Applied Energy 165 (2016) 522–536

Contents lists available at ScienceDirect

Applied Energy

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

Numerical model simulations for optimisation of tidal lagoon schemes

Athanasios Angeloudis *, Reza Ahmadian, Roger A. Falconer, Bettina Bockelmann-Evans

Hydro-environmental Research Centre, School of Engineering, Cardiff University, The Parade, Cardiff, UK

HIGHLIGHTS

- We discuss certain design aspects of tidal lagoons to inform future proposals.
- We demonstrate the tidal lagoon representation within a 0-D and 2-D hydrodynamic modelling framework.
- We examine the potential of simplified 0-D modelling techniques for operation optimisation.
- We highlight the extent where 2-D hydrodynamic model power predictions can deviate from 0-D modelling.

ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form 17 November 2015
Accepted 17 December 2015
Available online 7 January 2016

Keywords:
Tidal range
Tidal lagoons
Marine renewable energy
Numerical modelling
Hydrodynamic impact

ABSTRACT

This study considers environmental impacts and the power production potential of a number of coastally attached tidal lagoons, proposed along the North Wales coast, UK. Initially, the impoundment shape, turbine and sluice gate locations were modified according to the regional bathymetric data. A refined 0-Dimensional approach was implemented to optimise the lagoon operation, based on given turbine and sluice gate specifications. In turn, a two-dimensional numerical model, based on an unstructured triangular mesh, has been refined to simulate the hydrodynamic processes, initially without and subsequently in the presence of the lagoons. The hydrodynamic model adopts a TVD finite volume method to solve the 2D shallow water equations, based on a second-order accurate spatial and temporal numerical scheme. An encouraging performance is apparent in reproducing the established conditions encountered in the region through comparisons against available data. The incorporation of tidal lagoons in the model appears to have a considerable effect on the flow structure in the region, by inducing high velocity accelerations near the sluices and turbines, depending on the stage of the tidal cycle. Considering a two-way generation regime, it is outlined that the loss of intertidal regions can be minimised, which is a major source of concern with regards to the environmental impact of such schemes through an ebb-generation operation. Particular focus is directed towards the comparisons between the 0-D and 2-D modelling results, an aspect which has not been reported previously. Predictions of the models diverge as the scale of the lagoon project increases, but it is highlighted that the 0-D methodology can be utilised for the optimisation of the processes in the initial stages of design before proceeding to more sophisticated numerical model simulations.

1. Introduction

The UK has a considerable opportunity to generate large quantities of renewable energy from some of the largest tides in the world. Practical estimates suggest that tidal energy systems can provide a significant proportion of national electricity demand, reliably and safely [1]. In the light of EU commitments to meet renewable energy targets, there is an emerging interest towards marine renewable energy schemes, seeking to harness the energy resource offered by the high tidal range reported around the UK. coastline. This can range from 6 to 10 m along the North Wales coast during spring tides while exceeding 14 m within the Severn Estuary [2–4].

Tidal range structures are constructed on the basis of creating an artificial tidal phase difference by impounding water, and then allowing it to flow through turbines to generate electricity when appropriate. It is known that these schemes can have a range of near- and far-field impacts on the hydro-environment, which can be positive and/or negative. These can occur mainly through alterations to the tidal flow characteristics, with changes to the hydrodynamic regime potentially having corresponding effects on the sediment transport rates, and the geomorphological, ecological and water quality processes in an estuary or along a coastline

* Corresponding author.
E-mail address: angeloudisa@cf.ac.uk (A. Angeloudis).

http://dx.doi.org/10.1016/j.apenergy.2015.12.079
0306-2619/

[3,5,6]. There are also numerous other factors, beyond the environmental impacts, to be taken into account before converging towards a reasonable tidal impoundment design. They span across a range of disciplines and can be of a geotechnical, electrical, mechanical or socio-economic nature. The influence of each of these challenges individually is beyond the scope of this paper, as they are the subject of associated studies (e.g. [3,6–11]).

For power generation, the prevalent technology currently reported for tidal range structures is the low head bulb turbine. The La Rance Barrage in France makes use of 24×10 MW bulb units of 5.35 m rotor diameter each [12]. More recently, as of 2011, the construction of Lake Sihwa tidal power station in South Korea came to completion where 10×26 MW bulb units, of 7.5 m diameter, are operated to harness the regional tidal power resource [13]. The majority of the options considered for the Severn Estuary also involve using bulb turbines as discussed by the Department of Energy and Climate Change (DECC) [14].

Tidal impoundments featuring the aforementioned turbine types have attracted interest amongst marine renewable energy experts and there have been numerous proposals to construct such schemes around Wales and the North West coast of England. Examples include the Severn Barrage [15,16] and the Swansea Bay lagoon [8], both encompassed within the Severn Estuary and Bristol Channel located in the South West of the UK. Numerical modelling techniques have been implemented widely to simulate flow and water quality processes during the operation of tidal range structures, with a view to assessing the feasibility of various proposals [4,6,17–19]. The application of numerical models on tidal range projects specifically around Wales has predominantly been focused on proposals across the Severn Estuary [4,20–25]. However, the theme of this work relates to the potential of tidal lagoon concepts along the North Wales coast.

The study of this area can be justified on the grounds of several of its characteristics, which could make such projects attractive in the near future, as also supported by preceding investigations reported in the literature [26–28]. Specifically, the flow along the coastline is subject to a tidal range exceeding 8 m during mean spring tides and therefore becomes suitable for the deployment of contemporary tidal range turbine technologies. Considering that power extraction from these schemes is predictable, but intermittent according to the tidal cycle, an additional incentive is that it could complement other tidal range projects in locations where the cycle is out of phase, such as a barrage in the Severn Estuary. Simultaneously, there is mounting concern over coastal flooding along the North Wales coast. Interest in reducing the flood risk has heightened over the impending detrimental effects of sea-level rise [29] that could substantially increase the severity of coastal flood damage unless properly addressed. Coastal flood protection can be provided on the upstream side of a lagoon since it acts as a barrier to wave impacts, high tides and surge effects along the impounded coastline. In addition, the appropriate regulation of flow control structures (i.e. turbines and sluices) facilitates a control mechanism for upstream peak water levels when necessary. Therefore, tidal-range marine renewable structures could play an important role in protecting susceptible regions, contributing to the benefits of such large-scale schemes.

The intention of this analysis is not specifically to suggest a particular lagoon design, but it is rather to inform future proposals in North Wales and beyond. Certain location characteristics are discussed with a view to demonstrate how they will invariably dictate the lagoon impoundment shape and annual energy output. Initially, a preliminary 0-D modelling approach was adopted to optimise and identify reasonable design and operational characteristics of 4 coastally-attached lagoon concepts in the vicinity of the North Wales coast. In turn, 2-D numerical model simulations are presented investigating the hydrodynamic flow structure developed during the tidal cycle, firstly without and subsequently in the presence of the tidal range schemes. A distinguished point of this investigation was to ascertain the correlation of the refined 0-D modelling of energy output against the more detailed 2-D numerical modelling, that accounts for the complex hydrodynamics close to impoundment hydraulic structures. The correlation of simplified 0-D model results against more elaborate 2-D hydrodynamic predictions has yet to be investigated, as outlined in the review of Adcock et al. [17] and is therefore a key aspect of this work. Thus, the objectives contemplated can be hitherto summarised as:

- Highlighting certain design aspects of tidal lagoons to be taken into account that can be used to inform future proposals.
- Reviewing the approach adopted to represent computationally the lagoon impoundment, sluices and turbines for a refined 0-D modelling strategy and the 2-D hydrodynamic models.
- Examining the potential of 0-D modelling techniques to provide optimum operational parameters, based on the given specifications of the turbine technology and sluices.
- Assessing the hydrodynamic impact of the tidal lagoon and demonstrating the extent where 2-D hydrodynamic model predictions can deviate from the 0-D modelling approach.

2. Research methodology

2.1. North Wales Bathymetry and lagoon design considerations

Fig. 1(a) provides an overview of the study area bathymetry, as contained by the seaward (Western and Northern) and land boundaries imposed for the hydrodynamic simulations. In terms of its characteristics, apart from the highly dynamic tidal flow conditions, the area is subject to strong wind effects as demonstrated by the presence of the Gwynt y Môr Offshore Wind Farm. The Colwyn Bay coastline has occasionally been subjected to extreme storm events which led to substantial coastal flooding in residential areas such as Towyn and Rhyl (e.g. 1990). There are also several inflows along this part of the coast which include the Menai Strait and the Conwy, Clwyd, Dee and Mersey rivers.

The bathymetric data was collated from a combination of UK admiralty charts (No. 1977 and 1978) and digitized data provided by Seazone Solutions with a resolution of 1 arc second, which was in turn used for the assessment of tidal lagoons through the 0-D and 2-D methodologies discussed subsequently. The bathymetric data were reduced to the level of Lowest Astronomical Tide (LAT) and are consistent with the UK Admiralty Chart No. 1978. Four tidal lagoons were selected to form the basis of the analysis herein and follow the conceptual designs of Anderson [30]. The principle of their design aims towards providing flood protection along the coast, whereas their shape attempts to take advantage of shallow parts of the coastal bathymetry. The impoundments extend to a sufficient depth to enable the introduction of turbines or sluices and the overall configuration can be observed in Fig. 1(b).

In the absence of further details for the operation of these lagoons, this study assumes that the power generation is conducted through 7.5 m rotor diameter low head bulb turbines, with a capacity of 25 MW as utilised in similar projects [13]. The power and the discharge through these turbines was represented according to Fig. 2(a). The hill chart of Fig. 2(a) relates the power (P), water elevation difference (H) and discharge (Q) for 25 MW turbines. These specifications were adopted from the previous hydrodynamic study of Falconer et al. [20], taking into account the proven performance of bulb turbines in the existing tidal impoundments of La Rance and Lake Sihwa. In order to converge to a realistic turbine arrangement, it is of interest to highlight some influential characteristics of their design. Essentially, the minimum