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The impact of seabed rock roughness on tidal stream power extraction

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ABSTRACT

Numerical assessments of environmental disturbances induced by a tidal farm project rely usually on local modifications of the friction coefficient over the area covered by a proposed array. Nevertheless, no study has investigated the sensitivity of predictions to surrounding seabed friction. The present investigation focuses on impacts of roughness parameterisation of rock outcrops, a typical seabed of tidal stream sites. A high-resolution depth-averaged circulation model is implemented in the Fromveur Strait off western Brittany, a region with strong potential for array development, integrating the heterogeneity of sediment bottom types. Rock roughness strongly influences initial predictions of tidal current and kinetic energy in the Strait with variations of available power up to 30 %. Tidal energy extraction induces noticeable reductions of tidal currents and bottom shear stresses up to 15 km from the array considered till surrounding sandbanks. Rock roughness impacts farm-induced modifications of tidal currents, bottom shear stresses and stream powers till north-eastern and southward edges of the Strait with major absolute differences identified in its central part. Surrounding sandbanks are finally suggested to variations of shear stresses from 9 to 17 % over the Bank of the Four with possible implications on local sediment deposition.

1. Introduction

The exploitation of tidal stream power is currently considered as a promising solution for rising the proportion of marine renewable energy to the worldwide energy production [1,2]. Major well-known advantages are the highly predictable and regular characteristics of the resource, the substantial degree of modularity in extracting the energy [3], the high load fluid factor and the reduced visual impact of tidal stream devices in comparison with wind or waves systems. Tidal kinetic power has thus attracted significant interest from leading developers of tidal energy converters (TEC) with numerous full-scale devices tested in the real environment [4]. Considering the increasing technical development of devices, the question of the hydro-environmental impact of tidal stream farms is of major interest to guarantee successful deployment in the marine environment. Indeed, besides a local modification of available power distribution, potential far-field effects are expected with modifications of hydrodynamics components and associated transport of particles at several kilometres from the proposed array [5–7].

As observations in the real environment with tidal stream farms are not available today, investigations of far-field impacts rely nowadays on regional numerical modelling. Hydrodynamic effects of tidal stream devices, which generally take the form of horizontal axis turbines [8], are most of the time approached with an equivalent drag force term redistributing the sum of turbines' thrust and structural drag forces over the area covered by a proposed array [9–12]. Whereas uncertainties exist about parameterisations of drag coefficients, upstream velocities [13,14] or wake-wake interactions within the array [15], these formulations provide a global assessment of tidal stream power extraction particularly suited for the early stages of a tidal farm project while restricting the computational costs of simulations. Numerical sensitivity studies to the array-drag coefficient have thus helped potential developers to optimize projects of stream farms in terms of size, thrust and structural drag coefficients and number of turbines [7,16,17].

Nevertheless, in spite of local sensitivity studies to array-drag coefficients, no additional investigation has been devoted to the influence of surrounding seabed friction on TEC-induced modifications. Indeed, numerical sensitivity studies devoted to the hydrodynamic impact of seabed roughness have primarily focused on the regional influence of bottom friction on tides exhibiting, in continental shelf environments, its effects on currents amplitude

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and asymmetry, and transport of particles [18–20]. These aspects have however been set aside in numerical assessments of available tidal stream power and TEC effects assuming uniform bottom friction coefficients, based (1) on Manning-Strickler [7,10] or Chezy [21] formulations in depth-averaged models or (2) on uniform quadratic friction law in three-dimensional approaches [22–24]. Further investigations about the influence of bottom friction, integrating the spatial heterogeneity of sediment bottom types, are thus necessary as (1) induced modifications of tidal stream array depend on initial estimates of current fields and (2) more significant effects are expected on predicted energy outputs and sediment transport rates which vary with a power of tidal current amplitude.

The present study investigates the numerical sensitivity of tidal stream power extraction to the parameterisation of bottom roughness. Bottom friction depends however on different settings and forcings including bed-sediment composition and morphology of the sea bottom [25], and influence of hydrodynamic processes such as interactions of wave and current bottom boundary layers [26]. Taking into account the difficulty to separate each contribution, the influence of time-variable bottom roughness is disregarded here focusing on effects of intrinsic seabed properties. The attention is devoted to sensitivity of numerical predictions to roughness parameter of rock outcrops, a typical seabed of tidal stream sites whose roughness is characterised by a relative uncertainty in relation to the shape of seabed features [25]. This sensitivity study will furthermore give further insights about the calibration of seabed roughness in numerical assessments of TEC effects at the early stages of a farm project.

After a description of the study site (Section 2.1), the emphasis is put on the theoretical formulation and implementation of hydrodynamic model (Section 2.2). Predictions are first assessed against available in-situ observations of current amplitude and direction (Section 3.1) exhibiting the local numerical sensitivity to roughness parameterisation of rock outcrops (Section 3.2). Synoptic effects on tidal current amplitude and associated kinetic energy are then evaluated in spring tidal conditions. Modifications induced by the presence of a tidal stream farm are finally investigated focusing on key parameters of maximum currents amplitude and available stream power 10 m above the seabed (the assumed technology hub height for the region considered), and bottom shear stress (Sections 3.3 and 3.4).

2. Materials and methods

2.1. Study region

The site of application is the Fromveur Strait, off western Brittany, separating the isle of Ushant from a group of islets and rock belonging to the Molène archipelago (Fig. 1). With annual peak velocities exceeding 4 ms^{-1} [27] and mean water depths of 50 m, this location is one of the largest tidal stream resource along the coasts of France. A restricted area of interest of 4 km^2 has thus been identified by the French government for the development of tidal farm projects. The exploitation of tidal kinetic energy from this site is a promising alternative for restricting current energy consumption of the isles of Ushant and Molène, currently based on expensive and polluting fuel power station. In this perspective, a horizontal axis turbine known as Sabella D10 is currently tested in the Fromveur Strait by the French company Sabella SAS and connected to the electricity grid of the isle of Ushant. This turbine with rated power output of 0.5 MW for a tidal current velocity of 3 ms^{-1} is a first step toward the implementation of a tidal stream farm in the Strait.

Tide propagates from the Gulf of Biscay in the South towards the English Channel in the North travelling around western Brittany thus generating clockwise rotating currents in the area of interest. The Strait is furthermore characterised by a strong asymmetry of tidal currents with a north-eastern flood-dominated sector and a southward ebb dominated region [28]. This asymmetry, likely associated with the funnel shape configuration of the Strait, decreases toward the centre of the area where the tidal flow is balanced with equivalent magnitudes of flood and ebb components. The seabed presents finally a highly heterogeneous spatial distribution of bottom-sediment grain sizes characterised by a succession of gravel deposits and localised sand supplies [29] (Fig. 2). Rocky substrates cover the major part of shallow water areas surrounding islands and islets of the Ushant-Molène archipelago spreading over nearly all the north-eastern part of the Fromveur Strait. Surrounding seabeds in deep waters are dominated by gravel deposits with localised sand supplies over the sand banks of Ushant (point #1, Fig. 1) and the Four (point #2, Fig. 1) [30].

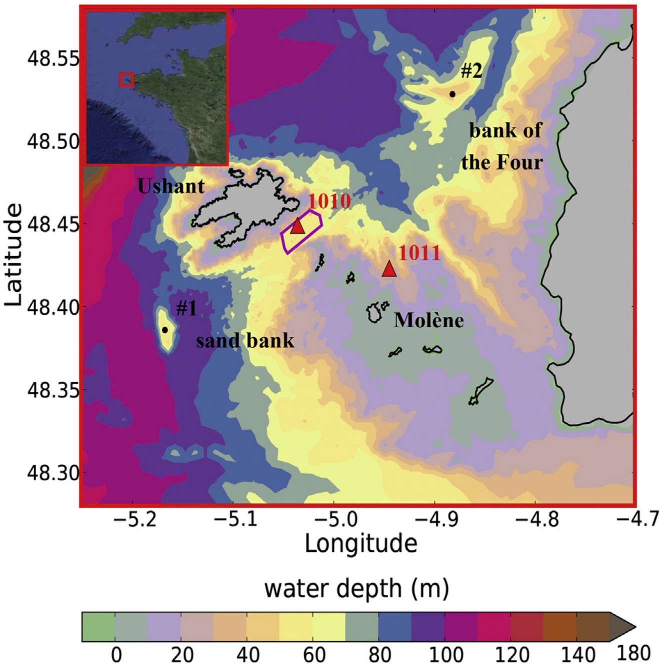

Fig. 1. Bathymetry of Ushant-Molène archipelago with locations of available current meters (▲). The magenta line in the Fromveur Strait delimits the region of interest for implementation of tidal stream devices. Water depth is relative to mean sea level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Numerical model

Simulations are performed with the bi-dimensional horizontal (2DH) model TELEMAC 2D (version 6p3) of the finite-element modelling system TELEMAC [32]. The major advantage of this simulation tool in comparison with other shallow-water models is the use of an unstructured mesh particularly suited, in the present investigation, (1) to capture the complex coastline geometry of the isles and islets of Ushant-Molène archipelago and (2) to reach a refined spatial resolution over the tidal stream site while sparing prohibitive computational costs with a reduced number of grid nodes. TELEMAC 2D solves the shallow water Barré de Saint-Venant equations of continuity (Eq. (1)) and momentum (Eq. (2)), derived from the three-dimensional Navier-Stokes equations by averaging over the water column. The derivation of depth-averaged shallow-water equations rely on major assumptions of hydrostatic pressure, negligible vertical velocity and impermeability of the surface and the bottom. These equations take the following mathematical