Renewable Energy 101 (2017) 204–213

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Numerical model simulation of island-headland induced eddies in a site for tidal current energy extraction

Jie Lin, Binliang Lin, Jian Sun*, Yaling Chen

*State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, 100084, China*

ARTICLE INFO

*Article history:*
Received 22 December 2015
Received in revised form
22 August 2016
Accepted 25 August 2016

*Keywords:*
Tidal current energy
Island wake
Coastal eddy
Energy fluctuation
Shallow water equations

ABSTRACT

As an important marine renewable energy resource, tidal stream energy has increasingly attracted public attention. However, the detailed hydrodynamic properties are often poorly understood at potential tidal stream energy sites, where local topographical features usually induce complicated current structures, such as eddies. In the present study a three-dimensional hydrodynamic model is employed to reproduce the flow field at a promising coastal site for tidal current energy extraction, where there is an island located near a headland. Comparisons between the model predictions and the survey data show good agreement. Two large eddies are found near the island-headland system in each tidal cycle. The eddies form during the flood and ebb tides, and the rotation does not cease until slack water. When the eddies move across the island-headland system, fluctuations are detected both in current speed and direction. The eddies induced velocity fluctuations cause a significant change in the energy density, with its magnitude being about half the maximum, whilst the water elevation change is limited. Therefore, the impact of eddies should be taken into account seriously in practical tidal stream energy explorations.

## 1. Introduction

Tidal current energy is one of the most promising forms of renewable energy due to its high predictability. A number of coastal areas have been identified as prospective tidal energy extraction sites. However, the hydrodynamic details at these specific sites are often poorly understood [1]. These sites are often located in coastal zones where the tidal current energy is concentrated to an exploitable level as the flow is constrained by coastlines, sea bed, islands and straits [2–6]. However, in such complex coastal topography, the tidal current is rather different from a simple reciprocating flow, or an elliptical tidal flow [7–9]. The local tidal flow distribution can be rather complicated due to the existence of tortuous coastlines, islands and uneven seabed, which often induce complex eddies. These irregular variations of tidal current pose a potential issue for site selection, turbine design and power plant operation.

Island and headland induced eddies have been observed in previous field studies and their formation conditions have been linked to certain dimensionless numbers. Eddies with length scales of 1–10 km are commonly observed in coastal waters [10]. In existing studies on wakes induced by islands or headlands, various relationships have been developed to link the formation of wakes with the inertial, Coriolis and frictional forces, and local acceleration effects, which are thought to be the key factors that determine the final regime of the flow influenced by the headland and island. For example, the classical Reynolds number ($Re$) is adopted as a criterion to group different flow patterns [11], which represents the relative importance of inertial force to viscous force. The use of a Reynolds number ($Re_e$) based on eddy viscosity allows for a possible comparison of numerical model predictions with laboratory measured wakes [12]. It has been shown that eddies or unstable wakes may form beyond a specific value of Reynolds number [13]. On the other hand, the rotation of the Earth imposes Coriolis force on the moving water, with its effect on island wakes often being assessed using Rossby number ($Ro$) and Ekman number ($Ek$), to describe the relative importance of the inertial and viscous forces to the Coriolis force, respectively. When the values of these dimensionless numbers are within certain ranges, flow separation or even instable wakes may occur, which can notably disturb the flow field [13,14]. Specifically, the formation of wakes in shallow coastal waters was described by Wolanski et al. [15], and an island wake parameter $P$ has been introduced to classify flow patterns.

In practice, tidal current energy is usually captured using tidal

---

* Corresponding author.
*E-mail address:* jsun@mail.tsinghua.edu.cn (J. Sun).

http://dx.doi.org/10.1016/j.renene.2016.08.055

stream turbines [16,17]. During the process of energy exploitation, the performance of tidal stream turbines depends highly on natural current regimes. Furthermore, the cubic relationship between the incoming flow velocity and energy density means that irregular variations of tidal currents have a substantial effect on the energy density distribution. This means that eddies in wakes may result in significant fluctuations of energy density, and they can reduce the power output by increasing yaw angles to turbines [18]. However, despite the significance of such phenomena, there are relatively few studies looking into the effect of detailed tidal current structure in tidal power sites and the impact of velocity fluctuations on tidal current energy potential [1].

Numerical models based on the shallow water equations (SWE) are widely used to simulate the hydrodynamic process in coastal waters. In recent years, tidal current energy resources have been frequently assessed based on the model predicted water depth and velocity distributions [19,20]. Moreover, the far field impacts of tidal turbines on coastal water movements have been investigated by parameterizing the turbines as momentum sinks in the SWE [3,21–23]. Generally, the velocity is found to decrease inside, upstream and downstream of a turbine array, while the velocity usually increases along the two sides of the array by turbine-encouraged flow [23]. However, the impact on the tidal elevation is generally not significant [21,23]. It is found that energy extraction has caused an increase in the residence time [24]. Evolution of island wakes have also been investigated with SWE [9,12,25], however, the connection between natural hydrodynamic processes of wakes and tidal current energy resources has been rarely studied. Knowledge of island-headland induced eddies' impact on the distribution of tidal current energy is limited.

This study focuses on the flow distribution at a marine energy extraction site where the tidal currents are significantly influenced by an island-headland system. The generation and evolution processes of eddies around the island are investigated, and the effects of velocity fluctuation on the energy density distribution are considered. Section 2 describes the hydrodynamic model used in this study and an island wake parameter which can be used to classify flow patterns qualitatively. In Section 3, details of the numerical model are presented, including the model domain, geometry, meshes, boundaries and verification. Model results and discussions are given in Section 4, while the main conclusions are highlighted in Section 5.

## 2. Methods

### 2.1. Hydrodynamic model

In coastal areas, the horizontal length scale is often 2 to 3 orders greater than the vertical scale. Therefore, the shallow water equations (SWE) are commonly used to describe the water movement in coastal waters. In this study, a three dimensional model, i.e. Delft3D, is employed to solve the SWE. The model is widely applied to investigate coastal flow processes, such as distributions of tidal currents, bed friction and Coriolis force. The $k$-$\varepsilon$ model is used for turbulence closure. To fit the curved boundaries of coastlines, the governing shallow water equations are discretized based on an orthogonal curvilinear coordinate system in the horizontal plane, and local grid refinements are allowable to achieve higher resolutions at sites of interest. In the vertical plane, the $\sigma$ coordinate system is applied. The three-dimensional governing equations in the coordinate system are in the following form:

$$\begin{aligned}&\frac{\partial u}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial \xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial \eta}+\frac{\omega}{(d+\xi)}\frac{\partial u}{\partial \sigma}+\frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}-fv\\&=-\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi+F_\xi+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu_{\mathrm{v}}\frac{\partial u}{\partial\sigma}\right)\end{aligned} \tag{1}$$

$$\begin{aligned}&\frac{\partial v}{\partial t}+\frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial \xi}+\frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial \eta}+\frac{\omega}{(d+\xi)}\frac{\partial v}{\partial \sigma}+\frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}+\frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}+fu\\&=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta+F_\eta+\frac{1}{(d+\zeta)^2}\frac{\partial}{\partial\sigma}\left(\nu_{\mathrm{v}}\frac{\partial v}{\partial\sigma}\right)\end{aligned} \tag{2}$$

$$\frac{\partial \zeta}{\partial u}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left((d+\zeta)u\sqrt{G_{\eta\eta}}\right)}{\partial\xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left((d+\xi)v\sqrt{G_{\xi\xi}}\right)}{\partial\eta}+\frac{\partial\omega}{\partial\sigma}=0 \tag{3}$$

where $\xi$ and $\eta$ are the horizontal curvilinear coordinates; $\sigma$ is the scaled vertical coordinate; $u$ and $v$ are the horizontal velocities in the $\xi$ and $\eta$ directions (m/s), respectively; $\omega$ is the vertical velocity component relative to the moving $\sigma$-plane; $\zeta$ is the water level (m); $f$ is the Coriolis coefficient ($s^{-1}$); $\rho_0$ is the water density ($kg/m^3$); $P_\xi$ and $P_\eta$ are the pressure gradients in the $\xi$ and $\eta$ directions ($kg/m^2s^2$), respectively; $F_\xi$ and $F_\eta$ are the horizontal Reynolds stresses in the $\xi$ and $\eta$ directions ($m/s^2$), respectively; $\nu_{\mathrm{v}}$ is the vertical eddy viscosity coefficient ($m/s^2$); $\sqrt{G_{\xi\xi}}$ and $\sqrt{G_{\eta\eta}}$ represent the coefficients related to the curvilinear coordinates.

The 3D shallow water equations are solved using a mode splitting method, with a depth-averaged two dimensional equations being solved at each step. An alternating direction implicit (ADI) method is adopted in the solution procedure of the depth averaged equations and the terms of governing equations are discretized