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Hydrodynamic changes imposed by tidal energy converters on extracting energy on a real case scenario

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HIGHLIGHTS

- Momentum source approach is used to represent floatable tidal energy converters.
- Aggregated drag coefficient for different device array schemes is determined.
- Simulations for one-month periods with nested models are performed.
- Capacity Factor is quantified based on simulations and theoretical concepts.
- Water-level differences and velocity deficit compared with no-extraction scenario.

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ABSTRACT

The development on tidal turbine technology is ongoing with focus on several aspects, including hydrodynamics, operation and environment. Before considering an area for exploitation, tidal energy resource assessments in pre-feasibility energy extraction areas must include the relevant characteristics of the device to be used. The present paper uses the momentum source approach to represent a floatable tidal energy converter (TECs) in a coastal hydro-morphodynamic model and to perform model simulations utilising different TEC array schemes by quantifying the aggregated drag coefficient of the device array. Simulations for one-month periods with nested models were performed to evaluate the hydrodynamic impacts of energy extraction using as output parameters the reduction in velocity and water-level variation differences against a no-extraction scenario. The case study focuses on representing the deployment of floatable E35 Evopod TECs in Sanda Sound (South Kintyre, Argyll, Scotland). The range in power output values from the simulations clearly reflects the importance of choosing the location of the array, as slight changes in the location (of <1 km) can approximately double the potential power output. However, the doubling of the installed capacity of TECs doubles the mean velocity deficit and water-level differences in the area surrounding the extraction point. These differences are amplified by a maximum factor of 4 during peak flood/ebb during spring tides. In the simulations, the drag coefficient is set to be constant, which represents a fixed operational state of the turbine, and is a limitation of coastal models of this type that cannot presently be solved. Nevertheless, the nesting of models with different resolutions, as presented in this paper, makes it possible to achieve continuous improvements in the accuracy of the quantification of momentum loss by representing turbine characteristics close to the scale of the turbine.

1. Introduction

The hydrokinetic energy that can be extracted from tidal currents is one of the most promising renewable energy sources [1]. Tidal energy extraction is very site specific, that is, the methods for determining the limits of and potential for energy extraction from a channel differ from site to site. Although the effects of removing energy may not be detectable when one or even ten tidal turbines are concerned, extracting tidal energy at commercial scales can potentially have several impacts on the environment, including a reduction in tidal amplitude, disruptions to flow patterns and concomitant changes in the transportation and deposition of sediments, changes in the population distributions and dynamics of marine organisms, modifications to water quality

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and marine habitats, increases in ambient noise, and greater levels of mixing in systems in which salinity and temperature gradients are well defined [2–7]. Disruptions to flow patterns may also have consequences for the downdrift energy extraction potential, endangering implementation schemes and their efficiency; for example, the efficiency of a Tidal Energy Converter (TEC) positioned in the wake of another device within TEC array schemes.

An understanding of the hydrodynamic shifts induced by TEC devices can be obtained through the use of numerical modelling techniques, calibrated using databases for different test case sites. When modelling the flow across turbines, a decision has to be made about how the properties of TECs should be represented in the coastal model, that is, how the drag forces associated with power extraction are modelled. The representation of those forces aims to “upscale” the effects of the detailed flow and turbulence around a simplified turbine to give a coarse representation of the hydrodynamic forces acting on a turbine or on a group of turbines [8]. In the open source Delft3D model, this can be effectively performed using porous plates by analogy with the actuator disc theory. The data needed for applying this approach require the determination of a momentum loss term able to represent the extraction of energy from the free flow. Ideally, this loss term should be determined by analysing the turbulence scales and velocity profile distortion under different flow conditions while operating TECs in real conditions. However, because the availability of data on operating TECs in real conditions is scarce, the momentum loss term is calculated based on TEC prototype characteristics, physical assumptions, and/or data collected from testing scale models in physical tanks. Prior to adding the momentum loss term into the modelling equations and evaluating different energy extraction scenarios based on simulations, the numerical models first need to reproduce the hydro-morphodynamic characteristics of the area of interest.

This paper presents the methods for setting up the Delft3D model at Sanda Sound, South Kintyre Peninsula (Argyll, Scotland) to gain realistic insights into the hydrodynamic impacts of energy extraction in confined channels and to consider different solutions for effectively simulating energy extraction with reference to the installation of an array of devices (E35 Evopods) within the study area. The paper explains the modelling set-up, the calibration factors used, and the validation procedures adopted both before and after incorporating turbine effects. The turbine characteristics were obtained using drag data from prototype testing in both physical tanks and real conditions. These values were used for determining the momentum loss term induced by the energy extraction, which was then implemented on the numerical mesh via porous plates and using appropriate scaling factors. This procedure allowed the momentum loss term derived from the energy extraction of an idealised array scheme to be determined and simulations to evaluate the potential impacts of energy extraction on flow patterns to be performed.

The novelty of the present paper can be stressed by two main points: (1) this is the first paper trying to model floatable tidal devices (e.g. such as the Evopod) on a numerical model using the aggregate drag approach to reproduce the effects of energy extraction by an array scheme. The attempt relates directly to the local 1 MW project that has the potential in the future to be implemented at Sanda Sound; and (2) the methodology used to achieve the proposed goals is focused on the use of coupled nested models using Delft3D Dashboard, an approach that can be easily implemented elsewhere. Although direct comparisons with experimental data will be carried out as soon as the prototype is fully functional in the water, the present paper addresses the challenges of setting up a model on a remote coastline such as Sanda Sound making the best use of the available information (e.g. coupling available bathymetric and hydrodynamic data, existing data on Evopod testing in the Newcastle wave-current-wind tank and on the real case scenario of Strangford Narrows). Those tests allowed determining the drag forces associated with energy extraction from the free flow, which complemented the available data on the characteristics of the 1:4 scale Evopod prototype (E35 kW).

2. Study case

2.1. Site characteristics

The study site is Sanda Sound, which is located close to the Mull of Kintyre in southwest Scotland (Fig. 1). Sanda Sound is a channel that flows between Sanda Island and the Kintyre Peninsula, and connects the North Channel to the Firth of Clyde. The North Channel is the strait between north eastern Ireland and southwestern Scotland; it connects the Irish Sea with the Atlantic Ocean, and is part of the marine area officially classified as the “Inner Seas off the West Coast of Scotland” by the International Hydrographic Organization (IHO). The minimum width of the North Channel of 21 km is located between the Mull of Kintyre (the southwest point of the Kintyre Peninsula, Scotland) and Torr Head (Northern Ireland). The Firth of Clyde is the largest and deepest area of coastal water in the British Isles, and is sheltered from the Atlantic Ocean by the Kintyre Peninsula.

2.2. Oceanographic setting

Scotland’s location in the northern part of the British Isles and the steep bathymetry of the continental slope together act as a barrier between the oceanic regions and the shelf sea systems, reducing the amount of water that is able to move from the deeper waters of the North Atlantic into the shallower waters of the Scottish continental shelf. Scotland has a maritime climate that is strongly influenced by the oceanic waters of the North Atlantic and the prevailing southwesterly winds. As these winds blow over the regions of the North Atlantic, warmed by the North Atlantic Current, they pick up heat that gives Scotland a relatively mild, wet climate considering its latitude [9].

The wave climate of Scotland is influenced mainly by conditions in the North Atlantic Ocean, where the fetch is sufficiently long to establish large, regular waves (i.e., swell) [10]. The north and west of Scotland (the Hebrides, Orkney Islands, and Shetland Islands) and the west coast of Ireland are most exposed to these conditions [11,12]. Wave heights are greatest in the most exposed waters of the north and west, and decrease markedly into the North Sea and southwards from there into both the Irish Sea and the English Channel [13]. Within the Irish Sea, the waves tend to be locally generated, have fairly short periods (50-yr return value of the mean zero up crossing period (T_z) is in the order of 10 s within the Irish Sea and 15 s at its outer entrances), and are relatively large (50-yr significant wave heights ranging from 8 m within the Irish Sea to 12 m at its entrances) [14]. Sanda Sound is protected from NW waves by the Kintyre Peninsula, but is relatively exposed to W-SW waves of 2–3 m amplitude that propagate into the Sound in the winter months [15].

Overall, the peak tidal range along Scotland’s coast is generally between 4 and 5 m, with the highest tidal ranges being found in the inner Solway Firth where the mean spring tidal range lies between 7 and 8 m [9]. The tidal range is a minimum between Islay and the Mull of Kintyre and in the northeastern North Sea (amphidromic points). The tidal range at Sanda Sound is indicated on the Admiralty Chart to be 2.8 m at spring tides. The tidal currents are intensified in localised areas, usually where the flow is constrained by topography. This includes areas such as between the Orkney Islands and Shetland Islands, the Pentland Firth, off the Mull of Kin-