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The influence of waves on the tidal kinetic energy resource at a tidal stream energy site

Nicolas Guillou [a,*], Georges Chapalain [a], Simon P. Neill [b]

[a] Laboratoire de Génie Côtier et Environnement (LGCE), Cerema/DTecEMF/DS, 155 rue Pierre Bouguer Technopôle Brest-Iroise – BP 5, 29280 Plouzané, France
[b] School of Ocean Sciences, Bangor University, Menai Bridge, UK

HIGHLIGHTS

- We model the influence of waves on tidal kinetic energy in the Fromveur Strait.
- Numerical results are compared with field data of waves and currents.
- The introduction of waves improve predictions of tidal stream power during storm.
- Mean spring tidal stream potential is reduced by 12% during extreme wave conditions.
- Potential is reduced by 7.8% with waves forces and 5.3% with enhanced friction.

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ABSTRACT

Successful deployment of tidal energy converters relies on access to accurate and high resolution numerical assessments of available tidal stream power. However, since suitable tidal stream sites are located in relatively shallow waters of the continental shelf where tidal currents are enhanced, tidal energy converters may experience effects of wind-generated surface-gravity waves. Waves may thus influence tidal currents, and associated kinetic energy, through two non-linear processes: the interaction of wave and current bottom boundary layers, and the generation of wave-induced currents. Here, we develop a three-dimensional tidal circulation model coupled with a phase-averaged wave model to quantify the impact of the waves on the tidal kinetic energy resource of the Fromveur Strait (western Brittany) - a region that has been identified with strong potential for tidal array development. Numerical results are compared with in situ observations of wave parameters (significant wave height, peak period and mean wave direction) and current amplitude and direction 10 m above the seabed (the assumed technology hub height for this region). The introduction of waves is found to improve predictions of tidal stream power at 10 m above the seabed at the measurement site in the Strait, reducing kinetic energy by up to 9% during storm conditions. Synoptic effects of wave radiation stresses and enhanced bottom friction are more specifically identified at the scale of the Strait. Waves contribute to a slight increase in the spatial gradient of available mean tidal stream potential between the north-western area and the south-eastern part of the Strait. At the scale of the region within the Strait that has been identified for tidal stream array development, the available mean spring tidal stream potential is furthermore reduced by 12% during extreme waves conditions. Isolated effects of wave radiation stresses and enhanced bottom friction lead to a reduction in spring tidal potential of 7.8% and 5.3%, respectively. It is therefore suggested that models used for tidal resource assessment consider the effect of waves in appropriately wave-exposed regions.

1. Introduction

Among the different sources of marine renewable energy, the kinetic power of tidal currents has, because of its astronomical origin, the major advantage of being predictable. In addition, tidal stream devices, which generally take the form of horizontal axis turbines [1], have the advantage of a reduced visual impact which is helpful for public acceptance, particularly by coastal users and communities. Tidal stream technologies are thus developing very rapidly, with several projects in the process of pre-commercial full-scale testing, including the twin rotor SeaGen device in Strangford Lough (Northern Ireland), the Andritz Hydro turbine off

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[*] Corresponding author.

E-mail addresses: nicolas.guillou@cerema.fr (N. Guillou), georges.chapalain@cerema.fr (G. Chapalain), s.p.neill@bangor.ac.uk (S.P. Neill).

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Nomenclature

d	total water depth (m)
E	directional spectrum of variance density ($\text{kg s}^{-1}\ \text{rd}^{-1}$)
F_x, F_y	wave induced forces (m s^{-2})
f_ω	wave friction factor (–)
g	acceleration due to gravity (m s^{-2})
H_s	significant wave height (m)
N	wave action density function ($\text{m}^2\ \text{s}^2\ \text{rd}^{-1}$)
P	tidal stream energy per unit area (W m^{-2})
S_{ij}	components of the radiation stress tensor with $(i,j) \in [x,y]$ ($\text{m}^3\ \text{s}^{-2}$)
R	Pearson's correlation coefficient (–)
RE	index of agreement (–)
T_p	peak wave period (s)
u	amplitude of the horizontal current component (m s^{-1})
U_ω	wave bottom orbital velocity (m s^{-1})
u_{*c}	shear velocity arising from the current (m s^{-1})
$u_{*c\omega}$	total wave and current friction velocity (m s^{-1})
$u_{*\omega}$	shear velocity arising from the wave (m s^{-1})
z_0	bottom roughness parameter (m)
$z_{0,b\omega}$	apparent bottom roughness parameter (m)
δ_ω	thickness of the wave boundary layer (m)
ρ	water density (kg m^{-3})
σ_ω	intrinsic wave frequency (s^{-1})
τ_c	current-induced bed shear stress (N m^{-2})
$\tau_{c\omega}$	total wave and current bed shear stress (N m^{-2})
τ_ω	wave-induced bed shear stress (N m^{-2})
$\phi_{c\omega}$	angle between wave and current directions (rd)
ω	wave frequency (s^{-1})

Kvalsund (Norway), and the OpenHydro turbines off Paimpol-Bréhat (France), or the Sabella device near the isle of Ushant (France) [2]. Successful device deployment relies however on access to accurate and refined assessments of available tidal stream power. Numerical modelling tools are most of the time retained for the site selection process at the scale of continental shelves [3,4] or locations identified for array implementation [5–8]. However, whereas model predictions provide developers with key information for optimizing design and implementation of tidal energy converters [9], influences of meteorological forcings such as wind-generated surface-gravity waves on available tidal stream power are rarely considered in such studies.

Waves may significantly impact tidal currents [10] and associated kinetic energy through two well-known major non-linear processes: interaction of wave and current bottom boundary layers [11], and the generation of wave-driven currents [12]. An increase in the apparent bottom friction felt by currents above the wave boundary layer may thus lead to a significant reduction of near-bottom velocity by up to 20% during storm events [13]. The additional forcing of waves in regions of wave breaking creates radiation stress gradients, which may drive strong currents and modulate tidal circulations [14]. As tidal power density varies with the cube of velocity, more significant effects are expected on available tidal kinetic energy. Taking into account the variability of wave power over exposed continental shelves [15–17], waves may finally significantly affect variability and predictability of tidal stream power.

Nevertheless, whereas numerous numerical investigations have focused on the effects of waves on near-bottom tidal currents to improve predictions of hydrodynamic components and associated transport of sediment, temperature and salinity [18–20], little effort has been devoted to wave-induced variations of available tidal kinetic energy resource. In the field of marine renewable energy, much more effort has been invested in characterising fatigue and loading induced by waves upon devices, focusing on potential failure and reduced performance [21–24] or investigating the effect of tidal currents on wave power [25–27]. The only major studies on this topic have been conducted by Lewis et al. [28] and Hashemi et al. [29]. Nevertheless, whereas Lewis et al. [28] exhibited a reduction of the theoretical tidal resource by 10% for every metre increase in wave height, their numerical investigation was applied to an idealized headland case study, parameterised by the typical tide and wave conditions expected at tidal stream energy sites. A real application was performed by Hashemi et al. [29] to the planned tidal stream array off the north-western coast of Anglesey (UK) exhibiting a reduction in tidal stream power by 20% for extreme winter waves. But predictions were established relying on depth-averaged circulation models, neglecting the complex three-dimensional (3D) tidal circulation associated with tidal flow separation in the wake of islands [30]. While models' performances were assessed against in situ observations, improvements of numerical predictions reached by the integration of waves effects were furthermore disregarded.

The present study extends numerical investigations of waves effects on available tidal kinetic energy relying on (1) a 3D tidal circulation model applied to a real planned tidal stream array, and (2) in situ observations of hydrodynamic components. A method is proposed for the coupling between a 3D circulation model and a phase-averaged wave model focusing on isolated or combined effects of wave radiation stresses and enhanced bottom friction. Numerical results are compared with in situ measurements, which confirms improved performances in predictions of tidal stream power by the integration of waves effects. Besides an evaluation of this numerical method of broader interest for applications in wave-exposed regions, the present investigation quantifies the temporal and spatial effects of waves on tidal kinetic energy providing a first detailed analysis of the complex interactions between tidal currents, waves-driven circulation and modified bottom friction. These results promote finally the inclusion of waves effects for a refined assessment of the variability of tidal stream power in locations identified for array implementation.

The site of application is the Fromveur Strait off western Brittany (Fig. 1) considered, after the Alderney Race in the English Channel, to be the second largest French tidal stream resource, with a potential power estimated between 300 and 500 MW (Section 2.1). Model predictions are evaluated against available observations of wave parameters (significant wave height, peak period and mean wave direction) and current amplitude and direction 10 m above the seabed (the assumed technology hub height for the region considered) (Section 2.2). The modelling approach is based on a high-resolution 3D circulation model modified for coupling with simulations generated by a phase-averaged wave model (Sections 2.3 and 2.4). The comparison between predictions and in situ observations (Section 3.1) exhibits the local and synoptic effects of waves on available tidal kinetic energy resource over a spring-neap cycle (Section 3.2). A detailed analysis of these predictions is finally conducted for stationary offshore wave conditions quantifying the modulations of tidal stream power for both mean and extreme events (Section 3.3).