Waves reduce the tidal-stream energy resource

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Abstract— **If tidal-stream energy is to make a significant contribution to global renewable energy targets, understanding the influence of waves is essential as the majority of potential sites are exposed to waves. Wind waves add additional mass and momentum to the tidal flow, influencing the available resource as well as device performance and resilience. Here, the effect of waves to the resource and likely oceanographic conditions is presented. Oceanographic data from UK tidal-stream energy sites (directional wave-rider buoys, 4 and 5-beam ADCPs) were combined with dynamically coupled wave-tide regional model data (COAWST, which couples the SWAN wave model with the ROMS ocean model). The presence of waves altered the 15-minute averaged velocity profile and typically increased velocity shear. Averaged throughout a tidal cycle, the available tidal resource was also found to be reduced by ~10% per metre wave height increase. Further, waves were observed to be frequently aligned at an oblique angle to the tidal current. Therefore, realistic oceanographic conditions, such as the interaction of waves and tides, are needed to better understand the resource and improve device design criteria; for example, wave-current misalignment should be considered in device-scale studies of performance and resilience (e.g. CFD models).**

***Keywords*— Tidal-stream energy; Resource assessment; Wave-tide interaction; Oceanographic conditions; Coupled processes.**

I. INTRODUCTION

Realistic oceanographic conditions are essential to understand to inform resilient and efficient tidal energy devices designs [1]. Likely wave-loadings on tidal turbines are needed for optimal device design during operating conditions, and potential shut-down limits to avoid wave-damage is of important when predicting the potential electricity generated.

Analysis of global oceanographic data products (ERA-interim and FES2012 tidal currents) indicates a significant wave climate at the majority of tidal-stream energy sites around the world [2]. Therefore, if tidal-stream energy is to make a significant contribution to renewable energy targets and provide a high-tech low carbon industry, the fundamental challenge of wave-tide interaction with these renewable energy devices must be understood [3].

Waves add additional mass and momentum to the tidal flow [4], influencing the available tidal-stream energy resource as well as device performance and resilience [5], and impact assessment [6].

The interaction between waves and tides (tides affect waves and waves affect tides) is well known [4]; making a dynamically coupled modelling approach necessary for hydrodynamic simulations of wave-tide interaction, with the additional challenge of resolving wave effects within observation data.

Typically, devices-scale studies of performance or resilience use scaled tank experiments or high-fidelity computational fluid dynamics (CFD) studies; with realistic ocean conditions parameterised and imposed at the boundaries (e.g. [1-3]). Wave-tide conditions at tidal energy sites around the world are uncertain due to a lack of data; therefore, realistic conditions at tidal energy sites is the focus of our study. For example, to date, research on tidal turbine loading in waves has largely addressed waves that travel in-line with tidal currents (waves following or opposing the current); yet waves co-existing obliquely to a current are known to occur.

Observations of tidal flow and wave data was collected at the Crown Estate’s tidal-stream energy Northwest Anglesey Demonstration Zone, in the UK (see Figure 1). The oceanographic data was compared to wave data from a potential tidal-stream energy site the Pentland Firth [4], and wave-tide coupled modelling theory of the effect of waves to the tidal flow and thus tidal-stream energy resource.

This paper will summarise the main effects of waves on tidal-stream energy, and using examples that demonstrate the importance of understanding realistic oceanographic conditions with three key topics:

1. Waves directly affect the available tidal-stream resource by reducing the mean current speed within a tidal cycle [4].
2. Waves influence the wave-average (i.e. 15minute average) velocity profile [7], which will effect device fatigue [8].
3. Wave-current misalignment was observed at potential tidal-stream energy sites, requiring new methods to characterise wave-tide-device interaction in device-scale studies (e.g. CFD models).

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II. METHOD

Data from ADCPs deployed at a number of potential tidal stream energy sites in the Irish Sea, UK, were made available through the SEACAMS project (www.seacams.ac.uk see https://www.imardis.org/ for data); typically the 600kHz 5-beam (which can also record wave climate data) and 4-beam ADCPs. Data from these ADCP deployments was time-averaged to understand wave averaged effects suitable for resource assessment or boundary conditions in engineering-scale models (e.g. CFD). Wave-averaged 3D velocity data (15mins to 1 hour time averaging) and compared to other met ocean variables (observations and model hindcast).

Directional wave climate was observed with a nearby waverider buoys; located at the Crown Estate tidal-stream demonstration zone Anglesey UK (53.32°N 4.78°W) during a 2 month (Sept – Nov 2014), and another Datawell Waverider buoy located in the Pentland Firth (see [4]). The locations of oceanographic data presented in this study are shown in Figure 1, with simulated peak tidal current speed (from [4]) coloured.

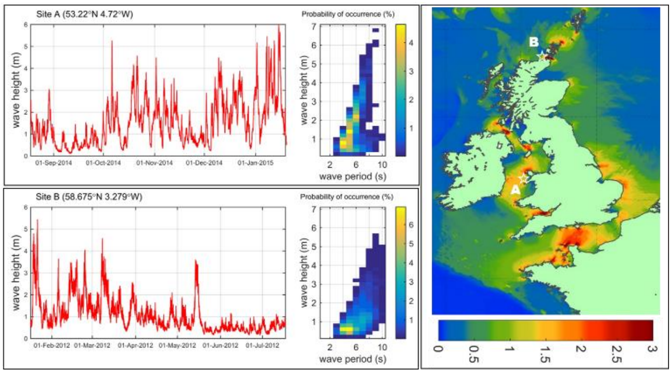

Fig. 1 Wave data from two potential tidal-stream energy sites (A and B) in the UK, with their locations shown within a map of the simulated monthly peak tidal current speed (m/s).

The effect of waves upon the mean flow (15 minute average moving window) was estimated using oceanographic data from Crown Estate's tidal-stream energy Northwest Anglesey Demonstration Zone (Site A). Comparing observed flow speed to the harmonically predicted tidal current speed (using the t_tide Matlab package on the observed time-series) and coupled wave-tide model outputs, the effect of waves to ocean conditions and the available resource can be assessed.

Dynamically coupled wave-tide models simulate both the effect of waves on the tide (1), and tides on waves (2):

1. The effect of wave on the tide: Additional conservative and non-conservative forces of momentum and mass fluxes induced by waves (parameterised through stokes drift, radiation stress and wave roller terms in the hydrodynamic model)
2. The effect of tides on waves: Wave action density (not spectral density) is conserved in the presence of currents. Therefore 3rd generation spectral wave models can simulate the effect of varying (in space and time) currents and water depth. This is achieved with enhanced bottom stress terms and the parameterisation of the current induced Doppler shift in frequency and phase speed of the surface waves.

One successful example of a dynamically coupled model is the Coupled Ocean Atmosphere Wave Sediment Transport (COAWST) model. The COAWST modelling system dynamically couples ROMS (tide), WRF (Weather Research and Forecasting atmospheric model), and SWAN (waves) models together using the Model Coupling Toolkit [4].

A number of dynamically coupled models have been developed that can be applied to tidal energy research; however, to date, the most applied research tool appears to be this COAWST system. The COAWST model is highly flexible with many dynamical parameterization options (cpp options), has an active user community, and has been successfully applied to study wave energy resource in European waters (e.g., [9]).

III. RESULTS

Oceanographic data (directional wave and tidal-current climate) at Site A in the Irish Sea UK (53.32°N 4.78°W water depth ~87m; see Figure 1 is shown in Figure 2 for a 2-month deployment (Sept-Nov 2014). The misalignment of tidal current and wave direction is clear in Figure 2. Oblique wave events were categorised when the misalignment between the axis of tidal flow (thus irrespective of flow or ebb direction) was >20°.

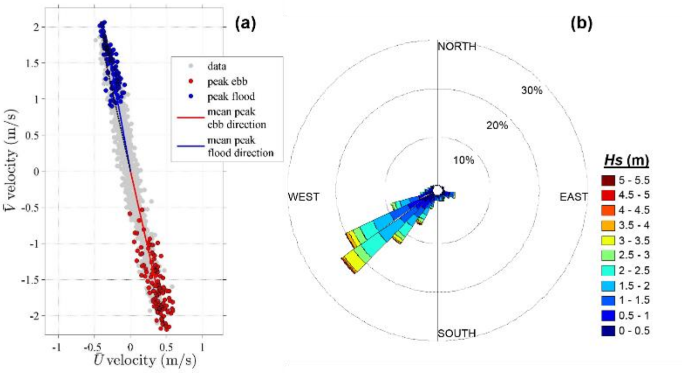

Fig. 2 Oceanographic conditions observed at a potential tidal energy site in the UK (the Crown Estate tidal-stream demonstration zone, Anglesey UK). Depth-averaged tidal current (a) and the directional wave climate (b), shown here for wave direction (propagating from °N) and significant wave height (Hs)

Analysis of the data in Figure 2 revealed misalignment occurred for 82% of the 61 day record, with larger waves more likely to occur out-of-line to the tidal current; as shown in the wave height probability of exceedance for grouped directions in Figure 3. Waves propagating at angles of 90° to tidal current direction were observed in the record when significant wave height (Hs) was above 1m, and the largest wave events (Hs>4m) were observed to be oblique (waves propagating >20° relative to the current).

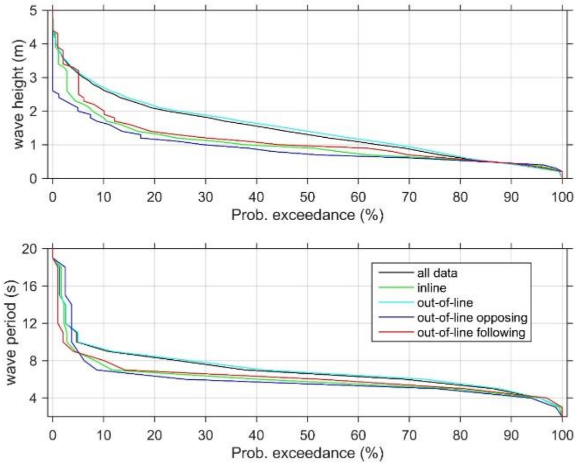

Fig. 3. Exceedance probability of wave-tidal current misalignment for the 61 day record at Site A, a tidal energy site in the UK.

The misalignment of the wave climate relative to the tidal current is clear when the data are grouped into 20° and 1m wave heights; as shown in Figure 4 for Site A. Wave climate observations from the Pentland Firth (Site B) in 2012, which is considered to be a more channelized tidal energy site [4], were also found to be oblique: >65% of the record were oblique wave events, and the maximum wave event (Hs of 9.48 m and mean wave period of 7 s) found to be 28° out-of-line to the direction of tidal flow [4].

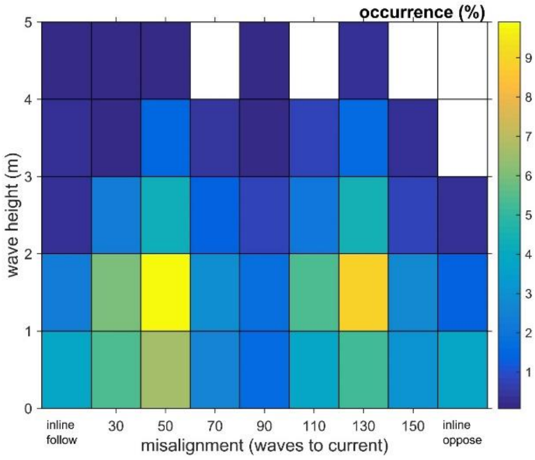

Fig. 4 The existence and frequency of waves co-existing obliquely to a current at a potential tidal energy site in the Irish Sea (Site A).

The results for wave-tide coupled tidal-energy resource modelling of Lewis et al. [4] demonstrate that surface waves will have a significant impact upon the power available for tidal stream energy production as waves reduce the mean tidal current speed. Waves were simulated to alter the shape and magnitude of tidal velocities, which averaged over a tidal-cycle (flood and ebb) directly reduced the available resource by 10% per metre wave height increase [4]. Furthermore, times of extreme waves are likely to lead to the device/array being shut down to avoid damage; hence further increasing the technical tidal-stream energy resource. For example, assuming a turbine is to be "shut down" when wave height exceeded 2m, Figure 3 suggests this would occur ~20% of the time at Site A.

Analysis of tidal velocity data in Lewis et al. [7] found the hypothesized pattern of decreasing tidal current speed with wave height to be much less clear than that predicted by Lewis et al. [4]. The major axis (CMAX) of the semi-diurnal lunar consistent (M2) was calculated using a 25hour moving average window and compared to the observed wave height (see [7]), and is shown in Figure 5 for data collected close to Site A.

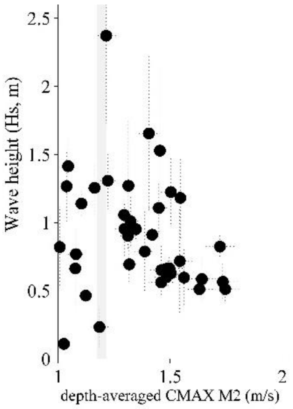

Fig. 5. The effect of waves on the mean tidal flow, modified from Lewis et al. [7] for a potential tidal energy site close to Site A in the UK. Depth-averaged semi-major axis of the semi diurnal lunar tidal constituent ellipse (CMAX M2), is compared to the daily-averaged wave height (Hs). The shaded region is the mean tidal current speed (CMAX M2) from the entire record.

The general trend of reduced tidal velocity with an increased wave height was observed (see Figure 5), with the variability assumed to be the result of wave-current misalignment. New analysis shown in Figure 6 revealed that when the data is grouped into wave-current misalignment conditions, the reduction in the tidal velocity becomes much clearer; with wave following current conditions showing a decrease in the depth averaged current speed compared to that predicted, and wave opposing current conditions showing a slight increase.

Further analysis of the data shown in Figure 6, by grouping data, found that relative wave direction was extremely important to depth-averaged tidal current speed variations. The effect of waves on mean-flow conditions is clearly shown in Figure 7, where predicted and observed depth-averaged tidal current speeds are compared with the observed wave climate. Two clear results can be seen in Figure 7: (1) The presence of waves can reduce tidal current speed and the available resource; (2) Waves can occur out-of-line to the tidal current flow.

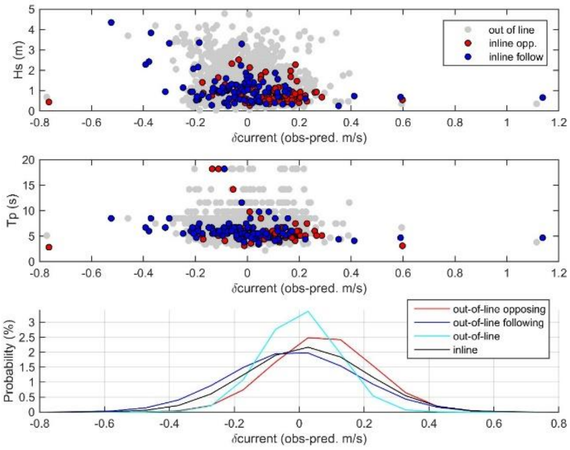

Fig. 6 The difference in depth-averaged tidal current speed between that observed (with ADCP, see Fig 1) and that predicted compared to the wave climate observed (top panel shows significant wave height, *Hs*; middle panel shows peak wave period, *Tp*). Data grouped into directional wave conditions (bottom panel) to indicate the variability to tidal current speed due to waves.

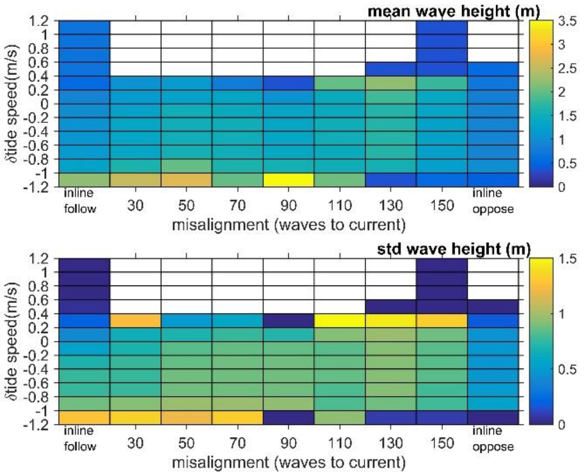

Fig. 7 The difference in depth-averaged tidal current speed between that observed at Site A (with ADCP, see Fig 1) and that predicted (using harmonic theory) for grouped wave misalignment conditions – with the mean and standard deviation (std) of wave height shown as colours.

IV. DISCUSSION

Waves co-existing obliquely to a current could be an important design condition at tidal stream sites [11]. The existence and frequency of wave-tide misalignment is shown in the results presented here; therefore, device design and resilience studies must account for this effect in device-scale studies (e.g. tank and CFD).

The influence of waves on the available tidal-stream resource has been hypothesized using a dynamically coupled wave-tide model [4]. Waves have been observed to reduce tidal currents at potential tidal energy sites [7], but without a clear trend due to a large amount of scatter (e.g. Fig. 5). The lack of a clear trend in wave reduction of tidal energy is likely due to wave-tide interaction and wave-current misalignment. When the data are grouped by wave-current misalignment, a clear trend in waves reducing the tidal flow can be seen for “wave following current” cases, with a slight increase for “wave opposing” cases (Fig. 6). Therefore, wave-tide interaction effects, within the context of tidal energy, should also consider wave-current misalignment. Furthermore, wave-current misalignment is likely to affect velocity shear and the mean velocity profile – which will effect tidal turbine performance and resilience (loadings and fatigue estimates).

The vertical structure of flow at tidal-stream energy sites was characterised by Lewis et al. [7] using ADCP observations and a 3D tidal model – using Equation 1: where depth averaged flow ($\bar{U}$) can be extrapolated to a velocity profile (U_z) based on height above the seabed (z) and water depth (h).

$$U_z = \bar{U}\left(\frac{z}{\beta h}\right)^{1/\alpha} \quad \text{[Eq. 1]}$$

On average the 1/7th power law (α=7) with roughness coefficient β=0.4 was found to accurately represent the velocity profile [7]; however, the observed temporal variability to velocity shear (the observed profile varied between 1/4th and 1/11th power law) was attributed to waves. Analysis shown in Figure 6 suggests the relatively weak correlation (Pearson correlation of ~20%) of velocity shear to the presence of waves in Lewis et al. [7] could be due to wave-current misalignment. Future work will investigate the role of wave-current misalignment in this relationship and will be presented at the conference.

V. SUMMARY

Dynamically coupled wave-tide models, 5-beam ADCP and directional wave buoy data has shown the presence of significant wave events at a number of tidal energy sites in the UK. Placed into context, this highlights wave-tide understanding to be a barrier to the global development of the tidal energy industry. The fundamental problem of intermediate water depth waves, propagating over turbulent sheared flow, requires further research. New techniques are required to better understand the interaction of waves, tides and tidal energy devices; for example, oblique waves co-existing in strong tidal flows.

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