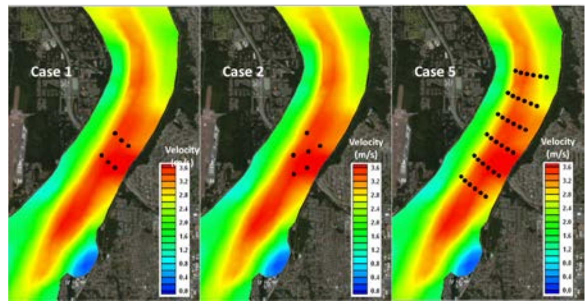

FIGURE 3. TURBINE ARRAY LAYOUTS FOR CASE 1 (CENTERED) AND CASE 3 (STAGGERED) WITH 6 TURBINES AND CASE 5 (CENTERED) WITH 36 TURBINES. COLOR CONTOURS REPRESENT THE DEPTH-AVERAGED MAXIMUM CURRENT VELOCITY DISTRIBUTION IN TACOMA NARROWS.

TABLE 1. ARRAY CONFIGURATIONS FOR DIFFERENT SIZES OF TIDAL TURBINE FARMS.

Case	Total Turbines	Row × Turbine	Turbine Layout
1	6	2x3	Centered
2	6	2x3	Staggered
3	6	1x6	Lateral
4	6	6x1	Longitudinal
5	36	6x6	Centered
6	36	6x6	Staggered
7	36	3x12	Lateral
8	36	12x3	Longitudinal

RESULTS AND DISCUSSIONS

The hydrodynamic model was run for a 40-day period with the tidal turbine farm in place. The first 10-day simulation served as model spin-up time and results from the last 30-day simulation were analyzed for energy extraction. The total extractable energy by a tidal turbine farm at any given time can be calculated based on following formula [4]

$$P_{total} = \sum_{i=1}^{M} \left(N \times \frac{1}{2} \rho C_T A_b \overline{|\vec{u}|^3} \right)_i \qquad (4)$$

where ρ is water density; C_T is the turbine thrust coefficient for the amount of thrust force exerted on the fluid; A_b is the total flow-facing area swept by turbine blades; $\vec{u}$ is the velocity vector at hub height; N is the number of turbines in each model element; M is the total elements containing turbines.

Time series of total extractable powers by the 6-turbine farms (Case 1 to 4) and the 36-turbine farms (Case 5 to 8) during spring tide were plotted in Figure 4. Power outputs for all array arrangements in each set of experiment show very similar patterns with strong tidal variations. In general, extractable powers for centered, staggered, and longitudinal arrangements are similar while extractable power for the lateral arrangement is slightly less than the rest. The reason that the lateral arrangement does not produce the highest power is likely due to the fact that turbines on the edges of the arrays are in the weaker tidal current region close to the shore (see Figure 3).

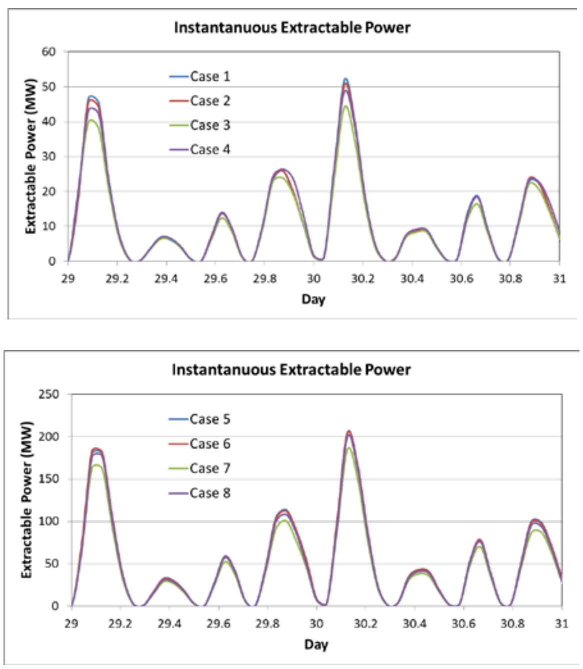

FIGURE 4. INSTANTANEOUS EXTRACTABLE POWER DURING SPRING TIDE BY 6-TURBINE (UPPER PANEL) AND 36-TURBINE (LOWER PANEL) TIDAL FARMS SIMULATED BY THE MODEL

30-day averages of extractable power for all turbine arrangements were calculated and compared in Figure 5. The average powers for the lateral layouts are about 10% lower than the rest of the layouts for both 6- and 36-turbine farms.

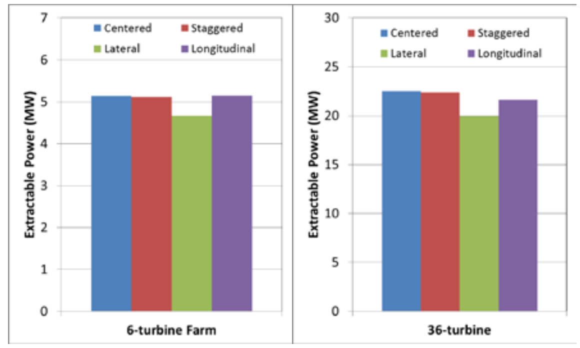

FIGURE 5. INSTANTANEOUS EXTRACTABLE POWER DURING SPRING TIDE FOR 36-TURBINE TIDAL FARMS SIMULATED BY THE MODEL

The efficiency of power extraction by different array configurations can be also evaluated by the averaged unit extractable power per turbine. Figure 6 shows the comparison of extractable power per turbine for all the turbine layouts simulated in this study. It is seen that unit extractable power by the 36-turbine farms are lower than those by the 6-turbine farms. The average unit power for the 36-turbine tidal farms is 600 KW, which is about 28% lower than the average unit power of 836 KW for the 6-turbine farm.

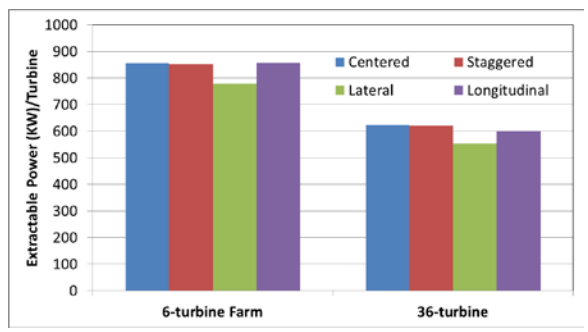

FIGURE 6. INSTANTANEOUS EXTRACTABLE POWER DURING SPRING TIDE BY 36-TURBINE TIDAL FARMS SIMULATED BY THE MODEL

CONCLUSIONS

To explore the effect of different turbine array configurations on extractable tidal energy in a real-world site, an unstructured-grid coastal ocean model with a tidal energy device module was applied to Tacoma Narrows in Puget Sound through a series of numerical experiments with different array layouts. To accurately simulate the extractable energy and interaction between the devices and the flow field, the model grid resolution was refined locally in the area of the tidal turbine farm. Preliminary model results indicate that optimization of turbine arrays in a real-world site is a very complex process as it is strongly constrained by many factors, such as spatial variations of water depth and current speed. In order to determine the optimal power output in a real world site, larger number of model simulations with different turbine configurations and more thorough analysis are necessary. Nonetheless, numerical models are very useful tools for device siting and array arrangement in real-world sites.

REFERENCES

[1] C. Garrett, P. Cummins. 2007. The efficiency of a turbine in a tidal channel. *Journal Fluid Mechanics*, 588, 243-251.

[2] R. Vennell. 2011. Turning tidal turbines in-concert to maximize farm efficiency. *Journal Fluid Mechanics*, 671, 587-604.

[3] R. Draper and T. Nishino. 2014 Centered and staggered arrangements of tidal turbines. *Journal Fluid Mechanics* (in press)

[4] Z. Yang, T. Wang, A. Copping. 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*, 2013. 50, 605-613.

[5] C. Chen, H. Liu, R.C. Beardsley, An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries, J. Atm. & Oceanic Tech. 20 (2003) 159-186.

[6] Polagye, B., M. Previsic, G. Hagerman, and R. Bedard. System level design, performance, cost and economic assessment – Tacoma Narrows Washington tidal in-stream power plant, EPRI Technical Report EPRI-TP-006 WA, 2006.

[7] Z. Yang, T. Khangaonkar. Multi-scale Modeling of Puget Sound Using an Unstructured-grid Coastal Ocean Model: from Tide flats to Estuaries and Coastal Waters. *Ocean Dynamics*. 2010, 60, 1621-1637

[8] Yang, Z. and T. Wang, 2013. Tidal Residual Eddies and Their Effect on Water Exchange in Puget Sound. Ocean Dynamics, 63, 995-1009. DOI: 10.1007/s10236-013-0635-z